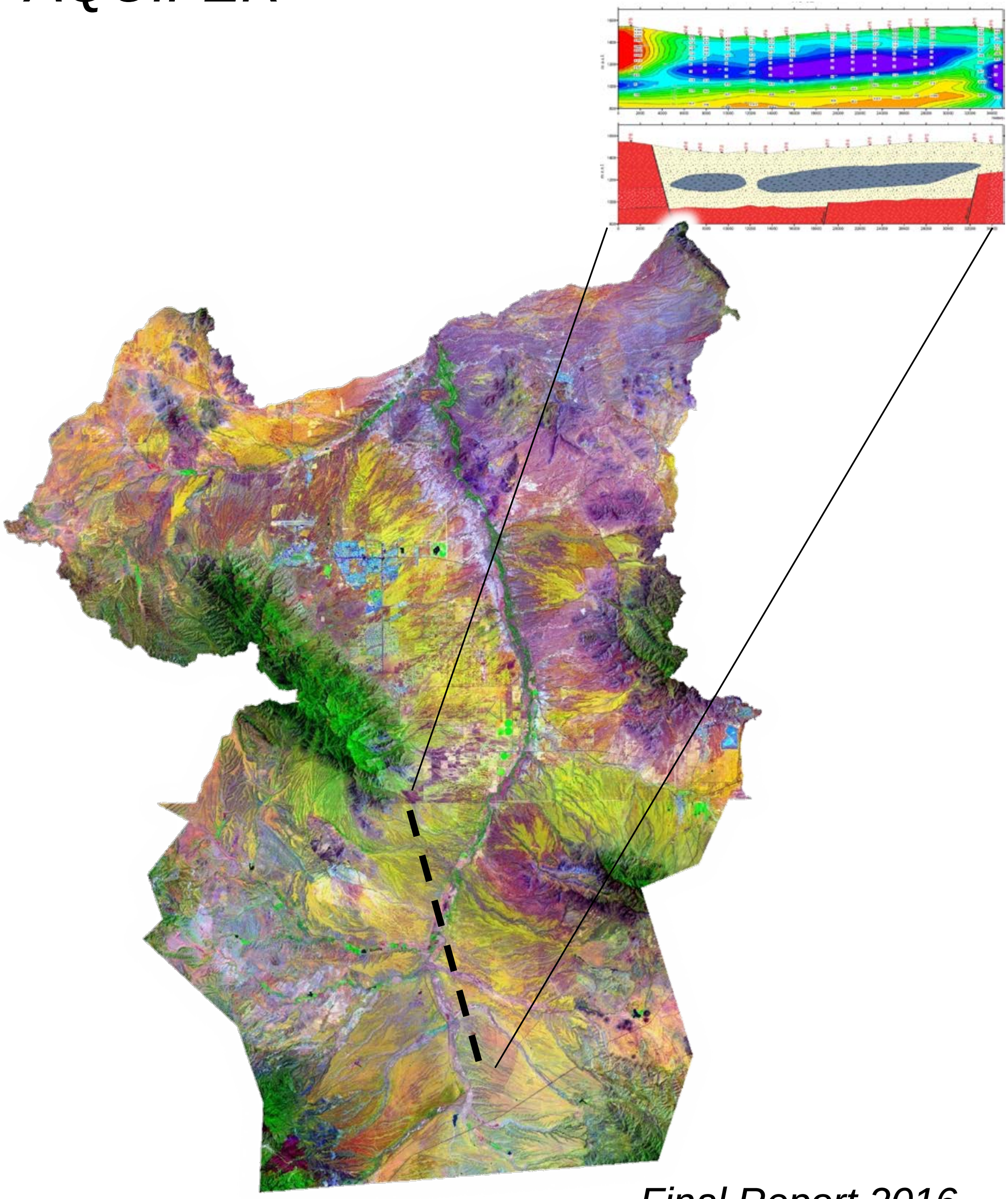
BINATIONAL STUDY OF THE TRANSBOUNDARY SAN PEDRO AQUIFER



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AUTHORITY

This study was carried out by the United States and Mexico in accordance with resolution 6 of Minute 242 of the International Boundary and Water Commission, United States and Mexico (IBWC) entitled “Permanent and Definitive Solution to the International Problem of the Salinity of the Colorado River”, dated August 30, 1973; and the "Joint Report of the Principal Engineers Regarding the Joint Cooperative Process United States-Mexico for the Transboundary Aquifer Assessment Program”, dated August 19, 2009.

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PARTICIPATING AGENCIES

International Boundary and Water Commission
United States and Mexico

For Mexico:

National Water Commission
University of Sonora

For the United States:

United States Geological Survey
The University of Arizona Water Resources Research Center

Authors: J.B. Callegary, I. Minjárez Sosa, E.M. Tapia Villaseñor, P. dos Santos, R. Monreal Saavedra, F.J. Grijalva Noriega, A.K. Huth, F. Gray, C.A. Scott, L.A. Oroz Ramos, S.B. Megdal, M. Rangel Medina, J.M. Leenhouts

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BINATIONAL STUDY GROUP

For the International Boundary and Water Commission, United States and Mexico:
- Edward Drusina, Commissioner, United States Section
- John L. Merino, Principal Engineer, United States Section
- Jose A. Nuñez, Principal Engineer, United States Section
- Gilbert Anaya, Division Chief, Project Coordinator, United States Section

- Roberto F. Salmón Castelo, Commissioner, Mexican Section
- Luis Antonio Rascón Mendoza, Principal Engineer, Mexican Section
- Manuel Alejandro Morales Galván, Engineer, Project Coordinator, Mexican Section
- Ramiro Luján Godínez, Engineer, Project Coordinator, Mexican Section
- Jesús Quintanar Guadarrama, Representative in Nogales, Sonora, Mexican Section

For the United States Geological Survey:
- James Leenhouts, Director, Arizona Water Science Center
- Bruce Gungle, Hydrologist
- James Callegary, Hydrologist, Principal Investigator
- Floyd Gray, Geologist, Principal Investigator

For the University of Arizona Water Resources Research Center:
- Sharon Megdal, Director, Principal Investigator
- Plácido dos Santos, Coordinator, Principal Investigator
- Christopher Scott, Principal Investigator
- Anne Huth, GIS Research Investigator

For the National Water Commission:
- Rubén Chávez Guillén, Director, Office of Groundwater
- Roberto Sención Aceves
- Lucas Oroz Ramos
- José Arturo López
- Victor M. Castañón Arcos

For the Sonora State Water Commission:
- Roberto Molina Acedo
- Alberto Bustamante Juvera

For the University of Sonora:
- Ismael Minjárez Sosa, Coordinator, Principal Investigator
- Rogelio Monreal Saavedra, Principal Investigator
- Elia María Tapia Villaseñor, Principal Investigator
- Francisco Javier Grijalva Noriega, Principal Investigator
- Miguel Rangel Medina

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AGENCIES

ADEQ	Arizona Department of Environmental Quality
ADWR	Arizona Department of Water Resources
ARS	Agricultural Research Service, U.S. Department of Agriculture
BLM	Bureau of Land Management, United States
CIAT	Center for Tropical Agriculture
CONAFOR	National Forest Commission, Mexico
CONAGUA	National Water Commission, Mexico
FAO	United Nations Food and Agriculture Organization
IBWC	International Boundary and Water Commission - United States and Mexico
INEGI	National Institute of Statistics and Geography, Mexico
NRCS	Natural Resources Conservation Service, United States
SGM	Mexican Geological Service
UA WRRC	University of Arizona Water Resources Research Center
UNISON	University of Sonora
USDA	United States Department of Agriculture
USEPA	United States Environmental Protection Agency
USFS	United States Forest Service
USGS	United States Geological Survey
USPP	Upper San Pedro Partnership
WMO	World Meteorological Organization

KEY TECHNICAL TERMS

AMA	Active Management Area
BSPA	Binational San Pedro Aquifer
BEHI	Border Environmental Health Initiative, U.S. Geological Survey
BSPB	Binational San Pedro Basin
CEC	Contaminants of Emerging Concern
COTAS	Technical Groundwater Committee, Mexico
DOF	Official Gazette of the Federation, Mexico
EOP	Environmental Operations Plant, Sierra Vista
Eh	Redox Potential
ENSO	El Niño-Southern Oscillation
ET	Evapotranspiration
FAOCLIM	FAO World Climate Data
GHCN	Global Historical Climatology Network
GIS	Geographic Information Systems
GWSI	Groundwater Site Inventory
K	Hydraulic Conductivity
MCL	Maximum Contaminant Level
MODIS	Moderate Resolution Imaging Spectroradiometer
NAM	North American Monsoon
NED	National Elevation Dataset, U.S. Geological Survey
NOM	Official Mexican Standard
NWIS	National Water Information System, U.S. Geological Survey
PDO	Pacific Decadal Oscillation
pH	Hydrogen Potential

REPDA	Public Registry of Water Rights, National Water Commission, Mexico
SIGMAS	Geographic Information System for Groundwater Management, Mexico
SPRNCA	San Pedro Riparian National Conservation Area, U.S. Bureau of Land Management
Ss	Specific Storage
Sy	Specific Yield
SVSA	Sierra Vista Subwatershed in Arizona
TAAP	Transboundary Aquifer Assessment Program
TDS	Total Dissolved Solids
TEM	Transient Electromagnetic
USPSS	Upper San Pedro Subbasin in Sonora
UTM	Universal Transverse Mercator
Kh/Kv	Vertical Anisotropy
WGS	World Geodetic System

EXECUTIVE SUMMARY

The United States and Mexico share waters in a number of hydrological basins and aquifers that cross the international boundary. Both countries recognize that, in a region of scarce water resources and expanding populations, a greater scientific understanding of these aquifer systems would be beneficial. In light of this, the Mexican and U.S. Principal Engineers of the International Boundary and Water Commission (IBWC) signed the "Joint Report of the Principal Engineers Regarding the Joint Cooperative Process United States-Mexico for the Transboundary Aquifer Assessment Program" on August 19, 2009 (IBWC, 2009). This IBWC "Joint Report" serves as the framework for U.S.-Mexico coordination and dialogue to implement transboundary aquifer studies. The document clarifies several details about the program such as background, objectives, roles and responsibilities, funding, relevance of the international water treaties, communication, and the use of information collected or compiled as part of the program. Based on the aforementioned Joint Report, it was agreed by the parties involved, which included the IBWC, the Mexican National Water Commission (CONAGUA), the U.S. Geological Survey (USGS), and the Universities of Arizona and Sonora, to study two priority transboundary aquifers in the Arizona–Sonora region, the San Pedro River basin and the other in the Santa Cruz River basin.

This report focuses on the Binational San Pedro Basin (BSPB). Reasons for the focus on and interest in this aquifer include the fact that it is shared by the two countries, that the San Pedro River has an elevated ecological value because of the riparian ecosystem that it sustains, and that water resources are needed to sustain the river, existing communities, and continued development. This study describes the aquifer's characteristics in its binational context; however, most of the scientific work has been undertaken for many years by each country without full knowledge of the conditions on the other side of the border. The general objective of this study is to use new and existing research to define the general hydrologic framework of the Binational San Pedro Aquifer (BSPA), to gather hydrogeological and other relevant data in preparation for future work such as an updated groundwater conceptual model and budget and to establish the basis for a binational numerical model.

The specific objectives are as follows:

- Understand the current state of knowledge with respect to climate, geology, soils, land cover, land use, and hydrology of the aquifer in its binational context;
- Compile and create a database of scientific information from both countries;
- Identify data gaps and identify what data would be necessary to update, in a subsequent phase, the hydrologic model of the aquifer system, including surface- and groundwater interactions on a binational level.

The BSPB is one of the most studied basins in the region, and a database of publications has been compiled as part of this project. Previous studies include topics that range from geophysics and hydrogeology to biology and ecosystem services. The economic drivers on each side of the border are quite different. In the Arizona portion of the basin, military and tourism dominate while in the Sonoran portion, mining is the most important industry. Water management is also different in the two countries. In Mexico, primary authority for management of water resources devolves from the federal government. In the United States, primary authority rests with the states except in cases of interstate surface waters. Binational waters are not currently jointly managed by the two countries except in cases where treaties have been negotiated such as for the Rio Grande and Colorado Rivers in accordance with the 1944 Water Treaty. Thus, there is currently no comprehensive agreement between the two countries regarding the management of groundwater.

A number of studies and technical activities were carried out during the course of this work in both Sonora and Arizona in a cooperative effort between academic institutions and federal agencies in the United States and Mexico. The technical work was performed by the Geology Department at the University of Sonora (UNISON), CONAGUA, the University of Arizona Water Resources Research Center (UA WRRC), and the USGS. The IBWC coordinated the scientific dialogue and the exchange of information to enable the preparation of this U.S.-Mexico Binational Report. The technical work comprises geophysical, geological, hydrological, hydrochemical, governance, and socio-economic analyses.

The BSPB is located along the eastern portion of the Arizona-Sonora border and includes the towns of Cananea, Sierra Vista, Tombstone, and Naco-Bisbee. It is in a zone that is transitional between the Sonoran and Chihuahuan Deserts with altitudes ranging from 1,100 meters above sea level (m.a.s.l.) in the northernmost part of the basin to 2,620 m.a.s.l. east of Cananea, and in excess of 2,700 m.a.s.l. in the Huachuca Mountains. Both soils and vegetation in the BSPB have been classified using different criteria on each side of the border and are therefore difficult to compare. The climate is arid to semi-arid with warm summers and an annual average temperature that varies between 12 and 18°C. Temperatures above 38°C frequently occur in the low-elevation areas during the summer. In winter, the average minimum temperature is close to 0°C. Precipitation occurs mainly during the summer and winter. Summer precipitation events are generally of greater magnitude than those of winter, and higher elevations receive more precipitation than lower elevations, about 33 cm annually at Tombstone and up to 96 cm annually on the high peaks of the Huachuca Mountains. Estimated annual average potential evaporation ranges from about 1.5 to 2 meters. The primary land uses in the Arizona portion of the BSPB, called the Sierra Vista Subwatershed in Arizona (SVSA) are domestic, commercial, industrial, and agricultural. Most of the land in the SVSA belongs to the federal and state governments. Land use in the Sonoran side of the basin, called the Upper San Pedro Subbasin in

Sonora (USPSS), is primarily for agriculture, tourism, and mining.

The geologic units in the BSPB are the product of a complex tectonic evolution. The diversity of these tectonic events and deformations produced a region with geological complexity. Within the northeast portion of Sonora and the southeast portion of Arizona, the oldest rocks form a Precambrian basement, which is covered by sedimentary platform sequences, mainly carbonates. The oldest rocks from the Mesozoic within this region are represented by a Jurassic-age volcanic-sedimentary sequence. Cretaceous-Tertiary rocks are widely distributed in both portions of the BSPB. The geology of the region in which the aquifer is located is represented by intrusive, metamorphic, volcanic-sedimentary, sedimentary, and volcanic rocks. To simplify the mapping and description of these units on both sides of the border, a series of informal lithostratigraphic and lithodemic units was proposed broadly encompassing those that have similar lithology and age.

On the U.S. side of the BSPB, a series of geophysical as well as hydrogeological studies were previously conducted that produced geologic cross-sections and subsurface models. Little previous work has been done on the subsurface characteristics of the USPSS. Substantial work, however, was carried out in the USPSS for this study, including electromagnetic and gravimetric surveys and modeling. This information is integrated to define the basin's structure on both sides of the border. Previous work proposed that the U.S. side of the BSPB is oriented northwest-southeast. Two main subbasins were identified on the west side of the San Pedro River separated by a bedrock high under Sierra Vista. In the USPSS, it was established that the depth to basement is primarily tectonically controlled and highly variable, with the greatest depths found near the border. The sedimentary fill within the SVSA was deposited in structural basins between the mountains during the Plio-Pleistocene. Although there are few detailed studies on the stratigraphy of these sediments in the USPSS, the known physical characteristics indicate equivalence with the geology in the United States. Previous studies identified a silty-clay zone within the upper basin fill located mainly along the San Pedro river channel. Geophysical surveys done in the USPSS corroborate the presence of this zone.

Groundwater development in the SVSA began early in the 20th century, and has increased relatively consistently since about 1935. Several economic sectors are responsible for the majority of the BSPB pumping. These include mining, municipal, agricultural-livestock, industrial, and domestic sectors. With respect to the Mexican side, about 60% of all groundwater use is by livestock, which is nearly double that of the next largest use which is agricultural. An assessment of piezometry included a survey of wells, most of which are close to and south of the city of Sierra Vista. A series of hydrographs are included as examples of particular hydrologic processes and/or geographic settings. The shallowest water levels in the BSPB are typically found near the San Pedro River and other stream channels. Groundwater elevations generally increase from the river toward the mountains except in the cones of depression in and around the cities of Sierra Vista and Tombstone. Increases in water levels have occurred in several areas, among which are wells influenced by the Sierra Vista Environmental Operations Plant (EOP: Sierra Vista wastewater treatment plant) and at locations near the River where agricultural pumping ceased in the mid-2000s. Hydraulic parameters derived from analysis of field samples and aquifer tests are available from several previous studies. Additional data were derived from thirteen aquifer tests conducted in Sonora specifically for this study. In addition, model calibrated values are available for saturated hydraulic conductivity, vertical anisotropy, and specific yield.

Based on the integration of previous studies and newly available information presented here, a simple classification of units in the alluvial aquifer was proposed based on differences in particle size distribution. Three hydrostratigraphic units were identified:

Hydrostratigraphic Unit 1: Corresponds to the coarse granular fraction of sedimentary basin fill represented by gravels and sands. It corresponds to the more hydraulically conductive portions of the Upper- and Lower-Basin fill. This unit has the highest hydraulic conductivity, although at depth this probably decreases, since typically a greater degree of compaction and cementation occurs at greater depths.

Hydrostratigraphic Unit 2: This unit incorporates the fine sediments with low hydraulic conductivity that mainly comprise the upper basin fill. These low-conductivity silts and clay units occur, mainly in the central portion of the basin. It is possible that these are responsible for creating the confined conditions found in Hydrostratigraphic Unit 1. The extent of the confined conditions reflects the extent of this unit.

Hydrostratigraphic Unit 3: Included in this unit are those rocky units that could be lumped together as fractured-rock aquifers, among which are the conglomeratic units of the Báucarit Formation, the Tc unit (See Chapter 4), the Tertiary felsic volcanic rocks that lie between these, and the fractured or weathered portions of the basement, such as limestone, that could possibly contain groundwater.

Hydrogeochemistry is also an important factor in understanding the hydrologic condition of the BSPB. In the SVSA, the Arizona Department of Water Resources (ADWR) and the USGS visit a small set of wells annually. In addition, there are more data generated by state, local, and federal agencies as well as non-governmental organizations (NGOs). In Arizona, water quality is managed by the Arizona Department of Environmental Quality (ADEQ) in coordination with the United States Environmental Protection Agency (USEPA). The water quality data for Sonora was collected during a survey of the San

Pedro River aquifer done by the University of Sonora Geology Department. Twenty samples were taken from pumping wells and measured for electrical conductivity, pH, and temperature. No new samples were taken in Arizona. The groundwater type in the transboundary aquifer is calcium bicarbonate, generally alkaline and low salinity. The geographic distribution of ions in the groundwater indicates high concentrations of calcium and magnesium near the mountains, and higher concentrations of sodium and potassium in samples located near the river. Total dissolved solids generally peak near the border. Stable isotope patterns in the SVSA indicate that groundwater on the west side of the River is largely dominated by recharge of high elevation precipitation from the Huachuca Mountains. Between Palominas and Lewis Springs, a progressively larger portion of baseflow in the river is derived from groundwater. Below this reach, the proportion of groundwater in baseflow declines.

The behavior of groundwater in the BSPB is determined by key factors such as climate, geology, and time. The majority of precipitation falls in the higher parts of the basin, and this is where the majority of recharge occurs through infiltration and deep percolation through permeable rocks. Another significant source of recharge occurs in perennial streams and rivers, as well as in ephemeral channels. In the alluvial sediments of the basin, groundwater flows toward areas of discharge along perennial or intermittent reaches of streams and rivers, through ET by phreatophytes, and to adjacent down-gradient basins. Mountain springs occur more commonly in the lower elevations, in canyons that intersect faults, or layers of sandstone or limestone that overlie materials of low permeability. There is also groundwater discharge into the downgradient Benson subbasin through the alluvial sediments. As evidenced by the shape of the static water level water surface, most groundwater flows out of the BSPA through the sedimentary basin fill near and to the east of the San Pedro River. Baseflow (groundwater discharge to the river channel) at the four gages along the San Pedro River is in decline. There has been no clear consensus on the cause of the decline, but the most recent work, involving numerical modeling, points toward multiple causes with climate cycles and pumping playing significant roles. Although the methods to calculate pumping rates by sector differ on each side of the border, values for similar categories of groundwater extraction were combined for the year 2012. The total estimated binational extraction volume was about 39.4 hm^3. The largest use was industrial at 15.2 hm^3 (38.5%), followed by public/municipal/water company use 13.56 hm^3 (34.4%), agricultural/irrigation 8.27 hm^3 (21%), domestic/rural exempt wells 1.79 hm^3 (4.5%), and livestock 0.60 hm^3 (1.5%).

1. INTRODUCTION

1.1. Background

The United States and Mexico share waters in a number of hydrological basins and aquifers that cross the International Boundary. In spite of this hydrologic interconnection, no treaty exists on the management of groundwater in these shared aquifers. Both the United States and Mexico recognize that, in a region of scarce water and expanding populations, better scientific understanding of water quantity and quality in these aquifer systems would benefit decision makers planning and managing water resources on both sides of the border.

In light of the interest of governmental and non-governmental institutions in Mexico and the United States in understanding the conditions of certain aquifers along the common border, the Principal Engineers of the IBWC signed the "*Joint Report of the Principal Engineers Regarding the Joint Cooperative Process United States-Mexico for the Transboundary Aquifer Assessment Program*" on August 19, 2009. This IBWC "Joint Report" serves as the framework for U.S.-Mexico coordination and dialogue to develop joint transboundary aquifer studies (IBWC, 2009). The document clarifies several details about the program such as background, objectives, roles and responsibilities, funding, relevance of the international water treaties, and the use of information collected or compiled as part of the program.

In the Arizona-Sonora border region, it was agreed by the IBWC, CONAGUA, the USGS, and the Universities of Arizona and Sonora to study two priority aquifers, one in the San Pedro River basin and the other in the Santa Cruz River basin both of which have been included in UNESCO's transboundary aquifer maps and reports (UNESCO, 2007, 2008, and 2010; Figure 1.1). On October 15, 2010, the Mexican Section of the IBWC signed two contracts with UNISON for its joint cooperation on the assessment of the two aquifers. The Geology Department of UNISON was the entity designated by UNISON to perform this technical work. The academic counterparts of UNISON in the United States for this program were the Water Resources Research Center (WRRC) and the Udall Center for Studies in Public Policy at the University of Arizona (UA). The USGS and CONAGUA are the lead co-investigators for this binational study in coordination and under the IBWC framework.

For a number of reasons, a focus on the sustainability of the aquifer and the San Pedro River which it supports would benefit both Mexico and the United States. These include the fact that the aquifer is transboundary in nature, the river has an elevated ecological value because of the riparian ecosystem it sustains, and that water resources are needed to permit continued development. Recognizing these goals, an agreement was made to integrate hydrologic and other pertinent data from both countries and to proceed with this joint binational study of the San Pedro River transboundary aquifer.

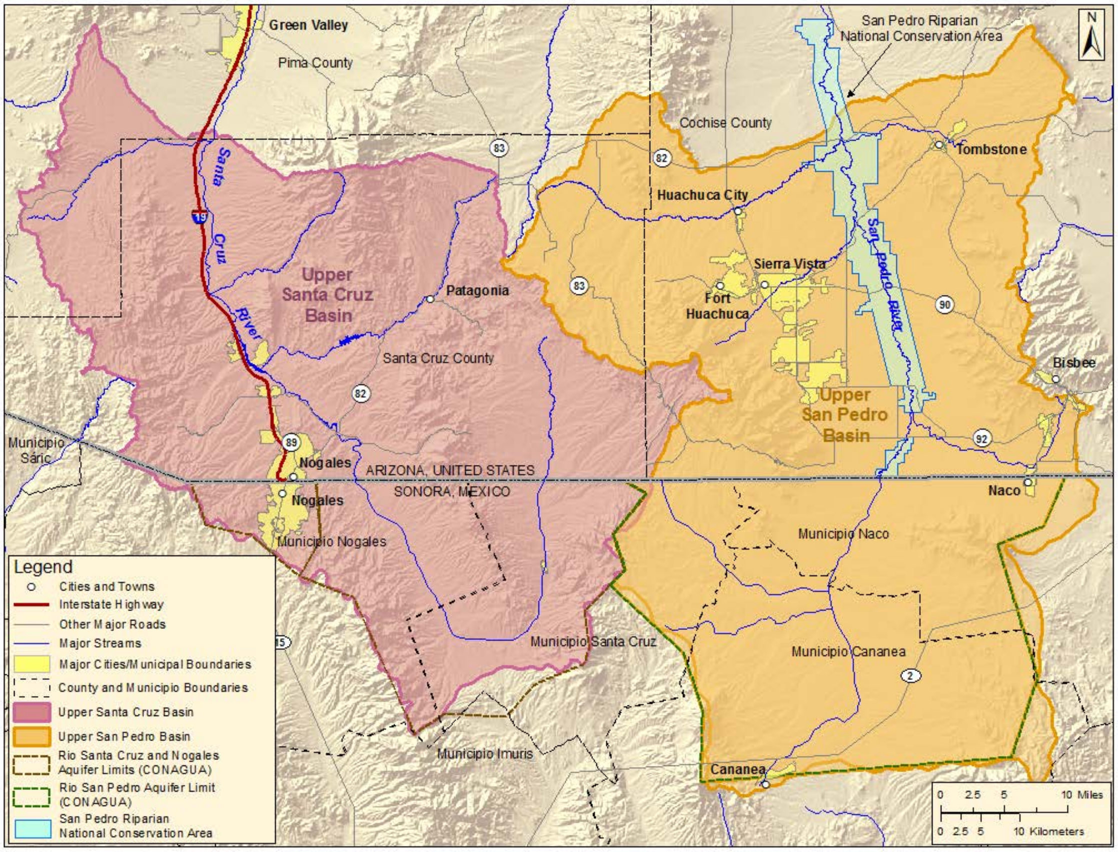


Figure 1.1 San Pedro River and Santa Cruz River Binational Basins.

1.2. Study Area

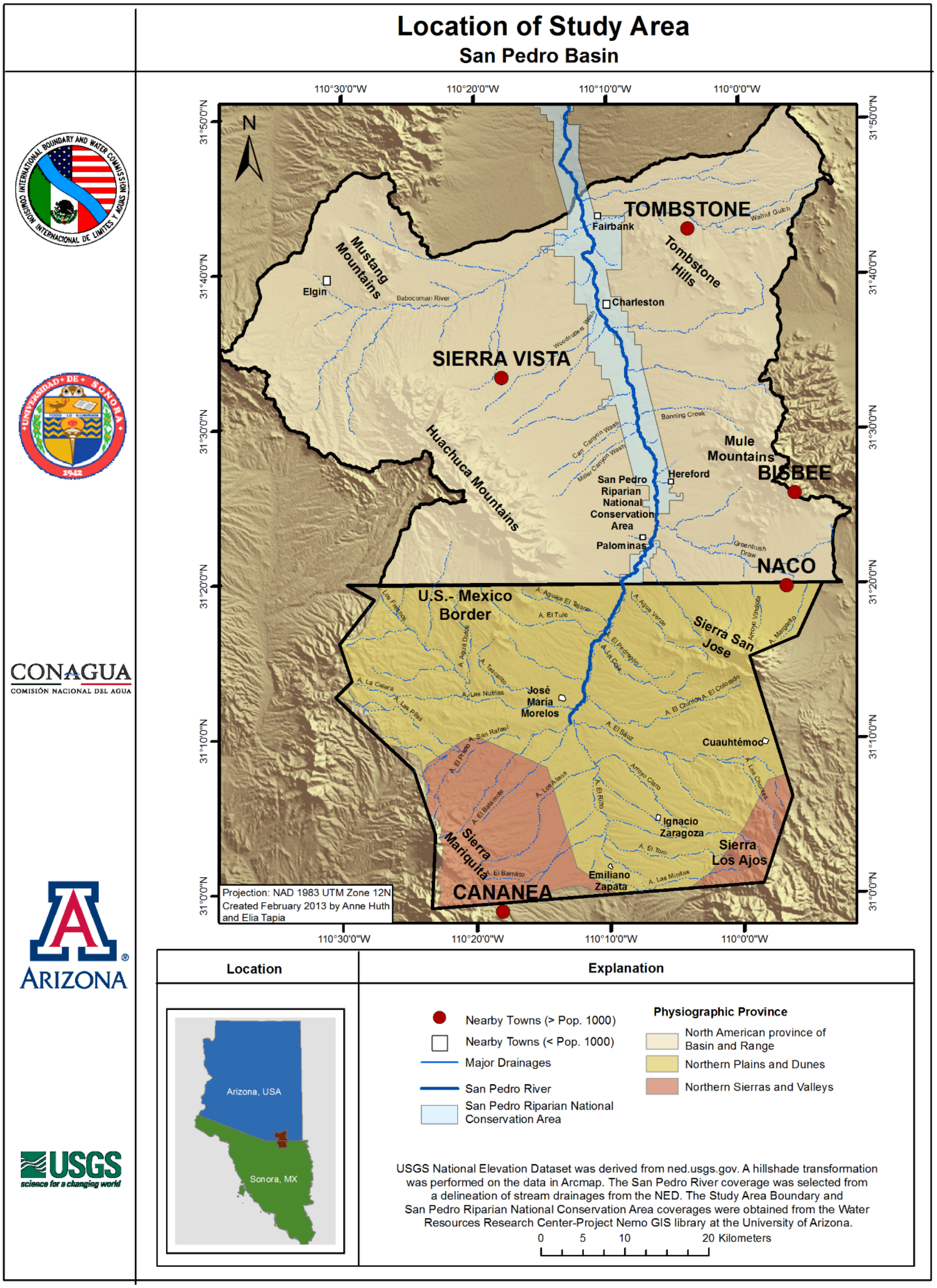
The San Pedro River basin (and associated aquifer) straddles the boundary between the U.S. and Mexican states of Arizona and Sonora (Figure 1.2), in a zone that is transitional between the Sonoran and Chihuahuan Deserts. It is bounded on the southwest by the Sierra Mariquita, on the southeast by Sierra Los Ajos, and on the south by a low-elevation ridge that divides it from the basin to the south. To the west, it is bounded by the Cuitaca and Santa Cruz River Basins, to the east by the Douglas-Agua Prieta Basin, and to the north by the Benson subbasin of the San Pedro River. The southern boundary of the watershed is about 50 km south of the U.S.-Mexico border in the Sierra Los Ajos and Sierra La Elenita mountain ranges. From south to north, along the eastern aquifer boundary, are the Sierra San José, the Mule Mountains, and the southern portion of the Dragoon Mountains. On the west are the Sierra La Mariquita, the Huachuca Mountains, and Mustang Mountains. The northern boundary of the aquifer is approximately 43 km north of the international boundary, and crosses the San Pedro River near the town of Fairbank, Arizona (Coes and Pool, 2005). The southernmost tributaries originate in Sonora in the Sierra Los

Ajos, Sierra La Elenita, and near the city of Cananea.

The binational basin has an approximate surface area of over 5,000 km^2. The USPSS has an approximate area of 2,892 km^2 (CONAGUA, 2009) and the U.S. side has an area of 2,460 km^2 (Coes and Pool, 2005) (Figure 1.2). This study describes the aquifer's characteristics in a binational context; however, most of the scientific work on these aquifers was undertaken for many years by each country on a national basis, without full knowledge of the conditions on the other side of the border. The full binational integration of all previous work is outside the scope of this study. It was therefore necessary to explain or describe various aspects of or topics related to the aquifer unilaterally. For this reason, this report makes use of the following four distinctions:

(1) the binational area – "Binational San Pedro Basin" (BSPB),
(2) the binational aquifer – "Binational San Pedro Aquifer" (BSPA)
(3) the Mexican portion – the "Upper San Pedro Subbasin in Sonora" (USPSS) and
(4) the U.S. portion – the "Sierra Vista Subwatershed in Arizona" (SVSA)

Although the phrase "Sierra Vista Subbasin in Arizona" would be more consistent with the terms defined above, it has already been used by ADWR to describe a larger portion of the Upper San Pedro River Basin (Putnam et al., 1988). We will therefore use the phrase "Sierra Vista Subwatershed in Arizona" or "SVSA" which has been widely used to describe the area in Arizona that is included in the Transboundary Aquifer Assessment Program (TAAP) (Alley, 2013; Upper San Pedro Partnership, variously dated; Pool and Coes, 1999). The limits of the basin as used in this report generally reflect the surficial watershed divides. However, the binational *aquifer* is the set of permeable geological formations or strata that permit circulation of groundwater in pores or fractures in the subsurface. The Mexican portion of the San Pedro River aquifer, identified with the code 2616 in CONAGUA's Groundwater Management Geographic Information System (SIGMAS), is located on the far northeast edge of the State of Sonora, delimited by the following officially delineated boundaries (CONAGUA, 2009): on the north by U.S.-Mexico border, on the west by the boundaries of the Santa Cruz River and Cuitaca aquifers, on the east by the Agua Prieta River aquifer boundary and to the south by the boundary of the Bacoachi River aquifer (CONAGUA, 2009). The U.S. portion of the aquifer is bounded on the west by the Santa Cruz aquifer, on the east by the Willcox aquifer, and on the north by the lower San Pedro aquifer. For the most part, these aquifer boundaries are delimited by impermeable or low permeability rocks that minimize groundwater connections with the adjacent aquifers. Smaller portions of the aquifer boundaries are delimited by groundwater divides or areas of groundwater discharge (such as at the northern limit of the study area).



USGS National Elevation Dataset was derived from ned.usgs.gov. A hillshade transformation was performed on the data in Arcmap. The San Pedro River coverage was selected from a delineation of stream drainages from the NED. The Study Area Boundary and San Pedro Riparian National Conservation Area coverages were obtained from the Water Resources Research Center-Project Nemo GIS library at the University of Arizona.

Figure 1.2 San Pedro Binational Aquifer.

1.3. Study Objectives

The primary objectives of this study were to define the general hydrogeologic framework of the San Pedro Binational Aquifer, gather hydrogeological and other relevant data for its subsequent assessment through a groundwater budget, and establish the basis for a binational numerical model of the groundwater flow system.

The specific objectives are as follows:

- Compile scientific information from both countries with the goal of understanding the current state of knowledge with respect to climate, geology, soils, land cover, land use, and hydrogeology in its binational context
- Identify data gaps and identify data necessary to update, in a subsequent phase, the numerical model of the groundwater flow system, including surface and groundwater interaction on a binational level

1.4. Previous Studies

On the Mexican side of the San Pedro River basin, we used previous studies to gain analytical insight into project topics including stratigraphy, geology, economics, structural geology, hydrogeology, and environmental geology. These include studies of water quality (Gómez-Álvarez, 1997), a study by Contreras-Montijo (1986) on the functioning of the aquifer near Cananea, one of the earliest studies on the San Pedro aquifer published in Mexico, as well as more general information on the aquifer characteristics and groundwater monitoring network derived from the state Groundwater Atlas (Rangel et al., 2005) compiled for CONAGUA. Due to the extensive nature of these studies, a more detailed description of each is included in Appendix 11.1. Another important study entitled *Hydrogeologic Study of the San Pedro River and Upper Sonora River Basins in Cananea*, *Sonora*, prepared in 2000 by Consultores en Agua Subterránea for Grupo México was used to determine groundwater availability in the aquifer. It was published in the Official Gazette of the Mexican Federation (DOF) on August 13, 2007. A study prepared in 2011 by UNISON for the IBWC Mexican Section includes climatological, geological, geomorphological, and geochemical assessments, as well as a well survey, aquifer tests, and piezometric and hydrometric activities, yielding results that formed part of the basis for the preparation of this report (Minjárez et al., 2011).

The Sierra Vista Subwatershed is one of the most studied hydrologic systems in Arizona. The list of hydrologically related studies carried out in this region is long and not included here, but bibliographies are available at the University of Arizona (Sustainability of semi-Arid Hydrology and Riparian Areas - SAHRA), 2010: http://web.sahra.arizona.edu/publications/documents/SAHRA_FinalReport.pdf), including a bilingual database of publications that has been developed as part of this project (https://wrrc.arizona.edu/TAAP). One of the earliest studies considering groundwater was conducted by Lee (1905). This was followed with varying degrees of focus on the study area by Bryan, Kirk, and Waring (San Pedro Valley; 1934), Heindl (Upper San Pedro Basin; 1952), Davidson and White (San Pedro Valley; 1963), Hollyday (Tombstone; 1963), and Brown et al. (Fort Huachuca; 1966). In 1973, USGS scientists Roeske and Werrell published a study of the hydrologic conditions in the San Pedro Valley with a discussion of water quality, surface water, and groundwater resources and the effects of development. The link between climate and the hydrologic functioning of the basin has been investigated by a number of researchers including Serrat-Capdevila et al. (global circulation models, climate change scenarios, and uncertainty; 2007), Hanson et al. (groundwater response to climate cycles; 2006), Thomas and Pool (trends in streamflow and precipitation; 2006), and Dickinson et al. (inferring climate-driven recharge rates from groundwater levels; 2004). For decades, hydrogeological studies have focused on the federally-protected San Pedro Riparian National Conservation Area (SPRNCA), established by decree of the United States Congress in 1988 (Leenhouts et al., 2006). In addition, a series of reports has been published monitoring the progress toward sustainability of the San Pedro River. These include the annual reports by the Upper San Pedro Partnership (USPP) on water management of the regional aquifer (Upper San Pedro Partnership, variously dated).

The first binational-level groundwater flow model of the aquifer was published by Pool and Dickinson (2007). This numerical model incorporates information from many previous efforts including, from the Mexican side, work performed by UNISON (Esparza, 2002: groundwater modeling; and Aguinaga, 2002: groundwater modeling), and the work of Coes and Pool (unsaturated zone investigation; 2005), Dickinson et al. (recharge rates; 2004), Goode and Maddock (groundwater modeling; 2000), Gettings and Houser (gravity modeling of depth and structure; 2000), Pool and Coes (SVSA hydrogeology; 1999), Coes (geochemical constraints on groundwater flow; 1997), Correll et al. (groundwater modeling; 1996), Anderson et al. (geohydrology of basins in southern Arizona and New Mexico; 1992), Vionnet and Maddock (groundwater modeling; 1992), Konieczki (groundwater conditions Upper San Pedro Basin; 1980), Freethey (hydrologic analysis SVSA; 1982), and Drewes (geology; 1980). These and other studies will be summarized and discussed in the subsequent chapters of the report.

1.5. Binational Socioeconomic Environment

The majority of residents in the binational basin live in the cities of Sierra Vista, Arizona, and Cananea, Sonora (Table 1.1). Cananea and Naco, Sonora are the administrative centers of the two municipalities with the same name, which together cover most of the study area in Sonora. Bisbee, Arizona is the county seat of Cochise County which covers the majority of the study area in Arizona. The mining industry has been and continues to be an important economic driver for the region. In Sonora, the Cananea area has mineral reserves that include one of the largest copper deposits in the world where mining has been ongoing for more than a century (Instituto Nacional para el Federalismo y el Desarrollo Municipal, 2014). In Arizona, silver mining in Tombstone and copper mining in Bisbee took place on a large scale for almost a century, but activities have almost entirely ceased (Hollyday, 1963; Pool and Dickinson, 2007; Graeme, 2014). The region's mining history still serves as a tourist attraction. The military base in the United States at Fort Huachuca is the largest source of employment in this region of Arizona. The base is located adjacent to the city of Sierra Vista and the town of Huachuca City. Because all of Fort Huachuca has been annexed by Sierra Vista, Sierra Vista's reported population, about 44,000 (U.S. Census Bureau, 2010), typically officially includes the population of Fort Huachuca. Agricultural production is not intensive in the binational basin.

After establishing the SPRNCA in 1980, around 800 hectares were taken out of production as part of a U.S. federal program to protect the river (ADWR, 2005). In general, agricultural production does not represent a significant economic force in the basin on a binational level.

Community	Estimated Number of Residents (2010)
Sierra Vista, Arizona (including Fort Huachuca and Huachuca City)	44,000
Cananea, Sonora	32,000
Naco, Sonora	6,000
Bisbee, Arizona	5,600
Tombstone, Arizona	1,400
Naco, Arizona	1,000

Table 1.1 Population in the Main Population Centers in the San Pedro Binational Basin.
(Population data from INEGI, 2010 census and the U.S. Census Bureau, 2010)

1.6. Binational Water Management Environment

Differences in the manner in which the two countries manage water in this border region were analyzed in a study by the University of Arizona (Megdal and Scott, 2011). It is extremely important to recognize these binational differences as part of the cooperative assessment of transboundary waters, and with this knowledge obtain scientific information that can help decision making about long-term management within each country. The San Pedro River aquifer in Sonora belongs to Hydrological-Administrative Region II, Northwest Mexico, and is subject to the provisions of the type-II prohibition decrees, where the aquifer capacity only permits extractions for domestic use, "*Conservation of the Aquifers in the State of Sonora West of the 110th Meridian*" and "*Various Municipalities of the State of Sonora*" which include Naco and Agua Prieta, published in the DOF on September 19, 1978, and September 24, 1984, respectively; which state that "*Except in the case of withdrawals for domestic use and [livestock] watering performed manually, from the effective date of this decree, no one may build* *groundwater delivery structures within the prohibited area without first obtaining a construction permit issued by the Water Authority, nor extract or use the aforementioned waters, without being granted a concession or allotment*"; additionally, it stipulates that: "*a construction permit for works will be granted only in cases where the pertinent studies have concluded that they will not cause the damage that this ban was established to prevent.*"

According to the Mexican Federal Water Rights Law (2012), the municipality of Cananea is classified as an availability zone 4, Santa Cruz as zone 6, and Naco as zone 7. The largest groundwater users are industrial (the Cananea mine), and public-urban (supplying water to the region's communities). The aquifer is not located in any irrigation unit or district, nor has a Technical Groundwater Committee (COTAS) been established. According to United States law, the states are the primary authority for groundwater management.

ADWR regulates the use of groundwater in accordance with state laws. There are five areas of the state designated as Active Management Areas (AMAs) where the use of groundwater is subject to specific laws and regulations. The state agency ADWR published analyses in 1988 and 2005 to determine if the Sierra Vista Subwatershed qualified to be designated as an AMA (Putnam et al., 1988; Arizona Department of Water Resources, 2005). The 2005 study concluded that the area did not qualify for the AMA designation by the state government. One of the State of Arizona regulations that is most relevant in this region is the requirement to carry out a 100-year water availability study before any development that meets particular criteria (such as size and density) is approved. If, after completing this hydrological, economic, and legal study, it cannot be shown that there is a sufficient water supply for 100 years, the entity that is selling the property has the obligation to disclose this finding to the buyer before closing the sale. The local authority, the Cochise County administration, has passed its own regulation that prohibits development if the required supply cannot be proven and guaranteed for 100 years.

Although Arizona has not designated this area as an AMA for groundwater management purposes, the region has a history of taking proactive steps toward water sustainability. In 1998 the USPP was formed with 21 member organizations. They include municipal, state, and federal agencies, and non-governmental organizations working together to achieve sustainable water use, as well as the following objectives:

(1) To preserve the SPRNCA.

(2) To guarantee the long-term viability of the Fort Huachuca military base.

Coordination through the USPP has resulted in several comprehensive projects and policies being implemented by the participants, both individually and jointly. They include the construction of recharge projects, wastewater reuse, conservation programs, public outreach, and projects to protect priority environmental areas.

1.7. Technical Work Undertaken

The two sections of the IBWC coordinated the scientific dialogue and the exchange of information to enable the preparation of this U.S.-Mexico Binational Report. During 2007-2009, a bibliographic database was developed (Vandervoet, 2009), and several meetings and field trips were conducted in Arizona and Sonora to engage stakeholders and to solicit comments and suggestions from the public on the framework and implementation of the technical program to be implemented during the following years (Callegary et al., 2013). The University of Sonora was contracted by CILA to perform a technical study on the San Pedro aquifer in Sonora (Minjárez et al., 2011). The Mexican portion of the study that UNISON prepared in 2011 became the basis for this binational report. The field activities were carried out from February to March and May to August 2011. Initially a survey of groundwater wells was undertaken, gathering information about the number of existing wells and their location in UTM coordinates using the WGS 84 Datum, the well type, its use, operational status, equipment characteristics, outlet type, operating and gaging mechanisms. Static (non-pumping) water levels and physical and chemical parameters such as electrical conductivity, total dissolved solids (TDS), temperature, hydrogen potential (pH), redox potential (Eh), and salinity, among other parameters, were measured. Initially ten aquifer tests were conducted for a short period (between 6 and 8 hours); seven of them in the Cananea wellfield and three in other wells. Within the SVSA, the USGS and the UA measured and modeled runoff in ephemeral-stream channels in the Fort Huachuca-Sierra Vista area and estimated local recharge (Stewart et al., 2012; Stewart et al., 2014). Together they also carried out a groundwater vulnerability analysis using the USEPA DRASTIC model (Lincicome, 2011; Lincicome-Noriega et al., 2011). This model considers variables related to infiltration and the ability to recharge. Geological, geophysical, and hydrological data from previous studies were also compiled. All this information gathered on both sides of the border was compared and integrated where feasible, with the aim of achieving a better scientific understanding of the binational aquifer system within the San Pedro binational basin.

1.8. Methodologies and Techniques Applied

Initially, existing data from hydrogeological, geological, and geophysical studies were collected, and a series of maps, plans, and articles about the study area were analyzed. To prepare a base map and the related maps that were incorporated into the current study, topographic maps 1:50,000 scale and digital elevation models, edited by the National Institute of Statistics and Geography (INEGI), and geological mining maps, scale 1:250,000, edited by the Mexican Geological Service (SGM) were used. Similarly, USGS data were compiled and work previously done under the binational program known as the United States-Mexico Border Environmental Health Initiative (BEHI) was incorporated where possible. That program started in 2004 in the form of a collaboration between

INEGI and USGS to make the best harmonized binational data sets available to the public and to allow access to data in multiple Geographic Information Systems (GIS) developed under the binational BEHI program (Norman et al., 2010). A handheld Garmin GPS, model GPSMAP 60CSx, was used for the field work, as were 200 m probes to measure water levels, and portable equipment to measure the physical and chemical parameters of the water. Samples were also collected for physicochemical analyses, according to the protocol described in Chapter 7 Hydrogeochemistry. Procedures used for the geophysical surveys as well as results are described in Chapters 4 and 5. Subsurface hydrology, results of the well survey, water levels, and pumping tests are analyzed in the text, provided in maps, or in the appendices. Likewise, aquifer characteristics are discussed, defining the principal hydrostratigraphic units, the system geometry and behavior, and flow directions. Lastly, a series of conclusions and recommendations for future efforts are presented, along with bibliographic references and an appendix with sections including detailed information on soil and vegetation classification, meteorological data, and locations of streamgages and wells used for maps of water levels and geochemistry. The aquifer tests in Sonora were supervised and reviewed according to CONAGUA protocols.

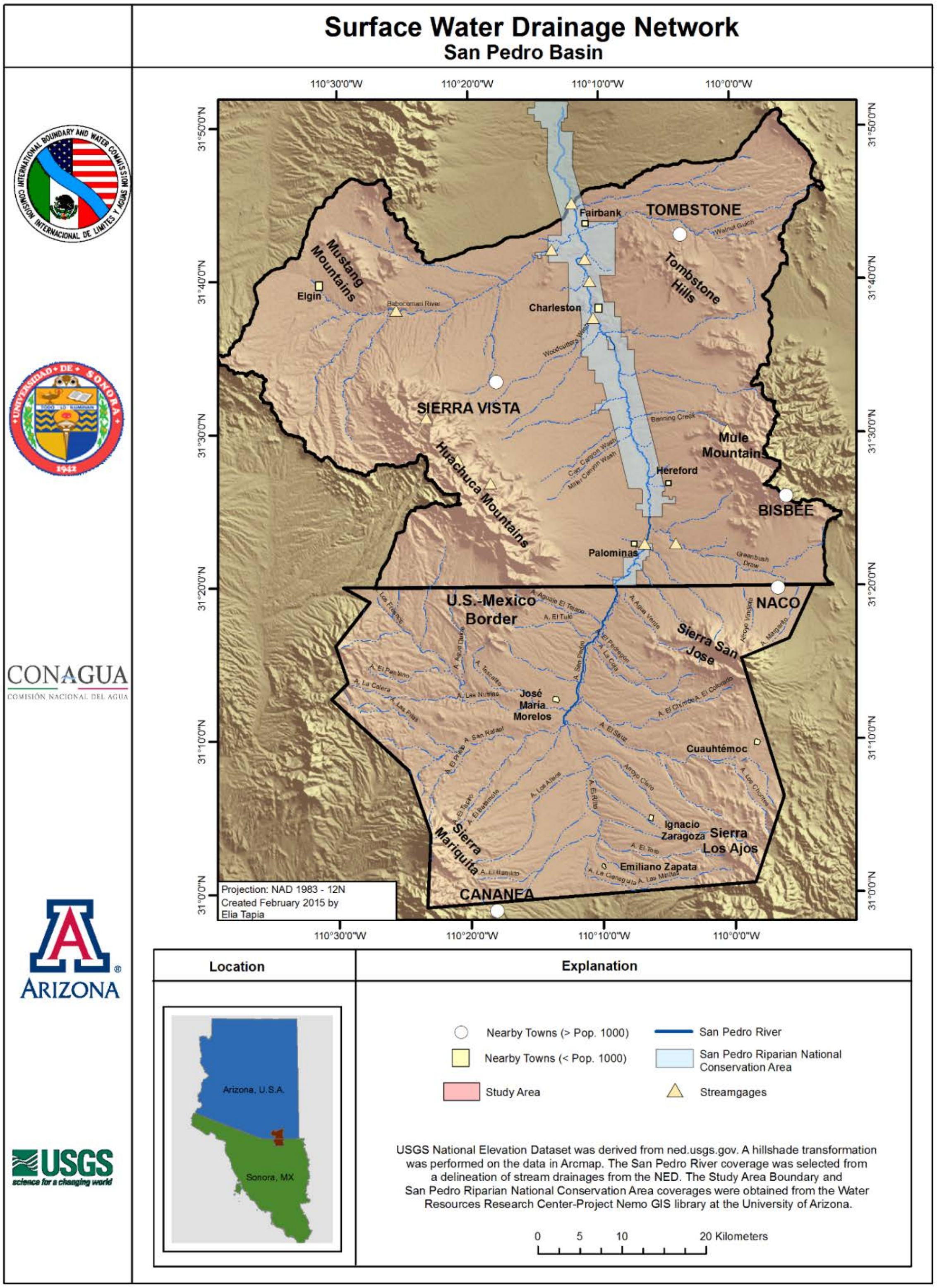
2. PHYSICAL GEOGRAPHY

2.1. Physiographic Province

The BSPB is located in the North American Basin and Range Province of Fenneman (1931). This province is primarily formed by mountain ranges separated by wide, parallel valleys oriented north-south, with aquifers found in valleys delimited by the mountain ranges. The altitude of the basin varies between about 1,100 m above sea level (m.a.s.l.) in the northernmost part of the basin to 2,620 m.a.s.l. east of Cananea; and in the Huachuca Mountains, altitudes exceed 2,700 m.a.s.l. (Figure 1.2). INEGI (2005) uses a different nomenclature for the Mexican portion of the study area, labeling the physiographic provinces as *Llanuras y Médanos del Norte* (Northern Plains and Dunes) and *Sierras y Valles del Norte* (Northern Sierras and Valleys), referencing the same mountain and valley geography described by Fenneman (1931). Acidic, volcanic rocks and sedimentary rocks dominate in the mountains. Continental sedimentary materials (Tertiary conglomerate, Tertiary and Quaternary alluvium) are abundant in the valleys.

2.2. Drainage Network and Drainage Basin

In the BSPB, ephemeral channels and reaches are more numerous and have greater total length than the intermittent or perennial channels. The main surface water body in the study area is the San Pedro River, which originates north of Cananea as El Barrilito arroyo coming down from the Mariquita Mountains, and as Las Minitas in the Sierra Los Ajos (Figure 2.1). The San Pedro River exits the study area just north of Fairbank, Arizona and its confluence with the Babocomari River and Walnut Gulch. The San Pedro River discharges to the Gila River in Winkelman, Arizona, which now flows only ephemerally into the Colorado River in Yuma, Arizona. The Colorado River crosses the border downstream of Yuma and empties into the Gulf of California in Mexico. The main tributaries to the San Pedro River are the Agua Verde, El Pedregón, La Coja, and El Chirrión Colorado arroyos, which come from the San José Mountains. The arroyos originating in the Sierra Los Ajos are: Los Patos, El Riecito, El Toro, Las Minitas, and El Claro. On the west side, originating in the mountains of Cananea, La Mariquita and El Tule, the principal streams are El Barrilito, El Piojo, El Batamote, El Tapiro, La Calera, El Tascalito, El Nogalar, El Tule, Aguaje, and El Tejano. Most of the arroyos are intermittent except for San Rafael and Las Nutrias. On the U.S. side, the primary streams on the west side are the arroyos Coyote, Woodcutter’s, Graveyard, Garden, Huachuca, and the Babocomari River. On the east side, they are Greenbush Draw, Banning Creek, and Walnut Gulch. All of them are ephemeral except the spatially intermittent Babocomari River.



Projection: NAD 1983 - 12N
Created February 2015 by
Elia Tapia

USGS National Elevation Dataset was derived from ned.usgs.gov. A hillshade transformation was performed on the data in Arcmap. The San Pedro River coverage was selected from a delineation of stream drainages from the NED. The Study Area Boundary and San Pedro Riparian National Conservation Area coverages were obtained from the Water Resources Research Center-Project Nemo GIS library at the University of Arizona.

Figure 2.1 Surface Water Drainage Network in the San Pedro Binational Basin (BSPB).

2.3. Hydrologic Region

In total, the BSPB covers almost 5,000 km^2. In Sonora, the study area falls within Hydrologic Region RH7, Rio Colorado, according to CONAGUA conventions. The majority of the study area lies within the basin of the Gila and San Pedro rivers. However, a portion of the officially recognized basin in Mexico lies in other watersheds, because the official boundary does not follow the watershed boundary exactly. The USPSS has an approximate area of 2,892 km^2. The San Pedro River aquifer occupies 99% of the subbasin with the same name; the remaining percentage corresponds to the Sonora-Arizpe River to the south, to the Cocospera arroyo to the west, and to the Agua Prieta River to the east. The SVSA has an approximate area of 2,460 km^2.

2.4. Soils

Information on the spatial distribution of soils is important for understanding hydrologic processes such as infiltration, recharge, and ET. In the BSPB, most of the soils come from igneous and sedimentary rocks. Normally the soils that were deposited on steep slopes and at higher elevations are thin and gravelly, some of which contain rock outcrops. The soils deposited on the plains and the areas of inundation are generally deeper and have a finer texture.

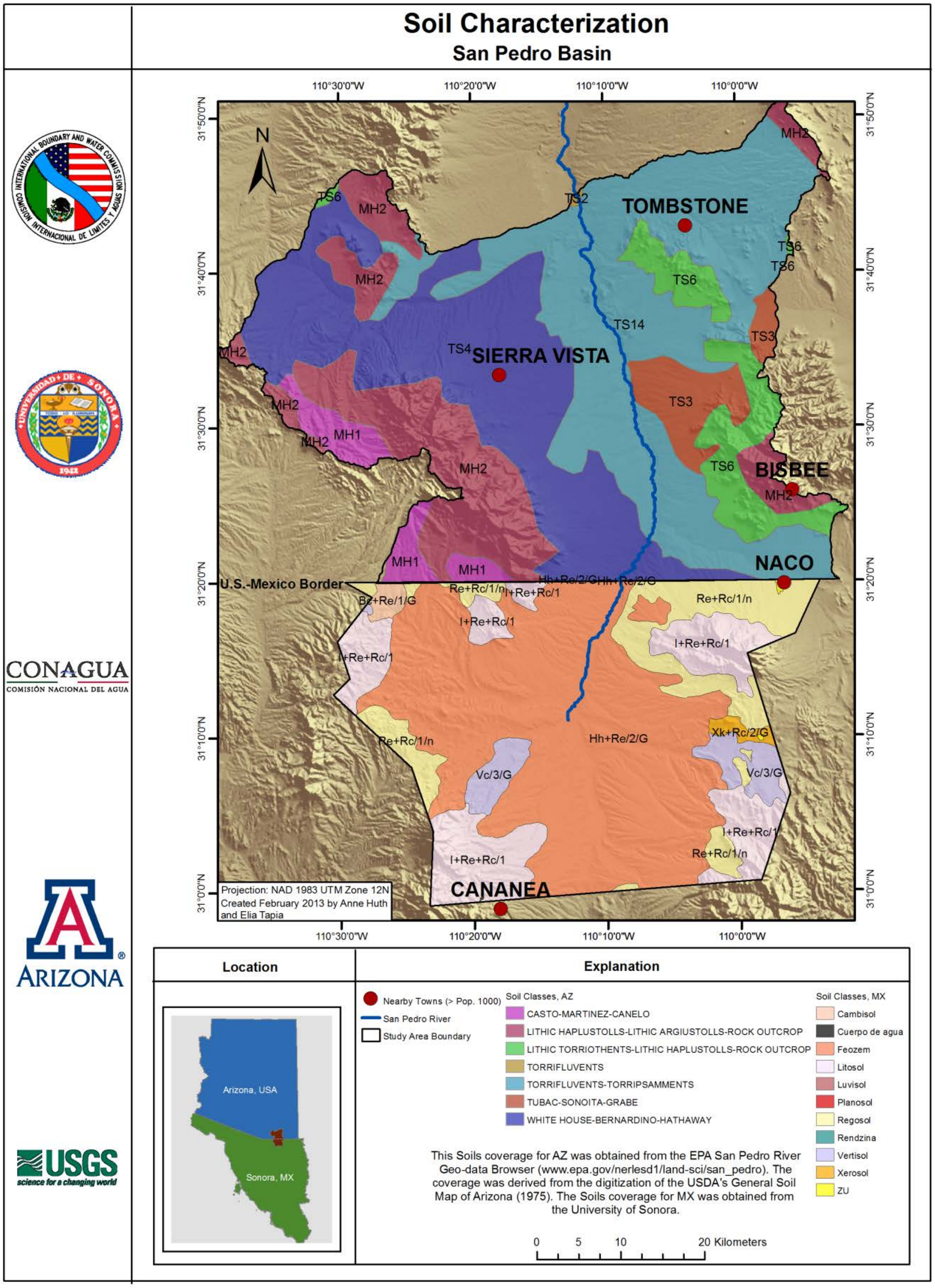
It is important to note that the soil classifications used for the U.S. and Mexican portions of the aquifer are not equivalent, because a unified classification was not available (Figure 2.2). On the Mexican side, the United Nations Food and Agriculture Organization (FAO) classification system is used. On the U.S. side, the classification system was derived from the digitization of the U.S. Department of Agriculture's (USDA's) General Soil Map of Arizona (Kepner et al., 2003). Higher resolution datasets such as the State Soil Geographic Database (STATSGO) and the Soil Survey Geographic Database (SSURGO) are available (Soil Survey Staff, 2014), but to keep the resolution comparable on both sides of the watershed these classifications were not used. In order to harmonize the soil classification on both sides of the border, binational surveys would need to be undertaken subject to an agreement establishing the spatial resolution (scale) and the methods for sampling, mapping, and analysis. The time required for the field work would depend on the methods used and map resolution.

Five factors are considered to be most important in the formation and development of soils: climate, organisms, parent material, topography, and time, with climate being the most important (Fisheries and Aquaculture Department of the Food and Agriculture Organization of the United Nations, 1987). Based on the FAO soil classification system, the surface of the San Pedro River aquifer on the Sonoran side is composed of eight soil types, known as Cambisol, Phaeozem, Lithosol, Luvisol, Planosol, Regosol, Vertisol, and Xerosol; each one combined with chromic, haplic, eutric, calcaric, and calcic-type subunits. Soil classification on the Mexican side is based on the physical and chemical properties of the area's soil horizons.

In the SVSA, the soils were classified by the Natural Resources Conservation Service (NRCS; Hendricks et al., 1985), which is an agency under the USDA. Soils are classified into groups or associations of soil types. There are eight different soil types (associations) in the SVSA that vary depending on topography, appearance, precipitation, temperature, vegetation, source rock, and other factors. These types are the Casto-Martinez-Canelo Association, the Lithic Haplustolls-Lithic Argiustolls-Rock Outcrop Association, the Torrifluvents Association, the Tubac-Sonoita-Grabe Association, the White House-Bernardino-Hathaway Association, the Lithic Torriorthents-Lithic Haplustolls-Rock Outcrop Association, the Latene-Nickel-Pinaleno Association, and the Nickel-Latene-Cave Association. A description of the soil units and their subtypes is given in the appendices.

2.5. Vegetation

Evapotranspiration (ET) is one of the main controls on hydrology in arid and semiarid climates (Tillman et al., 2012). Controls on interannual variability in ET and use of shallow-seasonal versus deep-stable sources of groundwater are complex and dependent upon topographic setting and vegetation assemblage (Scott et al., 2014). As with soils, the vegetation in the BSPB is classified differently on the two sides of the border. However, there are similarities, including oak-pine forests and evergreen forest, grasslands, and scrub. Various high-resolution regularly updated datasets are available in the US such as the National Land Cover Dataset with 30 m resolution (Homer et al., 2012) and the USDA's CropScape which focuses on annual changes in croplands and has a resolution of 30 and 56 m (Han et al., 2012). In addition, the European Space Agency led a consortium of agencies to publish GlobCover, a 300-m resolution global land cover dataset based on 2009 fine-resolution measurements of the MERIS satellite (Bontemps et al., 2011). Most recently and specific to the study area, the USEPA has published a binational vegetation map with 31 classes (Figure 2.3; Boykin et al., 2014, and Southwest Regional Gap Analysis Project, 2004; See appendices).



This Soils coverage for AZ was obtained from the EPA San Pedro River Geo-data Browser (www.epa.gov/nerlesd1/land-sci/san_pedro). The coverage was derived from the digitization of the USDA's General Soil Map of Arizona (1975). The Soils coverage for MX was obtained from the University of Sonora.

Figure 2.2 Soils in the San Pedro Binational Basin (BSPB).

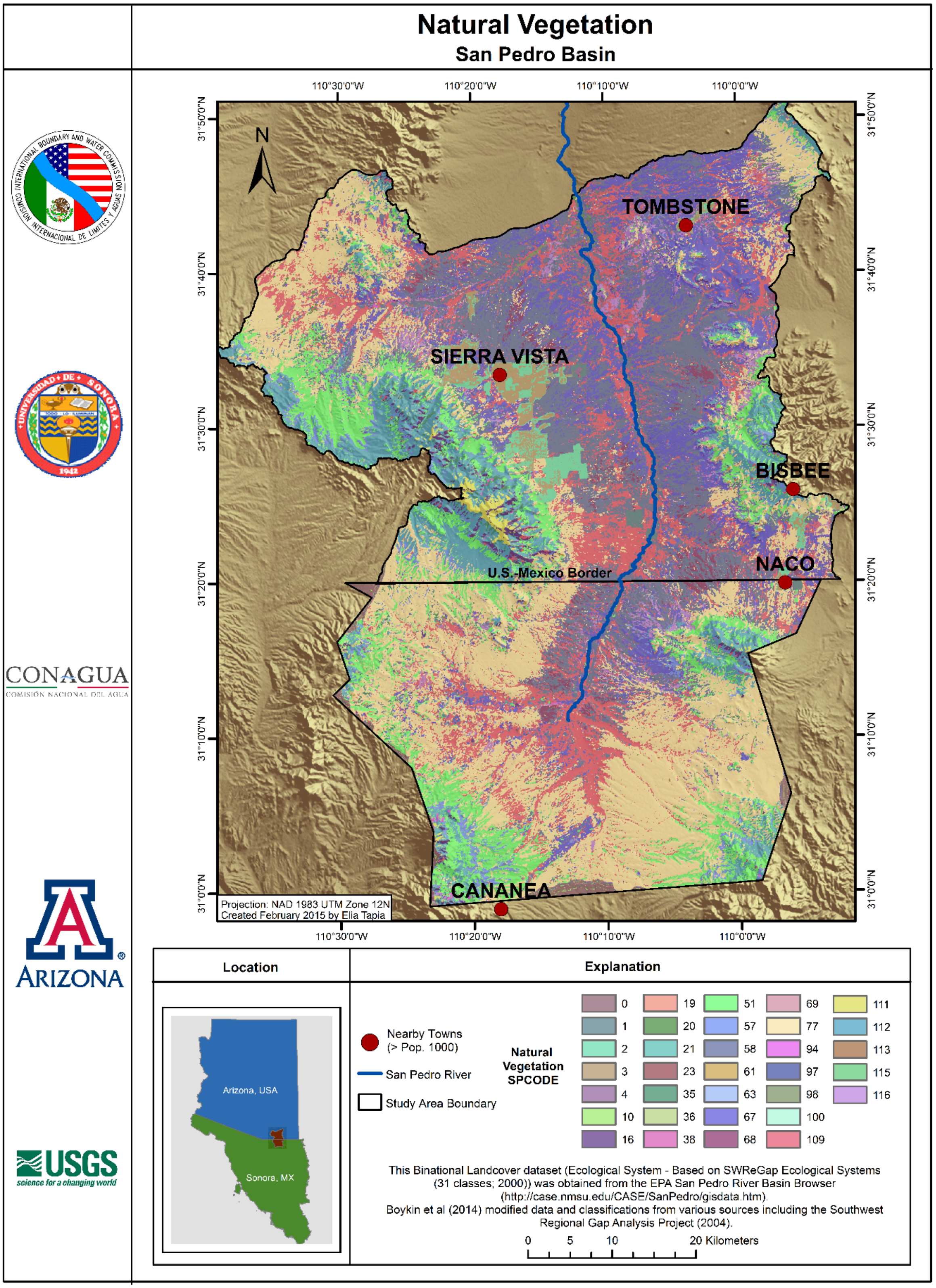


Figure 2.3 Vegetation in the San Pedro Binational Basin (Boykin et al., 2014).

3. SURFACE-WATER HYDROLOGY AND HYDROMETEOROLOGY

3.1. Climatological Analysis

According to the INEGI climate classification (1980, Climate Maps, 1:1,000,000), as well as the United States Western Regional Climate Center (2010), a semi-arid climate predominates over the majority of the basin with official Koppen classifications of Hot Summer Mediterranean in the Mexican portion of the basin and Hot or Cold Semiarid in the U.S. (Figure 3.1). Weather stations are sparse with the majority located in the U.S. side of the basin, but values have been interpolated to both sides of the border to predict precipitation, temperature, and rainfall intensity among others. Precipitation varies with altitude (Anderson et al., 1992) and the period of greatest rainfall intensity, probability, and volume coincides with the months of mid-June through October (about 65% of total annual rainfall on average), while winter precipitation averages over 20% of the total annual volume (Pool and Coes, 1999). The area is considered temperate with warm summers and, as previously noted, an annual average temperature that varies between 12 and 18°C over the period of record from 1960-2011 (Minjárez et al., 2011). Between the months of June and September, the average maximum temperature ranges from 29 to 34°C. Temperatures above 38°C frequently occur in the low-elevation areas during the summer but are uncommon in the region's higher elevations. In winter, the average minimum temperature is close to 0°C. In June 1960, Cananea recorded a maximum temperature of 45°C. Its lowest recorded temperature, -26°C, was recorded in February 2011. Figures 3.1, 3.2, and 3.3 show, respectively, the mean annual temperature for the binational basin, the maximum temperature in the hottest month, and the minimum in the coldest month. The interpolated grid with climatological data for the BSPB was obtained using the WorldClim database (www.worldclim.org), and was created by integrating the monthly temperature and precipitation data from climatological stations from different sources, including GHCN (Global Historical Climatology Network), WMO (World Meteorological Organization), FOACLIM (Food and Agriculture Organization of the United Nations World Climate Data), and other regional databases (Hijmans et al., 2005). The data were compared to previous studies including PRISM (PRISM Climate Group, 2013) and Daymet (Oak Ridge National Laboratory Distributed Active Archive Center, 2013) to assess their accuracy. Figure 2.2 shows the stations used on the U.S. side of the study area. For the Mexican portion, there is information from the CONAGUA stations 26057 Naco and 26315. Figures 3.4, 3.5, and 3.6 show the average annual precipitation for the San Pedro Binational Aquifer area, and the average monthly precipitation during the months listed as either more rainy or less rainy (August or January).

Past and predicted climate trends in the southwestern United States were summarized and discussed in Garfin et al. (2013). Some of the findings relevant to the present study are summarized here. Between 1910 and 2010, maximum daily temperatures at a station in Cochise

County increased between 2.0 and 3.6 ºC. Moreover, the period since 1950 has been warmer than any period of similar length in the last 600 years and possibly longer (Garfin et al., 2013). The drought between 2000 and 2010 was the second largest in the last century, but there have been more severe droughts during the last 2000 years (Garfin et al., 2013). They summarized a number of key points on future regional climate change as well. This includes the projection that climate trajectories will depend largely on carbon dioxide emissions. Summer heat waves are predicted to be longer and hotter. Cold snaps will be less common, but not less severe. Average precipitation will decline with consequent declines in streamflow and soil moisture. Droughts are predicted to become hotter, more severe, and more common. Changes in land cover will be significant due to changes in precipitation, temperature, aquifer storage, soil moisture, wildfire, and outbreaks of forest pests. This will cause changes in ET and contribute to changes in runoff and water quality.

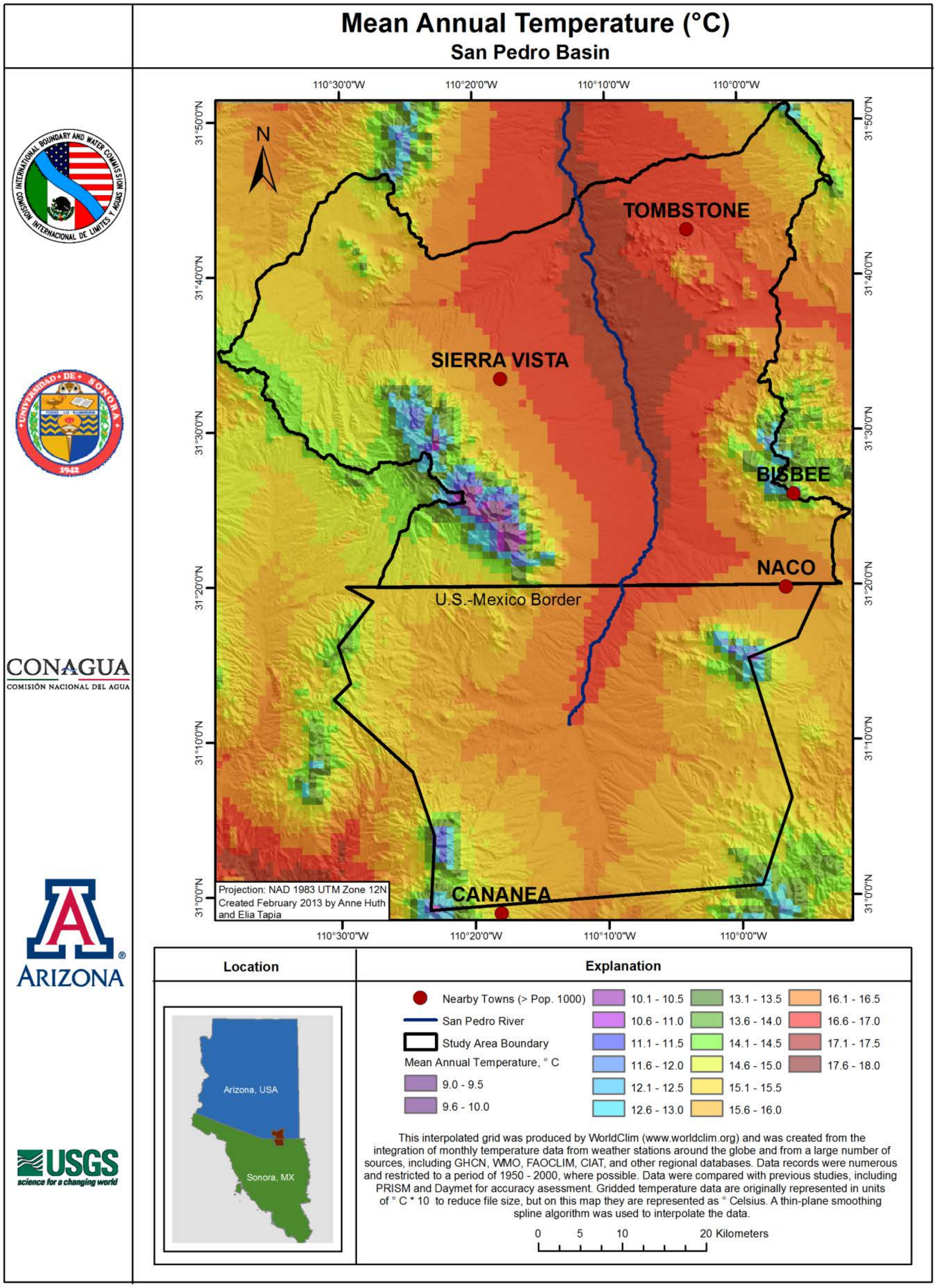
The link between climate and the hydrologic functioning of the basin has been investigated by a number of researchers. Price et al. (2005) modeled vegetation response and streamflow in response to climate change scenarios. Specifically, they used rainfall-runoff modeling to investigate the effects of four climate scenarios, ranging from “warm”, to “warm and dry”, and “warm and very wet”. Their model did not match summer streamflow, but they obtained reasonable agreement with winter flows. They found that declines in winter precipitation and increases in temperature had a much stronger effect on streamflow than increasing temperature alone. When the decline in winter precipitation fell to 50% of normal, winter floods ceased. Dickinson et al. (2004) inferred climate-driven recharge rates from groundwater levels and Hanson et al. (2006) investigated response of hydrologic variables (groundwater levels, tree rings, streamflow, and precipitation) to climate cycles. In the Upper San Pedro Basin, Hanson et al. (2006) found that the amount of influence a particular climate forcing has on hydrology likely varies through time as well as location in a basin (e.g. near the mountain front or near the San Pedro River). They also found that, on average, Pacific Decadal Oscillation (PDO)-type periods explained about 46% of the variability in the hydrologic data with a lag in effect ranging from 9 to 13 months. The second most influential climate index was the El Niño-Southern Oscillation (ENSO), explaining about 40% of the variability averaged across all data types, and 59% of the variability in the groundwater data, with the shortest lags and highest correlation in wells closest to the mountain front. This effect of lag and correlation was the opposite of what was found with the PDO (Hanson et al., 2006). Serrat-Capdevila et al. (2007) used a 3D groundwater-surface-water model of the San Pedro Basin, an ensemble of 17 global circulation models with downscaled precipitation, and 4 climate change scenarios to explain and predict spatially-distributed recharge and streamflow over the period 2000 to 2100. Holding groundwater pumping constant, they predicted a 17-30% decrease in recharge, a 31% decrease in ET, and a 50% decrease in stream baseflow.

3.2. Precipitation and Evapotranspiration

As previously mentioned, precipitation occurs mainly during the summer and winter. Summer precipitation events are generally of greater magnitude than during the winter. During the months of July through September, the average precipitation is around 21 cm in Tombstone and 27 cm at Coronado National Memorial located south of the Huachuca Mountains near the international border. During the months of October through March, the precipitation in these two stations drops to between 12 and 23 cm respectively (Pool and Dickinson, 2007). The estimated annual average precipitation for the San Pedro River basin in Sonora is around 55 cm (CONAGUA, 2009). The stations located at topographically higher areas receive more precipitation than the stations located in the plains (Figure 2.2). The average annual precipitation for the Sierra Vista Subwatershed in Arizona over the period from 1989 to 2012 from four weather stations was around 38 cm (Gungle et al., *In Review*).

Variations in precipitation on an interannual scale are also evident. El Niño periods have higher precipitation in the winter in this region (Pool, 2005). Decade-scale variations include greater winter precipitation during the 1940s and the 1956-1997 period. Hanson et al. (2006) found that variability in precipitation (along with streamflow and groundwater) followed the decline in the PDO in the 1940's, but showed deviations from the PDO during the period 1947-1977 that may have been influenced by other climate forcings. Winter rains and associated runoff have decreased overall during the second half of the last century.

Based on data from evaporimeters, estimated annual average potential evaporation for this region of Sonora is 2,117 mm (CONAGUA, 2009). Similarly, estimated potential evaporation for the region in Arizona is about 1,651 mm annually (Arizona State University, 1975). Tillman et al. (2012) using MODIS satellite data estimated that annual average groundwater discharge by vegetation (ET) in the SVSA for the period 2000-2007 to be 200 mm yr^{-1}. Scott et al. (2008) estimated ET for three riparian vegetation types over the period 2003-2005. They reported site-scale groundwater discharge ET rates, which if averaged over the 2003-2005 annual values, gives 490 mm (woodland), 381 mm (shrubland), and 368 mm (grassland).



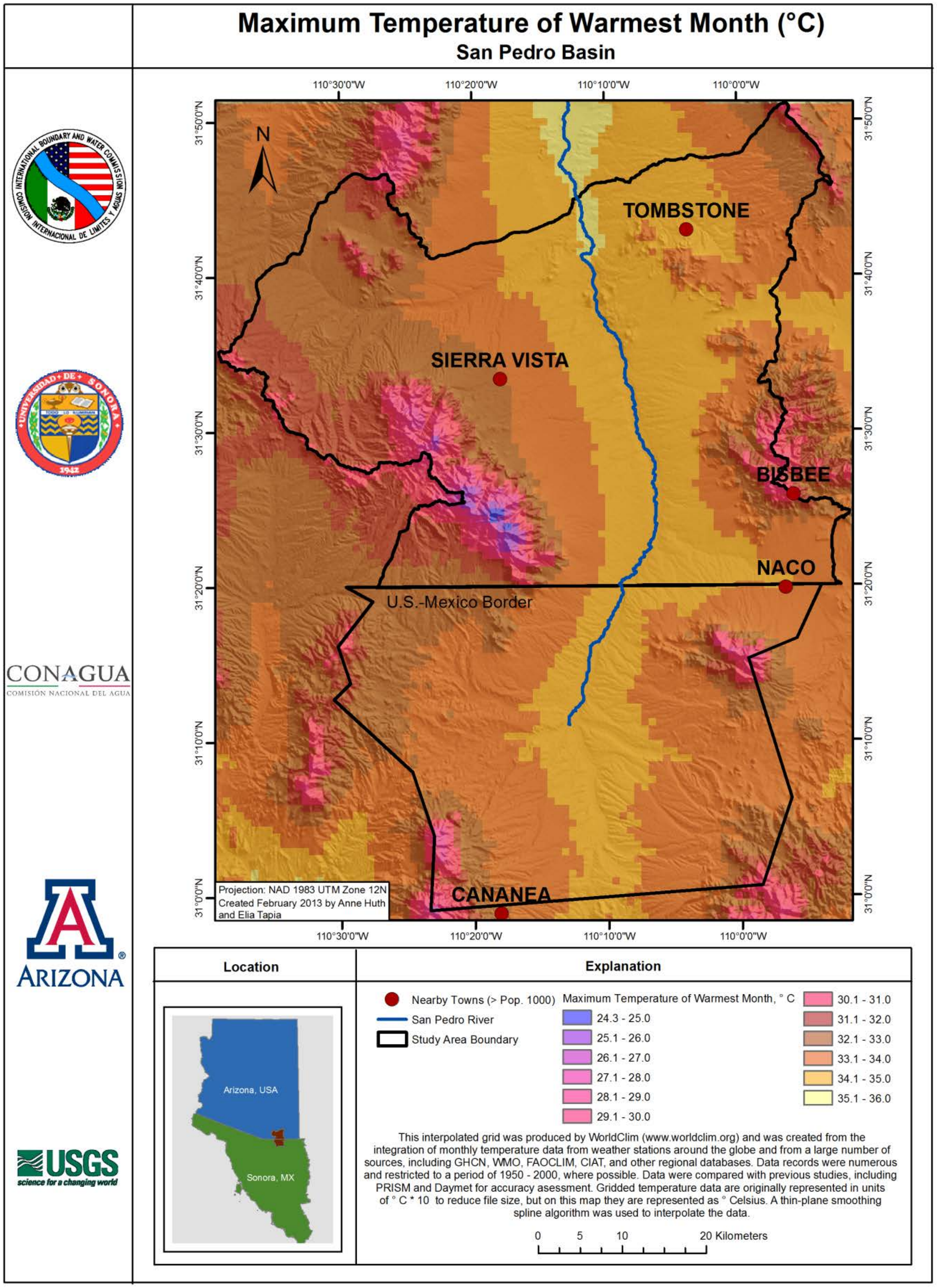
Mean Annual Temperature (°C)

San Pedro Basin

Projection: NAD 1983 UTM Zone 12N
Created February 2013 by Anne Huth and Elia Tapia

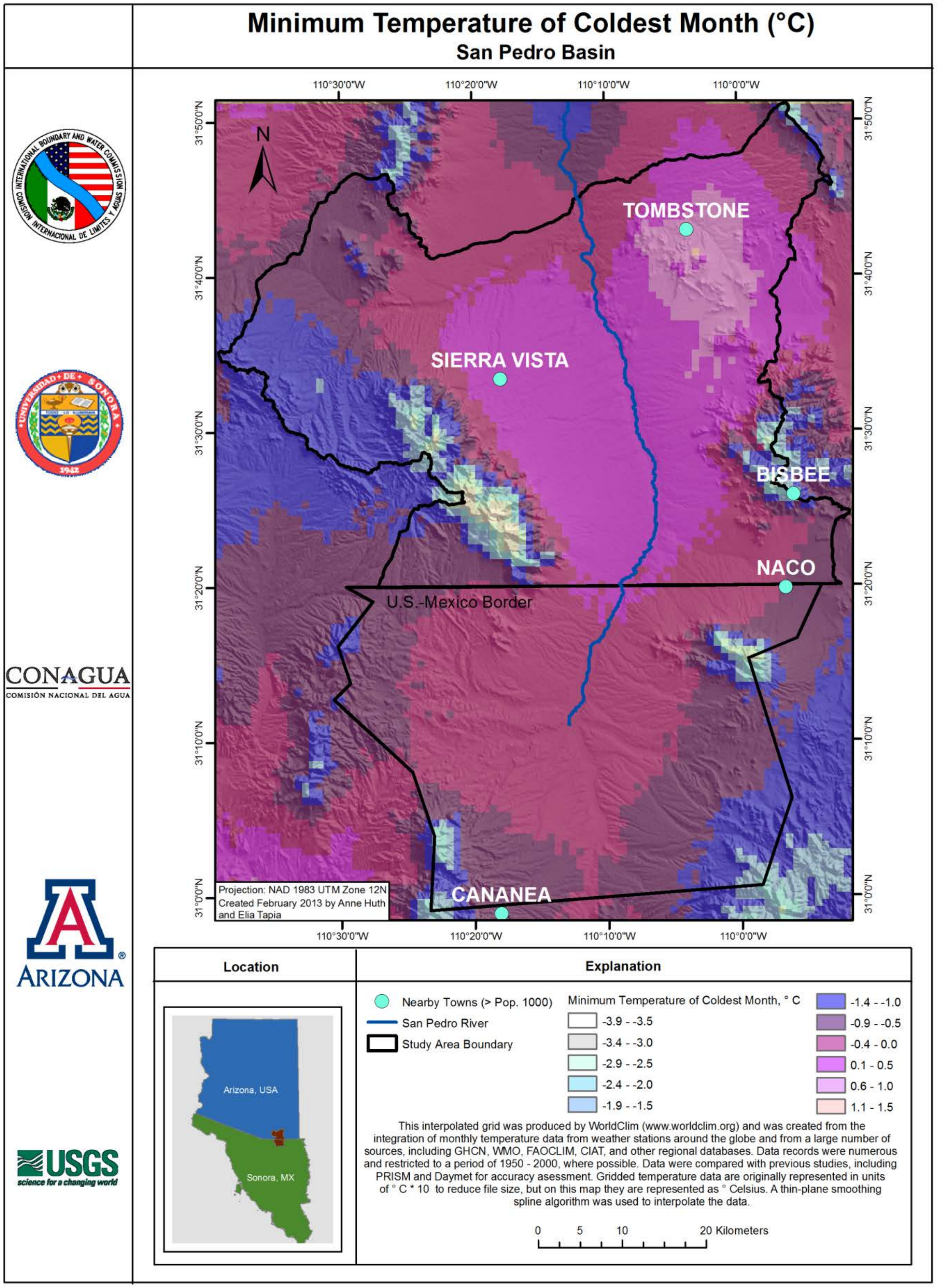
This interpolated grid was produced by WorldClim (www.worldclim.org) and was created from the integration of monthly temperature data from weather stations around the globe and from a large number of sources, including GHCN, WMO, FAOCLIM, CIAT, and other regional databases. Data records were numerous and restricted to a period of 1950 - 2000, where possible. Data were compared with previous studies, including PRISM and Daymet for accuracy asessment. Gridded temperature data are originally represented in units of ° C * 10 to reduce file size, but on this map they are represented as ° Celsius. A thin-plane smoothing spline algorithm was used to interpolate the data.

Figure 3.1 Annual Average Temperature in the San Pedro Binational Basin.



This interpolated grid was produced by WorldClim (www.worldclim.org) and was created from the integration of monthly temperature data from weather stations around the globe and from a large number of sources, including GHCN, WMO, FAOCLIM, CIAT, and other regional databases. Data records were numerous and restricted to a period of 1950 - 2000, where possible. Data were compared with previous studies, including PRISM and Daymet for accuracy asessment. Gridded temperature data are originally represented in units of ° C * 10 to reduce file size, but on this map they are represented as ° Celsius. A thin-plane smoothing spline algorithm was used to interpolate the data.

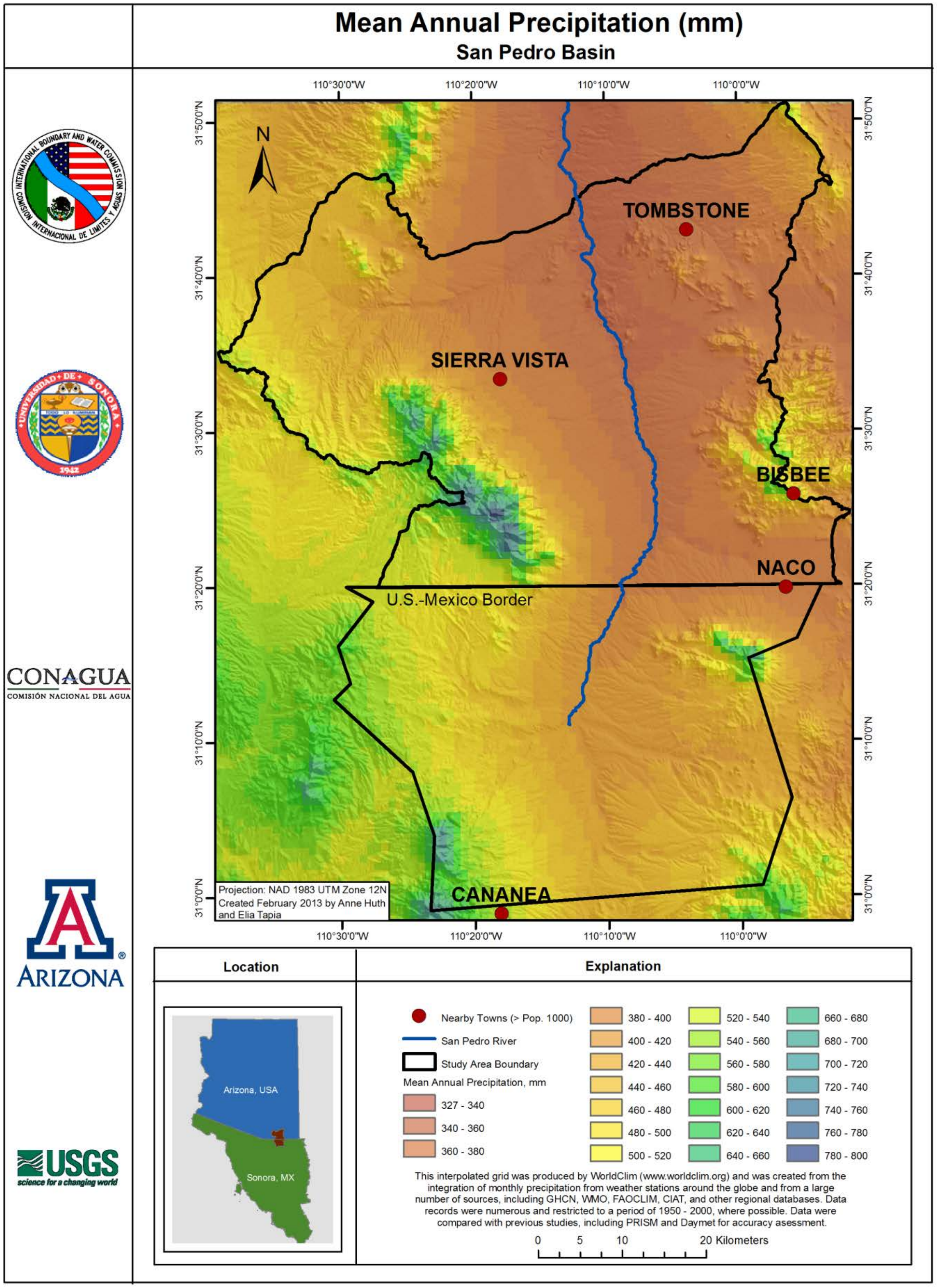
Figure 3.2 Maximum Temperature in the Hottest Month in the San Pedro Binational Basin.



Projection: NAD 1983 UTM Zone 12N
Created February 2013 by Anne Huth and Elia Tapia

This interpolated grid was produced by WorldClim (www.worldclim.org) and was created from the integration of monthly temperature data from weather stations around the globe and from a large number of sources, including GHCN, WMO, FAOCLIM, CIAT, and other regional databases. Data records were numerous and restricted to a period of 1950 - 2000, where possible. Data were compared with previous studies, including PRISM and Daymet for accuracy asessment. Gridded temperature data are originally represented in units of ° C * 10 to reduce file size, but on this map they are represented as ° Celsius. A thin-plane smoothing spline algorithm was used to interpolate the data.

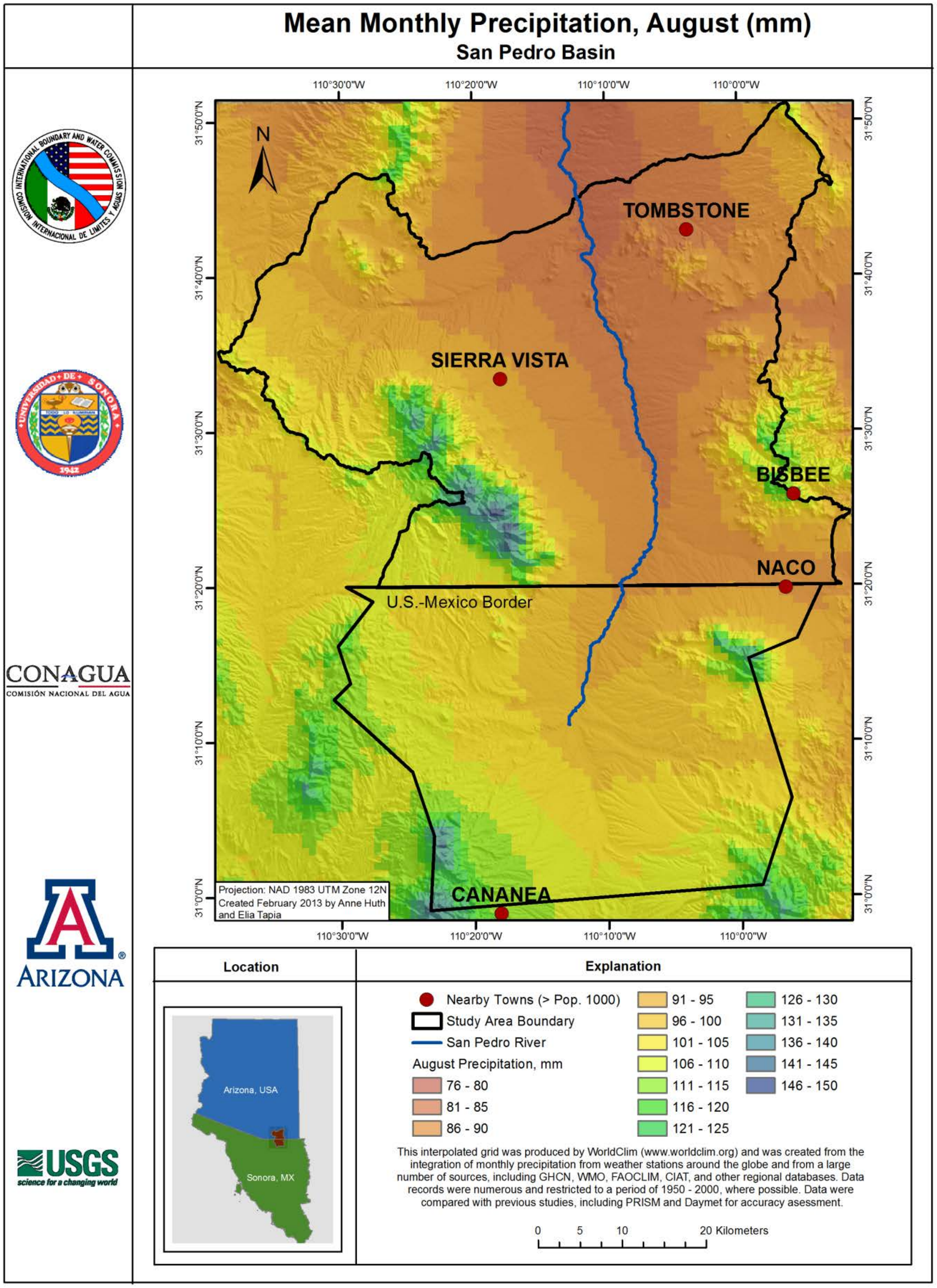
Figure 3.3 Minimum Temperature in the Coldest Month in the San Pedro Binational Basin.



Projection: NAD 1983 UTM Zone 12N
Created February 2013 by Anne Huth and Elia Tapia

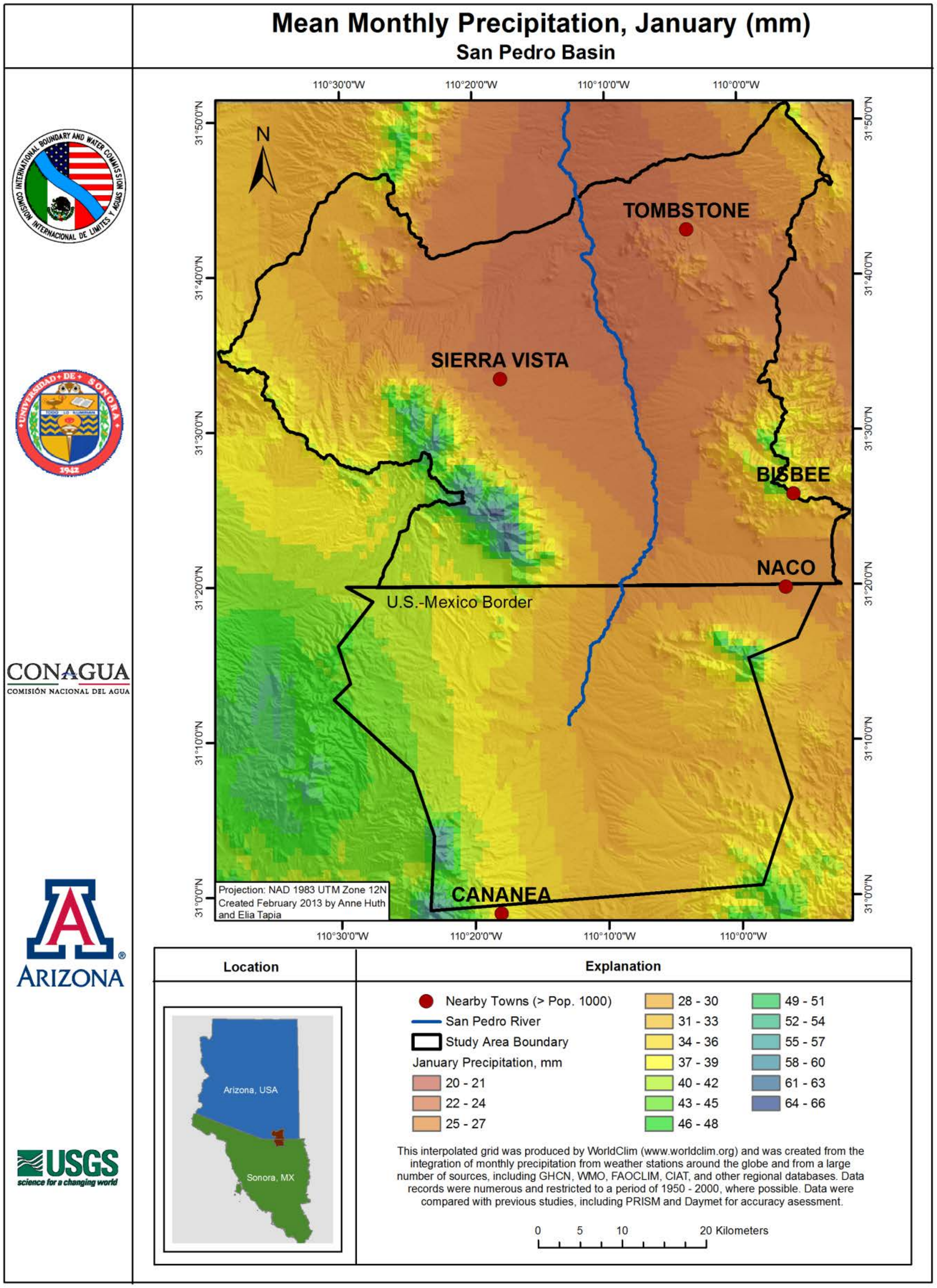
This interpolated grid was produced by WorldClim (www.worldclim.org) and was created from the integration of monthly precipitation from weather stations around the globe and from a large number of sources, including GHCN, WMO, FAOCLIM, CIAT, and other regional databases. Data records were numerous and restricted to a period of 1950 - 2000, where possible. Data were compared with previous studies, including PRISM and Daymet for accuracy asessment.

Figure 3.4 Annual Average Precipitation in the San Pedro Binational Basin.



This interpolated grid was produced by WorldClim (www.worldclim.org) and was created from the integration of monthly precipitation from weather stations around the globe and from a large number of sources, including GHCN, WMO, FAOCLIM, CIAT, and other regional databases. Data records were numerous and restricted to a period of 1950 - 2000, where possible. Data were compared with previous studies, including PRISM and Daymet for accuracy asessment.

Figure 3.5 Monthly Average Precipitation in the Month of August in the San Pedro Binational Basin.



Projection: NAD 1983 UTM Zone 12N
Created February 2013 by Anne Huth and Elia Tapia

This interpolated grid was produced by WorldClim (www.worldclim.org) and was created from the integration of monthly precipitation from weather stations around the globe and from a large number of sources, including GHCN, WMO, FAOCLIM, CIAT, and other regional databases. Data records were numerous and restricted to a period of 1950 - 2000, where possible. Data were compared with previous studies, including PRISM and Daymet for accuracy asessment.

Figure 3.6 Monthly Average Precipitation in the Month of January in the San Pedro Binational Basin.

3.3. Surface Hydrologic System

Several sections of the San Pedro River are perennial within the study area; the total length of the river within the study area is 62 km in Arizona and 44 km in Sonora (TNC, 2010). The Upper San Pedro River is intermittent, but, depending on location, individual reaches of the river are perennial, intermittent, or ephemeral.

No stream gaging stations exist on the Mexican side of the BSPB; however, the United States has records from a number of stations. The Palominas station (09470500) located five kilometers from the international boundary had an annual average runoff of 0.84 cubic meters per second (m^3/s) for the period from 1951 to 2010. Other gaging stations have records that range from a few years to one hundred years, the longest such being the gage at the San Pedro River at Charleston (09471000) with measurements beginning in 1904. As the result of this long, nearly continuous record, many hydrologic studies carried out in this region use the Charleston gage to study regional and historical variations. The Charleston gage is located 14 km south of the point where the San Pedro River discharges from the study area; the drainage area upstream of the gage is about 3,200 km^2, 56% of which is in Mexican territory and 44% in U.S. territory (Pool and Coes, 1999).

Additional streamflow gaging records are available for streams in the Huachuca and Mule Mountains and in several of the larger low-elevation tributaries to the San Pedro River such as Walnut Gulch (Stone et al., 2008) and the Babocomari River (USGS gages 09471400 and 09471380). Downstream, north of the Charleston gage, are the confluences of the Babocomari River and Walnut Gulch with the San Pedro River. The headwaters of the intermittent Babocomari River are on the northwest side of the study area in the Huachuca Mountains, near the community of Canelo, Arizona. Walnut Gulch is an ephemeral stream that drains the north side of the Mule Mountains and is located near the town of Tombstone, Arizona.

The most complete historical data in the basin come from the gaging station at Charleston that has operated since 1904, although it was moved slightly several times prior to 1942 (Pool and Coes, 1999). Thomas and Pool (2006) compared Charleston gaging station data with various factors in the SVSA after accounting for precipitation trends to explain the 50% decrease in annual flow measured during the 20th century. They concluded that an increase in upland and riparian vegetation in the SVSA was likely a major factor affecting the decline in flow. Groundwater pumping had a mixed influence on trends at Charleston that was dictated by the location and amount of groundwater pumped (Thomas and Pool, 2006). Kennedy and Gungle (2010) analyzed baseflow at the Tombstone gage (09471550). Median baseflow during the period 1997 to 2009 was found to be 3.55 hm^3. They found that baseflow is derived from the regional and alluvial aquifers with the majority occurring during the period November through May. The river dries out at other times of the year when ET exceeds groundwater discharge to the gaged reach. Baseflow was strongly correlated with mean-daily flow during the previous October and precipitation in December and January. All metrics calculated indicate declining baseflow over the period of record (metrics include total baseflow, start and end dates, the number of days of base flow, the 25th percentile mean daily flow, and the number of days of zero flow). Gungle et al. (*In review*) conducted an analysis of baseflow at four gages: Palominas (09470500), Charleston (09471000), Lower Babocomari (09471400), and Tombstone (09471550). They found a decline in streamflow at all four gaging stations.

According to the Strahler classification system (Strahler, 1957), most of the main tributaries of the San Pedro River are of order 4-7. The river itself ranges from 4 to 6. It is of order 6 in the main transboundary reach. It reaches a maximum stream order of 7 in the reach between the confluence of the Babocomari River and the northern boundary of the study area (Figure 3.7).

3.4. Terrain Slopes

In order to determine the slopes in the San Pedro Binational Basin, the USGS NED database (Gesch et al., 2009) and the Spatial Analyst tool in ArcMap 10.0 were used to determine the percentage of slopes in the area, which vary from 0 to 65°. The steepest slopes are found east of Cananea in the Sierra Los Ajos and in the Huachuca Mountains in Arizona (Figure 3.8).

3.5. Land Cover and Use

The primary land uses in the SVSA are domestic, commercial, industrial, and agricultural. Most of the land in the SVSA belongs to the federal and state governments (ADWR, 2009). The Fort Huachuca military base covers almost 30,000 hectares and, mostly through leases, there is access to 12,000 additional hectares for its operations. The U.S. Forest Service (USFS) manages extensive lands in the mountains and adjacent areas, where the uses include recreation, livestock and timber production. Another federal agency, the Bureau of Land Management (BLM), also controls a significant percentage of the Arizona region, including the SPRNCA, which covers about 23,000 hectares. The state government also controls a large percentage of the land on the Arizona side. Although these areas of Arizona are used primarily for private livestock, they are part of a state trust from which the economic profits are used to support public schools. Boykin et al. (2008), created an updated map of land cover and use in the San Pedro Binational Basin (Fig. 3.9). Land use in Sonora is primarily for agriculture, tourism, and mining. Portions of the southeast corner of the watershed lie in the Ajos-Bavispe National Forest Reserve and Wildlife Refuge. Figure 3.10 shows the land ownership data for the SVSA. Land ownership in the Arizona portion of the basin is primarily state, private, or federal (Fort Huachuca military reserve, National Forest, or BLM).

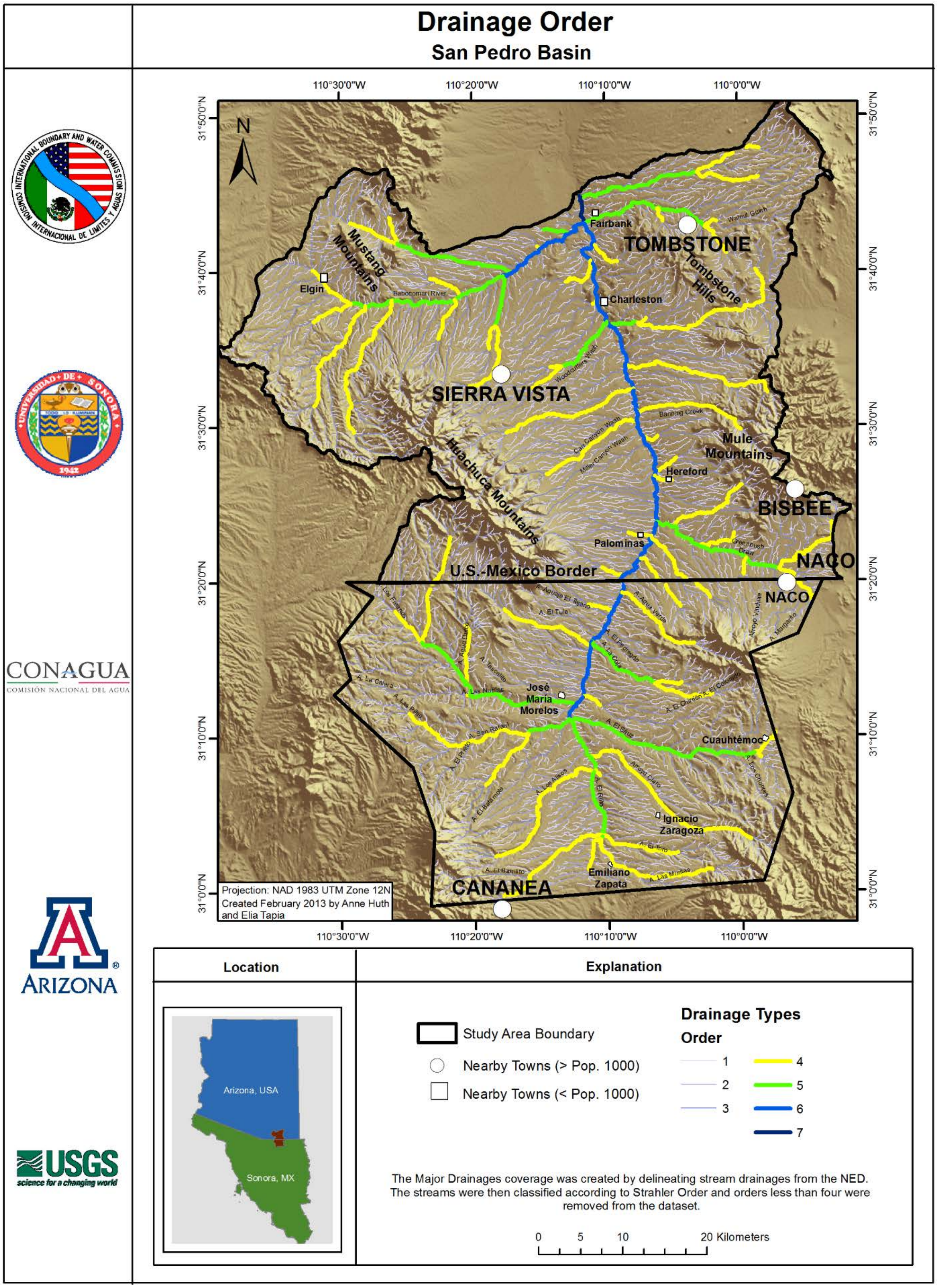


Figure 3.7 Drainage Types in the San Pedro Binational Basin.

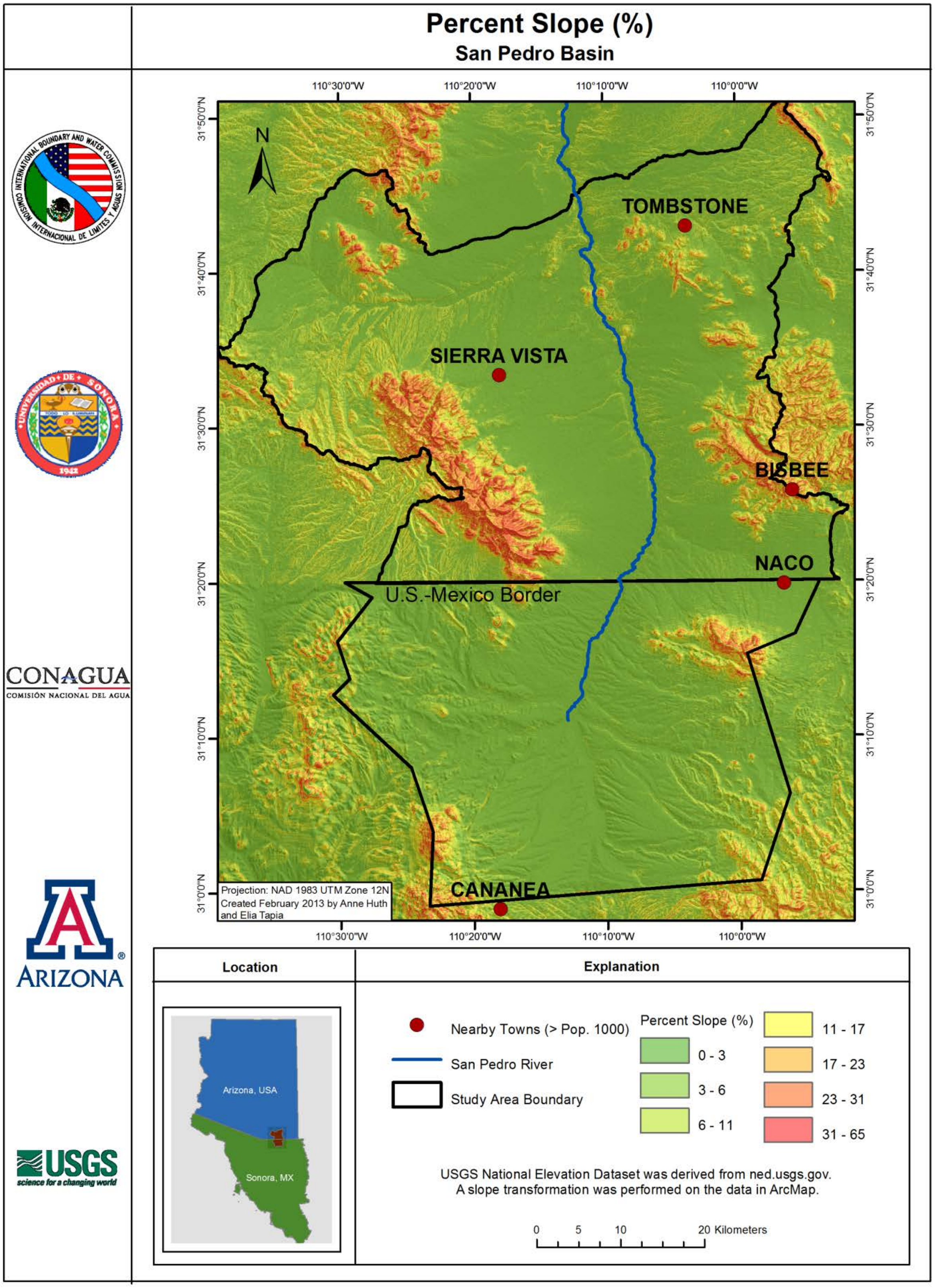
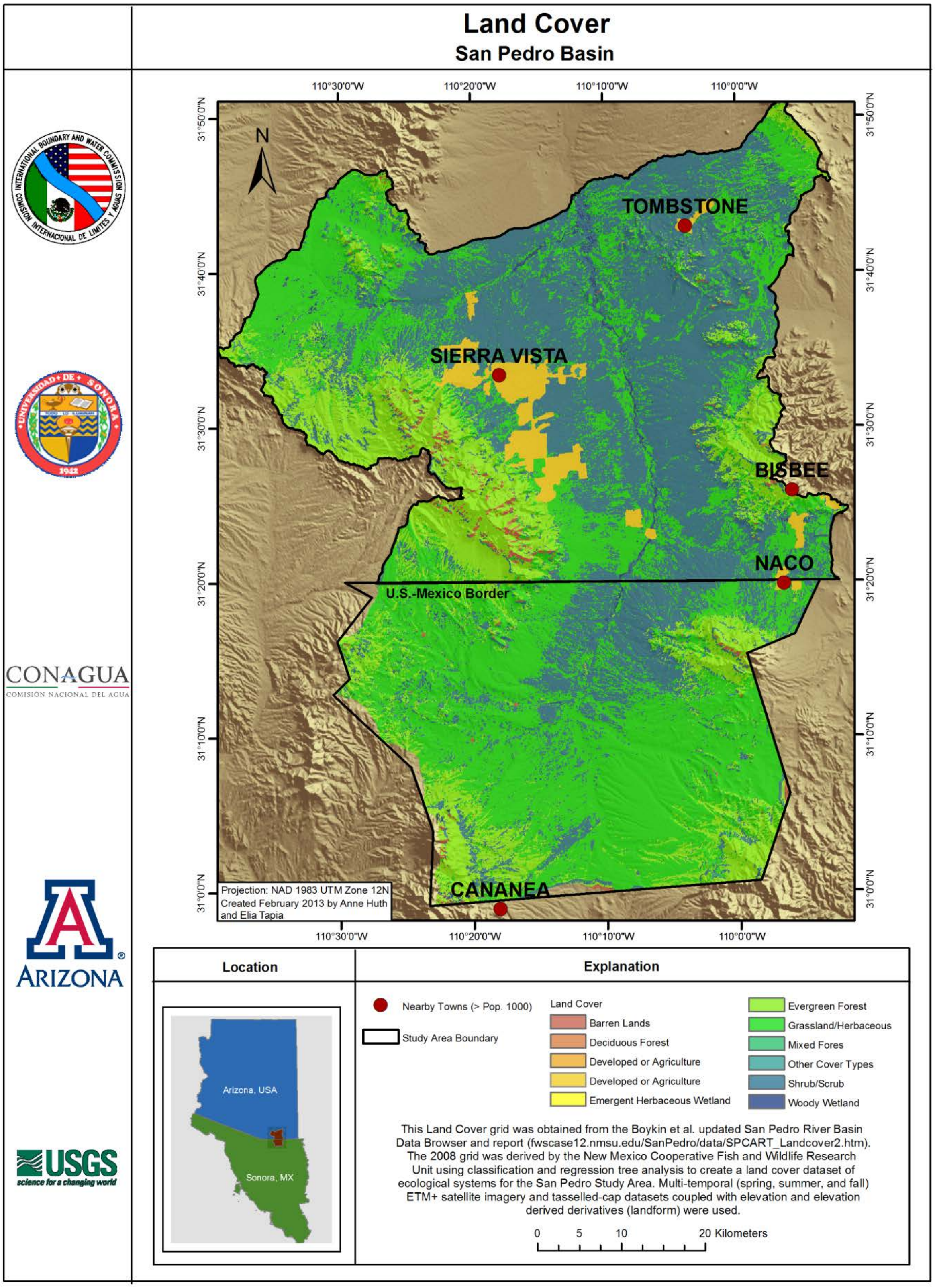


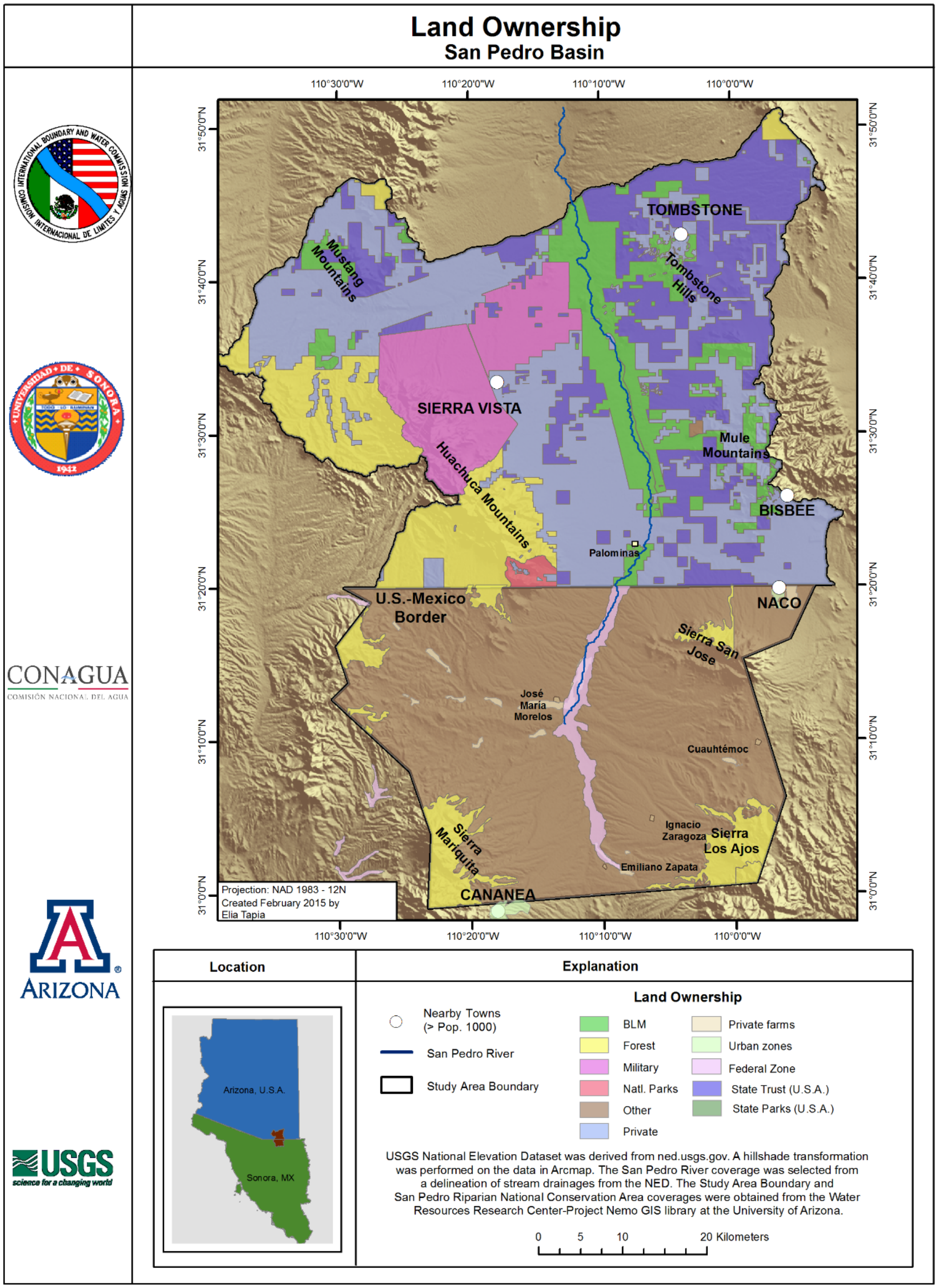
Figure 3.8 Slopes in the San Pedro Binational Basin.



Projection: NAD 1983 UTM Zone 12N
Created February 2013 by Anne Huth
and Elia Tapia

This Land Cover grid was obtained from the Boykin et al. updated San Pedro River Basin Data Browser and report (fwscase12.nmsu.edu/SanPedro/data/SPCART_Landcover2.htm). The 2008 grid was derived by the New Mexico Cooperative Fish and Wildlife Research Unit using classification and regression tree analysis to create a land cover dataset of ecological systems for the San Pedro Study Area. Multi-temporal (spring, summer, and fall) ETM+ satellite imagery and tasselled-cap datasets coupled with elevation and elevation derived derivatives (landform) were used.

Figure 3.9 Land Cover and Use in the San Pedro Binational Basin.



USGS National Elevation Dataset was derived from ned.usgs.gov. A hillshade transformation was performed on the data in Arcmap. The San Pedro River coverage was selected from a delineation of stream drainages from the NED. The Study Area Boundary and San Pedro Riparian National Conservation Area coverages were obtained from the Water Resources Research Center-Project Nemo GIS library at the University of Arizona.

Figure 3.10 Land Ownership in the San Pedro Binational Basin.

4. CONCEPTUAL GEOLOGIC MODEL

4.1. Regional Geologic Context

The geologic units in the BSPB are the product of a complex tectonic evolution; the diversity of these tectonic events and the deformations experienced produced a region with relatively large geological complexity.

Within the northeast portion of Sonora and the southeast portion of Arizona, the oldest rocks form a Precambrian basement characterized by the Pinal Schist (1680 million years before present (Ma)) and mesoproterozoic granitic intrusions, which is covered by sedimentary platform sequences, mainly carbonates, deposited throughout almost the entire Paleozoic. These Precambrian-Paleozoic rocks were initially considered to be part of the basement of the Pinal block by Haxel et al. (1980).

The oldest rocks from the Mesozoic within this region are represented by a Jurassic-age volcano-sedimentary sequence, which is exposed mainly in the Huachuca Mountains in Arizona and in the Mariquita Mountains in Sonora. The sequence is dominated by rhyolites and rhyolitic lahars that are intercalated with layers of quartz sandstone. Tectonically, these rocks represent the development of a continental volcanic arc with deposition of sand dunes during the Jurassic (Riggs and Haxel, 1990); they also correspond to the block defined by Haxel et al. (1980) as a region that extends from south-central Arizona to the north-central portion of Sonora, where volcanic and intrusive rocks are part of the Jurassic continental magmatic arc.

Cretaceous-Tertiary rocks are widely distributed in both portions of the BSPB and represent the product of a series of geological processes that took place during this time. The opening of the Gulf of Mexico as part of the evolution of a triple point (Rueda-Gaxiola, 2004) and the development of intra-arc basins in the late Jurassic (Busby et al., 2005), allowed these basins to be reached by the large Early Cretaceous marine transgression, generating the sedimentation found in the detrital-carbonate rocks of the Bisbee Group (Ransome, 1904; Dickinson et al., 1986; Gonzalez-Leon et al., 2008). During the late Cretaceous, this sequence was affected by the Laramide Orogeny developing wide folds with axes oriented northwest-southeast and a series of thrusts. In this same time period, the basins were created into which the Cabullona Group (Taliaferro, 1933) and the Fort Crittenden Formation (Epis, 1956) were deposited, represented by a dominantly detrital volcano-sedimentary sequence that was deposited in continental fluvial-lacustrine environments (González-Leon and Lawon, 1995). Synchronously with the deposit of the Cabullona Group, farther to the west a continental magmatic arc developed, also known as the “Laramide Arc”, which in this region is represented by a series of granite-granodioritic intrusions that affected pre-tertiary rocks, including their andesitic-dacitic volcanic cover, called the Mesa Formation in Sonora (Valentine, 1936; Valencia et al., 2006); this lithological association also outcrops in the Huachuca Mountains in Arizona (Drewes, 1980).

The primary effect of the migration of the magmatic arc toward the interior of the continent with its subsequent movement toward the trench, was the volcanism of the Sierra Madre Occidental during the Oligocene and early Miocene. This pattern of migration has been acknowledged for some time for the southwest part of the North American Cordillera between Late Cretaceous and the present (Damon et al., 1983). These products in the study region are mainly represented by the emplacement of rhyolitic intrusive (?) and ignimbrite extrusive (?) volcanic rocks.

The most important tectonic activity to which this region of northeast Sonora and southeast Arizona has been subject during the Middle Tertiary through the Holocene is intraplate extension. The most important effects produced by this extensional event are a series of continental basins bounded by normal faults, whose sedimentary fill, for those developed in Sonora, is represented by conglomeratic sequences that include synchronous volcanic activity (Báucarit Formation). At the end of the Miocene, the initiation of the Basin-and-Range regional structure occurred (Ferrari et al., 2005; Henry and Aranda-Gómez, 2000).

4.2. Stratigraphy

The geology of the region in which the aquifer is located within the BSPB is represented by intrusive, metamorphic, volcano-sedimentary, sedimentary, and volcanic rocks, with a stratigraphic record ranging from Mesoproterozoic to Quaternary. In order to simplify the mapping and description of these units on both sides of the border, we propose a series of informal lithostratigraphic and lithodemic units broadly encompassing those that have similar lithology and age (Figure 4.1).

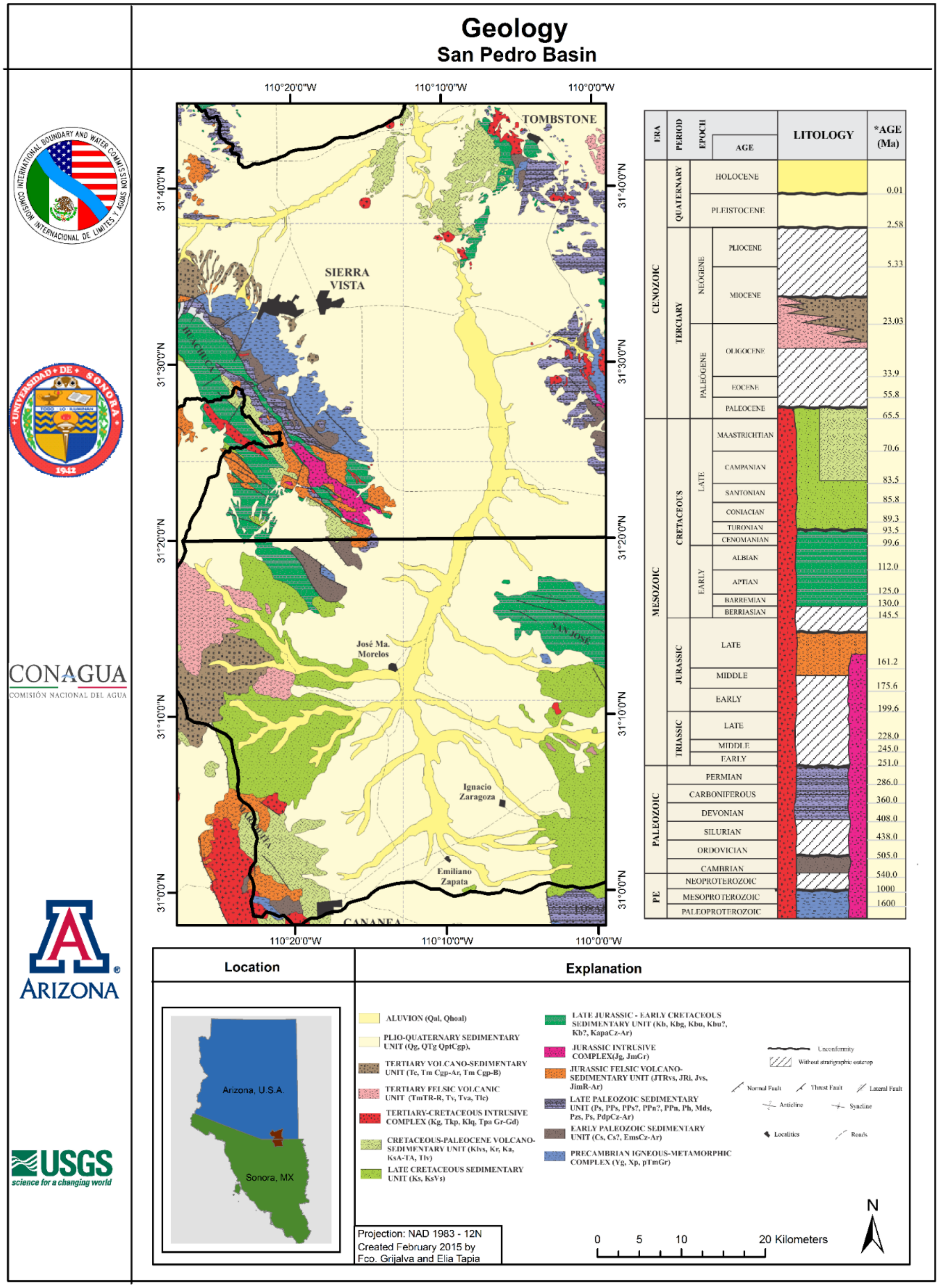


Figure 4.1 Geology in the San Pedro Binational Basin.

Precambrian Igneous-Metamorphic Complex (TmGr, Yg, Xp)

This unit is proposed to include all those outcrops of igneous and metamorphic rocks of Precambrian age that occur within the BSPB.

For the Mexican portion, an intrusion is included **(TmGr)**, whose outcrops occur on the northeast flank of El Caloso Peak, west of the city of Cananea, northwest of the Sierra Los Ajos, in the northern portion of the Sierra San José, and an isolated outcrop south of this location. This intrusion, also called the Cananea Granite by Emmons (1910) and Valentine (1936), is characterized by a light gray to pink weathered color, a phaneritic texture, whose mineral composition is dominated by quartz, feldspar, biotite, muscovite, hornblende, and iron oxides, with crystals of feldspar that can be larger than 1 cm in diameter. Locally there is hydrothermal alteration and silicification/sericitization, and it is cut by andesitic dikes and quartz veinlets (Sierra San José). Generally, it is considered that this granite forms part of the series of Precambrian anorogenic intrusions with a composition that varies from granite to granodiorite, and that extends throughout southwestern Arizona and northern Sonora with an age range between 1425-1475 Ma (Anderson and Silver, 1977).

For the U.S. portion of the basin, outcrops of this unit are represented by two dominant lithologies. The first is a hornblende-biotite granodiorite with phaneritic texture **(Yg)** exposed in the Tombstone hills, and more widely in the eastern portion of the Huachuaca Mountains; it correlates with the Johnny Lyon Granodiorite of the Mesoproterozoic in the Little Dragoon Mountains located farther to the north of the basin. The second is a sequence of schists and slates **(Xp)** from the Pinal Schist Formation identified in southeastern Arizona, which has as its protolith greywacke, shale, siltstone, and conglomerate lenses, as well as rhyolitic flows, amphibolite and chlorite schist lenses derived from basic volcanic rocks. This latter lithology crops up on the northern side of the Huachuca Mountains and near Tombstone.

Early Paleozoic Sedimentary Unit (EmsCz-Ar, Cs)

This informal unit is proposed to characterize a sequence of detrital-carbonate rocks of Cambrian age that have localized outcrops within the Mexican portion of the basin (González-León, 1986) and a detrital sequence exposed on the U.S. side.

The outcrops on the Mexican side are west of the city of Cananea, east of El Tejano Peak in the Tule Mountains. At these locations, the unit consists of medium-grain sandstone with sub-rounded to rounded quartz grains cemented by silica, with thin to medium stratification and crossbedding **(EmsCz-Ar)**. The thickest occurrence of this sequence is represented by a brown to gray colored limestone with interbedded siltstone; it has thin to very thin stratification containing mud cracks and trilobites (*Arapahoia sp.*) fossils. It also has a gray oolitic limestone with medium to coarse stratification, and another light gray limestone with intercalations and lenses of siltstone in very thin layers and remains of trilobites (*Tricrepicephalus sp., Llanoaspis sp., Coosella sp.*, and *Coosia sp.*). Based on this fauna, this unit is assigned to Middle-Late Cambrian, and correlates with the Abrigo Limestone of southeastern Arizona (González-León, 1986).

For the U.S. portion of the basin, outcrops of this unit are represented by the lithologies of the Middle Cambrian Bolsa Quartzite **(Cs)**, which are mainly in the eastern portion of the Huachuca Mountains, southern portion of the Mule Mountains, and in the vicinity of Tombstone. This unit consists of light gray quartz sandstone with local intercalation of layers of light reddish to purple gray conglomerate, shale, and limestone.

Late Paleozoic Sedimentary Unit (PdpCz-Ar, Ps, PPs, PPs?, PPn, PPn?, Ph, Mds)

This unit is included to group sequences of sedimentary rocks, mainly limestone and Devonian-Permian sandstone that surface in the main topographic highs that define the BSPB.

Within the Mexican portion of the basin, the main outcrops are in the Caloso and Tejano de la Sierra del Tule peaks (González-León, 1986), very close to the border between Sonora and Arizona, as well as towards the southeastern basin boundary, representing the northernmost outcrops in the Sierra Los Ajos. The basal sequence is represented by thin to medium stratified fossiliferous rocks containing abundant stromatoporoids (*Amphipora sp.*, and *Actinostroma sp.*), bryozoans, corals and silicified brachiopods from the Late Devonian.

Lying unconformably over the previous sequence of carbonate rocks, there are thin to thick strata with brachiopods and coral fauna from the Tournasian (Mississippian) age, and massive strata interbedded with thin layers containing abundant Pennsylvanian fusulinids **(PdpCz-Ar)**. The top of this Paleozoic unit is an incomplete Permian sequence, composed of sandstones and reddish-brown shales containing various fossils such as gastropods, brachiopods, and foraminifera including fusulinids. These sedimentary sequences described above correlate to the Martin, Escabrosa, Horquilla, and Earp formations respectively, which appear in various parts of southwestern Arizona (González-León, 1986).

In the U.S. portion of the basin, this unit is represented by several outcrops of Paleozoic lithostratigraphic units that are distributed in the mountains of the basin. In the northern part of the Huachuca Mountains and the Mule Mountains and much of the Mustang Mountains, there are outcrops of Permian formations (Rain Valley, Scherrer, and Concha), generally consisting of dolomitic limestones and cherts, dolomites, massive sandstones, and red siltstones **(Ps)**. In the locations stated above, detrital-carbonate units of Pennsylvanian-Permian **(PPs, PPs?)** also are exposed, including dolomites interbedded with limestones and reddish shales (Epitaph Dolomite), black limestones interbedded with sandstones and shales (Colina Limestone), and limestones and dolomites in thin and massive layers that weather to a reddish or orange color (Earp Formation). In the southern portion of the Huachuca Mountains, there are also detrital-carbonate outcrops **(PPn, PPn?)** that are found among the Rain Valley, Scherrer, Concha, and Epitaph Formations.

Both in the Tombstone Hills and in the northern portion of the Huachuca Mountains, the Pennsylvanian Horquilla Formation is exposed, which includes blue-gray limestone interbedded with thin layers of reddish shale **(Ph)**. In the eastern highlands of the Huachuca Mountains, and in the northern portion of the Mule Mountains, the main outcrops of the oldest sequence of this unit are found, characterized by Devonian-Mississippian formations **(Mds)**, which, in general, have a lithology that is represented by dark gray limestone and pinkish gray calcareous shale (Martin limestone), and light gray coarse-grain limestone with abundant fragments of crinoids (Escabrosa limestone).

Jurassic Felsic Volcano-Sedimentary Unit (Jim R-Ar, JRvs)

The unit is proposed to include an interstratified sequence of volcanic rocks, sandstones, agglomerates, basalt flows, sills, and intermediate composition domes of Jurassic age.

On the Mexican side of the basin, the main outcrops of this unit are in La Mariquita peak, as well as some other areas near the international border (Valentine, 1936). In these locations, a calc-alkaline volcano-sedimentary sequence appears consisting of rhyolitic tuffs and flows, interbedded with agglomerates, andesites, and dacites **(Jim R-Ar)**. While it is true that no radiometric ages for this sequence exist, Wodzicki (2001) considers it to be Middle to Late Jurassic (165-150 Ma).

The outcrops in the U.S. portion of the basin include a sequence of tuffs and rhyolite flows intercalated with aeolian sandstones, andesitic flows, and terrigenous red beds **(JRvs)**, which outcrop largely in the Canelo Hills and the southern portion of the Huachuca Mountains, as well as extensively in the Mustang Mountains north of the basin.

Jurassic Intrusive Complex (JRi, Jg)

The unit is proposed to group together a series of intrusive hypabyssal bodies that mainly outcrop on the U.S. side. There are, however, several outcrops of intrusive rocks that are too small to map at this scale that could be considered as part of this unit, appearing in the Sierra San José as dikes and sills, as well as on the base of the western flank of the Sierra Los Ajos.

In the Huachuca Mountains, very close to the border, there is an intrusive body of granitic composition **(Jg)** that is affecting the Paleozoic, Precambrian, and Jurassic sequences. Also, in the southern portion of the Canelo Hills, there are outcrops of plutons, dikes, and sills of granitic composition **(JRi)** affecting the Jurassic volcano-sedimentary sequence.

Late Jurassic - Early Cretaceous Sedimentary Unit (KapaCz-Ar, Kb, Kb?, Jbg, Kbu, Kbu?)

This unit is intended to include the outcrops of sedimentary rocks from the Late Jurassic-Early Cretaceous, which on both sides of the border are represented by the formations of the Bisbee Group (Dumble, 1902; Ransome, 1904; González-León, 1994).

Outcrops of this unit within the Mexican portion of the basin are located towards the northeast, and mainly in the Sierra San José, where Morita and Mural (González-León, 2008) formations are the predominant exposures **(KapaCz-Ar)**. Here there is a detrital-carbonate sequence that is exposed consisting of alternating limestones, sandstones, siltstones, and shales. The limestones are a gray color with medium to coarse stratification, bioturbation, and a fossil content dominated by pelecypods, ostreas, gastropods, rudists, corals, echinoderms, algae, and microfauna (*dictyoconus* sp., *Textularia* sp., Miliolids, *Orbitolina* sp., and planktonic foraminifera), faunal association typical of Aptian-Albian (Araujo-Mendieta and Estavillo-Gonzalez, 1987). There are also dark gray argillaceous limestones with thin stratification. The sandstone is reddish brown to reddish purple, fine to medium grain with medium stratification. The siltstone is light brown and calcareous, with laminations, and the shale is reddish brown with light green variations and thin stratification.

On the U.S. side of the basin, there are outcrops of this unit in the Huachuca Mountains and in the Tombstone Hills. In the first location, the dominant lithology are the Glance Conglomerate outcrops **(Jbg)**, which have a composition of clasts and may contain Paleozoic limestone and sandstones, shale, and Precambrian granites and schists, and Jurassic volcanic rocks; additionally there is a sedimentary sequence that, though not lithologically distinct, is equivalent to the upper units of the Bisbee Group **(Kbu, Kbu?)**. In the Tombstone Hills, there are shale and siltstone outcrops interspersed with sandstones, conglomerates, and limestones **(Kb, Kb?)**, also considered part of the Bisbee Group.

Late Cretaceous Sedimentary Unit (KsVs, Ks)

This unit is proposed to include all those outcrops dominated by Late Cretaceous sedimentary sequences that occur within the BSPB.

On the Mexican side of the basin, this unit is widely found dominating the outcrops lying to the west and east of the large fluvial valley developed in the center by the San Pedro River, with the most representative outcrops near the Ejido Cuauhtémoc. The representative lithostratigraphic unit is Cabullona Group **(KsVs)**, and generally consists of a light brown and light gray to green sandstone, fine-medium grained, locally coarse grained, with thin to medium stratification, mineralogically dominated by quartz, feldspar, mica, and iron oxides cemented by calcite; in some areas it appears as a tuffaceous sandstone. Also dominant are: 1) Dark brown shales that weather to yellowish-brown and light gray, and a whitish rhyolite, pseudostratified and slightly kaolinized tuffs with layers of green volcanic ash; 2) brown siltstones that weather to yellowish-brown, with medium stratification; 3) light brown and reddish brown conglomerates, with subrounded and rounded clasts of rhyolite, granite, tuff, and limestone in a sandy matrix; and 4) light gray andesite that is interbedded with tuffaceous sandstone and conglomerate. Based on paleontological studies, the Cabullona Group is assigned to the Late Campanian-Maastrichtian (Lucas et al., 1995).

Outcrops of this unit in the U.S. portion of the basin are restricted to the western portion of the Huachuca Mountains, where they are mainly represented by detrital sedimentary rocks **(Ks)**. These outcrops may correspond to the Fort Crittenden Formation in Arizona.

Cretaceous-Paleocene Volcano-sedimentary Unit (KsA-TA, Klvs, Kr, Ka, Tlv)

This unit is proposed to include a series of sequences that are predominantly volcano-sedimentary of intermediate composition, which include rhyolitic clastic and volcanic rocks.

In the Mexican portion of the basin, this unit is represented by the Mesa Formation **(KsA-TA)**, which is mainly exposed on the southwestern side of the Mariquita Mountains and in the outskirts of Cananea (Valentine, 1936). In these outcrops, the andesite is a greenish gray color, with porphyritic to aphanitic texture, and a mineralogical composition dominated by oligoclase-andesine, mica, apatite, iron oxides and altered minerals such as epidote, argillaceous minerals, sericite, chlorite, hematite, and calcite; some locations have latite facies. The andesitic tuff is greenish gray and light gray with purple tones, aphanitic-porphyritic texture, medium to coarse stratification, and interbedded with tuffaceous sandstones and agglomerates. The andesitic agglomerate is colored greenish gray, with clasts several centimeters in diameter made from intermediate composition rocks in a tuff matrix. The polymictic conglomerate presents a grey to greenish-brown color, with subangular and subrounded clasts of light grey-tan limestone, andesitic tuffs, andesites, and porphyritic rhyolites in a sandy matrix, whose clasts vary in size from gravels to blocks. The sandstone, found in medium layers intercalated with the previously described rocks, is medium-grained, well sorted, gray-violet and yellowish brown with greenish hues. The entire sequence shows effects from hydrothermal alteration such as propylitic, argillic, and sericitic oxidation. It is assigned to the Late Cretaceous-Paleocene from a radiometric dating of 69 ± 0.2 Ma (Wodzicki, 1995).

The outcrops of this unit on the U.S. side of the basin primarily have a northeast-southeast orientation in the Huachuca Mountains, and to the southwest of the Canelo Hills. In these locations the dominant lithology is andesitic to rhyolitic volcanic rocks that are intercalated with conglomerates and sandstones **(Klvs)**. Other important outcrops of this unit are in the eastern part of the Tombstone Hills, characterized by predominantly rhyodacitic Cretaceous tuffs **(Kr)**; in the same place, the unit also includes a series of andesitic-dacitic volcanic breccia **(Ka)**, as well as isolated outcrops of intercalated rhyolitic to andesitic flows, pyroclastic rocks and some clastic rocks **(Tlv)**, which have been dated at 57 Ma (Drewes, 1980).

Tertiary-Cretaceous Intrusive Complex (KsTpaGr-Gd, TeMz-qMz, Kg, TKp, Klq)

This unit is proposed to include a series of intrusive felsic bodies from the Late Cretaceous to Eocene (?) that surface on both sides of the BSPB.

Near the city of Cananea, mainly in the Mariquita Mountains, there are outcrops of a series of batholithic intrusions of granitic-granodioritic composition (**KsTpaGr-Gd**). The batholith varies in color from light gray-white to gray-green and pink; the texture is medium-grain phaneritic and porphyritic, consisting of K-feldspar, albite-oligoclase, quartz, biotite, with alteration minerals such as sericite, chlorite, and hematite. This Laramide batholith has been dated by several researchers, yielding ages of 64 Ma using U-Pb, Rb-Sr, and Sm-Nd methods (Wodzicki, 1995), and 64 ± 3 and 69 ± 1 Ma using the U-Pb method in outcrops from the Cuitaca region (Anderson and Silver, 1977).

Within this unit, a series of monzonitic and porphyritic intrusions of quartz monzonite composition **(TeMz-qMz)** are grouped together, which surface broadly around the Mariquita Mountains. The quartz monzonite appears as small apophyses intruding into the Laramide batholithic rocks and Jurassic-Cretaceous volcanic rocks; generally, it is altered so it is difficult to identify its mineralogy, however it has a quartz monzonite to granite composition, consisting of quartz, feldspar, and aphanitic biotite in a matrix of quartz and orthoclase. The quartz monzonite porphyries that surface in the Cananea area have a phlogopite K-Ar age of 59.9 ± 2 Ma (Damon et al., 1983). Other sub-volcanic rhyolitic bodies included within this unit have an age of 54.2 ± 2 Ma, dated near Cananea using the sericite K-Ar method (Steiger and Jäger, 1977).

These rocks are associated with porphyry copper mineralization of the María, Mariquita, and Milpillas deposits among others, which have significant hydrothermal alteration zones such as sericitization, argillization, silicification, oxidation, and propylitization.

On the U.S. side of the basin, primarily towards the eastern boundary, there is a series of stocks of granitic rocks that are intruding into the pre-Cenozoic sequences. These intrusions **(Kg)** are characterized by grey color, medium grain, and locally porphyritic rocks. Towards the eastern boundary, near the town of Tombstone, are outcrops of an intrusion in the form of small stocks, whose composition varies from monzonite to granodiorite **(Tlq)** and locally includes quartz-diorite and the associated mineralization; ages reported for these intrusions range between 70 and 76 Ma. Also in this portion of the basin there are outcrops of porphyritic and aplitic rocks **(TKp)**, primarily at the edges of the Mule Mountains.

Tertiary Felsic Volcanic Unit (TmTR-R,Tv, Tva, Tlc)

This unit is proposed to include the rhyolitic outcrops from the west central portion of the basin, mainly in the vicinity of Rancho Los Fresnos on the Mexican side, as well as others with rhyodacitic to andesitic composition appearing east of Tombstone, Arizona.

On the Mexican side, the unit is made of a rhyolitic tuff that is light gray with cream and light-gray tones; pseudostratified, it contains quartz, feldspar, plagioclase, and biotite crystals, and volcanic lithic fragments in a vitreous-crystalline matrix. Locally it has intercalations of brecciated and agglomeratic tuff. It also includes a gray rhyolite with spherulitic fluidal texture, consisting of quartz, glass, feldspars, iron oxides in a glassyspherulitic matrix **(TmTR-R)**. An age of 28 Ma obtained for this volcanic sequence (Floyd Gray, USGS, personal communication, 2012, unpublished data) and its stratigraphic position suggest that it corresponds with the Later Oligocene to the Middle Miocene.

On the U.S. side of the BSPB, and specifically east of Tombstone, there is a series of outcrops characterized by pyroclastic flows and rocks of rhyolitic to rhyodacitic composition, from pink to light gray in color, dated between 23 and 27 Ma **(Tv)**; there are also flows and pyroclastic rocks of andesitic-dacitic composition, and porphyries with the same composition, which together have ages between 24 and 39 Ma **(Tva)** (Drewes, 1980). Associated with the volcanic lithology in this same location, a reddish conglomerate and well rounded, non-volcanic clasts **(Tlc)**, which could eventually be included in the base of this unit because of its stratigraphic position (Gettings and Houser, 2000).

Tertiary Volcano-sedimentary Unit (TmCgp-Ar, Tc)

This unit is proposed to include a sequence of continental rocks dominated by conglomerates that have intercalations of sandstone and tuff, whose outcrops are predominantly associated with the topographic high points that delimit the western edge of the BSPB.

In the Mexican portion of the basin, this unit is represented by Báucarit Formation outcrops (Dumble, 1902; King, 1939), characterized by a light brown to reddish polymictic conglomerate, with thick stratification and sub-angular to sub-rounded clasts that vary in size, whose dominant composition is rhyolite, granite, andesite, and andesitic tuff within a sandy matrix, that in several outcrops is tuffaceous **(TmCgp-Ar)**. This conglomerate is intercalated with strata of coarse-grain sandstone with the same coloring. The outcrops that are characteristic of this formation include interstratifications of basalt coulees.

In the U.S. portion, major outcrops of this unit are located immediately adjacent to and on the basin side of the Huachuca Mountain range-front (Nicksville) fault (Drewes, 1980; Brown et al., 1966), and are represented by a well to moderately consolidated conglomerate with sub-rounded clasts **(Tc)**, which locally include some slip deposits and bodies of porphyritic tuffs and andesites. In Arizona, the Pantano formation is considered by some workers to be a correlative of this unit (Pool and Dickinson, 2007; Gettings and Houser, 2000). Generally this unit corresponds to deposits from alluvial and colluvial fans, and based on various radiometric ages obtained in both countries, the age of the sequence is considered Early Miocene to Middle Miocene.

Plio-Quaternary Sedimentary Unit (QptCgp, Qg, Qtg)

This unit is included to characterize a sequence of coarse sediments, gravels, and sands, whose outcrops are widely distributed in the center of the BSPB.

In the Mexican portion of the basin, there are lithologically variable terrigenous sediments, which consist of gravel, sand, and silt, normally in thick strata **(QptCgp)**. These sediments are found in the floodplains and the foothill areas.

On the U.S. side it is represented by gravels, sands, silts, and clay from alluvial, colluvial, and soil deposits; they are gray in color and have poorly rounded clasts of local origin **(Qg)**. This unit also includes some well sorted and rounded gravels beds **(Qtg)**. In this portion of the basin, these sediments are included as part of the Upper Basin Fill a well-known lithostratigraphic informal unit (Coes and Pool, 1999). In general, this unit discordantly covers the oldest rocks, and because of its stratigraphic position, it is considered to be from the Pliocene to the Holocene.

4.3. Structural Geology

The tectonic history of the region has been complex throughout the Phanerozoic. Compressional structures (thrusts and folds) generated during the early and middle Phanerozoic era (Drewes, 1980) were succeeded by the generation of larger, more pervasive normal faults and subsequently affected by regional stratigraphic discontinuities. The extensional structures within the BSPB appear as sets of faults with two preferential orientations, the first as a north-northwest-south-southeast system (Page et al., 2010), and the second oriented northeast-southeast. Locally in the Mexican portion (Sierra La Mariquita), normal faults are oriented approximately east-northeast-west-southwest. The normal faults from the first set are those that have the most nearly continuous lineaments with extents of up to 20 km near the Huachuca Mountains (Nicksville Fault (Wynn, 2006; Drewes, 1980)), and 15 km on the west flank of the Sierra Mariquita. On both sides of the BSPB, the sedimentary basin is bounded by these structures where the sediments that host the alluvial aquifer units were deposited.

4.4. Three-dimensional Geology of the Subsurface

One of the principal elements of a hydrogeological study is defining the conceptual model of subsurface geology. To create the model, direct information is required from wells drilled within the study area, as is indirect information obtained from airborne and terrestrial geophysical methods. The interpretation of the data obtained makes it possible to understand the fundamental elements needed to develop the conceptual model including: 1) the basin geometry, extent, and boundaries, defining the hydrogeological units that comprise it, and the structures that affect it; and 2) the characteristics of the sedimentary basin fill, as well as the systems of deposits they represent, which must include thickness, grain-size and lateral variations, hydraulic properties, barriers, and boundaries of the subsurface flow and hydrogeological basement.

In the BSPB, a series of geophysical studies have been published that aid in the determination of the structure of the basin, among them electromagnetic surveys (Bultman et al., 1999; Wynn, Gray, et al., 2003; Wynn, Mars, et al., 2003; Gray et al., 2005; Wynn, 2006; Bultman et al., 2006; Bultman and Gray, 2011), gravimetry (Gettings and Houser, 2000; Gray et al., 2004), and magnetics (Bultman et al., 1999; Wynn, Gray, et al., 2003; Wynn, Mars, et al., 2003; Gray et al., 2004; Wynn, 2006), as well as hydrogeological studies that include cross-sections and subsurface models (Brown et al., 1966; Bultman et al., 1999; Pool and Coes, 1999; Gray et al., 2005; Pool and Dickinson, 2007).

However, little work has been done on the subsurface characteristics of the Mexican portion of this basin with the exception of the two previously mentioned Gray et al. studies (2004 and 2007), which include data and analysis from a study developed for the Cananea mine that discusses the hydrogeologic properties of the San Pedro aquifer (Consultores en Agua Subterránea, S.A., 2000). Relevant to this discussion is the conclusion that there are a number of shallow subbasins in the San Pedro headwater in Mexico that range from 100 m near Cananea to 500 m near the U.S.-Mexico border. This information was integrated with data and analysis from the U.S. side of the border to aid in the definition of the subsurface structure of the BSPB binationally.

4.5. Depth to Basement and Structure

The Tertiary conglomeratic sequence **(Tc)** in U.S. territory and the Báucarit Formation on the Mexican side were emplaced during the Middle Oligocene to Middle Miocene. For the purpose of this paper these units are considered as part of the bedrock, given that they are lithified, tilted by a late extensional event, and faulted; they also are overlain by unconsolidated sediments that make up the BSPB regional alluvial aquifer.

Based on gravimetric and magnetometric data, Gettings and Houser (2000) proposed that the U.S. side of the BSPB is oriented northwest-southeast. By analyzing and interpreting these data to estimate depth to bedrock, they identified two main subbasins on the west side of the San Pedro River separated by a bedrock high under Sierra Vista. One subbasin is located to the north of the city, with depth to basement greater than 800 m, and another to the south located under the community of Palominas, where depth to basement is greater than 1000 m. It is important to note that these authors identify the base of the conglomeratic sequence **(Tc)** as the depth to basement. In addition, a subbasin to the northeast of Tombstone is interpreted as having a depth greater than 1100 m. Pool and Coes (1999) used seismic, resistivity, and cuttings logs of borehole to extend this information to other parts of the basin.

Within the USPSS, the gravity survey carried out for this study consisted of a total of 96 readings at a spacing of between 1 and 2 kms, taken with a Scintrex CG-5 meter. Conventional methods were applied to each one of the readings in order to correct for latitude, tides, instrumental drift, and free air, and thus to calculate the simple Bouguer anomaly. Once this anomaly was obtained, the database was imported into the Geosystem WingLink® software for interpretation and gravimetric modeling. The main objective of this gravity survey was to develop a general view of basement geometry. When carrying out the gravimetric interpretation, the main interest is to analyze the effect of the more surficial masses (residual anomaly), minimizing the effect produced by deeper masses; for this reason, the first step of this modeling consisted of carrying out the separation of regional-residual anomalies. One of the most common techniques to make the regional-residual separation is to use a polynomial fit, where local anomalies remain as the residue of the separation (Camacho et al., 1996). In the case of the San Pedro basin, this separation was obtained by applying a second order polynomial filter to the Bouguer anomaly.

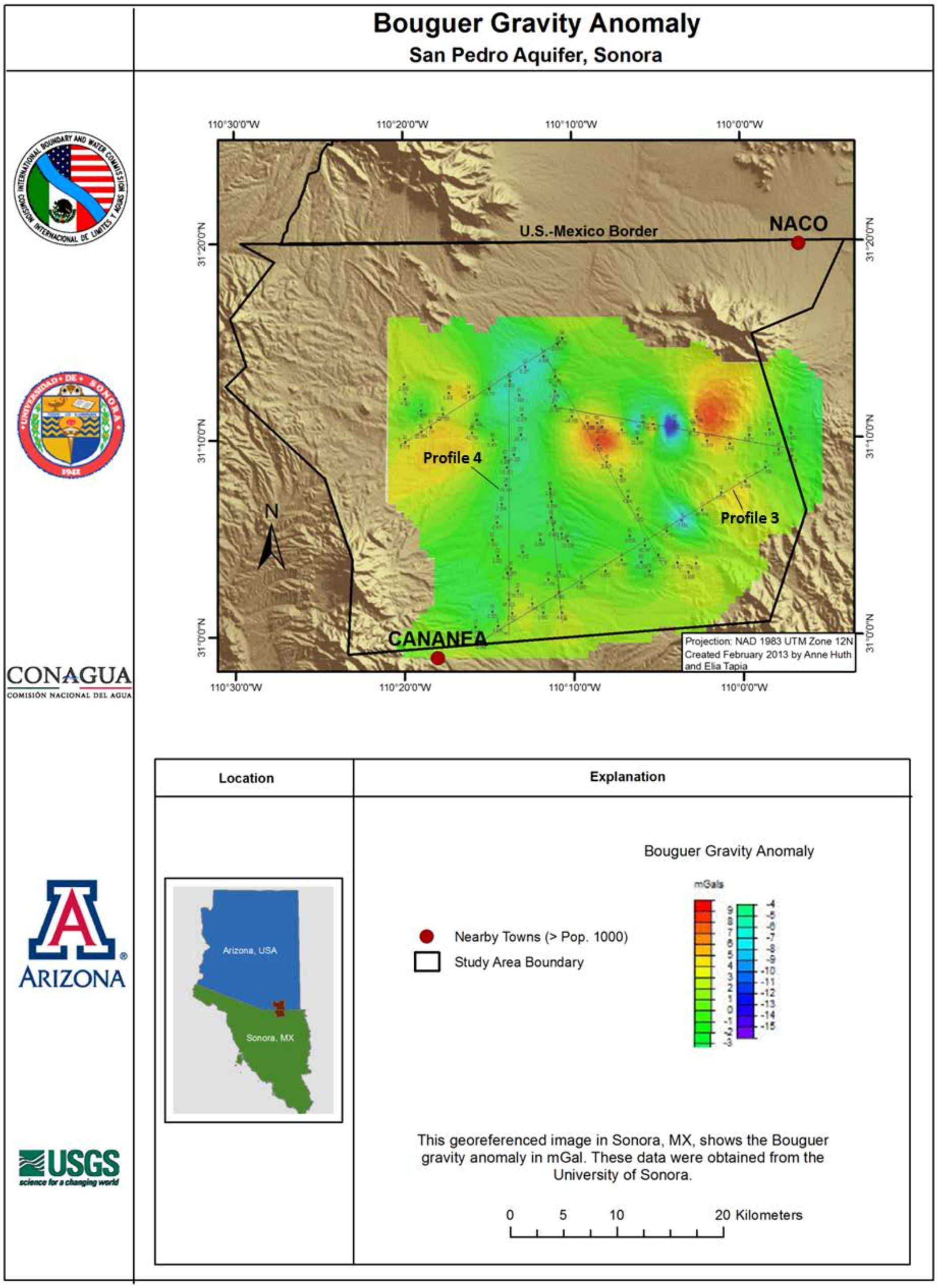


Figure 4.2 Map of Residual Anomaly on the Mexican Side of the San Pedro Binational Basin. Profiles 3 and 4 are shown as gravity models in Figure 4.4.

The Bouguer anomaly map (Figure 4.2) makes it possible to clearly distinguish several significant negative gravity anomalies (gravimetric lows), which here are interpreted as depressions in the bedrock. The first of them is located in the western portion of the USPSS, oriented north-northwest-south-southwest, and has anomalies between -6 and -9 mGals. Another is located in the northeast quadrant, where although the spatial extent of the zone of anomalies is not wide, it is the area with the lowest values, as low as -15 mGals. A third locally confined low is found south of this, with values between -7 and -10 mGals. The densities used for the lithology defined as basement in the model of the gravimetric profiles were derived from Gettings and Houser (2000). They are as follows: granite basement (2.67 g/cm^3), and volcano-sedimentary basement (2.55 g/cm^3), while for the sedimentary basin fill a density of 2.00 g/cm^3 was used. It is important to note that the densities were taken from the table of average values presented by Telford et al. (1984). For the interpretation of the depth to basement in the USPSS, the *top* of what herein is labeled the volcano-sedimentary basement was taken as the boundary, which includes, in addition to the older sedimentary and volcanic sequences, the Báucarit Formation, equivalent to the Oligo-Miocene unit **(Tc)** for the U.S. portion. Note that this is different from the interpretation followed by Gettings and Houser (2000) as described near the beginning of this section.

Modeling of gravimetric profiles allowed the depth to basement at each of the stations to be defined; from two of these profiles (Figure 4.3), it can be established that the depth to basement is highly variable, and that the greatest interpreted depths, between 430 and 510 m, are found at the northern boundary between stations 32 and 34 (Profile 4), near the town of José María Morelos. Also, the basement has the geometry of tectonic lows limited by structural highs, where the most important uplift is between stations 11 and 13 (Profile 3) located toward the southern portion of the basin along Highway 2. Closer to Cananea near the southern boundary of the basin, drill logs provide evidence of an alluvial-fill subbasin bounded by to the east and west by conglomerate and crystalline bedrock (Pool et al., 2005; Consultores en Agua Subterránea S.A., 2000). The subbasin is likely greater than 500 m deep.

In general, based on the information presented above it can be concluded that the basin is bounded to the west by a normal fault oriented north-northwest-south-southeast, with a high-angle dip to the east-northeast, and on the east side of the basin, there is a series of buried faults with dips to the west-northwest (Wynn, 2006; Drewes, 1980; Floyd Gray personal reference). Faults that are mapped in the Huachuca Mountains and northern Mexico (Cerros El Tule) are suspected to extend across the northern San Pedro Basin to Sierra San José, coincident with a structural high just south of the U.S.-Mexico Border.

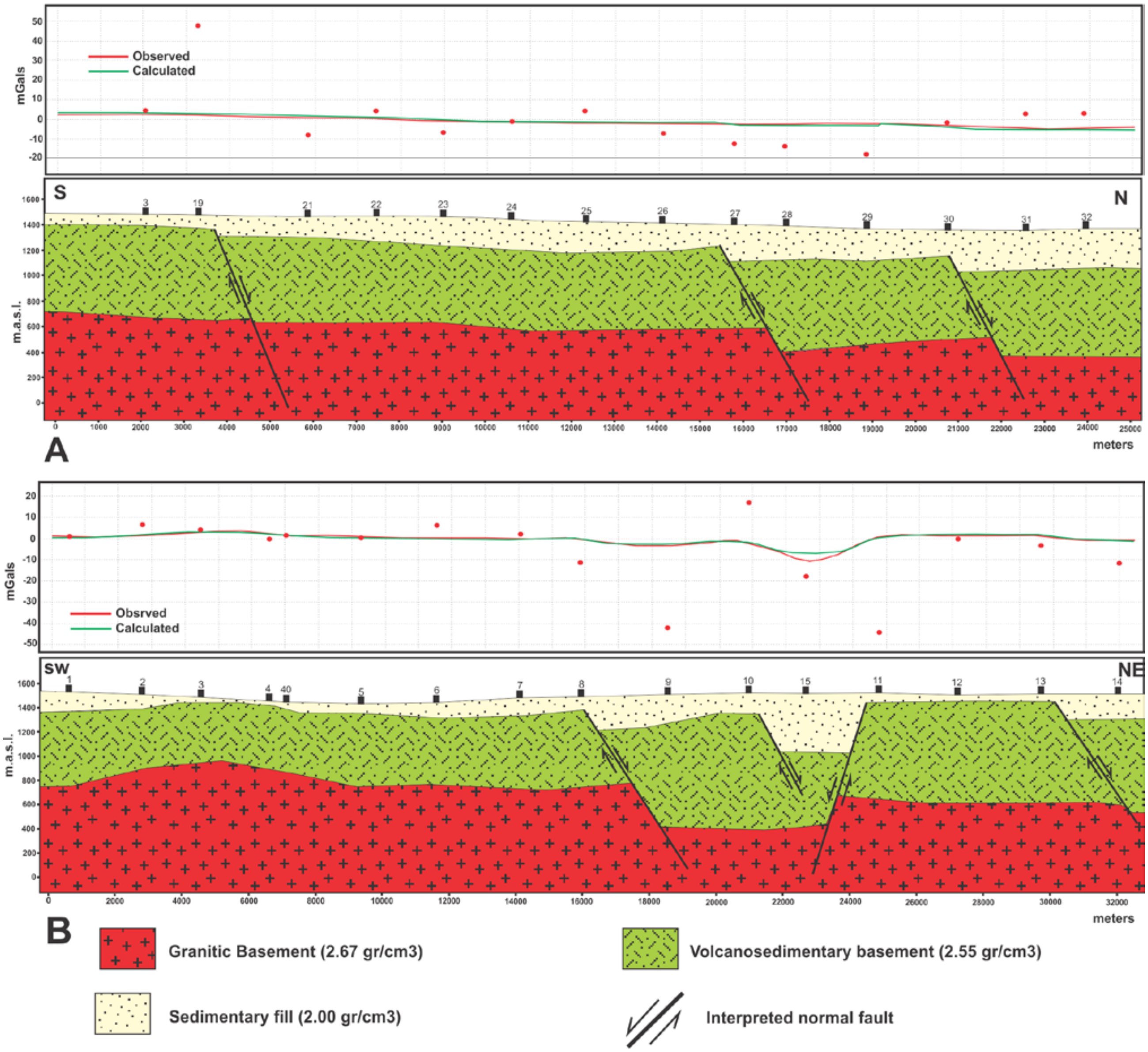


Figure 4.3 Gravimetric Profiles on the Mexican Side of the Binational San Pedro Basin: A) Profile 4 oriented north-south; B) Profile 3 oriented west-southwest-east-northeast. The location of the profiles is shown on Figure 4.3.

4.6. Characteristics of the Sedimentary Fill

The sedimentary fill within the U.S. portion of the BSPB has been divided into two informal units, called Lower Basin Fill and Upper Basin Fill (Brown et al., 1966), which were deposited in structural basins between the mountains during the late Miocene-Plio-Pleistocene. Although in the Mexican portion of the basin there are no detailed studies on the stratigraphy of these sediments which also represent the primary regional alluvial aquifer, the physical characteristics obtained from the lithologic descriptions of wells (Consultores en Agua Subterránea, S.A., 2000) suggest an equivalence with the division presented in the United States.

With data obtained from the lithological description of wells, vertical electrical soundings, and other geophysical methods (Pool and Coes, 1999; Consultores en Agua Subterránea, S.A., 2000; Fleming and Pool, 2002; Condor Consulting, 2001, 2003), Pool and Dickinson (2007) constructed continuous cross-border surfaces delineating the top and bottom of the silty-clay zone within the Upper Basin Fill. They estimated it to be from 10 to 300 m thick, and laterally confined to within a few kilometers of the San Pedro River channel. Based on these data, the elevations of this zone vary between 1400 and 1100 m.a.s.l.

Sixty-five transient electromagnetic soundings (TEM) were done in the Mexican side of the basin, trying to obtain an image of the resistive conditions of its subsurface, and these data were correlated with the granulometric characteristics of the basin fill and its basement. Particularly for this project, the TEM technique, consisted of using a loop or coil which was built by a wire in the shape of a square, with dimensions of 150 x 150 m (coil area 22,500 m^2), in a so-called arrangement "Matching Loop"; it uses a coil which alternately acts as a transmitter and receiver, with a resistance of 2.1ohms in the circuit, which was a Canadian manufactured 110 wire cable. These characteristics of the arrangement achieved a current intensity varying between 7 and 8 amp, this is to achieve a 600 m depth of investigation. The analysis of the modeled profiles with the results from the TEMs done on the Mexican side of the basin make it possible to corroborate the presence of this silty-clay zone, since the resistive characteristics of the clay (<12 Ohm-m) are clearly detected on several of the profiles. The west-east-10 resistivity profile, oriented west-east on the southern boundary of the Mexican portion (Figure 4.4, Figure 4.5), shows that the lower limit of the clay zone has an elevation of about 1100 m.a.s.l., while the upper limit is about 1400 m.a.s.l., which is consistent with the elevations submitted for these limits by Pool and Dickinson (2007) in the same portion of the basin.

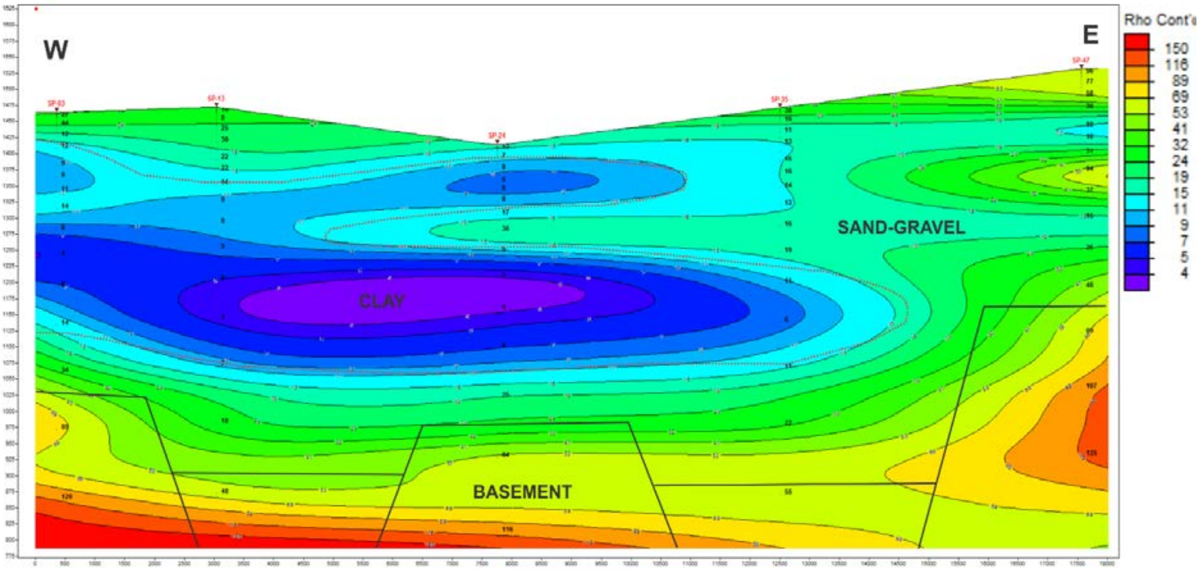


Figure 4.4 West-East Resistivity Profile showing the Base and the Top of the Argillaceous Zone in the Mexican Portion of the Binational San Pedro Basin.

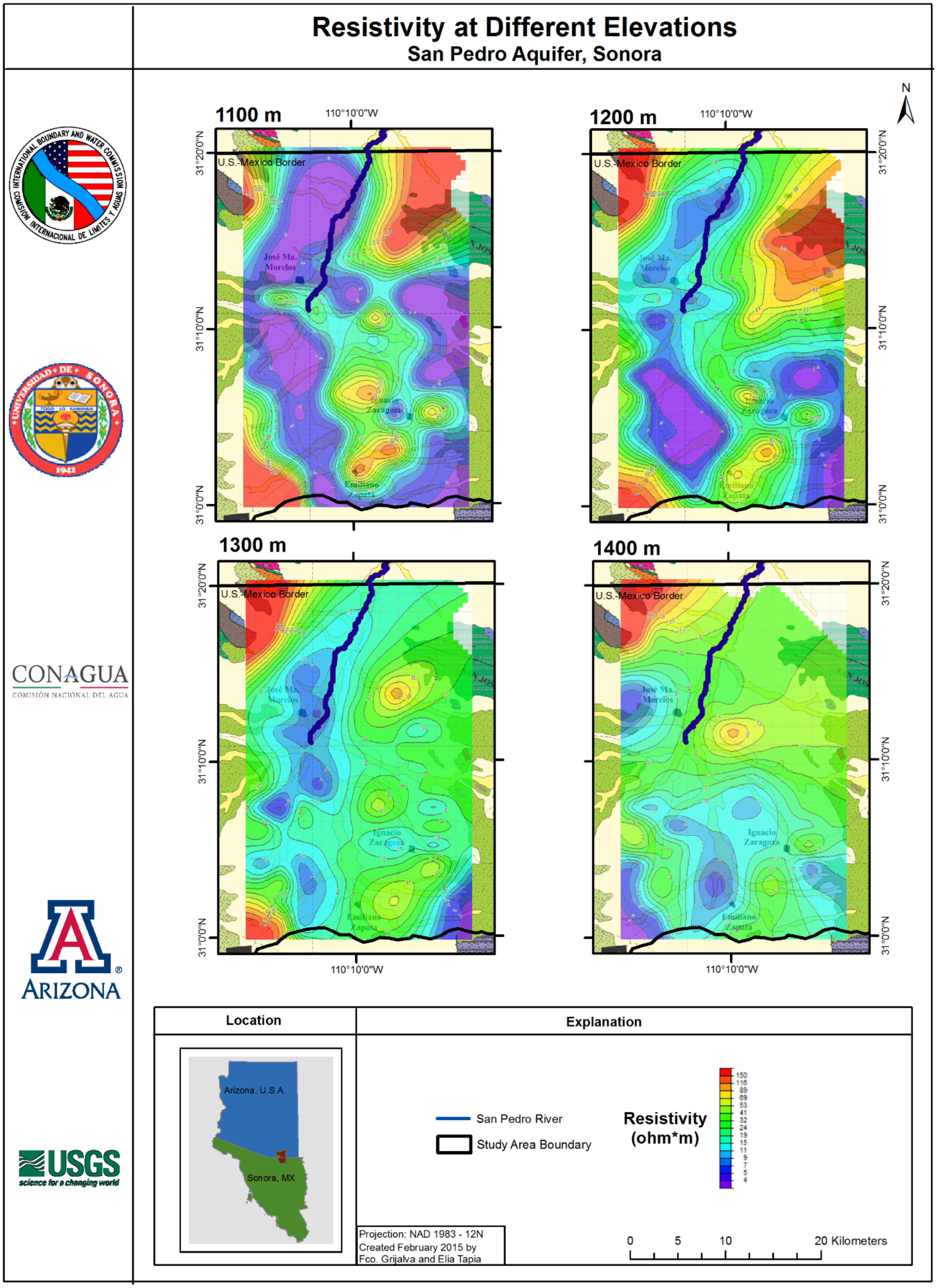


Figure 4.5 Resistivity Maps at Different Elevations on the Mexican Side of the Binational San Pedro Basin. Base map is geology clipped from Figure 4.1

Taking into account the interpretation of the geophysical data in both portions of the basin, and keeping in mind that the data and interpolations are not continuous over the whole area, our interpretation is that the basin was tectonically delimited and deepens toward the center, with a proposed maximum depth of 1500 m in the vicinity of the town of Palominas, Arizona (Figure 4.6), where the sedimentary fill is dominated by fluvial gravelly-sand sequences and fine sediments (gravimetric lows).

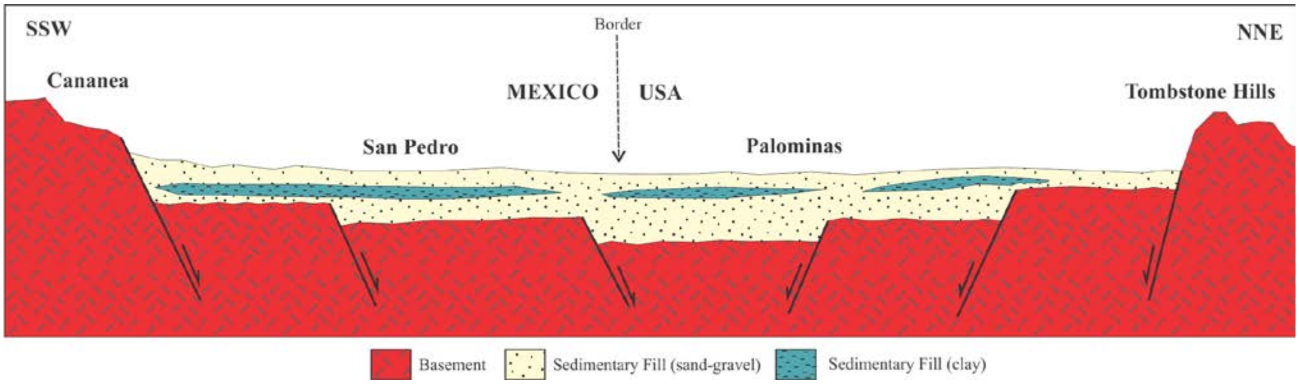


Figure 4.6 Schematic Interpretation of the Binational San Pedro Basin.

5. HYDROGEOLOGY

Hydrogeology is the description of the hydraulic properties (e.g. porosity), spatial distribution (thickness and extent), and structure (faulting) of the subsurface. As such, this section focuses on the interpretation of the geology discussed in the previous chapter in terms of its hydrologic significance. The hydrogeology of the BSPB has been studied and reviewed by a number of authors (Brown et al., 1966; Pool and Coes, 1999; Fleming and Pool, 2002; Coes and Pool, 2005; Pool and Dickinson, 2006).

5.1. Hydrogeologic Basement

Estimates of the location and nature (rock type, fracturing) of the hydrogeological basement are important to understand the size and limits of the aquifer, whether the aquifer boundaries are permeable or impermeable, and the likely types of geochemical interactions and constituents. The groundwater flow boundaries and barriers and the hydrogeological basement of the BSPB are mainly formed by sedimentary sequences and Paleozoic to Mesozoic volcano-sedimentary sequences, as well as tertiary granitic intrusions. It is important to note that from the resistivity work done in the USPSS, we have identified areas of low electrical resistivity (Figure 5.1: dark-blue and purple contours). Depending on a number of factors including measurement method, spatial variability, and contrasting material properties in the subsurface, electrical resistivity can correlate with rock or medium type, with the highest resistivities generally corresponding to unfractured bedrock and lower resistivities corresponding to increased clay, salt, or water content. In the northwest portion of the USPSS, the close spatial association of low electrical resistivity zones below higher resistivity areas (Figure 5.1: green and light-blue contours) as well as the depth at which they are found could indicate the presence of an aquifer associated with the Cretaceous sedimentary sequence, a Cretaceous mudstone (possibly containing salty water) beneath a more resistive sandstone, or intense fracturing of the basement (Figure 5.1). Aquifers found in fractured rock such as this can be productive; however, the potential for this at this location has not been evaluated; and the productivity of fractured-rock aquifers depends on their extent (local or regional), reliability, and source of recharge, and physical characteristics such as the size, connectedness, and number of fractures per unit area.

Based on the depth-to-bedrock mapping of Gettings and Houser (2000) and the discussion and analysis in Chapter 4, we conclude the following: 1) The U.S. side of the BSPB is oriented northwest-southeast; 2) The two main subbasins on the west side of the San Pedro River are separated by a bedrock high under Sierra Vista; 3) The subbasin north of the Sierra Vista has a depth to crystalline bedrock greater than 800 m; 4) The deepest portion of the subbasin south of Sierra Vista (> 1000 m) is under the community of Palominas. In addition, the subbasin to the northeast of Tombstone has a depth greater than 1,100 m. In Sonora, there is a subbasin located in the western portion of the area, oriented north-northwest-south-southeast. Another narrower subbasin is located in the northeast portion of the study area; and a third locally confined subbasin is found south of this. Based on the analysis of geophysical data in Chapter 4, depth to basement in the USPSS is highly variable, with the greatest depths, between 430 and 510 m, found near the border, near the town of José María Morelos. Although there is a depression with depths of greater than 250 m in the south-central portion of the basin, the most significant uplift is located along Highway 2 with bedrock at or near the surface.

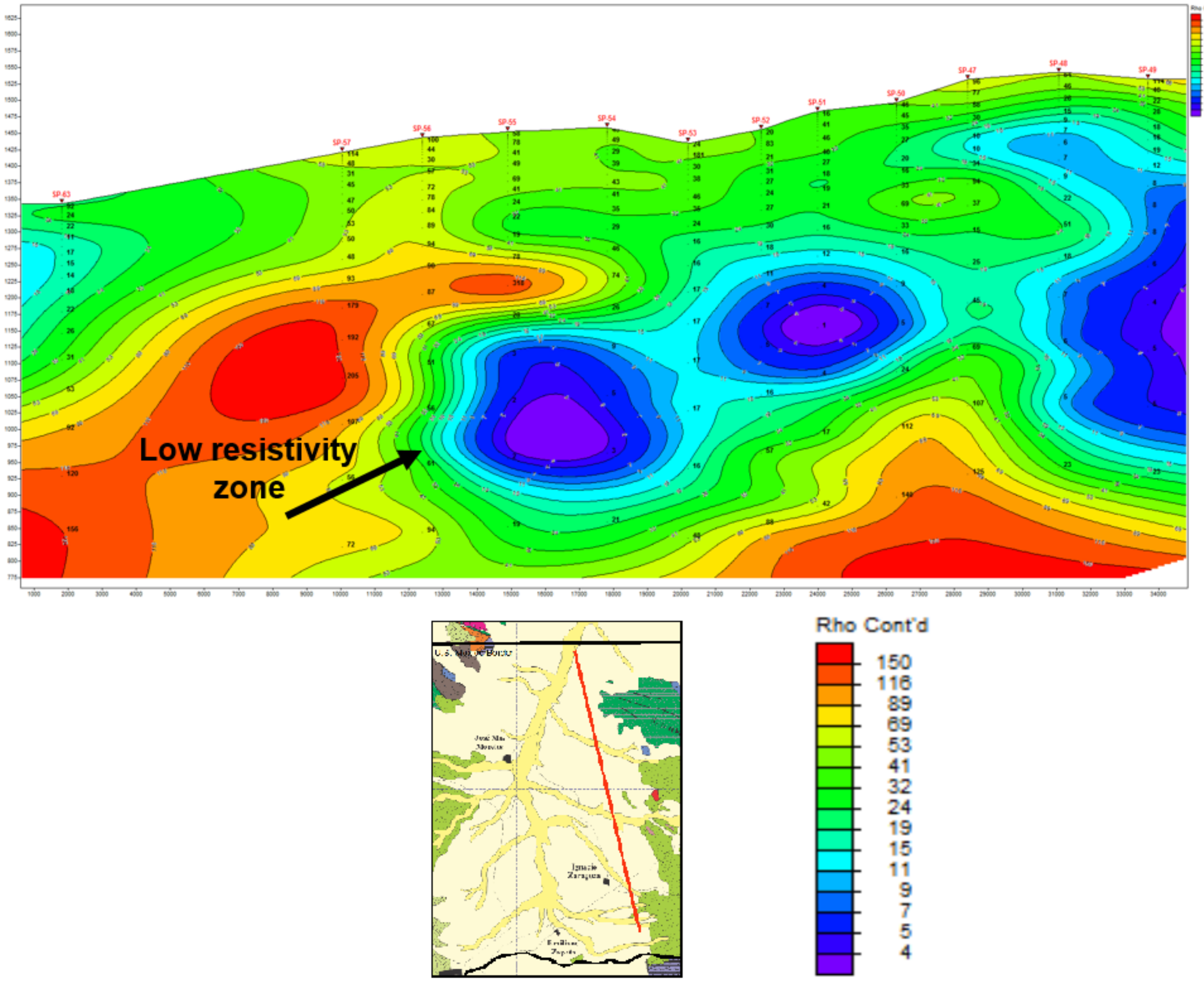


Figure 5.1 North-South Resistivity Profile (TEM) developed on the Eastern Boundary of the Mexican Side of the Binational San Pedro Basin, showing the low resistivity zone (dark-blue and purple contours) that could be associated with faulting of the basement. Location of the profile is indicated by the red line on in the geologic map in the lower portion of the figure (For detailed geology see Figure 4.1). Distances on resistivity profile and map are in meters.

For purposes of defining the depth and thickness of the sedimentary basin fill that is mentioned in Chapter 4, both the felsic volcanic unit and the Tertiary conglomeratic volcano-sedimentary sequences **(Tc)** on both sides of the border were considered to be part of the bedrock; however, they may not be part of the hydrogeological basement if they play an important role in the movement of groundwater, and are hydraulically connected with the basin fill aquifers. Limestone outcrops in nearly all of the mountain ranges bordering the BSPB (Pool and Dickinson, 2007). It functions locally as aquifers, but its true extent and function in the hydrology of the BSPB is unknown.

5.2. Hydrostratigraphic Units

Hydrostratigraphic units as described by Maxey (1964) are laterally extensive bodies of rock (or alluvium) that act as distinct hydrologic systems. As discussed in Chapter 4, Pool and Dickinson (2007) among others established that the regional basin-fill aquifer in the U.S. portion of the basin is composed of unconsolidated and consolidated sedimentary fill that may be divided stratigraphically into Upper and Lower Basin-Fill Units. The sedimentary fill is also the most important aquifer in the Mexican portion of the basin. These same authors mention the likely presence of a rock aquifer in the detrital sequence of the Tc unit (See geology section 4.2 for description), the presence of which can also be established in the Mexican portion in the Báucarit Formation, and the Tertiary felsic volcanic unit as well. As was the case with Pool and Dickinson (2007), however, and despite the new geophysical information used for this analysis, there remains insufficient information to distinguish Upper and Lower Basin-Fill within the USPSS. In the interest of developing a basis for binational comparison and integration, and until such time as the work to distinguish Upper and Lower Basin Fill can be carried out in the USPSS, we propose and describe a series of hydrostratigraphic units for the BSPB aquifer that are differentiated on the basis of particle-size and porosity. Based on depth, typical basin geometry and spatial distribution of particles related to basin evolution, these can be used to estimate zones of higher and lower hydraulic conductivity and location of fractured rock versus alluvium (see Figure 5.2 for example). An advantage of this is that the division of the aquifer into hydrostratigraphic units is a necessary step in the development of a groundwater flow model. Taking all of this into account, the studies in the Arizona portion of the aquifer, the resistive characteristics obtained from the TEM surveys in the USPSS (See chapter 4), the previously defined hydraulic parameters, and their correlation with neighboring aquifers in the Agua Prieta, Santa Cruz, Bacanuchi, and Cananea areas, the following hydrostratigraphic units are defined for the BSPB:

Hydrostratigraphic Unit 1: Corresponds to the coarse granular fraction of sedimentary basin fill represented by gravels and sands. It corresponds to the more hydraulically conductive portions of the Upper- and Lower-Basin Fill. This unit has the highest hydraulic conductivity, although at depth this probably decreases, since typically a greater degree of compaction and cementation occurs at greater depths.

Hydrostratigraphic Unit 2: This unit incorporates the fine sediments with low hydraulic conductivity that mainly comprise the upper basin fill. These low-conductivity silts and clays occur mainly in the central portion of the basin. It is possible that these are responsible for creating the confined conditions found in Hydrostratigraphic Unit 1. The extent of the confined conditions reflects the extent of this unit.

Hydrostratigraphic Unit 3: Included in this unit are those rocky units that could be lumped together as fractured-rock aquifers, among which are the conglomeratic units of the Báucarit Formation, the Tc unit (See Chapter 4), the Tertiary felsic volcanic rocks that lie between these, and the fractured or weathered portions of the basement, such as limestone, that could possibly contain groundwater.

The location, spatial relationships, and distribution of these hydrogeologic units were established based on hydrogeologic sections derived from the geoelectric profiles measured on the Mexican portion of the basin.

5.3. Definition of the Aquifer System

By comparison with the alluvial aquifers, crystalline rocks, and pre-Cenozoic and Cretaceous sedimentary rocks (with the exception of limestone and fracture zones) probably store little water in the BSPB; however, they represent the most important recharge zones for the primary alluvial aquifers since they form the mountains where most precipitation falls (Pool and Dicksinson, 2007). As such, they function as fractured aquifers, but are used by comparatively few individuals or entities as their sole source of water. Fractured tertiary conglomerate **(Tc)** in the U.S. portion is locally important and productive as an aquifer (Pool and Dickinson, 2007; included in Hydrostratigraphic Unit 3). Although there are some wells that draw water from this unit, their flow is so minimal that it is only enough for minor uses such as livestock. This hydrogeological condition also characterizes the Báucarit Formation on the Mexican side of the basin. Groundwater in the San Pedro River basin primarily flows in the unconsolidated layers of coarse sediments that act as the sedimentary basin fill (Hydrostratigraphic Unit 1), and in the Plio-Quaternary surface deposits associated with terraces and alluvial deposits, so these act as the primary aquifers in the basin (Pool and Dickinson, 2007).

The aquifer system is unconfined mainly in the Upper Basin Fill sediments. Lower Basin Fill sediments, which have greater thicknesses towards the center of the basin, are confined by lenses of clay-rich sediments (Hydrostratigraphic Unit 2). This unit strongly affects the flow of water in the basin, including the hydrologic communication between the surface water in the San Pedro River and the regional aquifers. The units that make up the terraces and the alluvial deposits from the Late

Pleistocene act as important secondary aquifers (Coes and Pool, 1999).

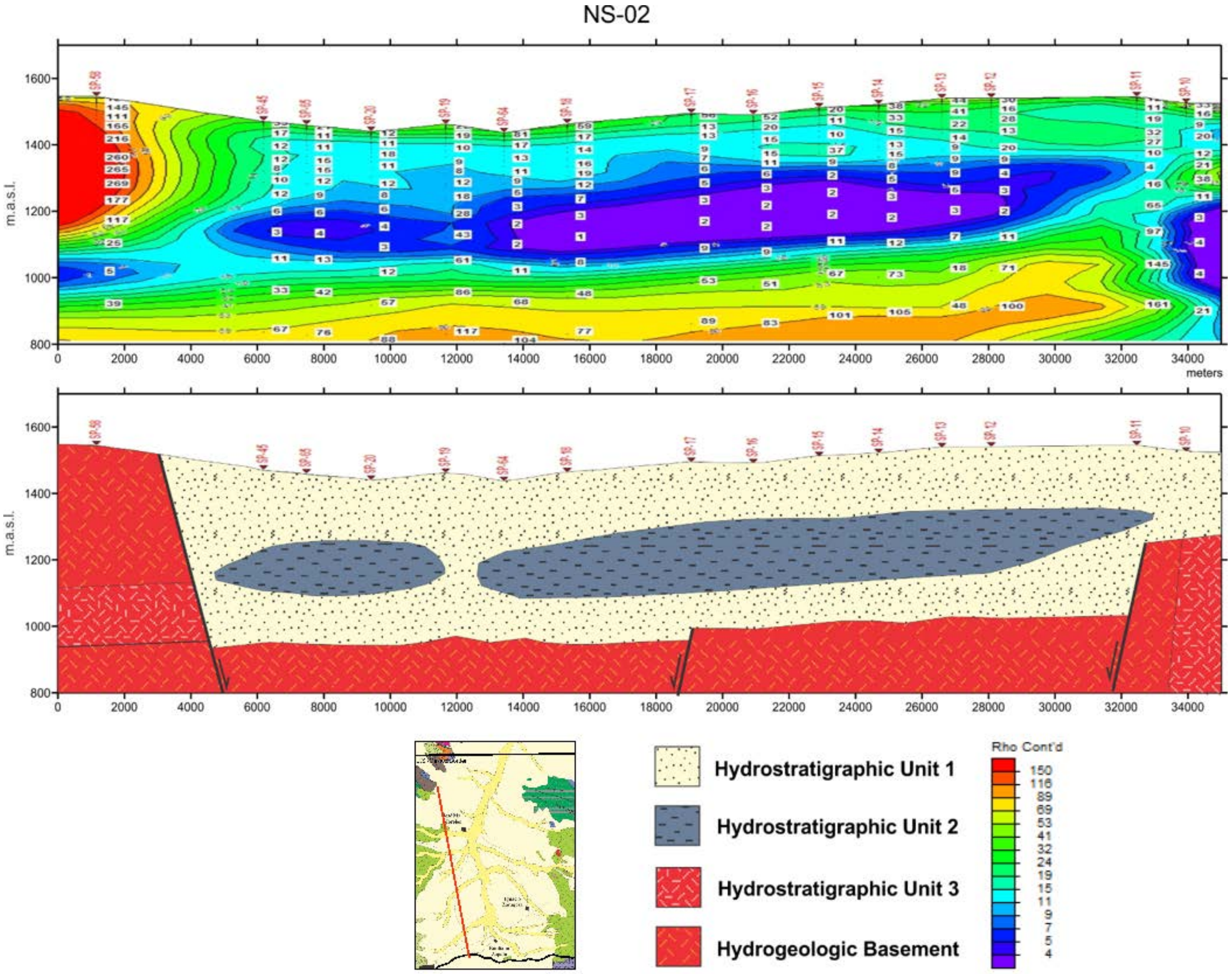


Figure 5.2 Proposed Distribution of Hydrostratigraphic Units Based on Resistivity (TEM) Profiles (and other information) carried out on the Eastern Boundary of the Mexican Side of the Binational San Pedro Basin. Location of the profile is indicated by the red line on in the geologic map in the lower portion of the figure (For detailed geology see Figure 4.1). Distances on resistivity profile and map are in meters.

6. PIEZOMETRY AND HYDRAULIC PARAMETERS

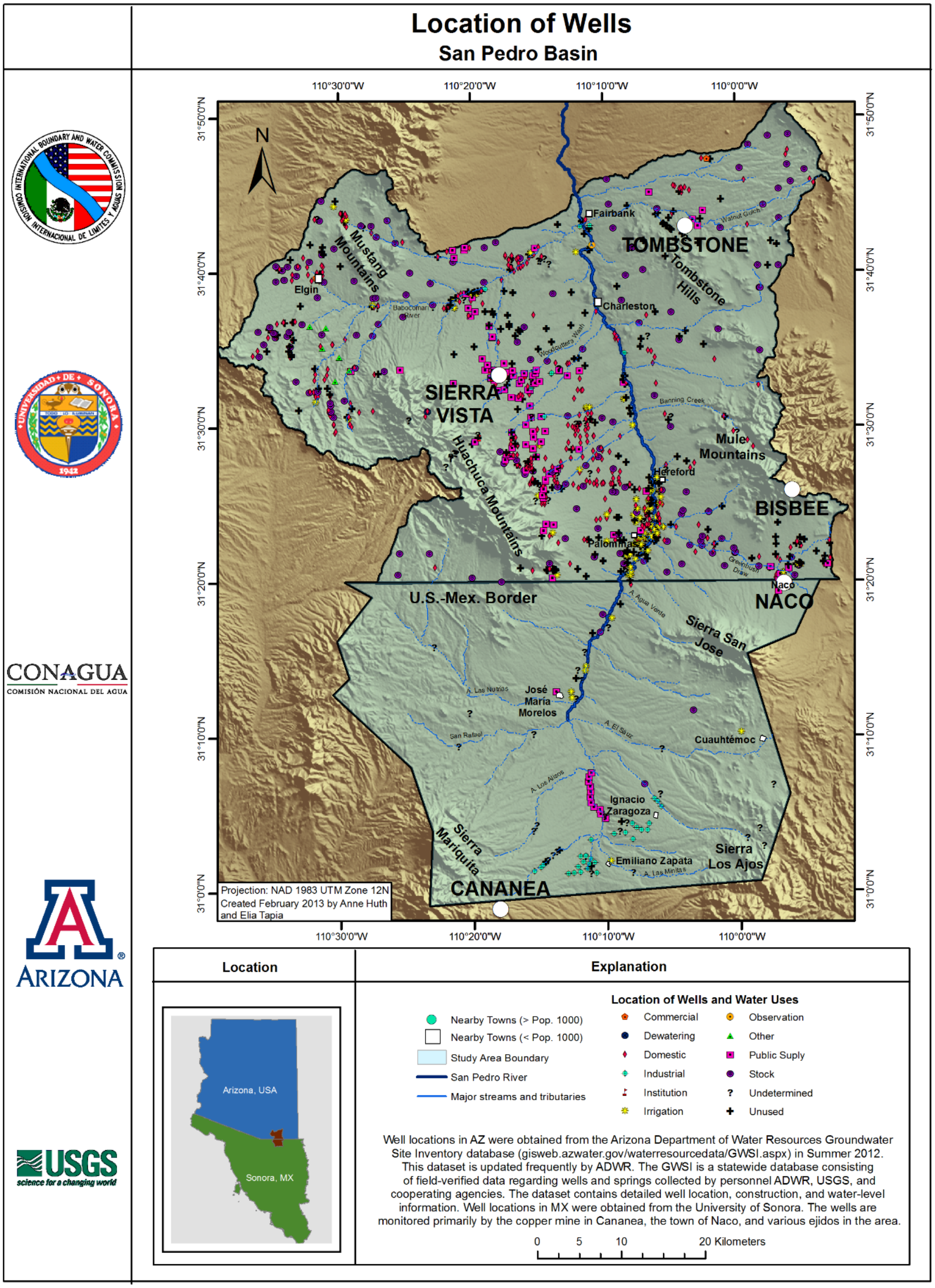
6.1. Comprehensive Well Survey

There are over 5000 wells in the BSPB (Figure 6.1), most of which are close to and south of the city of Sierra Vista (REPDA, 2012; ADWR, 2016). With regard to well construction and other types of information, most wells have data on total depth, casing material, elevation, depth of the screen, and a single measurement of the static water level taken while drilling and developing the well. There are more than 2,300 wells that have a depth of over 100 m, but only a small percentage of them have lithological records. Every year the ADWR, USDA Agricultural Research Service (USDA ARS), and USGS measure the water levels of more than 70 wells in the SVSA. Approximately every five years, ADWR measures the water levels in hundreds of wells, which together provide a more comprehensive understanding of regional groundwater level patterns.

According to the Public Registry of Water Rights (CONAGUA, 2012), on the Mexican side of the San Pedro aquifer there are 194 wells, which are mainly distributed along the San Pedro river channel and near Cananea (Figure 6.1). Of the total number of wells on the Mexican side, 11 are hand-dug wells, 39 are shallow wells (< 50 m), and 144 have a depth that exceeds 50 m. In Mexico, wells are used mainly for livestock (41% of wells), followed by industry (26% of wells), and agriculture (21% of wells). The remaining 12% are dedicated to municipal use.

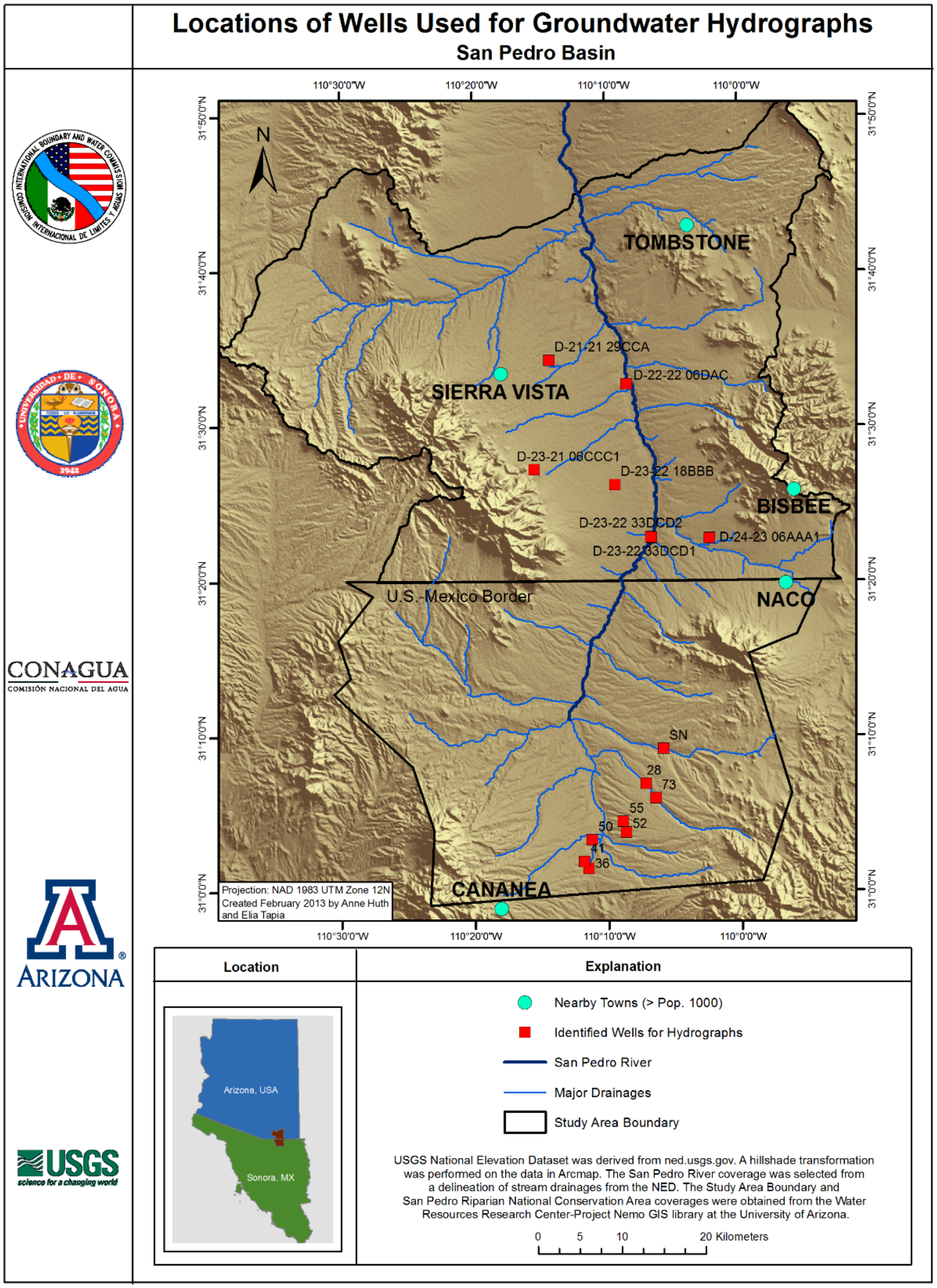
Figure 6.2 shows the location of selected wells used to show representative hydrographs in the U.S. and Mexico. Hydrographs of eight wells in the U.S. were chosen to serve as examples of particular hydrologic processes and/or geographic settings (Figures 6.3 A-H). The “Ranch (shallow)” well (313610110163201) is located in the area of unregulated development south of Sierra Vista in which most wells are privately owned. Since 2006, water levels in this well are declining linearly at a rate of about 0.24 m/yr. Monitoring wells 3 and 6 (MW3 (312830110102302) and MW6 (312555110074301)) were chosen to illustrate water level changes typical of wells within the cone of depression that underlies Fort Huachuca and Sierra Vista (Schmerge et al., 2009; Konieczki, 1980). Since 1995, these wells have also exhibited linear declines (0.18 m/yr). The hydrograph for Monitoring Well 1 (MW1 (312323110020901)) was chosen to show the change in behavior of water levels in this well which were in a fairly linear decline until about 2006. Although there are some fluctuations, water levels from the last few years appear to be stabilizing when compared with pre-2006 declines. This could be caused by recharge from Sierra Vista’s Environmental Operations Plant (EOP) which began recharging in July 2002 (EOP, 2015). The hydrograph for the 366 m deep Holder well (312250110063901) exhibits what appears to be recovery and stabilization, probably caused by the retirement of nearby agricultural wells especially prior to 2006 followed by some decline due to ongoing drought. The changes in water level due to nearby pumping and the great depth of the well indicate that it is mostly likely screened in the confined aquifer. The continued variability in the record is likely caused by seasonal recharge and nearby pumping of domestic wells. The Foudy well (312323110020901) is located near Greenbush Draw, one of the major eastern tributaries of the San Pedro River, located just north of the border. The well, Antelope Run #3, is located on the west side of the basin at the foot of the Huachuca Mountains near Garden Canyon Wash. The sharp rise in water levels at both of these wells after high precipitation in October 2000 and beginning in 2005-2006 suggest that precipitation and subsequent recharge in nearby channels are the processes most likely controlling water levels at these locations. In fact, Pool (2008) and Gungle et al. (*In review*) used discharge and water level data supported by gravity methods to suggest that recharge was a principal factor affecting water levels in the Antelope Run #3 well. The continuous water level record at LSP-1 represents the special case of daily and seasonal changes in water levels in wells close to the San Pedro River that are screened in the alluvial aquifer. At LSP-1, the highest water levels are associated with high flow during the monsoon season. A second rise in water levels begins in fall when ET ceases. In addition, it is likely that a number of otherwise difficult to explain groundwater level excursions such as in 2003 are due to slow filling and rapid emptying of beaver ponds after large flow events in the River (Gungle et al., *In review*).

In Sonora, depending on location, depth, and screened interval, some of the variability in the wells just described is probably due to long-term variability in climate cycles (See Chapter 3 and Dickinson et al., 2004, and Hanson et al., 2006). In particular, Hanson et al. (2006) and Dickinson et al. (2004) found that the strongest associations in the San Pedro basin are with PDO, NAM, and ENSO, with PDO contributing to climatic and hydrologic variations that typically range from 10-25 years, NAM (6-10 years), and ENSO (2-6 years).



Well locations in AZ were obtained from the Arizona Department of Water Resources Groundwater Site Inventory database (gisweb.azwater.gov/waterresourcedata/GWSI.aspx) in Summer 2012. This dataset is updated frequently by ADWR. The GWSI is a statewide database consisting of field-verified data regarding wells and springs collected by personnel ADWR, USGS, and cooperating agencies. The dataset contains detailed well location, construction, and water-level information. Well locations in MX were obtained from the University of Sonora. The wells are monitored primarily by the copper mine in Cananea, the town of Naco, and various ejidos in the area.

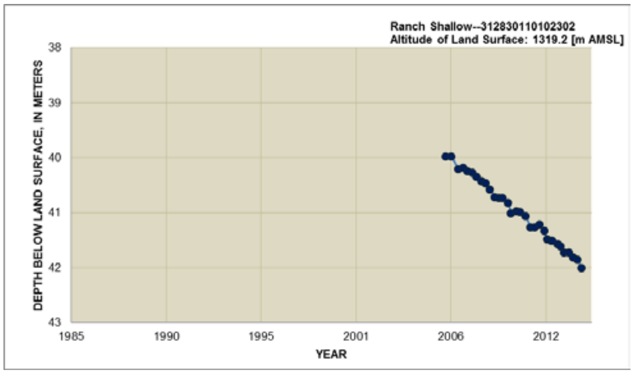
Figure 6.1 Selected Wells Distinguished by Use in the Binational San Pedro Basin.



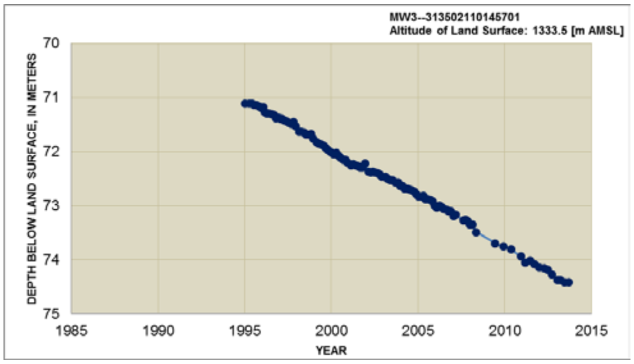
USGS National Elevation Dataset was derived from ned.usgs.gov. A hillshade transformation was performed on the data in Arcmap. The San Pedro River coverage was selected from a delineation of stream drainages from the NED. The Study Area Boundary and San Pedro Riparian National Conservation Area coverages were obtained from the Water Resources Research Center-Project Nemo GIS library at the University of Arizona.

Figure 6.2 Hydrographs for Selected Wells in the Binational Upper San Pedro Basin. Hydrographs in the U.S. were selected to highlight different geographic settings and hydrologic processes of interest. See text, appendices, and individual hydrographs below for further details such as individual hydrographs, USGS site identification numbers, and coordinates of locations.

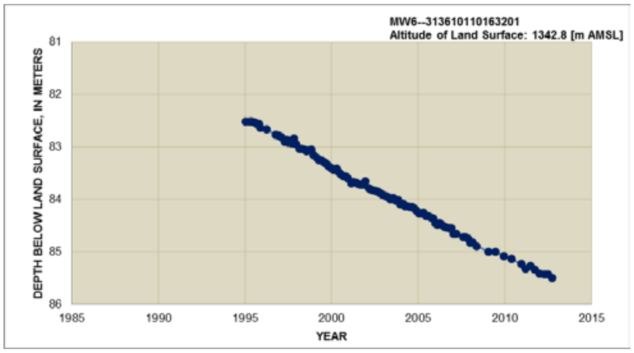
A.Ranch Shallow Well



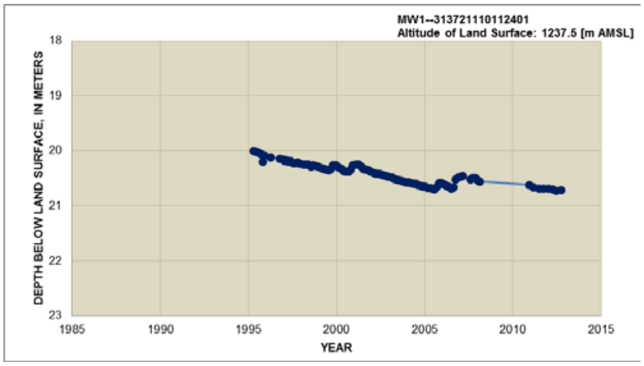
B. Well MW3



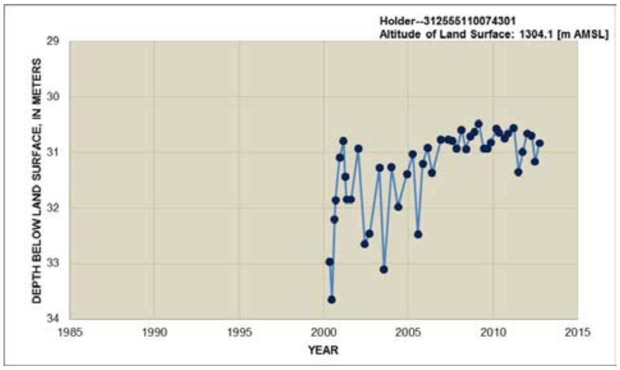
C. Well MW6



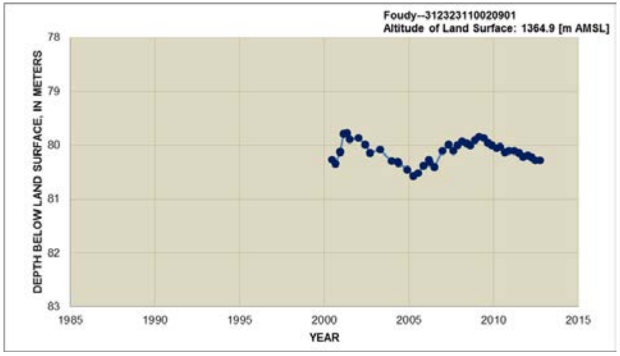
D. Well MW1



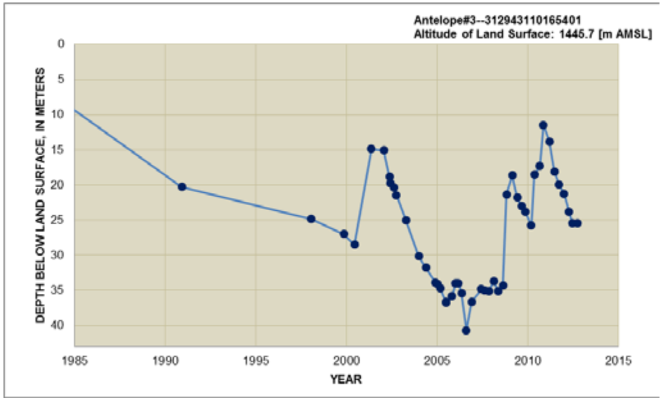
E. Holder Well



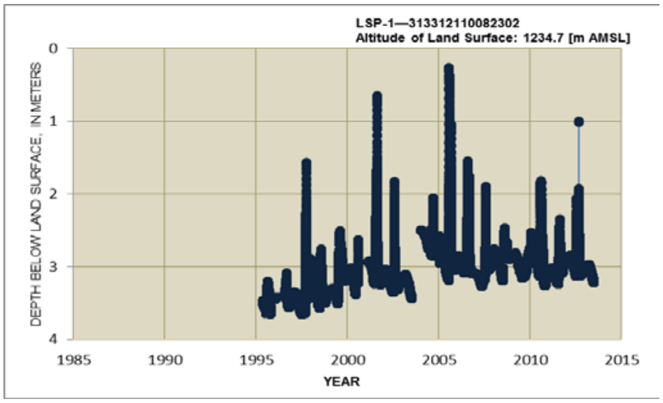
F. Foudy Well



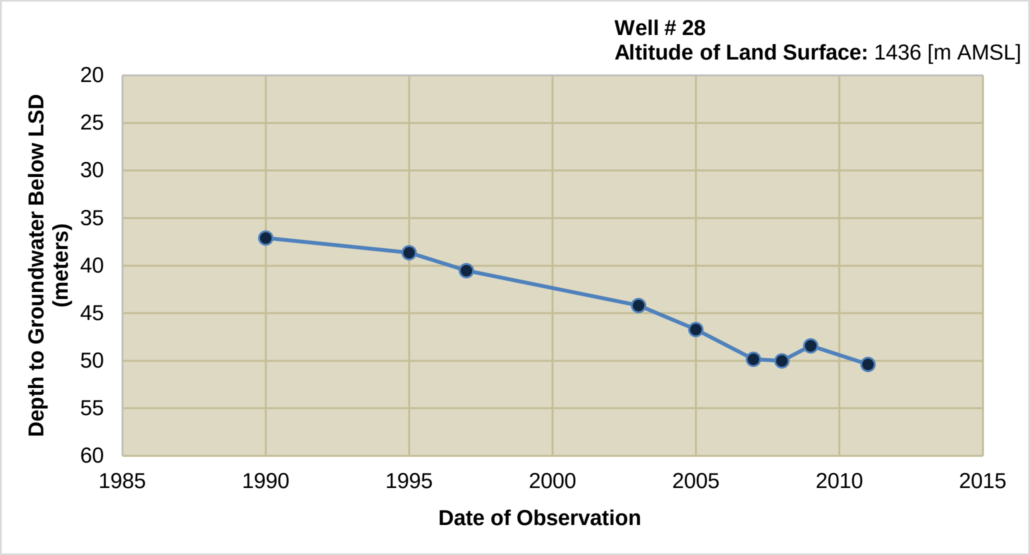
G. Well Antelope #3



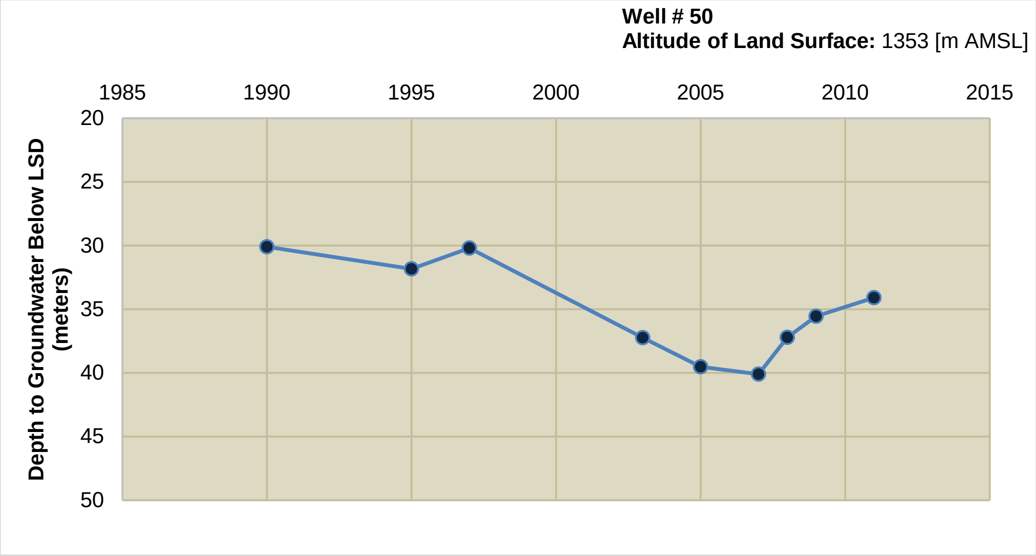
H. Well LSP-1



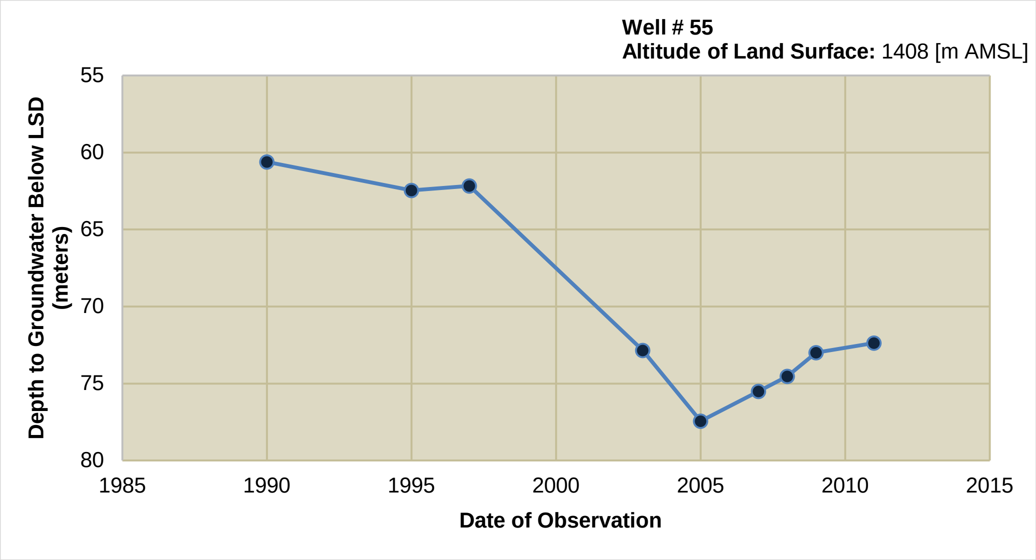
I. Well # 28



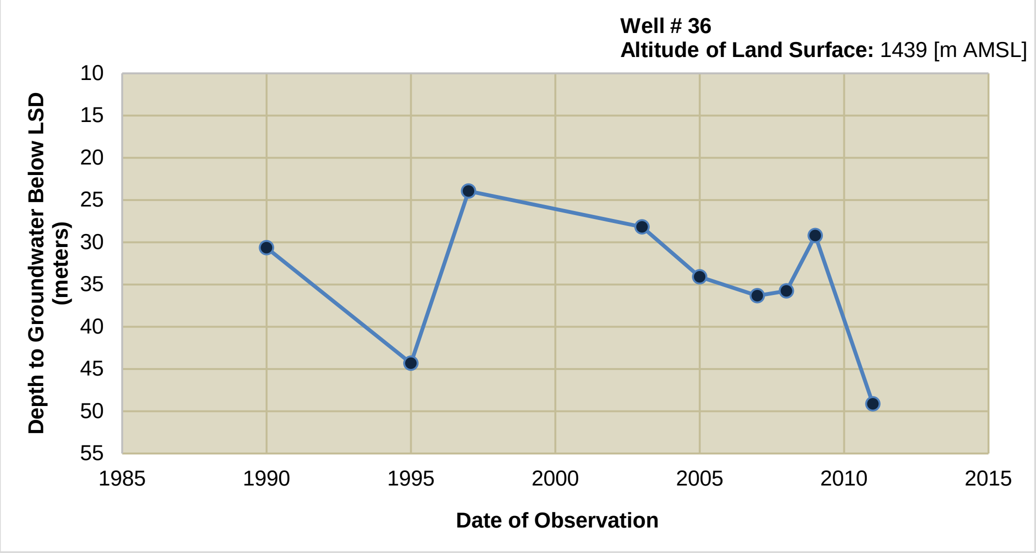
J. Well # 50



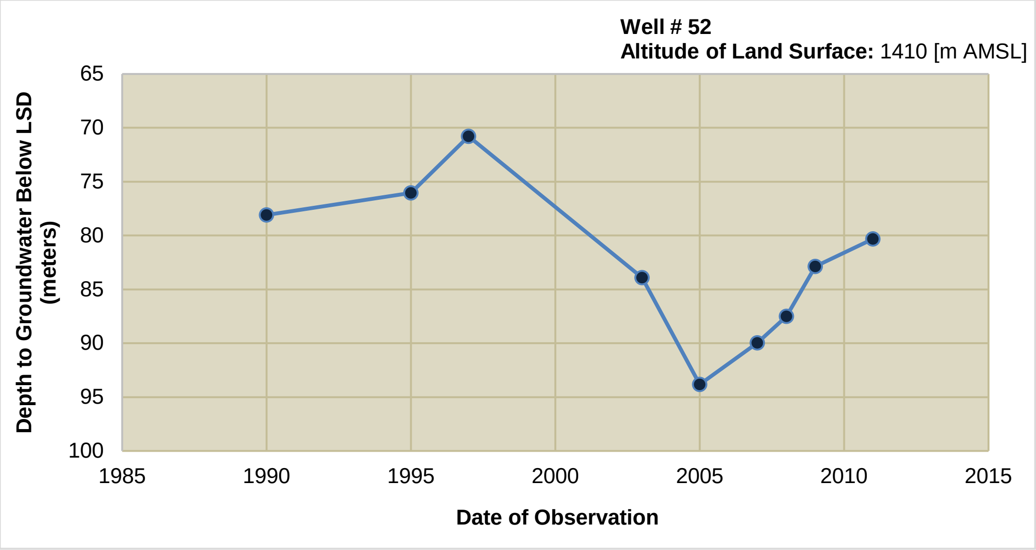
K. Well # 55



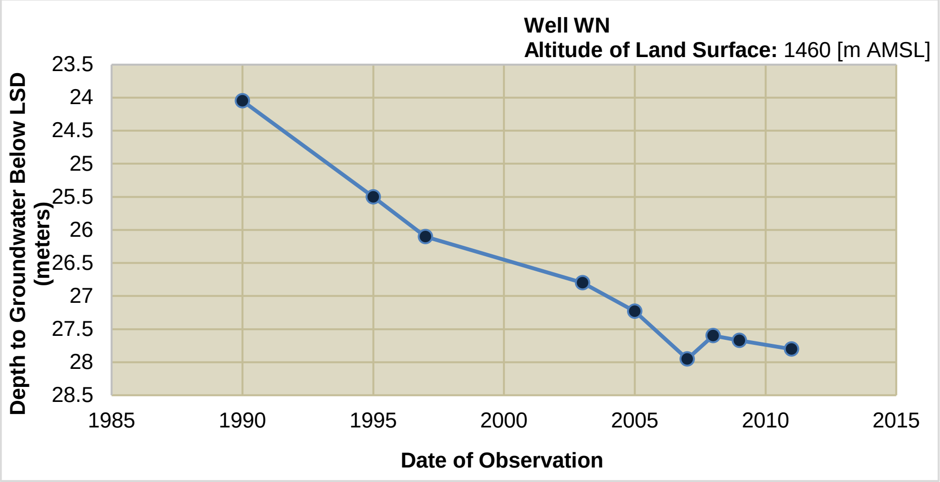
L. Well # 36



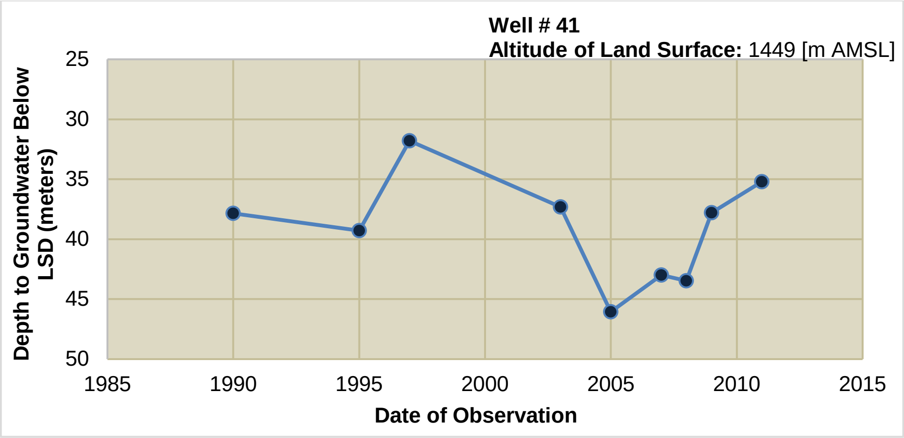
M. Well # 52



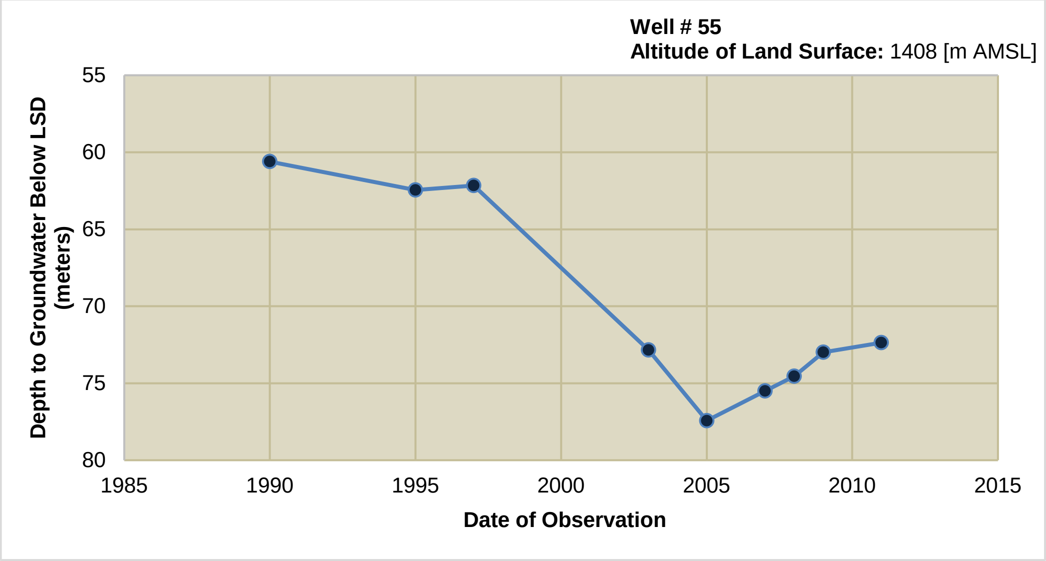
N. Well # WN



O. Well # 41



P. Well # 55



Use	Number of Wells	Volume (hm^3)
Agricultural	41	8.2
Domestic	4	9.7
Livestock	86	0.53
Public Urban	21	1.8
Industrial	51	13.8
Total	203	24.3

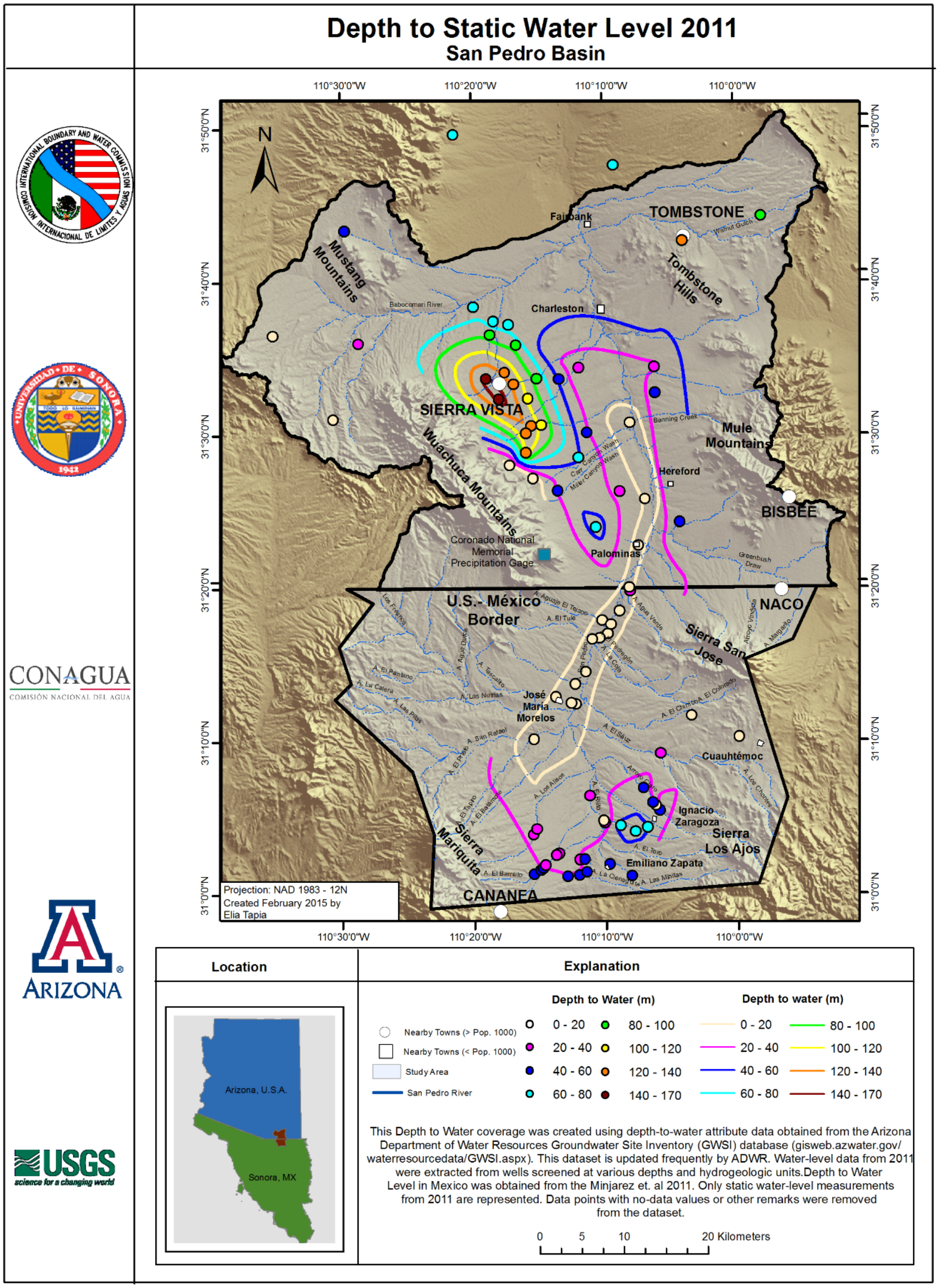
Table 6.1 Annual Concession Volume for the San Pedro River aquifer in Mexico (REPDA, 2012). Concessions for groundwater pumping are granted to users (individuals, municipalities, etc.) for a fixed time period by CONAGUA.

6.2. Description of Spatial and Temporal Variability of Water Levels

Water table elevations, representing both confined and unconfined conditions, generally increase from the San Pedro River to the mountains with the exception of cones of depression. The extensive clay and silt layer found on both sides of the border (See Section 4.6) acts as a confining unit which historically resulted in flowing wells at certain locations. Currently few wells remain in this condition. Depth to water is variable with shallower water levels typically near the mountain fronts and the San Pedro River, and greater depths in between. The depth to static water level in wells measured on the Mexican side ranges from 2.5 m to 72.4 m, with the former located in the southeast portion of the aquifer in Ejido Zaragoza, and the greater depth at well 55 (Figure 6.3). The greatest water level depths are found in the south, in the areas known as Arroyo Claro, Patos Sur, Barrilitos and Ampliacion del Rio; except for well 401, which is located southeast of the Ejido José María Morelos y Pavón, located west of the aquifer (See Appendix 11.5 for names and coordinates).

The static water level elevations in the USPSS fall within the range of 1290 to 1674 m.a.s.l. (Figure 6.4); the lowest elevations tend to be in the areas with greater topographic prominence, which are located in the southeast part of the aquifer near the Sierra Los Ajos. The maximum value for static water level elevation was found at the Ejido Zaragoza. The minimum value was 1290 m.a.s.l. in the southern portion of the aquifer. Overall, the static water level elevations decrease toward the north, indicating groundwater flow toward the San Pedro River and to the north.

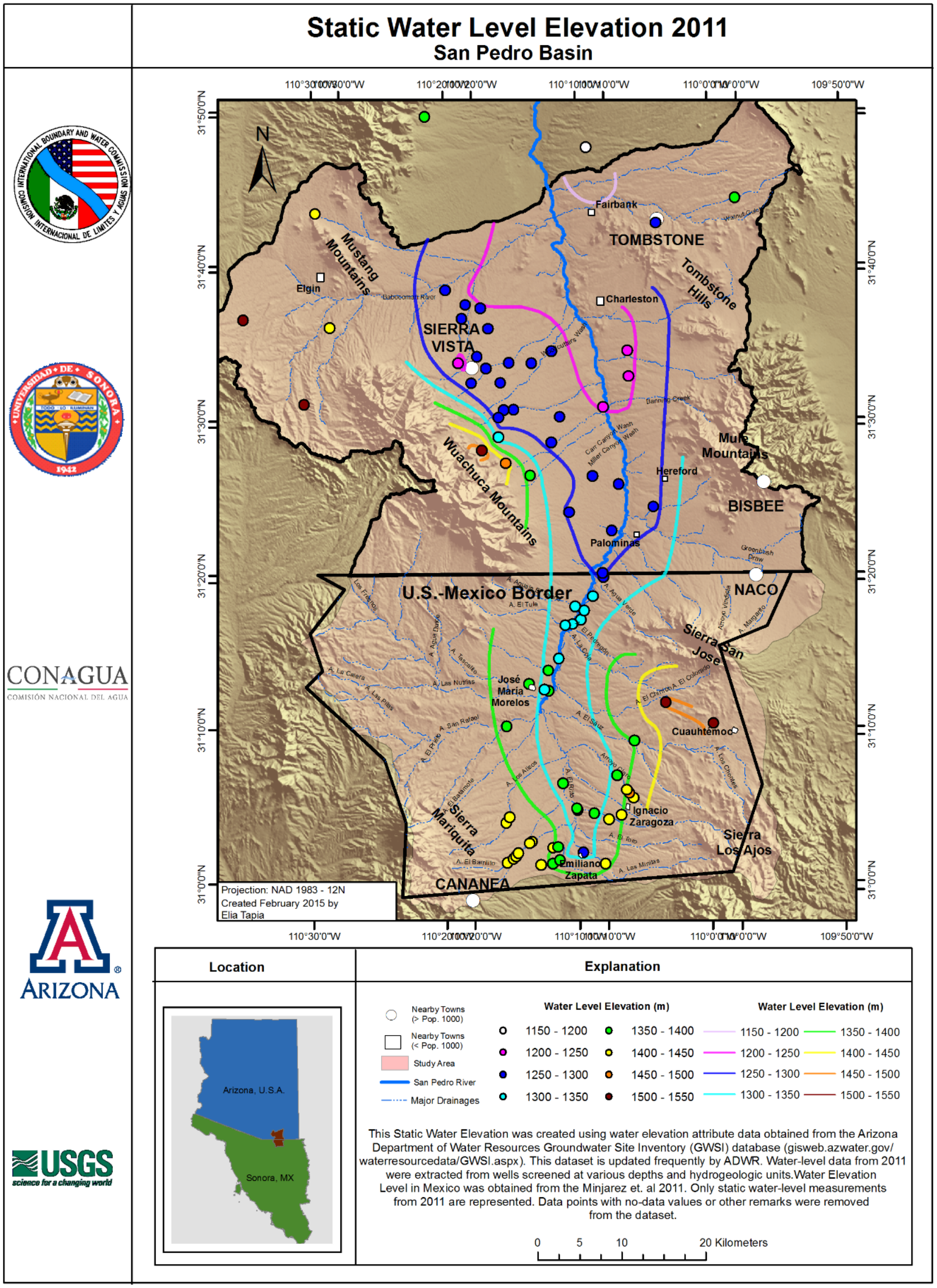
In the SVSA, within the city limits of Sierra Vista, depth to water is greater than 100 m in a number of wells. Previously published measurements and interpolations of static water level elevations and water level trends suggest cones of depression in and near the cities of Sierra Vista, Tombstone, and Cananea, caused by current and historical pumping (Roeske and Werrell, 1973; Konieczki, 1980; Schmerge et al., 2009). Water level changes between 2001 and 2006 for the SVSA were calculated by Schmerge et al. (2009). Near Tombstone, they found changes that ranged from an increase of 3.1 m to a decrease of 3.4 m. In the areas of Huachuca City, Sierra Vista, and Nicksville, water levels declined between 3.4 and 9.1 m over the same period. During this same period, in the area southwest of Charleston, most water levels recovered, with an increase of between 0.61 m and 5.8 m. The rise probably occurred as a result of the wastewater treatment plant that is recharging the aquifer with treated water (Brown and Caldwell, 2009). There is also an increase in water levels (generally between 0.3-1 m) near Hereford and south toward the border that could have resulted from the retirement, in the early to mid-2000s, of most agricultural pumping in this area. Localized areas of recharge near washes and/or the mountain front are possibly related to the high rainfall event of October 2000.



Projection: NAD 1983 - 12N
Created February 2015 by
Elia Tapia

This Depth to Water coverage was created using depth-to-water attribute data obtained from the Arizona Department of Water Resources Groundwater Site Inventory (GWSI) database (gisweb.azwater.gov/waterresourcedata/GWSI.aspx). This dataset is updated frequently by ADWR. Water-level data from 2011 were extracted from wells screened at various depths and hydrogeologic units.Depth to Water Level in Mexico was obtained from the Minjarez et. al 2011. Only static water-level measurements from 2011 are represented. Data points with no-data values or other remarks were removed from the dataset.

Figure 6.3 Depth to Static water level in 2011 in the Binational San Pedro Basin.

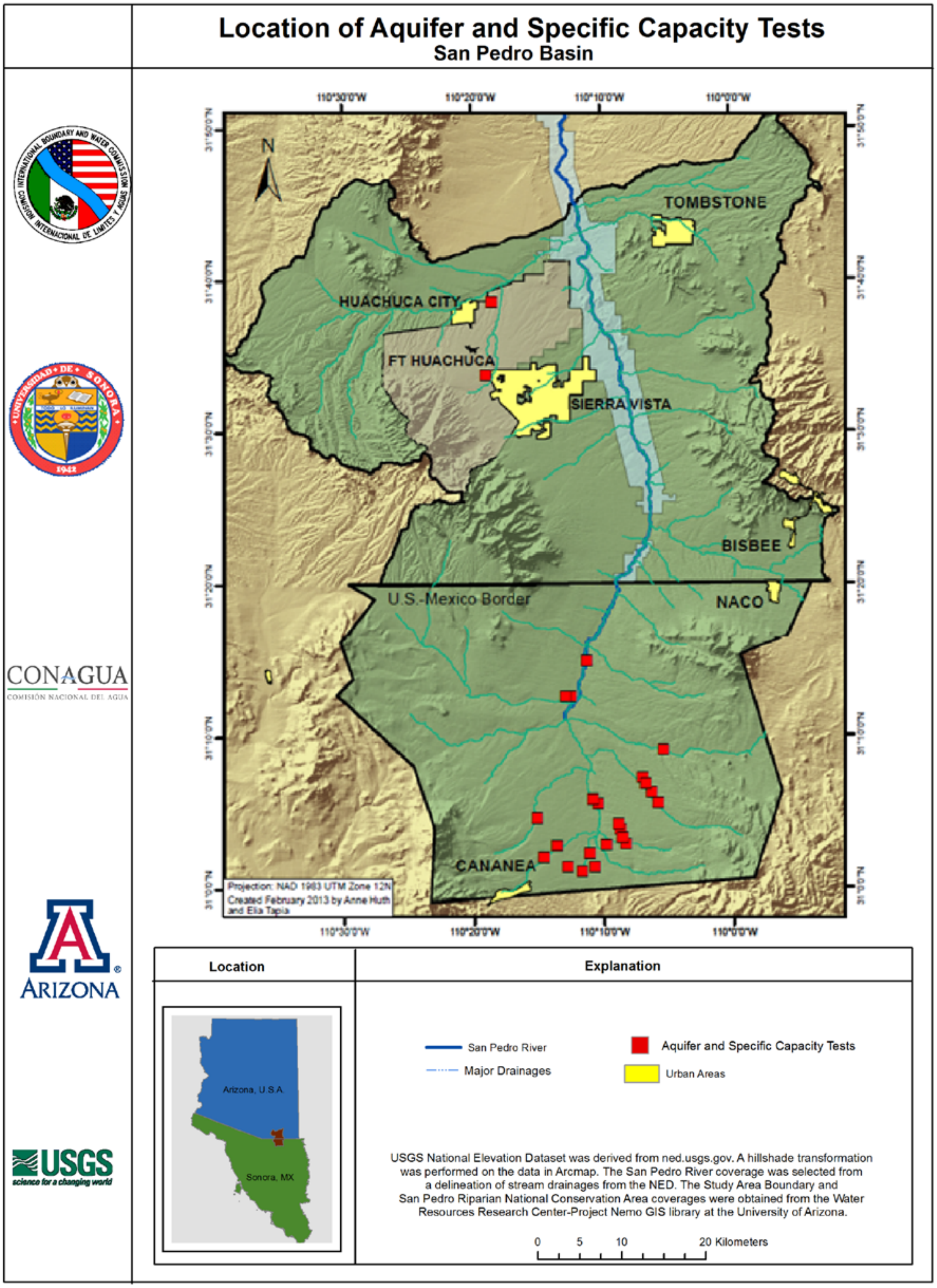


This Static Water Elevation was created using water elevation attribute data obtained from the Arizona Department of Water Resources Groundwater Site Inventory (GWSI) database (gisweb.azwater.gov/waterresourcedata/GWSI.aspx). This dataset is updated frequently by ADWR. Water-level data from 2011 were extracted from wells screened at various depths and hydrogeologic units.Water Elevation Level in Mexico was obtained from the Minjarez et. al 2011. Only static water-level measurements from 2011 are represented. Data points with no-data values or other remarks were removed from the dataset.

Figure 6.4 Static water level Elevation in 2011 in the Binational San Pedro Basin.

6.3. Definition and Interpretation of Subsurface Hydraulic Parameters

Hydraulic parameters represent the constraints on water flow imposed by physical, fluid, and spatial properties of a water-rock-porous-medium system. Estimating and understanding the spatial and temporal variability of these properties is critical to understanding and predicting fluxes, the behavior of water levels, and changes in aquifer storage in response to changes in factors such as climate, pumping, managed aquifer recharge, and land management practices among others. Pump tests (aquifer tests) can be used to test a large number of hypotheses about aquifer conditions near and between wells. Most commonly they are used to estimate aquifer transmissivity and storage properties. Transmissivity is the product of saturated thickness of the aquifer and hydraulic conductivity. Aquifer tests on the U.S. side are limited in number, but two were done in wells at Fort Huachuca (Brown et al. 1966). The first was carried out in 1958 in well D-21-20 33dbb (Site No.: 313338110185601) which had a total depth of 68.8 m, with 21.3 m in Upper Basin Fill and 47.5 m in Lower Basin Fill (Figure 6.5). A hydraulic transmissivity of 1,860 m^2/d was estimated. Two other wells (D-21-20 3bbb1 and 55-537824)) were used with one observation well to estimate a transmissivity of 2,860 m^2/d, with a storage coefficient of 1.6×10^{-5}. All three wells were screened only in the Lower Basin Fill (Hydrostratigraphic Unit 1). Aside from these, measured hydraulic parameters in the SVSA are limited. However, there are values from the calibrated model by Pool and Dickinson (2007, Table 6.2). These values were calculated for the Mexico and U.S. sides of the basin, and in general, the saturated hydraulic conductivity (K) varies between 0.0001 and 12.50 m/d. The sedimentary (including limestone), igneous, and metamorphic rocks have estimated K values that vary between 0.625 and 0.0001 m/d (Pool and Dickinson, 2007). The Upper Basin Fill has calibrated values from 7 m/d for sand and gravel up to 0.050 m/d for clay, silt, sand, and low permeability gravel with an average of 3.46 m/d. The Lower Basin Fill, which is more compact, varies between 6.25 m/d and 0.001 m/d, with an average of 0.98 m/d. There are areas in the aquifer where there are insufficient data for classifying the alluvium as either Lower or Upper Basin Fill (Pool and Coes, 1999; Pool and Dickinson, 2007). Nonetheless, the aquifer properties were estimated during the calibration of the model and they vary between 10 and 0.0013 m/d. The alluvium associated with the San Pedro River has the highest permeability in the basin ranging from 12.5 to 7.5 m/d.



Projection: NAD 1983 UTM Zone 12N
Created February 2013 by Anne Huth and Elia Tapia

USGS National Elevation Dataset was derived from ned.usgs.gov. A hillshade transformation was performed on the data in Arcmap. The San Pedro River coverage was selected from a delineation of stream drainages from the NED. The Study Area Boundary and San Pedro Riparian National Conservation Area coverages were obtained from the Water Resources Research Center-Project Nemo GIS library at the University of Arizona.

Figure 6.5 Location of wells on which aquifer and specific capacity tests were performed.

Vertical anisotropy (K_h/K_v) is the ratio of K in the horizontal direction (K_h) to K in the vertical direction (K_v). It is a measure of the relative ease with which water flows horizontally compared to vertically. In rocks and the undifferentiated fill, average anisotropy varies over less than an order of magnitude, from 3.5 to 9.4 (Pool and Dickinson, 2007). In the Lower and Upper Basin Fill, K_h/K_v was estimated to be 10.8 and 26.8 respectively in sands and gravels, and between 27.3 and 122.5 in intercalated rocks, and clay and silt. In the alluvium, K_h/K_v was estimated to be between 7.5 and 22.5 depending in part on geomorphic position.

Specific storage (S_s) is a characteristic of aquifers that describes the volume of water per unit aquifer volume produced by expansion of water and the compression of the porous medium per unit decrease inhydraulic head (Freeze and Cherry, 1979). The calibrated values of S_s for the aquifers are low and vary little in the BSPB, ranging from $1.0x10^{-6}$ m^{-1} up to $6.7x10^{-6}$ m^{-1} (Pool and Dickinson, 2007). The specific yield (S_y) is the water volume per unit area that is produced by an unconfined aquifer for a unit decrease in water table altitude (Freeze and Cherry, 1979). Typically, S_y is two or three orders of magnitude larger than S_s. In the BSPB, S_y ranges from a minimum of 0.001 in hard rock to 0.3 in the gravels and sands of the basin fills and alluvia. Microgravity methods and changes in well water levels were used to estimate a value of S_y of 0.09 for Antelope well #3 (Gungle et al., *In review*) and 0.14 for a well near Garden Canyon Wash (Pool, 2008).

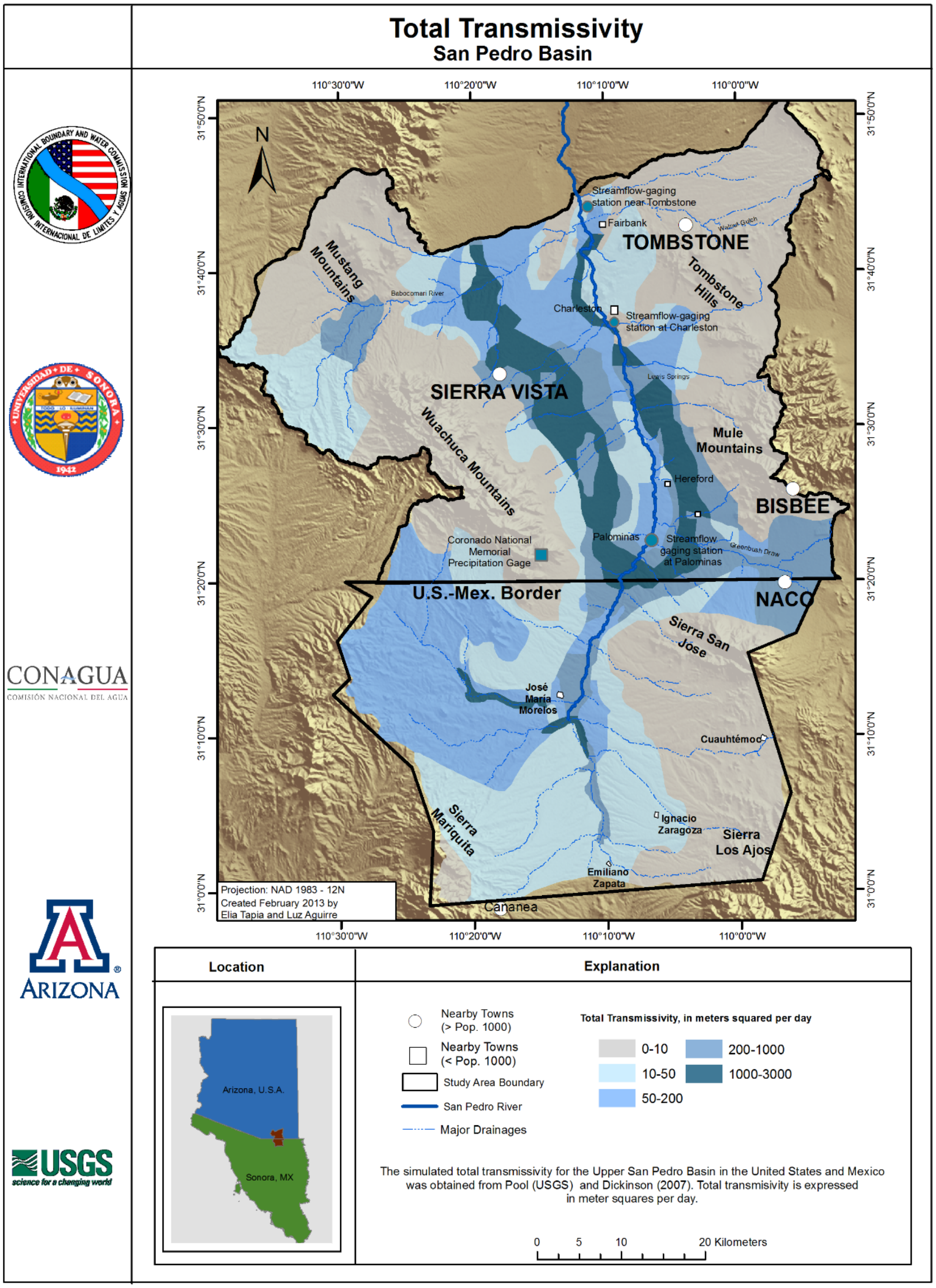
In the study "Geohydrologic Study of the San Pedro River and North of the Sonora River in Cananea, Sonora", there is information from 13 aquifer tests and 11 specific capacity tests (5 of the tests were performed during this project and the others were compiled from the literature (Consultores en Agua Subterránea, S.A., 2000)). In the USPSS, the value for K varies between 8.35 $x10^{-4}$ m/day and 5.14 m/day (Table 6.3). The minimum value was found in well 73, located at the Ejido Ignacio Zaragoza. The greatest K is found in well 30, located in the area of Patos Sur. With respect to aquifer transmissivity which is the product of hydraulic conductivity and aquifer thickness, the values ranged between 29.6 m^2/day and 1,990 m^2/s. The minimum value was found in COAPAES well No. 3 located in the Riito area and the maximum in well 28 near Ejido Ignacio Zaragoza. Pool and Dickinson (2007) published a binational map with simulated estimates of transmissivity (Figure 6.6). Values ranged from below 50 m^2/day in areas of silt and clay (near the center of the basin or along tributaries, see Figures 4.7 and 4.8), or sedimentary and crystalline rock (along the margins of the basin). The highest values, between 1000 and 3000 m^2/day, are found in zones of sand and gravel.

	Hydraulic Conductivity m/d			**Vertical Anisotropy Kh/Kv**			**Specific storage m^{-1}**			**Specific Yield**		
Hydrogeological Units	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max**	**Min**	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**
Limestone	0.072	0.625	0.0006	7.9	17.5	5	1x10^{-6}	1x10^{-6}	1x10^{-6}	0.011	0.02	0.01
Sedimentary Rocks	0.039	0.3	0.0001	7.3	17.5	5	1x10^{-6}	1x10^{-6}	1x10^{-6}	0.088	0.2	0.01
Granitic and metamorphic rocks	0.006	0.05	0.0001	8.8	17.5	5	1x10^{-6}	1x10^{-6}	1x10^{-6}	0.006	0.01	0.001
Volcanic Rocks	0.018	0.063	0.0001	7.1	17.5	5	1x10^{-6}	1x10^{-6}	1x10^{-6}	0.002	0.01	0.001
Undifferentiated Fill												
Undifferentiated sand and gravel	0.7978	10	0.0003	9.4	17.5	3.5	2.4x10^{-6}	5.0x10^{-6}	1.0x10^{-6}	0.12	0.2	0.01
Undifferentiated silt and clay	0.285	1.25	0.0013	3.5	3.5	3.5	5.0x10^{-6}	5.0x10^{-6}	5.0x10^{-6}	0.25	0.25	0.25
Upper **Basin Fill**												
Sand and gravel	3.459	7	0.05	26.8	75	8.8	1.5x10^{-5}	2.0x10^{-5}	1.0x10^{-6}	0.177	0.3	0.1
Intercalated Rocks	0.887	4	0.02	27.3	87.5	8.8	2.0x10^{-5}	2.0x10^{-5}	2.0x10^{-5}	0.15	0.25	0.05
Silt and clay	0.229	1	0.05	65	87.5	8.8	2.0x10^{-5}	2.0x10^{-5}	2.0x10^{-5}	0.057	0.1	0.05
Lower Basin Fill												
Sand and gravel	979	6.25	0.0002	10.8	36.1	3.5	3.5x10^{-6}	5.0x10^{-6}	1.0x10^{-6}	0.119	0.2	0.01
Intercalated Rocks	0.785	4	0.01	38.2	122.5	12.3	6.7x10^{-5}	1.0x10^{-6}	5.0x10^{-6}	0.092	0.1	0.05
Silt and clay	0.005	0.01	0.001	122.5	122.5	122.5	6.3x10^{-5}	1.0x10^{-5}	5.0x10^{-6}	0.05	0.05	0.05
Alluvium												
Undifferentiated	4.929	12.5	2.5	8.9	22.5	3.5	3.9*10^{-6}	5*10^{-6}	1*10^{-6}	0.264	0.3	0.25
Pre-trench	7.5	7.5	7.5	22.5	22.5	22.5	1*10^{-6}	1*10^{-6}	1*10^{-6}	0.291	0.3	0.2
Post-trench	7.5	7.5	7.5	7.5	7.5	7.5	1*10^{-6}	1*10^{-6}	1*10^{-6}	0.3	0.3	0.3

Table 6.2 Hydraulic Groundwater Parameters for the Upper Basin of the San Pedro River from Pool and Dickinson (2007).

Code	Phase	Coord. X	Coord. Y	Q (lps)	T (ft2/d)	K (m/d)
3	Drawdown	578820	3439956	19.69	319	0.114
4	Drawdown	578163	3440450	41.1	335	0.113
14	Drawdown	579837	3434918	33	1370	0.616
27	Drawdown	576849	3431730	57	6830	2.71
28	Drawdown	584235	3443171	50	21400	4.48
29	Drawdown	577795	3433957	40.1	2350	0.452
73	Recovery	585313	3441409	20.24	-	8.35E-04
87	Drawdown	582222	3435070	16.71	406	0.368
95	Drawdown	586811	3446573	9.08	7730	1.94
126	Drawdown	577348	3457302	19	11500	0.0760
147	Drawdown	575377	3452973	24.7	885	0.243
148	Drawdown	574825	3452912	24.05	1190	0.242
30	Recovery	575114	3432194	51	8270	5.14
34	Recovery	578426	3432287	28	6350	1.67
50a	Recovery	581554	3436863	33	2670	0.856
51	Recovery	581802	3435905	24	3710	2.54
53	Recovery	581265	3437451	33	3620	1.14
62	Recovery	572170	3433400	51	10900	3.60
66	Drawdown	573773	3434823	50	5670	0.887
	Recovery	573773	3434823	54.39	6170	-
68	Recovery	571302	3438109	76.96	4520	1.49
71	Recovery	586154	3440141	46	12800	2.53
75	Drawdown	584629	3442429	32.5	13600	2.25
	Recovery	584629	3442429	43.41	8690	-

Table 6.3 Pump Tests on the Mexican Side of the Binational San Pedro Basin (Consultores en Agua Subterránea, S.A., 2000, all tests were reviewed and approved by CONAGUA).



The simulated total transmissivity for the Upper San Pedro Basin in the United States and Mexico was obtained from Pool (USGS) and Dickinson (2007). Total transmisivity is expressed in meter squares per day.

Figure 6.6 Distribution of Transmissivity in the Binational San Pedro Basin (Pool and Dickinson, 2007)

7. HYDROGEOCHEMISTRY

7.1. Hydrogeochemical Sampling

Approximately every five years ADWR and the USGS sample water quality to acquire basic information including data about groundwater temperature, pH, and electrical conductivity, though both one-time and higher frequency project-specific sampling occur as well. All of this information appears in databases maintained by these agencies. The databases primarily include information collected by state and federal technical personnel (ADWR and USGS) according to established protocols including those published in the USGS National Field Manual (USGS, variously dated). The water quality portion of the USGS National Water Information System (NWIS) database is available here: http://waterdata.usgs.gov/az/nwis/qw/. The ADWR Groundwater Site Inventory (GWSI) database may be freely accessed at the following link: https://gisweb.azwater.gov/waterresourcedata/gwsi.aspx. In addition to these basic data on water quality in Arizona, there are additional data generated by state and federal agencies. In Arizona, water quality is managed by the Arizona Department of Environmental Quality (ADEQ) in coordination with the USEPA. In compliance with the state and federal standards, public and private utility operators must collect data on groundwater quality. In addition, state personnel periodically sample basins throughout the state. ADEQ keeps information on chemical and physical water quality parameters in its ADEQ Groundwater Database. USEPA maintains a database of water quality and other information called STORET (http://www.epa.gov/storet/). ADEQ and USGS previously prepared a joint groundwater quality report for the study area (Coes et al., 1999).

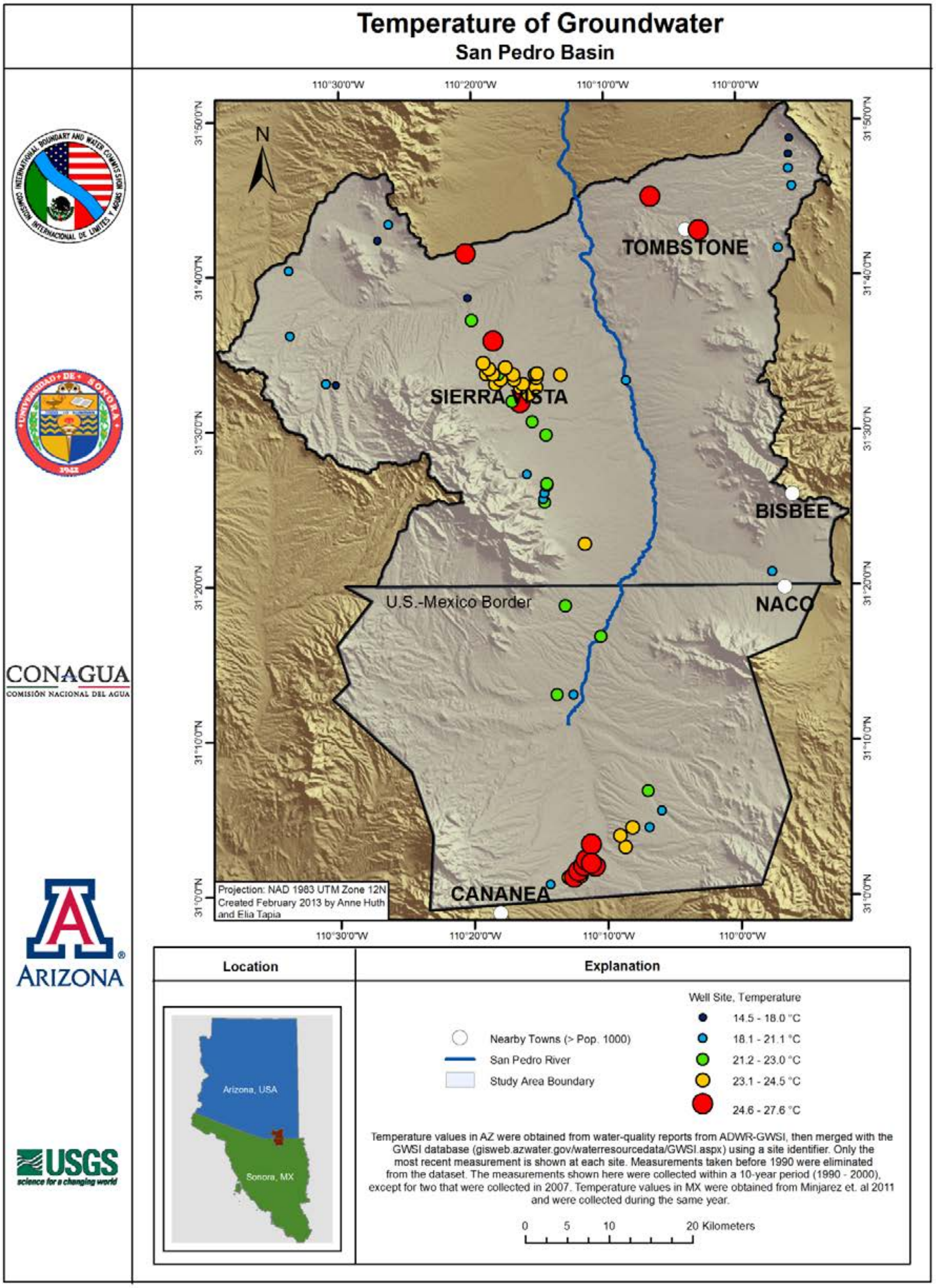
For the purposes of this report, water quality sampling of the San Pedro River aquifer was conducted in Sonora in July 2011 by the University of Sonora Geology Department (Minjarez et al., 2011), during which 20 samples were collected at various pumping wells. Samples were analyzed for field parameters (electrical conductivity, pH, alkalinity, and temperature), and subsequently submitted to a certified laboratory (Analítica del Noroeste) for analysis of anions and cations. With the intent of giving the widest possible representation of the chemical properties of the water in the San Pedro River aquifer, the spacing of sampling was chosen based on the density of groundwater wells to best represent existing hydrogeological conditions spatially and temporally as well as to cover the largest fraction of the study area possible. Samples were taken at well outlets, and in the case of large-diameter excavated wells without pumps, sampling was done using a plastic jar and a polyethylene rope, previously washed with deionized water; in the case of samples with excess organic matter, a plastic strainer was used. The wells were normally found to be in operation, but whenever they were found to be not operating, they were pumped for at least 15 minutes before taking the sample. At each sampling site, field calibration was performed on the instruments prior to the measurement of electrical conductivity, pH, and temperature of the sample. To estimate variability, these readings were taken three times for each sample. The data recorded in a log of each well included: weather conditions, time of sampling, physical parameters, and UTM coordinates.

7.2. Temperature and pH

The spatial distribution and temporal trends for water quality can also serve as indicators of the flow direction, of the interaction between different waters, of the origin or sources of the waters, and of potential contamination sources. The temperature of groundwater can be used as an indicator of hydrologic processes such as recharge, discharge, and groundwater-surface-water exchange (Blasch et al. 2007; Anderson, 2005). Subsurface temperature generally increases with depth, a phenomenon known as *geothermal gradient*. This gradient can range from 1°C per 20-40 m increase in depth. In addition, water from the surface can infiltrate and alter subsurface temperatures annually or even over longer scales due to variations in air temperature, insolation, and/or the volume and temperature of infiltrating water (Dowman et al., 2003; Smith, 1983). For these reasons, it is useful to measure temperature in wells.

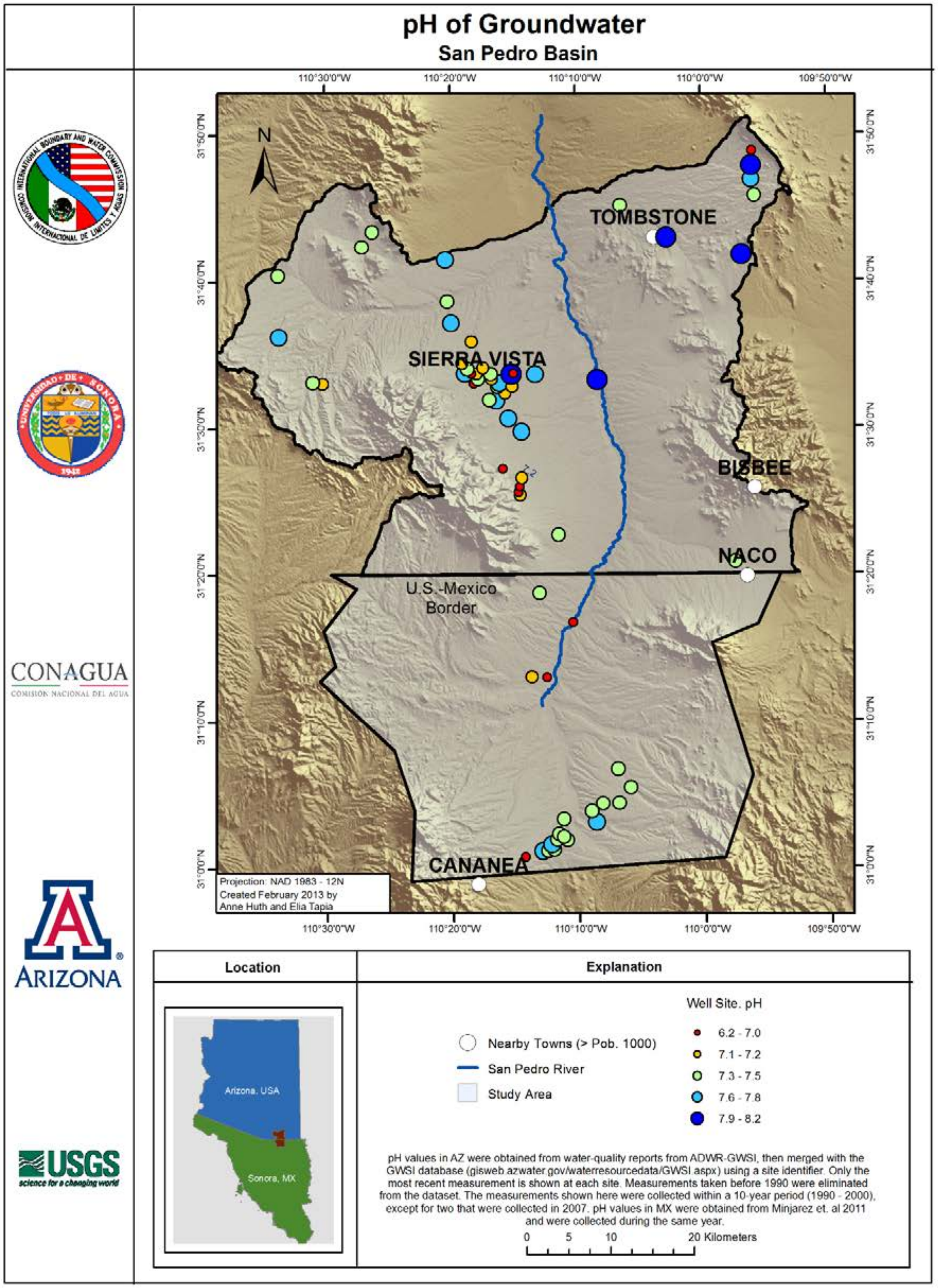
The hydrogen potential (pH) of a solution indicates the effective concentration of hydrogen ions (Mazor, 1997). It is typically determined in the field, because time, exposure to air, and temperatures different than those in the subsurface can all contribute to altering the pH of the sample. pH is both mediated by and influences many chemical processes such as mineral dissolution and precipitation, chemical transport, and biogeochemical cycling of nutrients. It is thus an important parameter to measure, because it influences various reactions, as well as the presence and concentration of different components in solution. If pH is around 7.0, the water is considered to be neutral; values above or below this are technically considered to be acidic (< 7) or alkaline (>7). However, both the USEPA and the Mexican Secretariat of Health regulate drinking water to be in the range of 6.5-8.5, such that acid water is considered to be less than 6.5 and alkaline water is greater than 8.5 (USEPA, 2014; Secretaría de Salud de México, 2014).

Figures 7.1 and 7.2 summarize temperature and pH at the wells sampled in Sonora and data from the ADWR (ADWR GWSI, 2013). As shown in the figures, the temperature in the Mexican portion ranged from 19.6 to 27.6 °C, with an average of 23.6 °C, while all pH values were within the maximum allowable levels outlined in the Official Mexican Standard (NOM-127-SSA1-1994) for water intended for human consumption, of pH 6.5 - 8.5. On the U.S. side, the temperatures ranged from 14.5 to 26.5 °C, with an average of 23 °C, while the pH values were between 6.2 and 8.2. pH in the San Pedro River at Charleston over the period 1987 to 2013 showed no significant trends (Gungle et al., *In review*), and the River was slightly alkaline with a pH of 8.3 during baseflow conditions. The grouping of temperature and pH are influenced by a variety of factors including depth, geology, and topographic setting, but the measurements and information on depth of screened interval are too sparse to support a clear interpretation.



Temperature values in AZ were obtained from water-quality reports from ADWR-GWSI, then merged with the GWSI database (gisweb.azwater.gov/waterresourcedata/GWSI.aspx) using a site identifier. Only the most recent measurement is shown at each site. Measurements taken before 1990 were eliminated from the dataset. The measurements shown here were collected within a 10-year period (1990 - 2000), except for two that were collected in 2007. Temperature values in MX were obtained from Minjarez et. al 2011 and were collected during the same year.

Figure 7.1 Groundwater Temperature in the San Pedro Binational Basin.



pH values in AZ were obtained from water-quality reports from ADWR-GWSI, then merged with the GWSI database (gisweb.azwater.gov/waterresourcedata/GWSI.aspx) using a site identifier. Only the most recent measurement is shown at each site. Measurements taken before 1990 were eliminated from the dataset. The measurements shown here were collected within a 10-year period (1990 - 2000), except for two that were collected in 2007. pH values in MX were obtained from Minjarez et. al 2011 and were collected during the same year.

Figure 7. 2 Groundwater pH in the San Pedro Binational Basin.

7.3. Water Quality

When required by statute or for the purposes of a particular study, water quality data are compared with the maximum allowable levels established in the Official Mexican Standard NOM-127-SSA1-1994 (Table 5.2) for human use and consumption, and on the U.S. side based on the maximum allowable levels established by USEPA and ADEQ, although they have not been established for most compounds. In general, results of water quality sampling and analysis indicate that most groundwater in the San Pedro River aquifer is generally of good quality and suitable for any human use (Pool and Coes, 1999; Coes et al., 1999; CONAGUA, 2009; Anning and Leenhouts, 2010). However, some wells in the SVSA contain concentrations of certain constituents that exceed the federal limits in the United States for potable water. Exceedances include arsenic, fluoride, iron, magnesium, dissolved solids, sulfate, and some volatile organic compounds (Coes et al., 1999; Gellenbeck and Anning, 2002; ADWR, 2009; Anning and Leenhouts, 2010). Contaminants of emerging concern (CECs) including wastewater compounds and personal-care products have been sampled in water at three springs near and across the River from Sierra Vista and at the Sierra Vista EOP (Gungle et al., *In review*). CECs as defined here are unregulated compounds generated directly or indirectly by human activities, the toxicity of which is unknown or poorly understood (Kolpin, 2002; Daughton, 2004). The number and concentrations of detections of CECs were highest at the treatment plant, followed by the Murray and Horsethief springs. Detections at the wastewater treatment plant included personal-care products (e.g. DEET), flame retardants (tris (dichloroisopropyl) phosphate), and pharmaceuticals (temazepam, carbamazepine). Detections at Murray Springs included plasticizers (para-nonylphenol) and pharmaceuticals such as phenobarbital and codeine among others.

Alkalinity is the capability of a filtered aqueous solution to neutralize acid due to the presence of carbonate and other ions (Rounds, 2006). Carbonate species exert significant control on the pH of natural waters (Hem, 1985) which is important for the health and maintenance of aquatic habitat, and water-rock interactions. Among the principal sources of alkalinity is the dissolution of atmospheric carbon dioxide in water. Soil-zone carbon dioxide and hence alkalinity may be elevated due to plant respiration, and the physical and biological oxidation of organic matter (Hem, 1985). In the BSPB, in wells that were sampled, the highest values of alkalinity (190-255 mg/L) were found just south of the border adjacent to the river (Figure 7.3). Higher values (160-190 mg/L) were also encountered north along the Huachuca mountain front. The lowest values (76-90 mg/L) were found in wells near Cananea.

Specific conductance, often used as a surrogate for TDS, is a measurement of the water's capacity to conduct electricity. As such, it is an indicator of the concentration of ions present, and this is a good approximation of the concentration of dissolved salts in the water. Specific conductance units are reported in Siemens/meter (S/m), but µS/cm is commonly used, resulting in values that are readily convertible to the parts per million (ppm) values used for measuring TDS. Because the technology for specific conductance is so widely available and easily applied, it is often used in the field and many studies report values in µS/cm instead of the ppm units that correspond to TDS. The conversion of electrical conductance values to ppm of TDS and vice versa is complex and depends on concentration among other factors, but a frequent simplification is the following (Weiner, 2012):

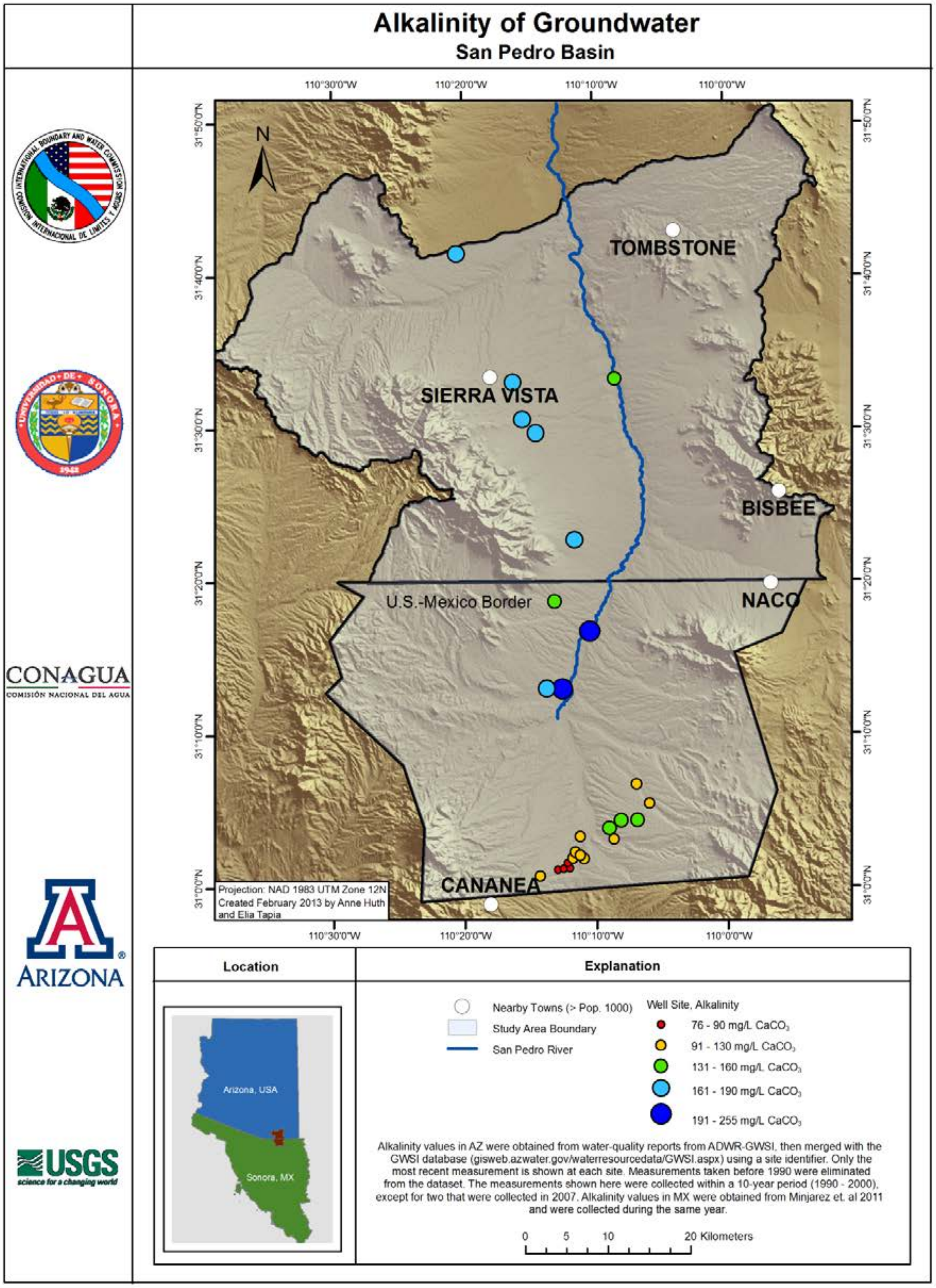
1.0 ppm of TDS ≃ 0.67 µS/cm of Specific Conductance

TDS and specific conductance are often used as first line indicators of water quality. They can also be used to suggest or clarify hypotheses about the occurrence of particular hydrologic processes in a given watershed. TDS is the sum of all dissolved constituents in a sample (Drever, 1997), and as such is important for a number of reasons including taste (it is regulated as a secondary drinking water standard by the USEPA), potential for aquatic health effects, and soil salinization (USEPA, 2014; Terrell and Perfetti, 1989; NRCS, 2014). It is assumed that long residence time of water in the subsurface increases concentrations of dissolved solids by dissolving minerals during transport, and a reduction in concentrations can occur through dilution by meteoric water or other chemical reactions (such as chemical precipitation) along groundwater flow paths (Pool and Coes, 1999).

The specific conductance of groundwater and surface waters is variable within the study area, but some temporal and spatial trends can be identified (Figure 7.4). In Sonora, values generally less than 400 µS/cm were observed, with an average of 338 µS/cm; the average value is higher than the data reported for the southern portion of the USPSS that has maximum values of 335 µS/cm (CONAGUA, 2009). According to the results obtained by Minjárez et al. (2011), the specific conductance values recorded at the sampled wells in Sonora range between 256 and 578 µS/cm. The three wells with the highest values are: 418, Barrilito, and 383. These are located in Ejido San Pedro, to the south in Barrilito, and in Ejido José María Morelos, respectively. The well with the lowest value of specific conductance was well 40 (with 256 µS/cm), located in Ejido Zapata on the south side of the aquifer. In Sonora, it was observed that electrical conductivity values generally increased northward toward the international boundary (CONAGUA, 2009; Minjárez et al., 2011). However, it should be noted that the highest values reported in the binational aquifer are located near the city of Cananea, where electrical conductivity of up to 737 µS/cm has been reported (See Appendix, Section 11.6).

According to analysis of water samples taken in the USPSS in 2000, most of the valley is dominated by TDS concentrations of less than 500 mg/L (CONAGUA, 2009). This report indicates that lower concentrations are found in the south-central portion of the subbasin and values tend to increase slightly heading north along the regional flow path for groundwater. This is similar to what was found in the specific conductance data mentioned above. At the same time, the geochemical survey done in 2011 by the University of Sonora found TDS values ranging from 182 to 844 mg/L, none of which exceeds the Maximum Allowable Limit established in Mexico’s NOM-127-SSA1-1994. In the SVSA, surface waters had values for specific conductance that averaged 558 µS/cm (Pool and Coes, 1999). However, the range of measurements varied from 235 to 610 µS/cm, with generally decreasing values in the river in the direction of surface flow. This points toward a potential TDS source near or south of the border.

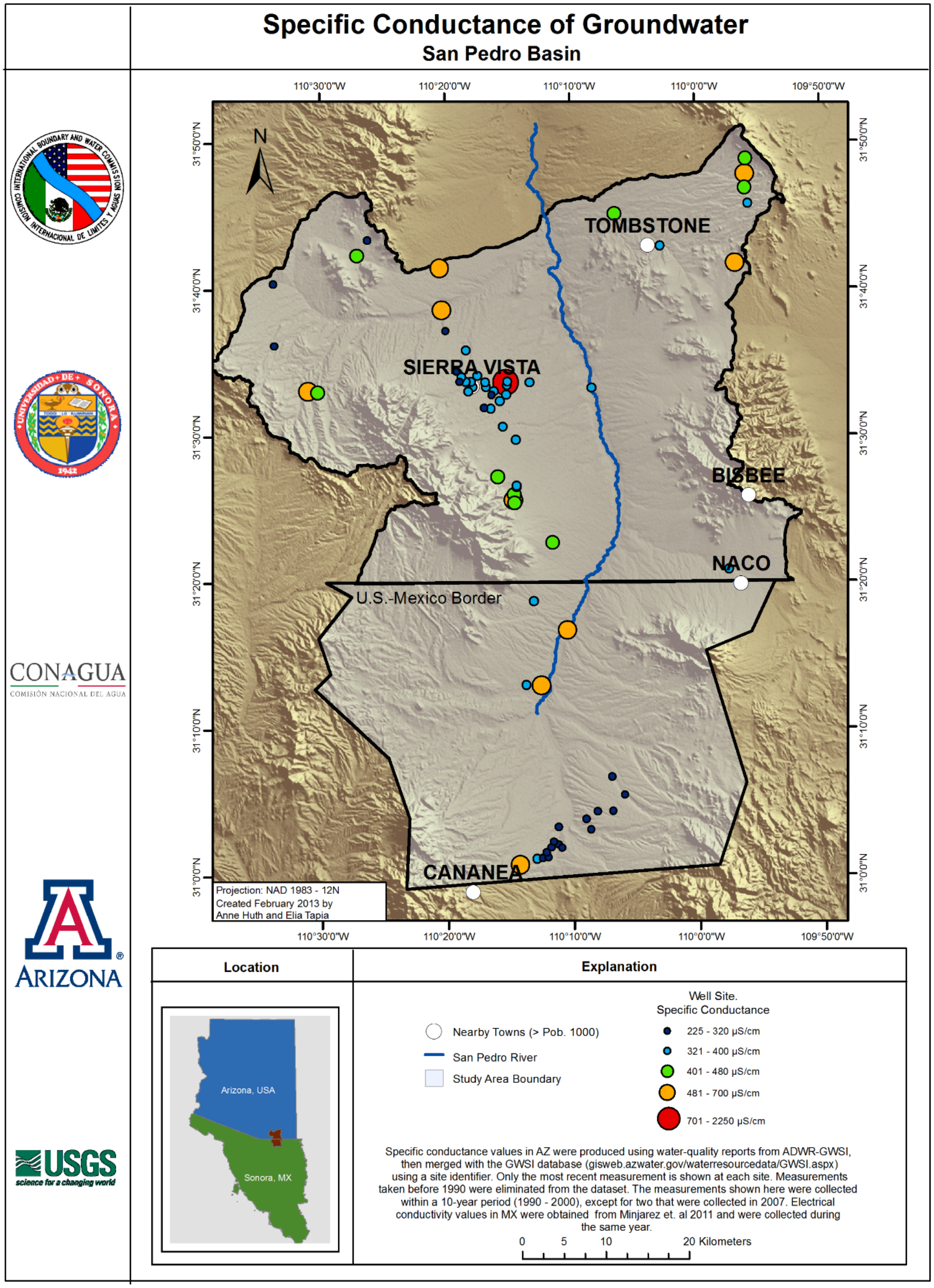
Pool and Coes (1999) found specific conductance values in the Holocene sediments had a very similar average to what was observed in the surface flows. The values had an average of 550 µS/cm, but they reached a maximum of 1,121 µS/cm and a minimum of 342 µS/cm during the study period (Pool and Coes, 1999). There is no clear explanation as to the cause of the high values in the Holocene alluvium, but it is possible that it is due to the concentration of salts by evaporation prior to infiltration and/or the dissolution of gypsum or other evaporite minerals present in the regional aquifer close to or south of the international boundary line, whose presence has been detected near the communities of Palominas and Hereford (Pool and Coes, 1999; McGuire, 1997), the dissolution of which can elevate the electrical conductivity of water.



Projection: NAD 1983 UTM Zone 12N
Created February 2013 by Anne Huth
and Elia Tapia

Alkalinity values in AZ were obtained from water-quality reports from ADWR-GWSI, then merged with the GWSI database (gisweb.azwater.gov/waterresourcedata/GWSI.aspx) using a site identifier. Only the most recent measurement is shown at each site. Measurements taken before 1990 were eliminated from the dataset. The measurements shown here were collected within a 10-year period (1990 - 2000), except for two that were collected in 2007. Alkalinity values in MX were obtained from Minjarez et. al 2011 and were collected during the same year.

Figure 7.3 Groundwater Alkalinity in the Binational San Pedro Basin.



Specific conductance values in AZ were produced using water-quality reports from ADWR-GWSI, then merged with the GWSI database (gisweb.azwater.gov/waterresourcedata/GWSI.aspx) using a site identifier. Only the most recent measurement is shown at each site. Measurements taken before 1990 were eliminated from the dataset. The measurements shown here were collected within a 10-year period (1990 - 2000), except for two that were collected in 2007. Electrical conductivity values in MX were obtained from Minjarez et. al 2011 and were collected during the same year.

Figure 7.4 Specific Conductance in the Binational San Pedro Basin.

7.4. Distribution of Major Ions and Identification of Water Families

The concentrations of major ions vary depending on the interaction between water sources, flowpaths, and physicochemical characteristics of rock and sediment in the aquifer (Somaratne and Frizenschaf, 2013; Uliana and Sharp, 2001). The predominant flow directions are from south to north through the alluvium, and from recharge areas at the mountain front through the regional aquifer. The geographic distribution of ions in the groundwater indicates high concentrations of calcium and magnesium near the mountains, and higher concentrations of sodium and potassium in samples located near the river (Minjárez et al., 2011).

The concentrations of calcium and magnesium in the waters of the San Pedro River and in the Holocene sediments in general are less than those occurring in the waters of the regional aquifer (Pool and Coes, 1999). In addition, concentrations of sodium, potassium, chloride, and sulfate are generally higher in the regional aquifer than in the Holocene sediments. Water in the Holocene sediments is likely derived from mixing of water from the regional aquifer and recharge of river water, though concentrations of chloride, sulfate, and bicarbonate tend to vary depending on the amount of surface-water runoff. Consistent variations in the major ions in the waters from the alluvium were not observed (Pool and Coes, 1999).

Piper diagrams are based on a classification of water by mass balance, enabling the presence of different regional hydrogeochemical families to be broken down into zones, as well as to highlight the differences between the water types regionally and within the same aquifer. Figure 7.5a is a Piper diagram characterizing the water type with sample locations mapped in Figure 7.5b. The groundwater type in the SVSA is calcium bicarbonate, generally alkaline and low salinity (Pool and Coes, 1999). According to the results of the 2011 sampling survey, carried out by the University of Sonora, the water family that predominates in the wells sampled in the USPSS is also calcium bicarbonate (80% of samples). This represents recently infiltrated water, with short residence times, that has circulated through volcanic rocks (Custodio and Llamas, 1996). Except for four samples located in the northern portion of the aquifer, these samples were mostly from the area known as Ampliación del Río and Los Patos. The calcium sulfate family was found in three wells in the Patos Sur zone. The sodium bicarbonate family was found in only one well.

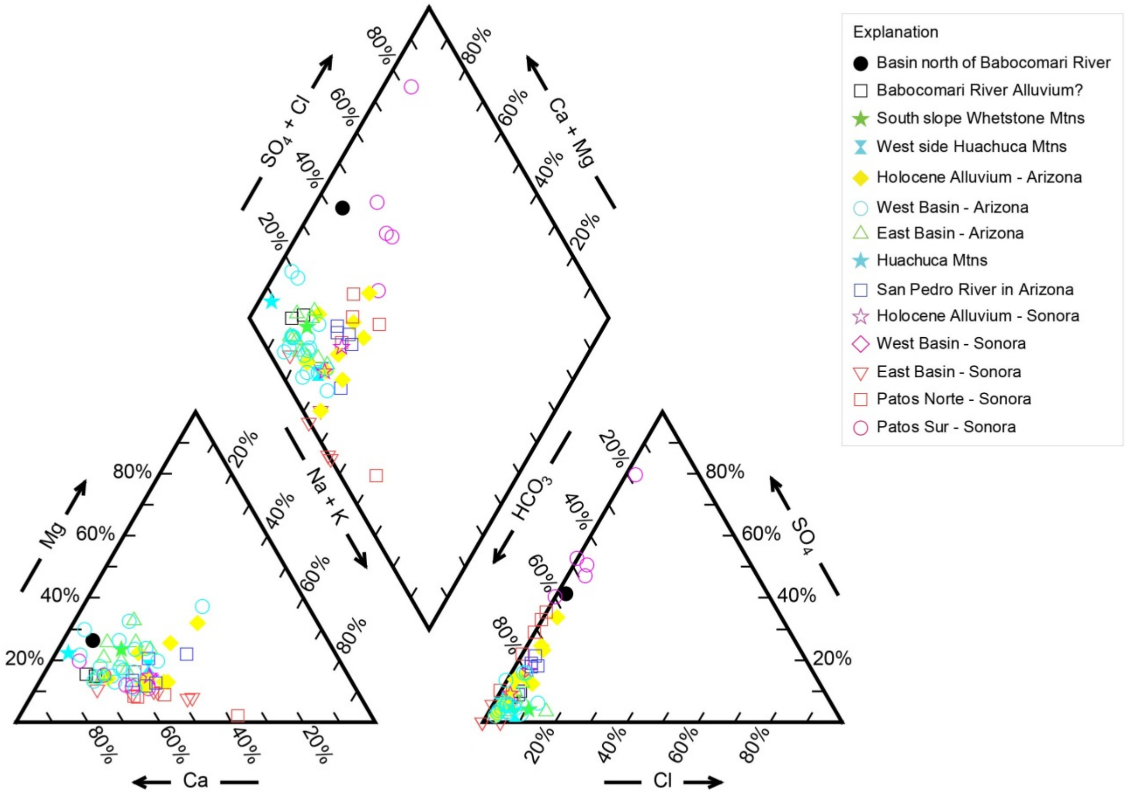


Figure 7.5 (a) Piper Diagram for the Binational San Pedro Basin using data available in USGS NWIS (2013) and data collected by UNISON (2011).

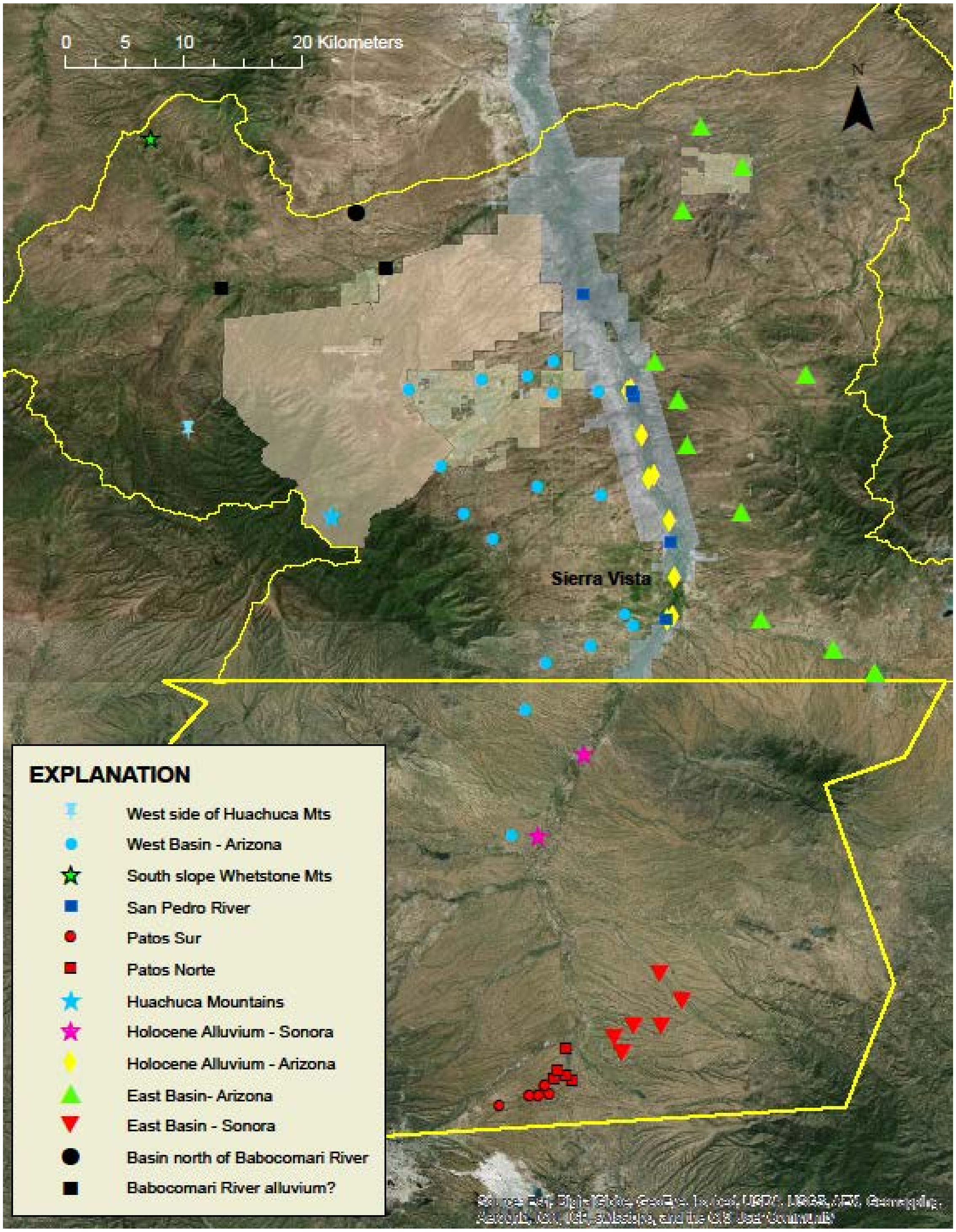


Figure 7.6 (b) Location of water sampling locations used in the Piper Diagram for the Binational San Pedro Basin.

Sodium

Sodium is commonly found in groundwater due to water-rock interactions. It may be derived from igneous rocks, mainly basalts and rhyolites, as well as urban and industrial pollution. The maximum sodium concentration permitted by the Mexican Official Standard (NOM-127-SSA1-1994), is 200 ppm. Concentrations in the aquifer range from 4 to 61 ppm. The maximum concentration was found at well D-23-22 22CCC and the minimum value at well D-23-19 01DBB. Both wells are located in the SVSA. The spatial distribution of samples shows higher sodium concentrations in the northern portion of the aquifer (Figure 7.6 and Figure 7.7).

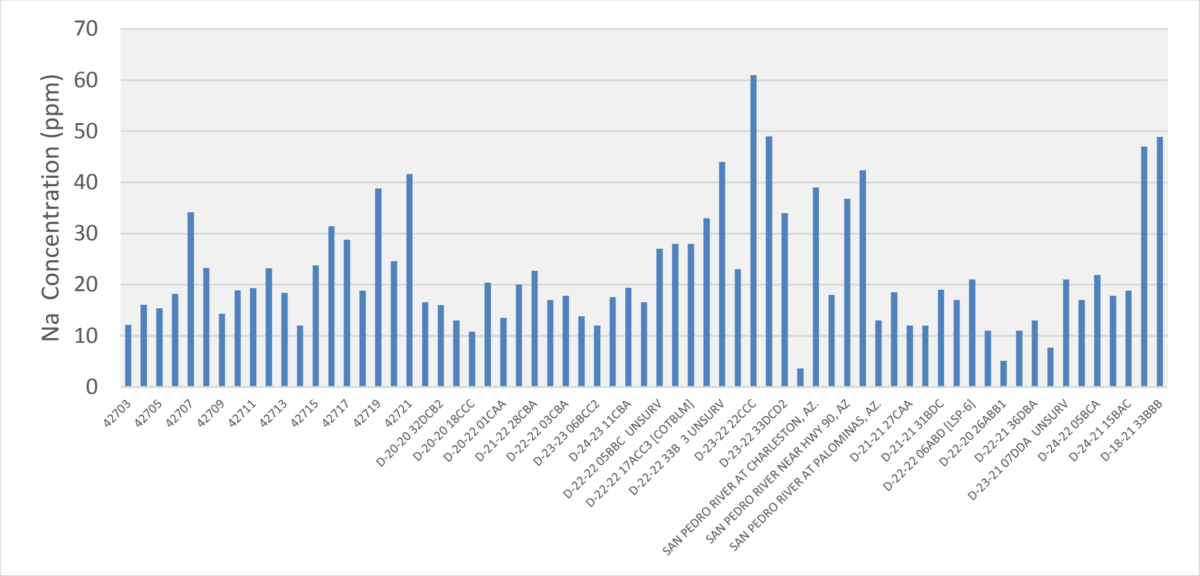


Figure 7.7 Sodium Concentration by Well (ppm) in the Binational San Pedro Basin.

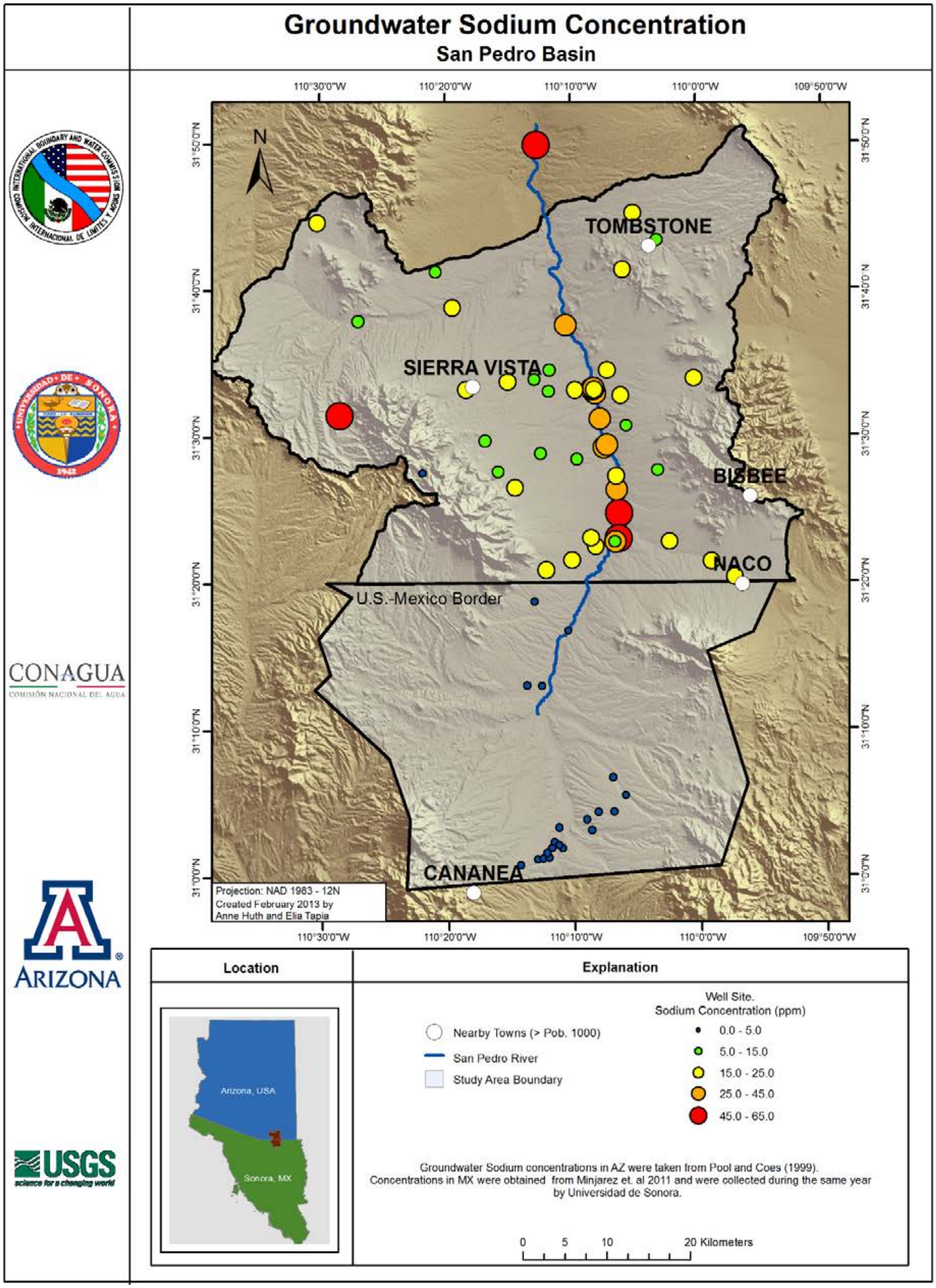


Figure 7.8 Spatial Variability of Groundwater Sodium Concentrations in the San Pedro Binational Basin.

Calcium

Calcium in groundwater is typically derived from aluminosilicate minerals that form part of the geological environment. The Official Mexican Standard does not set a maximum limit for calcium, but typical concentrations in drinking water can reach 250 ppm (Custodio and Llamas, 1996). Concentrations in the aquifer range from 17 to 169 ppm. The maximum concentration was found at well 42718 in Cananea, possibly related to mining activities. The minimum value was found at well D-22-22 06ABD in the SVSA. The spatial distribution of wells clearly show that in addition to the high value found in the city of Cananea, higher calcium concentrations are also located in the northern portion of the aquifer (Figure 7.8 and Figure 7.9).

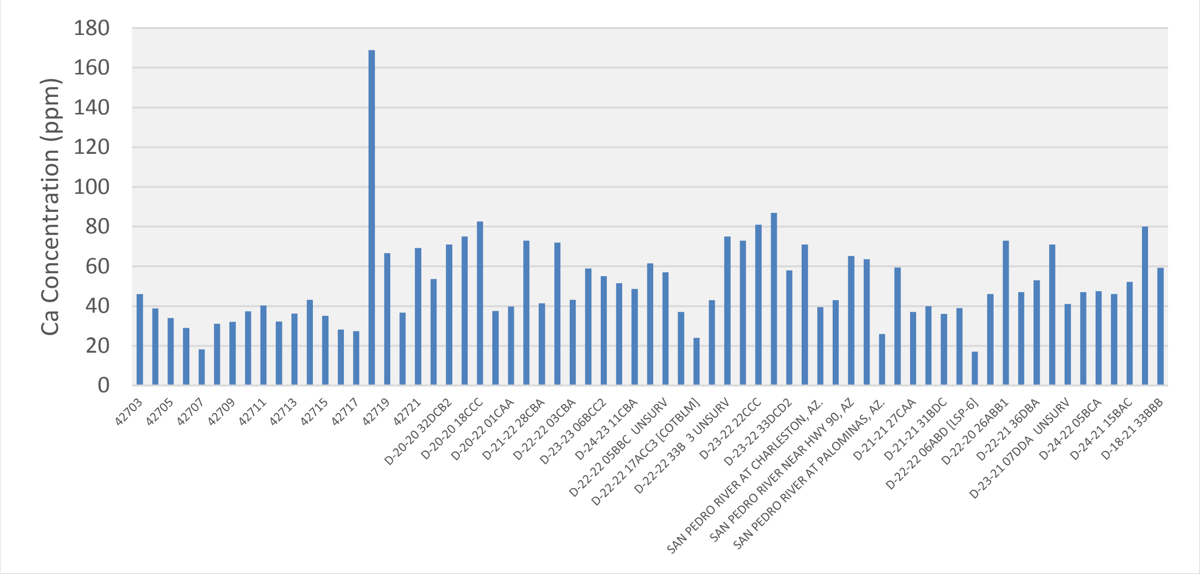
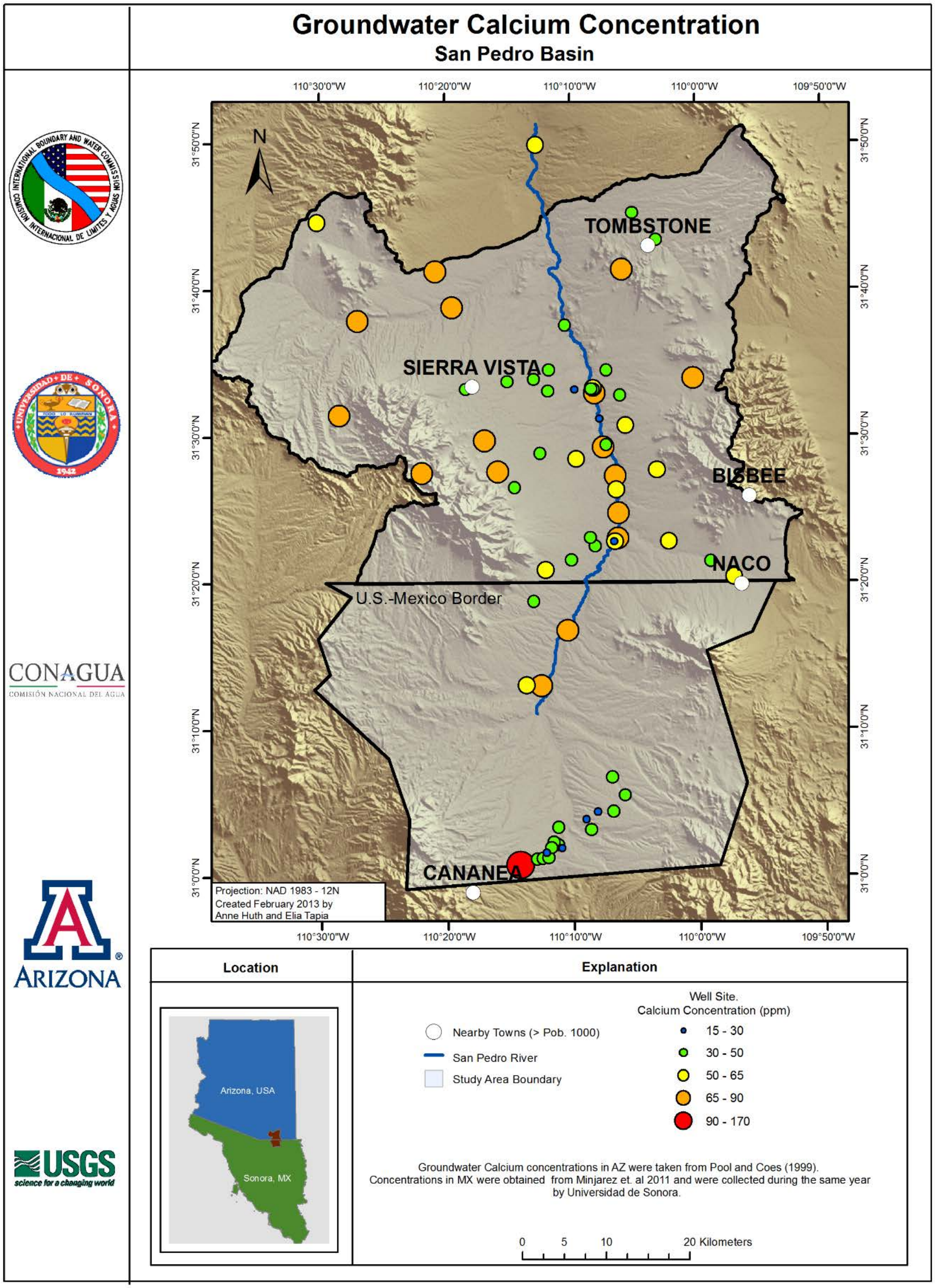


Figure 7.8 Calcium Concentration in Wells (ppm) in the Binational San Pedro Basin.



Groundwater Calcium Concentration

San Pedro Basin

Projection: NAD 1983 - 12N
Created February 2013 by
Anne Huth and Elia Tapia

Groundwater Calcium concentrations in AZ were taken from Pool and Coes (1999).
Concentrations in MX were obtained from Minjarez et. al 2011 and were collected during the same year by Universidad de Sonora.

Figure 7.9 Spatial Variability of Groundwater Calcium Concentrations in the San Pedro Binational Basin.

Magnesium

Magnesium is the third most abundant element in the earth's crust, surpassed only by aluminum and iron. It is part of both sedimentary and igneous rocks. The main source of magnesium in groundwater is typically dissolution of dolomite and dolomitic limestone, though whether or not that is the case in the BSPB is not known (Custodio and Llamas, 1996).

The Mexican NOM and USEPA do not establish a maximum permissible limit of magnesium for human use and consumption because it is not considered dangerous to human health. It may however have a laxative effect when mixed with sulfates. Another drawback of this element, is that when it is found at high concentrations it forms precipitates that can line pipelines and boilers. Concentrations in the aquifer range from 1 to 28 ppm. The maximum concentration was found at well 42718 while the minimum value was found at well 42707. Both wells are located in the USPSS. The spatial distribution of wells clearly shows that aside from the high value found in the city of Cananea, higher magnesium concentrations are also found in the northern portion of the aquifer, and lower concentrations are located in the southern portion (Figure 7.10 and Figure 7.11).

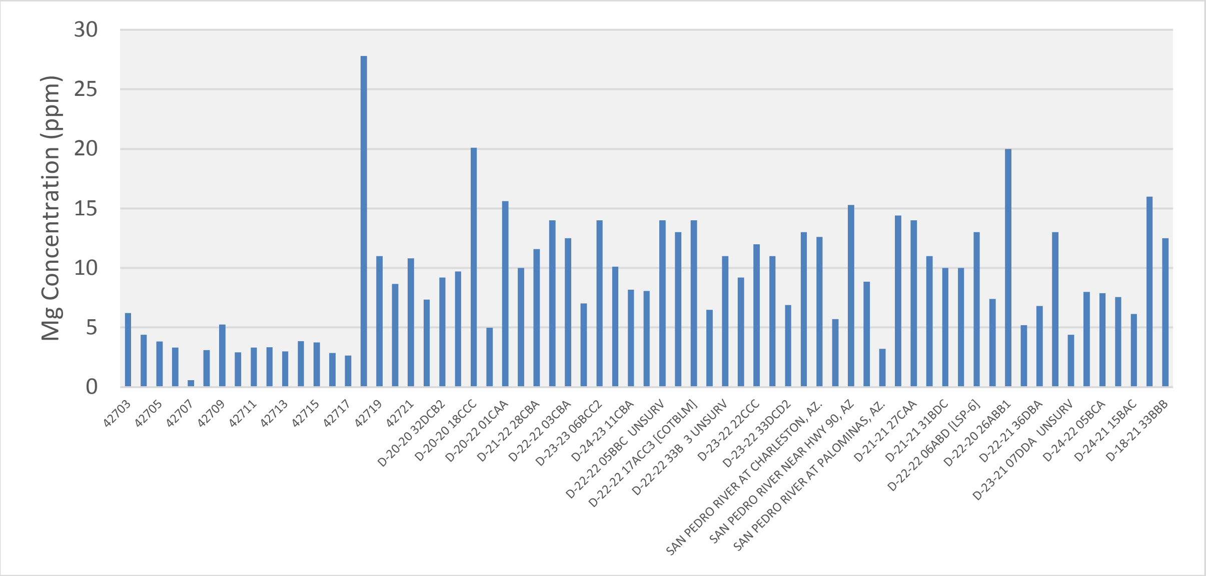
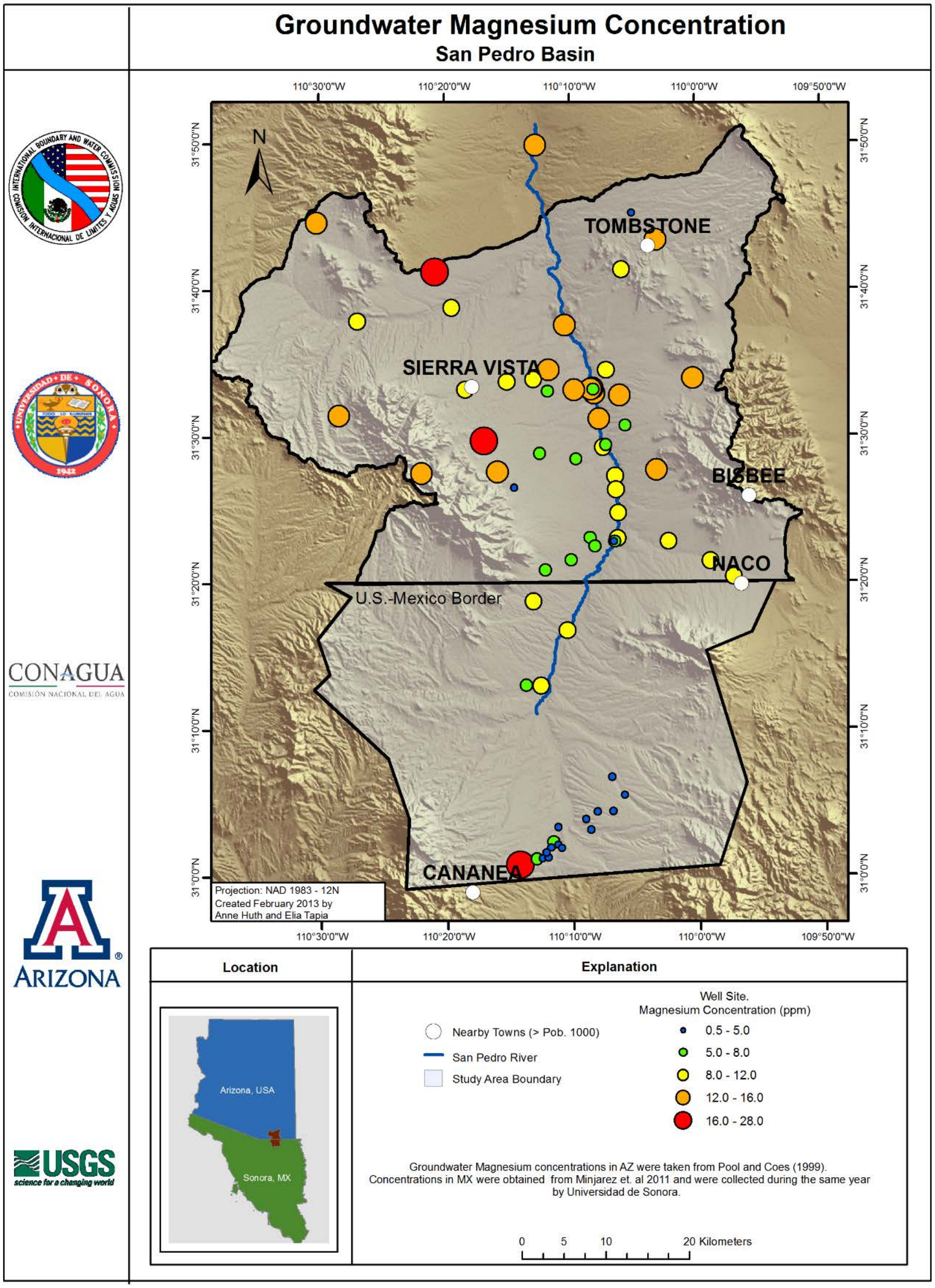


Figure 7.10 Magnesium Concentrations in Wells (ppm) in the Binational San Pedro Basin.



Projection: NAD 1983 - 12N
Created February 2013 by
Anne Huth and Elia Tapia

Groundwater Magnesium concentrations in AZ were taken from Pool and Coes (1999). Concentrations in MX were obtained from Minjarez et. al 2011 and were collected during the same year by Universidad de Sonora.

Figure 7.11 Spatial Variability of Groundwater Magnesium Concentrations in the Binational San Pedro Basin.

Potassium

Potassium concentrations in groundwater are usually found at very low levels, and are generally produced by leaching of aluminosilicate minerals, evaporites, organic matter decomposition, saline intrusion and anthropogenic pollution. The Official Mexican Standard does not set a maximum limit for Potassium. Nevertheless, Custodio and Llamas (1996) stated that potassium levels should not be higher than 10 ppm. Concentrations in the aquifer range from 0 to 5 ppm. The maximum concentration was found at the surface-water sampling site named SAN PEDRO RIVER AT PALOMINAS, AZ, while the minimum value was found at six wells in the Mexican portion of the study area, and is less than the possible detection limit. Higher values tend to cluster near or in the River and its tributaries (Figure 7.12 and Figure 7.13).

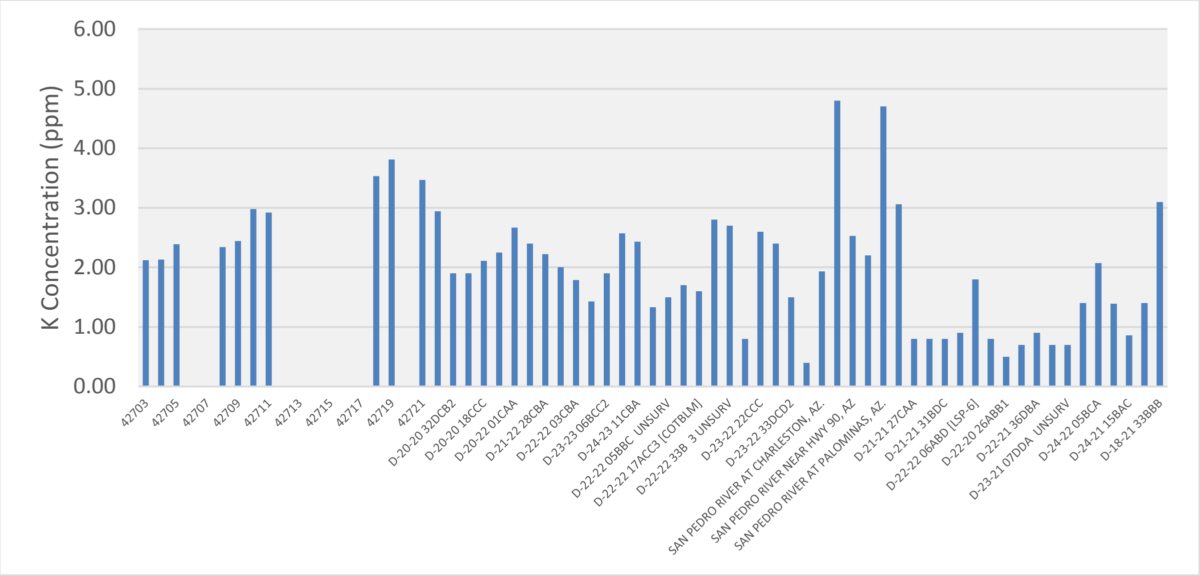


Figure 7.12 Potassium Concentrations in Wells (ppm) in the Binational San Pedro Basin.

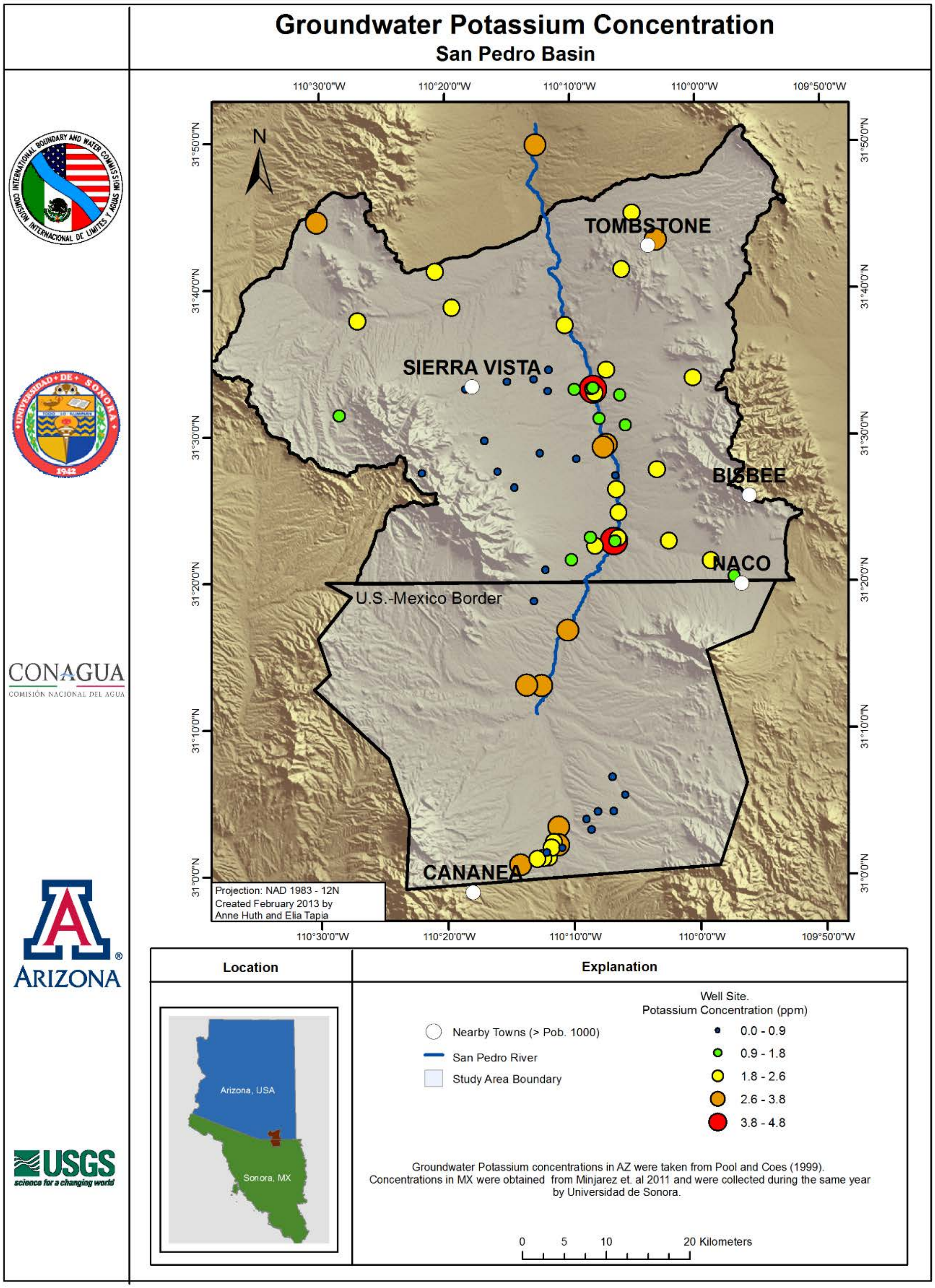


Figure 7.13 Spatial Variability of Groundwater Potassium Concentrations in the San Pedro Binational Basin.

Chloride

The Mexican NOM and USEPA (secondary standard) have established a maximum limit of 250 ppm for use and human consumption of chloride. Concentrations in the aquifer range from 0 to 23 ppm. The maximum concentration was found at well D-24-24 18CCB in the SVSA, values measured at eleven wells in the USPSS were below the detection limit of 5 ppm. Chloride concentrations do not follow any readily discernible patterns (Figure 7.14 and Figure 7.15).

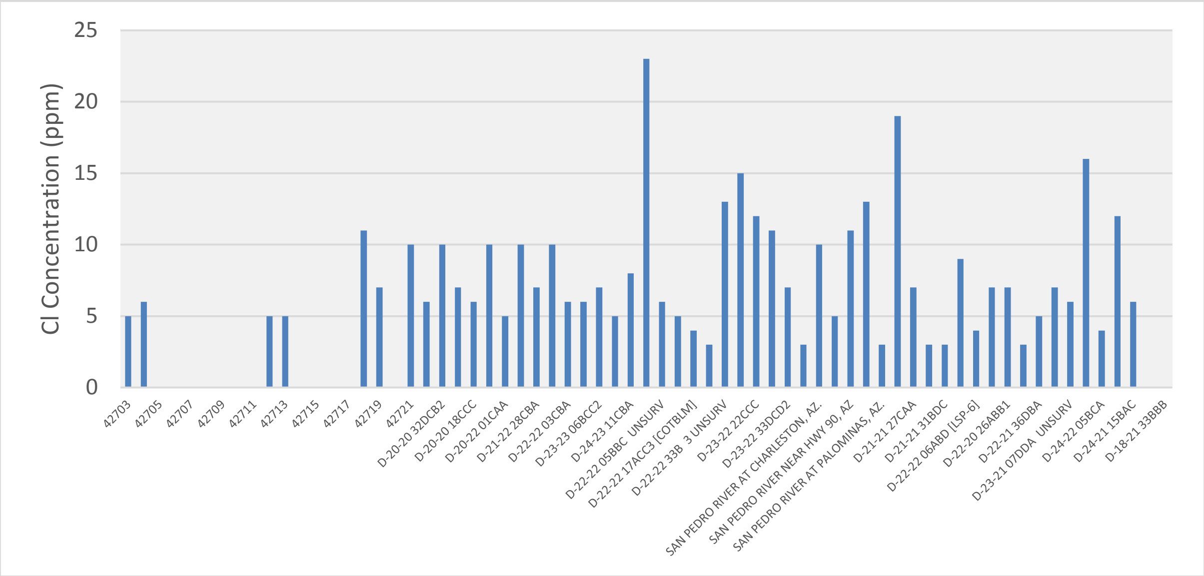
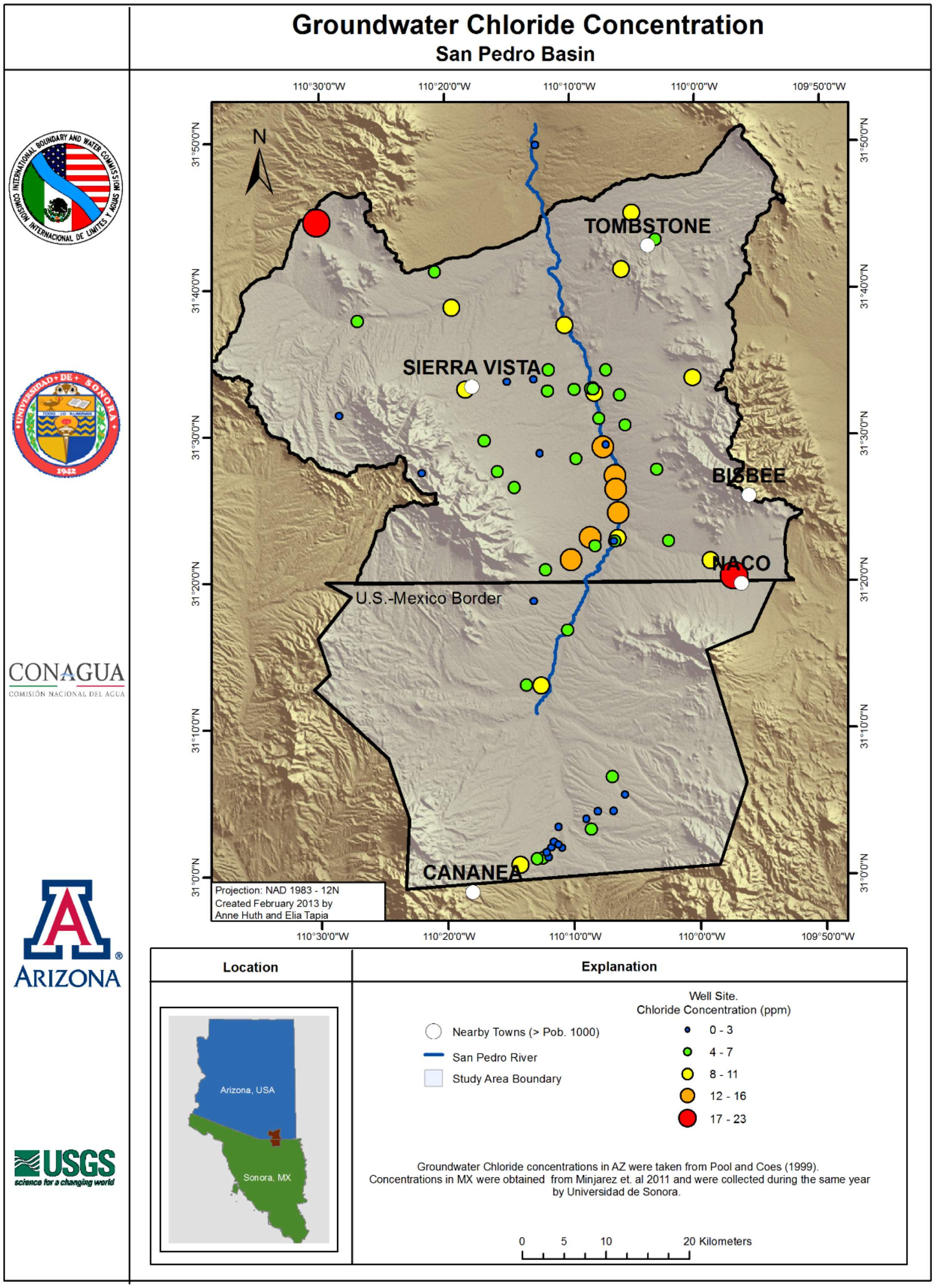


Figure 7.14 Chloride Concentrations in Wells (ppm) in the Binational San Pedro Basin.



Groundwater Chloride concentrations in AZ were taken from Pool and Coes (1999).
Concentrations in MX were obtained from Minjarez et. al 2011 and were collected during the same year by Universidad de Sonora.

Figure 7.15 Spatial Variability of Groundwater Chloride Concentrations in the San Pedro Binational Basin.

Sulfate

Groundwater sulfate concentrations range from 9 to 445 ppm. The maximum concentration was found at well 42718 in Cananea, Mexico, and surpasses the USEPA secondary standard of 250 ppm and the Mexican Official Standard Limit of 400 ppm. The minimum value was found at four wells in the Mexican portion of the study area, and is less than the detection limit. The highest sulfate concentrations in the USPSS are located near Cananea possibly due to the nearby sulfide mineral deposits (Figure 7.16 and Figure 7.17).

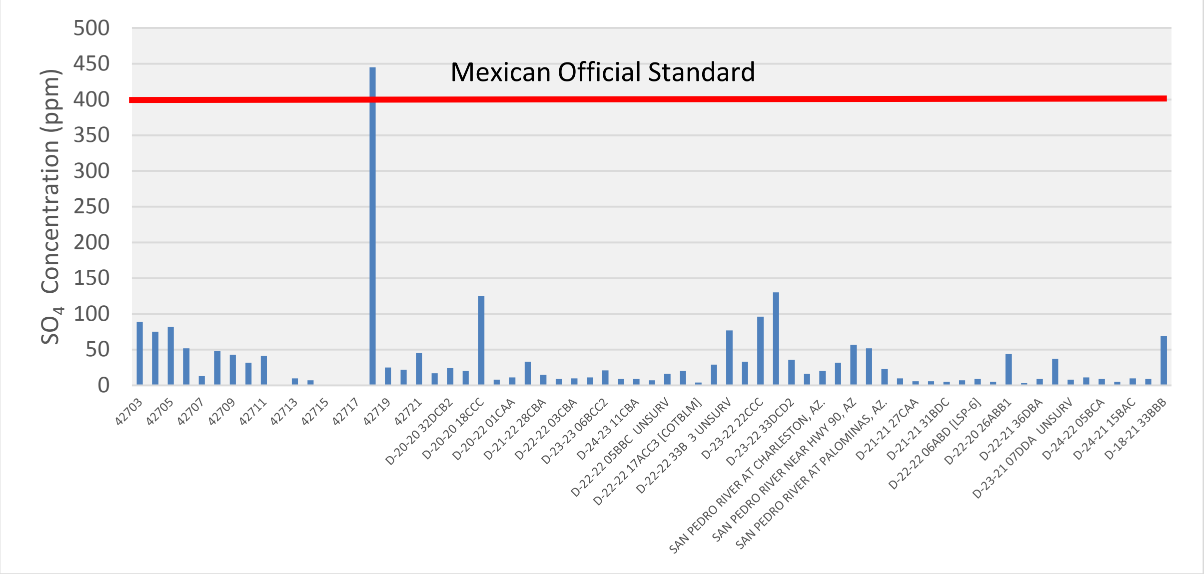
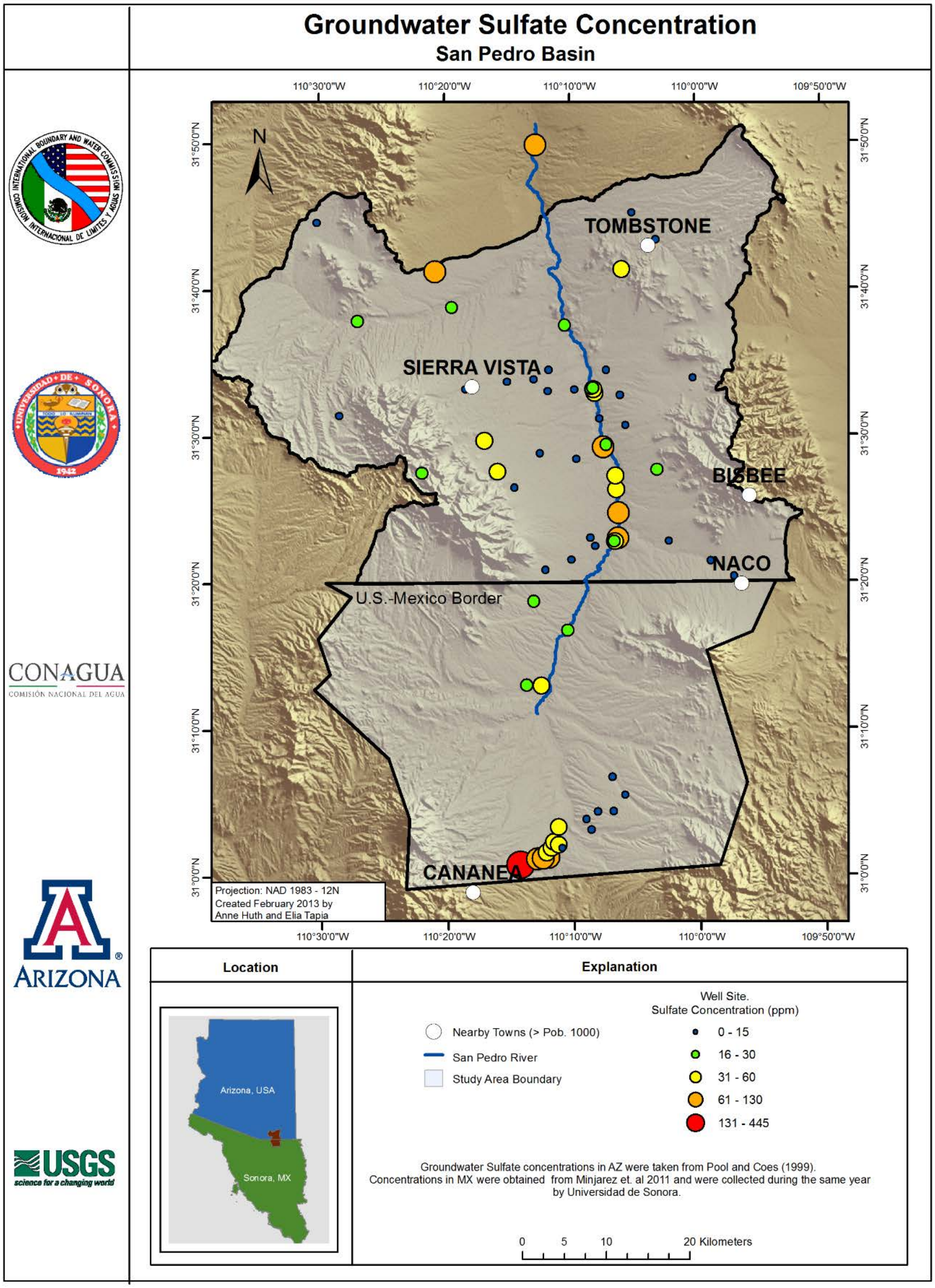


Figure 7.16 Sulfate Concentrations in Groundwater and Surface Water (ppm) in the Binational San Pedro Basin.



Projection: NAD 1983 - 12N
Created February 2013 by
Anne Huth and Elia Tapia

Groundwater Sulfate concentrations in AZ were taken from Pool and Coes (1999). Concentrations in MX were obtained from Minjarez et. al 2011 and were collected during the same year by Universidad de Sonora.

Figure 7.17 Spatial Variability of Groundwater Sulfate Concentrations in the San Pedro Binational Basin.

Bicarbonate

There is no Mexican Official Standard or USEPA drinking water standard with respect to bicarbonate. However, high concentrations of bicarbonate, along with Ca and Mg cause water to be hard, and can cause the buildup of scale. Custodio and Llamas (1996) indicate that bicarbonate in fresh water typically varies between 50 and 350 ppm. Concentrations in the aquifer range from 93 to 422 ppm. The maximum concentration was found at well D-22-18 13BBD in the United States and surpassed the maximum limit of Custodio and Llamas (1996). The minimum value was found at well 42705 in the Mexican portion of the study area. Values of bicarbonate tend to be lower in the southern portion of the aquifer (Figure 7.18 and Figure 7.19).

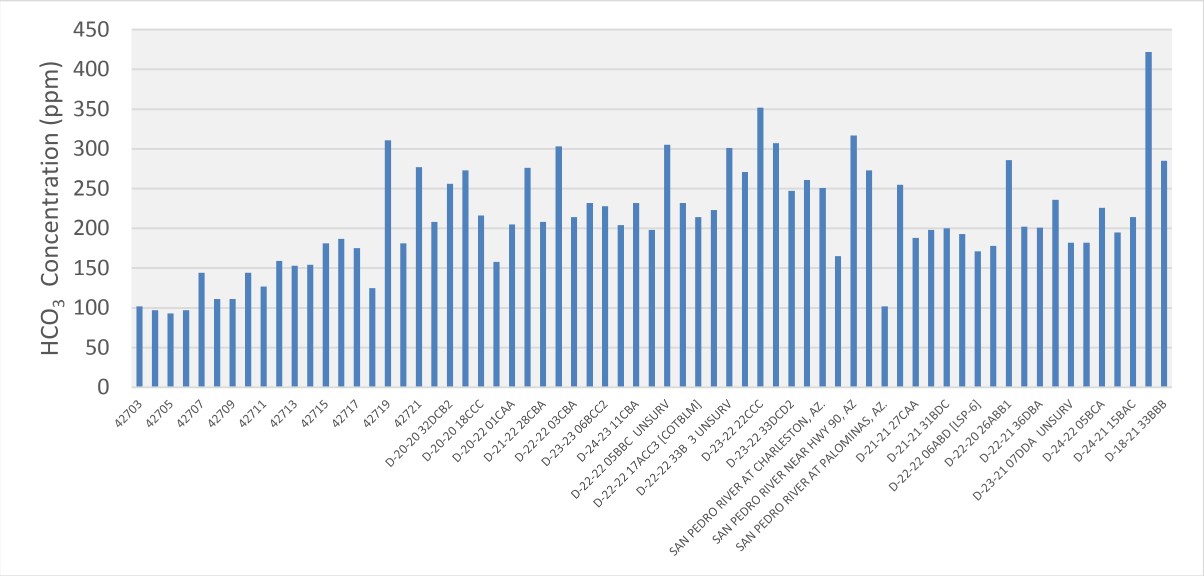
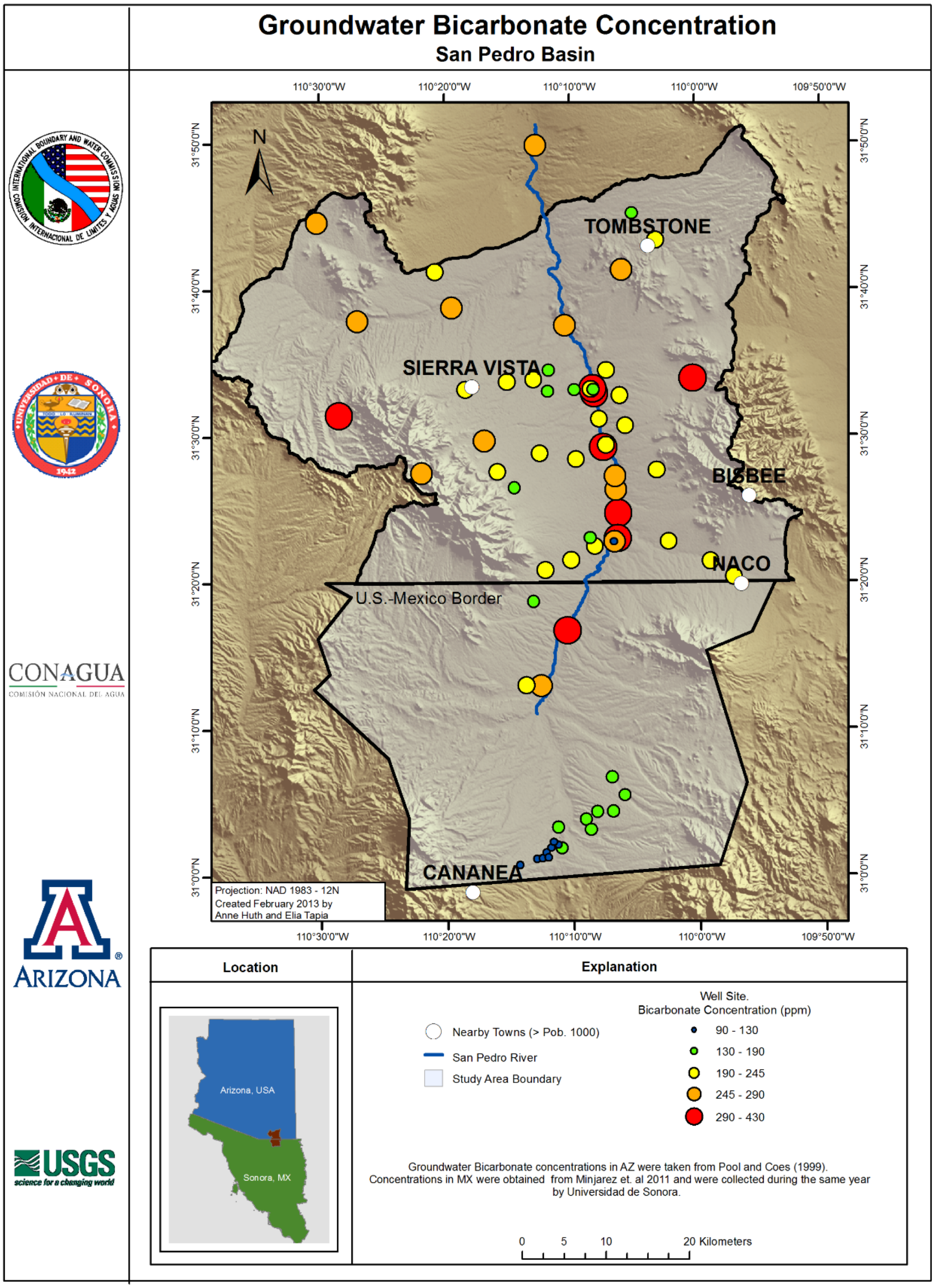


Figure 7.18 Bicarbonate Concentration in Groundwater and Surface Water (ppm) in the Binational San Pedro Basin.


Groundwater Bicarbonate Concentration
San Pedro Basin

Projection: NAD 1983 - 12N
Created February 2013 by
Anne Huth and Elia Tapia

Groundwater Bicarbonate concentrations in AZ were taken from Pool and Coes (1999). Concentrations in MX were obtained from Minjarez et. al 2011 and were collected during the same year by Universidad de Sonora.

Figure 7.19 Groundwater Bicarbonate Concentration in the San Pedro Binational Basin.

7.5. Stable Isotopes

Ratios of stable isotopes of hydrogen (δ^2H) and of oxygen ($\delta^{18}O$) are spatially and temporally variable in groundwater, surface water, and precipitation. The variability is controlled by a number of processes such as evaporation, condensation, and mixing. This variability can be used in conjunction with hydrogeologic and geochemical information to elucidate groundwater sources, flow paths, and mixing. This requires understanding of the manner in which isotope ratios vary in surface water and precipitation as inputs to the particular groundwater system under investigation. For example, although there is great variability from one event to another both globally and locally, mean δ^2H and $\delta^{18}O$ ratios in winter and/or high elevation precipitation tend to be low when compared to the mean summer and low elevation precipitation (Clark and Fritz, 1997; Eastoe and Dettman, 2014).

Up to the present, the distribution of stable isotopes in water has been sampled and analyzed only on the Arizona side of the basin. Pool and Coes (1999) analyzed water samples collected from 1994-1997. A number of other studies have also used stable isotopes to analyze flow patterns, aquifer recharge, and the water balance in this region (Coes, 1997; Wahi, 2005; Baillie et al., 2007; Wahi et al., 2008; Kennedy and Gungle, 2010; and Gungle et al., *In review*). Pool and Coes (1999) found the lowest ratios less than -70‰ δ^2H and less than -10‰ $\delta^{18}O$ in samples from springs in the Huachuca Mountains and in runoff in the San Pedro River during November and December 1994. The highest ratios of -50‰ δ^2H and -7‰ $\delta^{18}O$ were detected in samples from the San Pedro River after summer rains in 1994. The samples from the regional aquifer west of the River had ratios of -50 to -70‰ δ^2H and -8.3 to -9.6‰ $\delta^{18}O$. The distribution of these ratios is consistent with the flow patterns determined by the distribution of groundwater levels. Water with low isotope ratios occurs in flow paths originating at the base of the Huachuca Mountains. Along these flow paths, values vary little, indicating that little recharge of water enriched with heavy isotopes occurs away from the Huachuca Mountains (Pool and Coes, 1999). The groundwater near the international boundary has ratios of -55.1 to -57.8‰ δ^2H and -7.6 to -8.3‰ $\delta^{18}O$, similar to those detected near the Mule Mountains, east of the river, and to the ratios detected in waters from the Holocene alluvium of between -57.9‰ δ^2H and -8.2‰ $\delta^{18}O$ (Pool and Coes, 1999). Gungle et al. (*In review*) used isotopes in baseflow of the San Pedro River to examine spatial and temporal changes in groundwater inputs to the river.

Statistically significant temporal variations were found (increases in $\delta^{18}O$) at the Palominas, Lower Babocomari, and Lewis Springs gages. This was interpreted as declines in groundwater input upstream of the Palominas and Lower Babocomari gages. At the Lewis Springs gage, they suggested that the trend could be caused by infiltration of evaporated water from beaver ponds. Results of analysis of spatial trends generally support the conclusions of Pool and Coes (1999) that found that groundwater inputs from the west side of the river were most substantial between Hereford and Lewis Springs. Using a two-end member mixing model, Baillie et al. (2007) concluded that baseflow in the river is up to 80% monsoon-derived floodwater closer to the international border, decreasing to 55% in downstream reaches. Between 2003 and 2005, a study was carried out on the west side of the basin using a range of isotopes that estimated the amounts of natural recharge along the edges of the mountains in this region of Arizona. The authors estimated that 65% ±25% of the recharge on the edges of the mountains occurs during winter and 35% ±25% occurs during summer (Wahi et al., 2008). They also found that more than 90% of the non-runoff portion of precipitation is lost primarily as the transpiration component of ET.

8. CONCEPTUAL AND NUMERICAL MODELS OF GROUNDWATER COMPONENTS AND BEHAVIOR

The behavior of groundwater in the BSPA is determined by overarching factors such as geology, climate, and time. Together, they control the precipitation, vegetation, surface runoff, hydraulic properties, groundwater storage, and flow, and water recharge and discharge. Other important factors are variations in temperature, topography, season, slopes, aspect, and soils, as well as anthropogenic factors such as water use, and land-use and land-cover change.

8.1. Groundwater Flow System

Most groundwater in the study area originates through mountain front or mountain block recharge in the higher elevations of the basin (Corell et al., 1996; Wahi et al., 2008; Pool and Dickinson, 2007; Wilson and Guan, 2004). Mountain system recharge occurs by way of infiltration and deep percolation through permeable rocks of the mountain block as well as at the mountain front where stream channels converge with high permeability alluvial sediments at the edges of the mountains. Recharge is greater at higher elevations due not only to higher precipitation but also to lower rates of ET caused by generally lower temperatures (Pool and Dickinson, 2007). Another significant source of recharge occurs in perennial streams and rivers, as well as in ephemeral channels, where water is concentrated and permeable sediments facilitate infiltration (Coes and Pool, 2005; Baillie et al., 2007). In the alluvial sediments of the basin, groundwater flows toward areas of discharge along perennial or intermittent reaches of streams and rivers, through ET by phreatophytes (Tillman et al., 2011; Tillman et al., 2012), and to adjacent down-gradient basins (Coes and Pool, 1999). Mountain springs occur more commonly in the lower elevations, in canyons that intersect faults, or layers of sandstone or limestone that overlie materials of low permeability (Coes et al., 1999; Pool and Dickinson, 2007). This situation is more frequently found in the Sierra San José and in the Huachuca and Mule Mountains (Minjárez et al., 2011). Discharge areas at lower elevations are often found where the drainage network intersects the saturated sediments that overlie thick layers of clay and silt (Pool and Dickinson, 2007). These discharge points can be either stream or river reaches, or springs located in terraces on the flanks of the San Pedro River. There is also groundwater discharge into the Benson subbasin through the alluvial sediments. As evidenced by the shape of the static water level water surface, most of the groundwater crosses the boundary near and to the east of the San Pedro River, and little crosses to the west of it (Pool and Dickinson, 2007).

8.2. Pre-development Hydrology

To understand how water flow has changed through the influence of climate, pumping, and other factors, it is important to estimate the balance prior to agricultural, municipal, and industrial development when the system was in a quasi-steady state. The pre-development groundwater balance was estimated for the BSPB by Corell et al. (1996), and updated by Pool and Dickinson (2007) based on data available for water extractions, irrigated surface area, water consumption by riparian vegetation, and artificial recharge (Table 8.1).

	Annual Average	
Water Balance Component	**Inflows (m^3/d)**	**Outflows (m^3/d)**
Recharge	60,600	0
Base Flow	0	28,700
Evapotranspiration	0	26,400
Groundwater Flow	0	4,000
Drainage	0	1,500
TOTAL	60,600	60,600

Assumptions and clarifications with respect to Table 8.1:

1. Recharge is estimated to be equal to the estimated discharge.
2. Base flow represents the net base flow rate because the gaining or losing reaches are not well defined.
3. Drainage includes the springflow in the Huachuca Mountains.
4. It is assumed that no change in storage occurred in the period before development.

Table 8.1 Pre-Development Water Balance in the BSPB (Pool and Dickinson, 2007).

Pool and Dickinson (2007) used data from various years prior to 1940 (ET in 1935, discharge at Charleston 1935-1939, etc.) to estimate the pre-development (steady state) conditions, although the system was not in balance prior to 1940 due to factors such as the use and dewatering of Tombstone and Bisbee mines that began in the early years of the twentieth century, as well as climate variations such as the PDO and the ENSO (Dickinson et al., 2004; Pool, 2005; Hanson et al., 2006). The incision and widening of the San Pedro River also occurred during this period, starting before 1900 and not ending until the 1950s (Hereford, 1993). The changes in the channel had as a consequence the deepening of the water table, changes in riparian vegetation with associated changes in ET, and a probable increase in the base flow, but the sequence and magnitude of these impacts are unknown (Pool and Dickinson, 2007).

The baseflow discharge to the Benson Subbasin was estimated at 0.004 hm^3/d - 0.0027 hm^3/d through the alluvium east of the San Pedro River, 0.001 hm^3/d in the riparian alluvium associated with the San Pedro River near the Tombstone gage, and 0.0003 hm^3/d in the basin fill west of the River (Pool and Dickinson, 2007). The groundwater discharge to the channels and springs was estimated at 0.0287 hm^3/d and the discharge through ET at 0.0264 hm^3/d for a total discharge of 0.0606 hm^3/d. If the system is in a steady state, the value of the recharge is of the same magnitude as the discharge (Pool and Dickinson, 2007).

8.3. Post-development Hydrology

ET in the BSPB changed dramatically after 1935 as a result of the type of vegetation along the channels evolving principally from grasses and wetlands to mesquite forest and riparian vegetation, composed primarily of shrubs and trees such as ash and cottonwood. The mesquite and riparian forests have higher ET rates than grass and wetlands areas. For 2003, Pool and Dickinson (2007) used ET values that varied from 0.0324 hm^3/d to 0.0407 hm^3/d for the SVSA, and between 0.0045 hm^3/d and 0.0057 hm^3/d in the USPSS. Because of the change in vegetation along the channels, they estimated that the 2003 values are double the 1935 ET rate. Tillman et al. (2012), used the Enhanced Vegetation Index, a MODIS satellite product, to calculate ET for the 2000-2007 period in the SVSA. They found that ET varied between 0.031 hm^3/d and 0.0419 hm^3/d with an average of 0.0353 hm^3/d, which are in line with values used by Pool and Dickinson (2007). Scott, Williams, et al. (2006) estimated groundwater use along the San Pedro river; and Scott, Cable, et al. (2008) estimated groundwater use along the San Pedro and Babocomari rivers at about 0.0323-0.0408 hm^3/d for 2003, and Scott, Cable, et al. (2008) reported a value of 0.0411 hm^3/d for the period 2001-2005.

Historical reports indicate that extraction of groundwater varied considerably during the period after 1935 in industrial, domestic, and municipal uses. The extraction of groundwater in the BSPB started at the beginning of the 20th century and increased relatively consistently after about 1935, reaching an estimated rate of between 0.110-0.164 hm^3/d) during the last 25 years (Pool and Dickinson, 2007). Several sectors are responsible for the majority of the BSPB pumping, including mining, municipal, agricultural-livestock, industrial, and domestic. Prior to 1940, extraction was dominated by mines near Tombstone, Bisbee, and Cananea, but the increase in pumping that occurred after 1940 was due to the drilling of new wells and the installation of high capacity pumps (Pool and Dickinson, 2007). Water withdrawals for the mine near Tombstone were significant at the beginning of the 20th century, reaching an estimated 0.019 hm^3/d in 1910 and ceasing soon thereafter (Pool and Dickinson, 2007). The mine in Bisbee was open until 1987. Although the pumping rate ranged from 0.027 to 0.466 hm^3/d, it is likely that the main aquifer extraction was isolated from the BSPB and some unknown portion came from the adjacent basin. Non-mining uses in the SVSA began in the 1930s. Extraction for agricultural use on the U.S. side was significant through the mid-20th century, but declined over time and never exceeded 0.019 hm^3/d (Pool and Dickinson, 2007). Groundwater extraction for all uses combined has increased steadily, and continues to do so, reaching 0.054 hm^3/d (Pool and Dickinson, 2007). The maximum extraction associated with the Fort Huachuca military base occurred in 1993 and was estimated at about 5 hm^3/yr and has been declining on a gross and per capita basis since 1993 (Pool and Dickinson, 2007; Gungle, written commun., 2014). Groundwater extraction in the Sierra Vista area has continued to expand the cone of depression and alter groundwater gradients. Groundwater extraction for all uses combined increased with some variability through the 20th Century ranging between 50 and 55 hm^3/yr by 2002. Gungle et al. (*In review*) documented that horizontal gradients between Sierra Vista and the San Pedro continue to decline.

The post-development groundwater conceptual and numerical models developed by Pool and Dickinson (2007) for the BSPB include changes in recharge, ET, and pumping. In their numerical model, variations in natural recharge were not implemented, although they acknowledge that they occur and may be significant in their effects on water levels and streamflow. Their implementation of the artificial component of recharge, however, is both temporally and spatially variable. It has different sources such as surplus irrigation water, mine drainage water, and domestic wastewaters from the local towns and septic systems. Artificial recharge was varied over time and location to match, for example, the dates when sewage treatment facilities near Sierra Vista, Bisbee, Fort Huachuca, and Tombstone began operations, where they discharged their effluent (stream channels, ponds, crops), and at what rates (typically increasing through time). Using Sierra Vista as a case in point, the sewage treatment facility began operation in 1967 discharging to an ephemeral-stream channel. In 1978, the facility was expanded with discharge being used for crop irrigation starting in 1980. In 2002, the effluent discharge location was changed with the end point being recharge basins.

Recent updates to several components of the groundwater system and water budget were done by Kennedy and Gungle (2010), USPP (2010, 2012), Lacher (2012), and Gungle et al. (*In review*), in part as the result of 2003 U.S. Congressional legislation that required the USPP to prepare an annual report on the status, assessment, and maintenance of sustainable yield as part of the management of the regional aquifer in the SVSA. Gungle et al. (*In review*) has the most current analysis of many of the components of the SVSA portion of the groundwater system. Basin-wide water budget components are refined and re-analyzed, including an estimate of the annual water balance for 2002 through 2012. Categories in the budget include natural components of the system (recharge, groundwater inflow/outflow, stream baseflow discharge, and ET), groundwater pumping (municipal, water companies, rural/exempt wells, industrial, irrigation), active management measures (mesquite/tamarisk removal, municipal-effluent and detention basin recharge), and unintentional recharge (septic systems, turf facilities, etc. and urban-enhanced recharge). The long-term averages of fluxes to and from the natural components of the system were estimated from previous research and are held constant from year-to-year. All other budget components are estimated on an annual basis and are primarily focused on storage depletion via pumping, and recharge from various sources. Capture (e.g. as a volume of reduction in stream discharge or ET) was not an estimated budget component. The annual estimates are derived from a variety of methods and sources such as reported pumping, satellite and ground-verified estimates of irrigation, and discharge minus ET for estimating recharge from wastewater-treatment facilities.

Groundwater extraction is a significant part of the water budget in each country. In Mexico, primary authority for management of groundwater and surface water devolves from the federal government. Both can be used by individuals, municipalities, and institutions via a “concession” (See section 1.6), defined as a grant on behalf of the state which allows the use of a limited quantity of water resources. Concessions for groundwater pumping are granted to users for a fixed time period by CONAGUA. The volume granted in a concession may or may not be the actual volume of water used in any given year. The wells registered in REPDA 2012 within the Sonoran San Pedro Basin have a total concession volume of about 24.3 hm^3 annually (CONAGUA, 2012). Table 6.1 shows the summary of concession volumes, of which about 8.20 hm^3 (34 %) is used for agricultural activities, 1.8 hm^3 (7%) for public-urban water supply, 13.8 hm^3 (57%) in the industrial sector, 0.53 hm^3 (2%) to meet livestock needs, and the remaining 0.01 hm^3 (0.04%) used for domestic purposes. In the United States in 2012, the majority of water was pumped for municipal and water company uses 11.77 hm^3 (78%; Gungle et al., *In review*). In decreasing order, the remaining uses include rural exempt wells 1.78 hm^3 (11.8 %), industrial 1.41 hm^3 (9.3%), livestock 0.070 hm^3 (0.5%), irrigation 0.068 hm^3 (0.4%).

For the purpose of developing an approximate understanding of the distribution of binational water use, similar categories of groundwater extraction from both sides of the BSPB for 2012 were combined. These values represent approximations only, because the methods of arriving at each value differ by country. The values used in Sonora are the amount of water that each sector has as a concession. That is the amount of water for which permitees hold the right of use. It is possible that the amount actually used is different from this value. In Arizona, values were calculated using a variety of methods depending on the type of use and the data available. Binationally, the total extraction volume is about 39.4 hm^3. The largest use was industrial at 15.2 hm^3 (38.5%). This was followed by public/municipal/water company use 13.56 hm^3 (34.4%), agricultural/irrigation 8.27 hm^3 (21%), domestic/rural exempt wells 1.79 hm^3 (4.5%), and livestock 0.60 hm^3 (1.5%).

The Gungle et al. report (*In review*) includes details about the volume of the reduction in water use and the increase in recharge for each entity that is involved in the process. Summary water-budget results indicate that overdraft of the aquifer has declined, from about 14 hm^3 in 2002 to about 7 hm^3 in 2012 with an estimated uncertainty of about 5 hm^3 (Gungle et al., *In review*). However, as noted in Gungle et al. (*In review*), the value of using one basin-wide number for the various budget components and the total surplus or deficit is limited for a number of reasons. Occasionally annual variations in climatic factors such as precipitation and temperature result in changes in recharge to and discharge from the aquifer that dwarf changes in the other components making year-to-year interpretations of the surplus or deficit in terms of human-influenced factors unreliable. Moreover, the water-budget approach misses the spatial and seasonal variability of water-budget terms which are far more important when estimating effects on system components such as flow in the San Pedro. In addition, in many years, annual variability of water-budget terms is low compared with their uncertainty which means that conclusions drawn from interannual comparisons are also uncertain.

In the Gungle et al. report (*In review*), the variability of a number of components is considered spatially and temporally. For example, riparian aquifer water levels are stable along the San Pedro River, while regional aquifer water levels, are declining in the Sierra Vista area. Discharge from low elevation springs is declining slightly, possibly due to a climate signal, except for those near the Sierra Vista EOP. Baseflow in the San Pedro and Babocomari Rivers is declining. Change in storage in the aquifer was measured during the period 2008-2010 through microgravimetry. The measurements revealed higher resolution of spatial and temporal changes than is typical with other methods. Changes in gravity are a measure of combined changes in both the saturated and unsaturated zones. These data revealed little change in storage after wet monsoons (May 2008 to Nov. 2008, and May 2010 to Nov. 2010) as compared to a decrease after a dry monsoon (June 2009 to Nov 2009). It also shows decreases in storage in the Sierra Vista cone of depression during the relatively dry winter of 2008.

To deepen understanding of the system and improve predictions, Lacher (2011) updated the Pool and Dickinson (2007) model by simulating changes in the hydrological system between 1902 and 2105. Lacher (2011) also updated piezometric information and population growth forecasts to modify the location and rate of pumping. The update did not include changes in climate parameters. During the 2003-2105 period, the net pumping rate increase was estimated using population projections to be 0.0338 hm^3/d. Recharge remained relatively constant with a value around 0.0744 hm^3/d and the ET decreased, by approximately 0.0098 hm^3/d because of the decrease in the water table and the resulting decrease in riparian vegetation. A drawdown of more than 18 m was simulated in areas that continue to expand near Naco, between Sierra Vista and Palominas, and in a broad area northeast of Cananea.

An important part of the analysis of behavior and evolution of the aquifer system considers the effect of climate cycles and/or changes in components of the water balance on baseflow in the San Pedro River (Vionnet and Maddock, 1992; Pool and Coes, 1999; Hanson et al., 2006; Thomas and Pool, 2006; Pool and Dickinson, 2007; Leake et al., 2008; Kennedy and Gungle, 2010; Lacher, 2011; Lacher, 2012; Leake and Gungle, 2012; Gungle et al., *In Review*). Leake et al. (2008) used the Pool and Dickinson model (2007) to define and analyze the capture zones for simulated wells that induce flow from the river, springs, and riparian ET. They generated maps that illustrate the percentage of the pumped water that would be captured from these sources after 10 and 50 years of pumping. In essence, this shows the river's sensitivity to pumping in different areas in the basin. The greatest simulated drawdowns were associated with municipalities and other developed areas such as Sierra Vista and the developed areas south of the city, Tombstone, Bisbee/Naco, and Cananea.

There is significant variability among authors in their conclusions about the sources of change in baseflow. Hanson et al. (2006) noted that climate cycles are an important driver of streamflow variability with the strongest associations occurring with the PDO and ENSO indices. Thomas and Pool (2006) used statistics to explore the causes or origin of the decrease in base flow in the San Pedro River in the regional context of precipitation and flow. The possibilities that they considered included precipitation, changes in the characteristics of the basin, human activities, and water storage in the river and arroyo channels. They concluded that there were no significant monotonic trends in the variation of precipitation in the basin over the 1930-2002 period with the exception of summer which had a decreasing trend. However, like Hanson et al. (2006), they found that there were pronounced cycles in precipitation especially in winter and spring. While flow rates increased in the majority of the channels in the region in this same period, baseflow decreased in spring, summer, and fall in the San Pedro River and in two contiguous rivers, Whitewater Draw and the Santa Cruz River. They observed that the regional pumping did not affect the river flow; the only clear effect of pumping on streamflow was at specific agricultural areas located near the channel. They concluded that there were several potential explanations for the decrease in base flow. These include (1) a decrease in inflow from the regional aquifer, (2) increased ET due either to an expansion in vegetation or a longer growing season, or (3) due to model or data error. Lacher (2011) found that development (population, industrial, and agricultural) in the binational watershed reduced baseflow by about 28% at Palominas, 7% at Charleston, and 20% at Tombstone during the 20th century. An important conclusion by Lacher (2011) was that future baseflow will be captured through the increase in extraction caused by development, while discharge by ET will decrease as the result of lowered groundwater levels.

9. CONCLUSIONS AND RECOMMENDATIONS

9.1. Concluding Summary and Observations

The United States and Mexico share waters in several basins that cross the international boundary. But there is no treaty between the two countries regarding groundwater management for the transboundary aquifers. Hydrogeological information is needed to understand the behavior of this complex binational hydrological system, but the majority of the scientific studies have been completed at a national or state level, typically without knowledge or consideration of the hydrogeological conditions on the other side of the border. Scientific knowledge and binational data on these transboundary aquifer systems could be beneficial to decision makers in both countries, serving as a consistent baseline to support the decision process.

When an aquifer system is divided by an international border, coordination with scientists from both countries is desirable to enable a comprehensive understanding of the current system conditions to facilitate future management and administration of transboundary groundwater resources.

To facilitate transboundary scientific cooperation and coordination, the binational TAAP program was officially launched on August 19, 2009, with the signing by the Mexican and U.S. Principal Engineers of the IBWC of the "*Joint Report of the Principal Engineers Regarding the Joint Cooperative Process United States-Mexico for the Transboundary Aquifer Assessment Program*". This document serves as the framework for U.S.-Mexico coordination and dialogue to implement transboundary aquifer studies. The document clarifies several details about the program such as background, objectives, rolesand responsibilities, funding, relevance of the international water treaties, and the use of information collected or compiled as part of the program. Sharing data and information in both countries creates the basis for cooperation and a common understanding in support of sustainable use and protection of water resources and achieving sustainable economic development. In addition, the intellectual and interpersonal interaction improves the relationships needed to coexist in harmony at a local and international level.

The technical team for this study of the Arizona-Sonora aquifers included personnel from the two federal governments (CONAGUA and USGS) and two state universities (UNISON and UA) working together under the auspices of the IBWC. The participants in this Arizona-Sonora effort also included technical expertise from the faculty and staff of the Geology Department at the UNISON and the UA Water Resources Research Center, enabling a significant advance in the binational understanding of the basin. The participation of the two universities incorporated an academic aspect that reflected a culture of transparency and openness common to academia around the world. This academic collaboration brought flexibility to the information exchange and the development of a framework of mutual understanding that benefits both federal governments.

Considering the basin characteristics described in this study, binational information was available to estimate the parameters of the regional climate and vegetation system, but there were no previously existing binationally integrated maps with information for soils, geology, geophysics, piezometry, hydraulic parameters, or water quality. Differences on both sides of the border in hydrography, hypsometry, and terrain slopes were, at least in part, caused by differences in the resolution of digital elevation models. One of the important results of the study was to create binational maps and data sets for many of the data types needed for a regional hydrological analysis. The surface geology and geophysical information – electromagnetic, gravimetric, magnetic, and seismic– have been used to develop the conceptual model of binational hydrogeology. The available data for climate, hydraulic parameters, piezometry, and hydrogeology may be used to update a groundwater flow model. This process has also served to identify gaps in data and the importance of monitoring on a binational level. Notably, the information on soil types could not be integrated on a transboundary basis because each country uses a distinctly different classification system. This joint, uniform integration would require a complex, long-term project requiring bilaterally negotiated methods and the participation of a binational field team specializing in soil mapping. With this exception, the integration of transboundary hydrogeologic data was possible although sometimes requiring joint interpretation and dialogue among scientists from both countries.

9.2. Summary of Technical Findings

The BSPB is located on the eastern side of the Arizona-Sonora border, in a zone that is transitional between the Sonoran and Chihuahuan Deserts with altitudes ranging from 1,100 m.a.s.l. in the northernmost part of the basin to 2,620 m.a.s.l. east of Cananea, and in excess of 2,700 m.a.s.l. in the Huachuca Mountains. There are numerous tributaries to the San Pedro River which are important locations for aquifer recharge. Soils in the BSPB have been classified using different criteria on each side of the border, and are therefore difficult to compare. Based on the FAO soil classification system, the surface of the San Pedro River aquifer in Sonoran is composed of eight soil types. In the SVSA, the soils were classified by the NRCS, which is an agency under the USDA. Soils are classified into groups or associations of soil types. There are eight different soil types in the SVSA that vary depending on topography, appearance, precipitation, temperature, vegetation, source rock, and other factors. Like soils, the vegetation in the BSPB is classified differently on each side of the border. But there are similarities, including the classifications of oak-pine forest and evergreen forest, grasslands, and scrub.

The climate in the BSPB is arid to semi-arid. The area is considered to be temperate with warm summers and an annual average temperature that varies between 12 and 18°C. Temperatures above

38° C frequently occur in the low-elevation areas during the summer, but they are uncommon in the region's higher elevations. In winter, the average minimum temperature is close to 0°C. Precipitation occurs mainly during summer and winter, with summer precipitation events generally of greater magnitude than those in winter. Precipitation gages located at topographically higher areas typically record higher values than those located at lower elevations. Estimated annual average potential evaporation ranges from about 1.5 to 2 meters. There are a number of streamflow gaging stations on the U.S. side both in the San Pedro River and its tributaries, but none currently in Sonora. Slopes are generally 0-3% in the valleys and range up to 65% in the mountains. The stream order of the main tributaries to the San Pedro River is typically on the order of 4-5. The stream order of San Pedro River within the study area ranges from 4 to 7. The primary land uses in the SVSA are domestic, commercial, industrial and agricultural. Most of the land in the SVSA belongs to the federal and state governments. The Fort Huachuca military base covers almost 42,000 hectares through ownership or leases. The USFS manages extensive lands in the mountains and adjacent areas, where the uses include recreation, livestock and timber production. Another federal agency, the BLM, also controls a significant percentage of the Arizona region, including the SPRNCA, which covers about 23,000 hectares. The state government also controls a large percentage of the lands on the Arizona side. Land use in Sonora is primarily for agriculture, tourism, and mining. Portions of the southeast corner of the watershed lie in the Ajos-Bavispe Forest Reserve and Wildlife Refuge. A binational map of land use has been published by the USEPA.

The geology of the BSPB is the result of a complex tectonic evolution. The diversity of these tectonic events and the deformations experienced produced a region with great geological complexity. Within the northeast portion of Sonora and the southeast portion of Arizona, the oldest rocks form a Precambrian basement characterized by the Pinal Schist (1680 Ma) and mesoproterozoic granitic intrusions, which is covered by sedimentary platform sequences, mainly carbonates, deposited throughout nearly the entire Paleozoic. The oldest rocks from the Mesozoic within this region are represented by a Jurassic-age volcano-sedimentary sequence, which is exposed mainly in the Huachuca Mountains in Arizona and in the Mariquita Mountains in Sonora. Cretaceous-Tertiary rocks are widely distributed in both portions of the BSPB and represent the product of a series of geological processes that took place during this time. The geology of the region in which the aquifer is located within the BSPB is represented by intrusive, metamorphic, volcano-sedimentary, sedimentary and volcanic rocks. In order to simplify the mapping and description of these units on both sides of the border, a series of informal lithostratigraphic and lithodemic units was proposed broadly encompassing those that have similar lithology and age. The tectonic history of the region has been complex throughout the Phanerozoic. During the early and middle Phanerozoic, compressional events affected the region generating compressional structures (thrusts and folds); while for the Cenozoic, the largest, most representative discontinuities found in the BSPB are extensional normal faults. These extensional structures within the BSPB appear as normal faults that arise as sets with two preferential orientations, the first as a north-northwest-south-southeast-system, and the second oriented northeast-southwest.

On the U.S. side of the BSPB, a series of geophysical studies have been conducted aimed at determining the structure of the basin, among them electromagnetic, gravimetric, and magnetic surveys, as well as hydrogeological studies that produced cross-sections and subsurface models. Little prior work had been done on the subsurface characteristics of the Mexican portion of this basin. However, substantial work was carried out for this study, including electromagnetic and gravimetric surveys and modeling. Based on their gravimetric and magnetometric data, previous work proposed that the U.S. side of the BSPB is oriented northwest-southeast with a maximum depth greater than or equal to 1.5 km near the border. Two main subbasins were identified on the west side of the San Pedro River separated by a bedrock high under Sierra Vista. In USPSS, modeling multiple gravimetric profiles allowed the depth to basement at each of the stations to be defined; from two of these profiles, it can be established that the depth to basement is highly variable, and that the greatest depths, between 430 and 510 m, are found at the northern boundary, near the town José María Morelos. Also, the basement has the geometry of tectonic lows limited by structural highs, where the most important uplift is located toward the southern portion of the basin along the Cananea-Agua Prieta highway. The sedimentary fill within the U.S. portion of the BSPB has been divided into two informal units, called Lower Basin Fill and Upper Basin Fill which were deposited in structural basins between the mountains during the Plio-Pleistocene. Although in the Mexican portion of the basin there are no previous detailed studies on the stratigraphy of these sediments, which also represent the primary regional alluvial aquifer, the physical characteristics obtained from the lithologic descriptions of wells suggest an equivalence with the division presented in the SVSA. With data obtained from the lithological description of wells, vertical electrical soundings and other geophysical methods previous workers identified a silty-clay zone within the Upper Basin Fill on both sides of the border, with an estimated thickness ranging from 10 to 300 m, mainly along the San Pedro River channel. The elevations of this zone vary between 1400 and 1100 m.a.s.l. TEM surveys done on the Mexican side of the basin corroborate the presence of this silty-clay zone, since the resistive characteristics of the clay (<12 ohm-m) are clearly detected on several of the profiles. In a west-east oriented resistivity profile, on the southern boundary of the USPSS, the lower limit of the clay zone has an elevation of about 1100 m.a.s.l., while the upper limit is about 1400 m.a.s.l., consistent with previous estimates. The hydrologic function of the silty-clay zone in the USPSS has not been studied, but because it is continuous with and similar in areal extent to the silty-clay zone in Arizona, it probably functions in a similar manner with respect to recharge, confining conditions, and groundwater-flow directions.

The number of wells in the BSPB is over 5000, most of which are close to and south of the city of Sierra Vista with about 2,300 having a depth greater than 100 m. A series of hydrographs are included as examples of particular hydrologic processes and/or geographic settings. Some wells, especially those near the mountain fronts or stream channels, exhibit seasonal changes in water level in response to recharge events. Water levels near Sierra Vista, Fort Huachuca, and in the area of unregulated development to the south and east of Sierra Vista are experiencing linear declines, while wells close to the river are generally stable. Recharge at the EOP is potentially stabilizing water levels downgradient of its location. The shallowest water levels in the BSPB are typically found near the San Pedro River and other stream channels as well as in the foothills of the mountains near recharge areas. On the US side of the border, within the city limits of Sierra Vista, depth to water is often greater than 100 m. Static water-level elevations indicate cones of depression in and near the cities of Sierra Vista and Tombstone. Increases in water levels have occurred in wells influenced by the EOP and at locations near the river where agricultural pumping ceased in the mid-2000s.

The extraction of groundwater in the SVSA started at the beginning of the 20th century and increased relatively consistently, reaching an estimated rate of between 40 and 60 hm^3/yr in the 25 years prior to 2002. Several sectors are responsible for the majority of the BSPB pumping, including mining, municipal, agricultural-livestock, industrial, and domestic. The wells registered in REPDA 2012 within the USPSS have a total concession volume of about 24.3 hm^3 annually of which about 8.20 hm^3 (34 %) is used for agricultural activities, 1.8 hm^3 (7%) for public-urban water supply, 13.8 hm^3 (57%) in the industrial sector, 0.53 hm^3 (2%) to meet livestock needs, and the remaining 0.01 hm^3 (0.04%) used for domestic purposes. In the SVSA in 2012, municipal and water company uses accounted for 11.77 hm^3 (78%), and, in decreasing order, rural exempt wells 1.78 hm^3 (11.8%), industrial 1.41 hm^3 (9.3%), livestock 0.070 hm^3 (0.5%), irrigation 0.068 hm^3 (0.4%). Combining these values binationally, the total extraction volume was about 39.4 hm^3. The largest use was industrial at 15.2 hm^3 (38.5%), followed by public/municipal/water company use 13.56 hm^3 (34.4%), agricultural/irrigation 8.27 hm^3 (21%), domestic/rural exempt wells 1.79 hm^3 (4.5%), and livestock 0.60 hm^3 (1.5%).

Pump tests on the U.S. side are limited, but two were done previously in wells at Fort Huachuca. In Sonora, 13 were carried out for this study. Model calibrated values of saturated hydraulic conductivity vary between 0.0001 and 12.50 m/d. Vertical anisotropy was lowest in rocks and the undifferentiated fill (3.5 to 9.4), and highest in intercalated rocks, and clay and silt within basin fill (27.3 and 122.5). The calibrated values for Ss for the aquifers vary little in the BSPB, ranging from $1.0x10^{-6}$ m^{-1} up to $6.7x10^{-6}$ m^{-1}, with the highest values found in the Lower Basin Fill. In the BSPB, Sy ranges from a minimum of 0.001 in hard rock to 0.3 in the gravels and sands of the basin fills and alluvia, with a value of 0.09 measured with microgravity and well water levels near Garden Canyon Wash.

The groundwater flow boundaries and the hydrogeological basement of the BSPB are mainly formed by sedimentary sequences and Paleozoic to Mesozoic volcano-sedimentary sequences, as well as the tertiary granitic rock intrusions. Zones of low electrical resistivity at depth were interpreted as potentially being fracture zones, but this has not been confirmed by other methods. Both the felsic volcanic unit and the Tertiary conglomeratic volcano-sedimentary sequences on both sides of the border were considered to be part of the bedrock, but the possibility exists that these zones may be sufficiently fractured and hydraulically connected that they may prove to be an important part of the aquifer system. A new classification was proposed unifying the descriptions of hydrostratigraphic units on both sides of the border on the basis of differences in particle size distribution. Three have been identified:

Hydrostratigraphic Unit 1: Corresponds to the coarse granular fraction of sedimentary basin fill represented by gravels and sands. It corresponds to the more hydraulically conductive portions of the Upper- and Lower-Basin Fill. This unit has the highest hydraulic conductivity, although at depth this probably decreases, since typically a greater degree of compaction and cementation occurs at greater depths.

Hydrostratigraphic Unit 2: This unit incorporates the fine sediments with low hydraulic conductivity that mainly comprise the Upper Basin Fill. These low hydraulic-conductivity silts and clays units occur mainly in the central portion of the basin. It is possible that these are responsible for creating the confined conditions found in Hydrostratigraphic Unit 1. The extent of the confined conditions reflects the extent of this unit.

Hydrostratigraphic Unit 3: Included in this unit are those units that could be lumped together as fractured-rock aquifers, among which are the conglomeratic units of the Báucarit Formation, the Tc unit, the Tertiary felsic volcanic rocks that lie between these, and the fractured or weathered portions of the basement, such as limestone, that could possibly contain groundwater.

From the point of view of water extraction, crystalline rocks and pre-Cenozoic sedimentary rocks store little water in the BSPB; however, they represent the most important recharge zones for the primary alluvial aquifers since they form the mountains where most precipitation falls. Tertiary conglomerate **(Tc)** in the U.S. portion is locally important and productive as a source of groundwater, identifying it as a rock aquifer through networks of cracks (Hydrostratigraphic Unit 3). Groundwater in the basin primarily flows in the unconsolidated layers of coarse sediments that act as the sedimentary basin fill (Hydrostratigraphic Unit 1), and in the Plio-Quaternary surface deposits associated with terraces and alluvial deposits, so these act as the primary aquifers in the basin. This aquifer functions as an unconfined aquifer, mainly in the upper basin fill sediments, where the sediments are saturated and associated with the facies of the near and middle alluvial fans; however, the lower basin fill sediments, which have greater thicknesses towards the center of the basin, are confined by lenses of clay-rich sediments (Hydrostratigraphic Unit 2). This silt and clay zone is an important factor that strongly affects the flow of water in the basin, including the hydrologic communication between the surface water in the San Pedro River and the regional aquifers. The units that make up the terraces and the alluvial deposits from the Late Pleistocene act as important secondary aquifers.

Hydrogeochemistry is also an important factor in understanding the hydrologic condition of the BSPB. In the SVSA, the ADWR and the USGS visit a small subset of wells annually to make measurements. In addition to these basic data on water quality in Arizona, there are many more data generated by state, local, and federal agencies as well as NGOs. The water quality samples for the USPSS were collected during a geochemical sampling survey of the San Pedro River aquifer done by the UNISON Geology Department in July 2011, during which 20 samples were taken, all of which were wells used for pumping. Measurements of electrical conductivity, pH, and temperature were made on each sample. No new samples were taken in Arizona. Temperature in the Mexican portion ranged from 19.6 to 27.6 °C, with an average of 23.6 °C, while all pH values were within the maximum allowable levels outlined in the Official Mexican Standard for water intended for human consumption, 6.5 - 8.5. In the SVSA, the groundwater temperatures ranged from 14.5 to 26.5 °C, with an average of 23 °C; while the pH values fell between 6.2 and 8.2. In the USPSS, total dissolved solids were generally less than 500 mg/L. The groundwater type in the binational aquifer is calcium bicarbonate, generally alkaline and low salinity. The concentrations of calcium and magnesium in the waters of the San Pedro River and in the Holocene sediments in general are less than those occurring in the waters of the regional aquifer. The geographic distribution of ions in the groundwater indicates high concentrations of calcium and magnesium near the mountains, and higher concentrations of sodium and potassium in samples located near the river. In the SVSA, the values for the specific conductance of surface waters had an average of 558 µS/cm, ranging from 235 up to 610 µS/cm, with generally decreasing values in the direction of surface flow. In the USPSS, values generally less than 400 µS/cm were observed with values increasing to the north. Stable isotope patterns in SVSA indicate that groundwater on the west side of the River is largely dominated by recharge of high elevation precipitation from the Huachuca Mountains. Groundwater discharging to the River mixes with water from Mexico that has relatively larger (more positive) values of δ2H and $\delta^{18}O$. Isotope mixing trends indicate that, from

Palominas (about 3 miles north of the border) to the Charleston Bridge (about 17 miles downriver) a progressively larger portion of water in the river is derived from groundwater. Groundwater in Arizona east of the river and in Mexico, is largely composed of recharge from low elevation and/or summer precipitation.

The behavior of water in the aquifer is determined by key factors such as climate, geology, and time. Recharge is greater in higher elevations not only due to the amount of precipitation but also the low rate of transpiration through plants, and evaporation from surfaces and soils. Mountain system recharge occurs by way of infiltration and deep percolation through permeable rocks of the mountain block as well as at the mountain front where stream channels converge with high permeability alluvial sediments at the edges of the mountains. Another significant source of recharge occurs in perennial streams and rivers, as well as in ephemeral channels, where water is concentrated and permeable sediments facilitate infiltration. In the alluvial sediments of the basin, groundwater discharges along perennial or intermittent reaches of streams and rivers, through ET by phreatophytes, and to adjacent down-gradient basins. Mountain springs occur more commonly in the lower elevations, in canyons that intersect faults or layers of sandstone or limestone that overlie materials of low permeability. This situation is more frequently found in the Sierra San José and in the Huachuca and Mule Mountains. Discharge areas at lower elevations are often found where the drainage network intersects the saturated sediments that overlie thick layers of clay and silt. These discharge points can be either stream or river reaches, or springs located in terraces on the flanks of the San Pedro River. There is also groundwater discharge into the Benson subbasin through the alluvial sediments. As evidenced by the shape of the static water level water surface, most of the groundwater crosses the boundary near the north end of the study area and to the east of the San Pedro River. Baseflow at the four gages along the San Pedro River is in decline. Recent work, involving numerical modeling, points toward multiple causes with climate cycles and pumping playing significant roles.

Below we have included several technical recommendations recognizing that the availability of resources will limit what is feasible to undertake in the short term. However, what is possible and desirable to undertake in the long term is also mentioned to begin the dialogue that will make it possible to set priorities for these technical recommendations. We recommend that the TAAP binational technical group, with stakeholder consultation, develop detailed plans for the proposed next steps as “Phase 2" of this study.

9.3. Technical Recommendations

Both periodic and continuous monitoring are critical for understanding the movement of water through the BSPB as influenced by spatially and temporally-varying effects of climate, humans, and other organisms (vegetation, beavers, etc.). The following is a list of suggested monitoring types.

Water Budget Components – Estimation of water budget components is critical for the understanding of the evolution of water input, output and storage in the BSPA, but the data necessary to estimate these components are not necessarily collected with regularity or the appropriate spatial extent. The following five categories are a discussion of water budget components and details about the utility and needs for making estimates of each component and the data needed to support it.

Water Use and Groundwater Extraction - At a binational level, a monitoring network that includes all major groundwater withdrawals in the study area would improve information about the volumes of groundwater extraction. Prompt collection and exchange of these data will make the existing database, or any future ones, more robust, even in cases where computer models do not currently exist. Some water use data are currently compiled by both the USGS and CONAGUA, but the methods, categories, and frequency of data collection and publication differ.

Measure Piezometric Levels - A binational technical team assembled to take piezometric measurements throughout the entire basin twice a year, or annually at a minimum, would help to characterize the variability in aquifer storage and the effects of fluxes to and from the groundwater system. Because some fluxes vary at time scales far smaller than this, annual or biannual measurements could be augmented with continuous, or monthly or weekly measurements at locations such as near river or stream channels or within recharge ponds and detention basins. The data would allow characterization of the changes in piezometric levels associated with rain events and changes in groundwater extraction associated with riparian habitat and human infrastructure. When possible, static water level readings should be carried out when the pumping wells are not in operation to improve data integrity.

Measure Surface Flow – This study identified an imbalance in binational streamgage measurements in the BSPB; there are no streamgages in the USPSS. The absence of active gaging stations to measure streamflow in Sonoran territory is a limitation to fundamental hydrologic characterization of the basin. The measurement of streamflow is needed to gain greater understanding of stream-aquifer interactions, and confidence in recharge estimates and the water balance of the basin. Gaging stations at key locations such as Los Fresnos River, the major tributaries arising in the Sierra Mariquita and the Sierra Los Ajos, and at the headwaters of the San Pedro River near the community of Cananea would offer the greatest insight.

Expand Climate Observation Network - An increase in the number of meteorological stations collecting data on temperature, humidity, soil moisture, wind speed, and precipitation on both sides of the border would benefit understanding of climate change, natural recharge estimates, and water budget calculations. The lack of a weather radar system with binational applications in the San Pedro and Santa Cruz basins limits the utility of available hydrologic data. The data generated by a

Doppler weather station could provide key scientific information for hydrologic modeling. It would also be important to have a radar system on the Mexican side that could generate key data for a more accurate and early public warning notices for flooding, resulting in more efficient responses on the part of emergency personnel on both sdies of the border. It is possible that the installation of a single Doppler weather radar system on Sierra El Pinito, located southeast of Nogales, Sonora, could provide simultaneous coverage of the Nogales Wash, the Santa Cruz River basin and San Pedro River basin. These atmospheric data would work best in conjunction with the streamgaging mentioned above.

Evapotranspiration and Vegetation Change - The USGS has conducted a study of the hydrological requirements and ET through the hydrological functioning of riparian habitat on the Arizona portion of the San Pedro River (Leenhouts et al., 2006; Tillman et al., 2012), in part to have a better understanding of the potential effects of development and climate change. The study by Leenhouts et al. (2006) examined ET, the hydrological connectivity requirements of different plants and the relationship between the hydrological regime of a particular reach, the structure and diversity of vegetation, and the presence of water at different depths and annual water table fluctuations for better understanding the water needs of the riparian habitat. Similarly, the University of Arizona has done several studies in the Santa Cruz River to define the hydrologic interaction between the aquifer, streamflow, and the riparian habitat (McCoy 2009, Treese 2009). Ongoing binational studies could be implemented to document changes in land use, and vegetation type and distribution. These studies could include analysis of satellite data and establishment and monitoring of long term vegetation plots such as those of Scott et al. (2014). Such information would also result in a better understanding of the non-saturated system as part of the hydrological system and its importance as a vehicle for recharge transmission and water supply to the binationally shared ecosystems.

Water Quality and Stable Isotope Sampling - Monitoring of groundwater quality on a binational level using uniform standards and methods is important for several scientific and practical reasons. The historical data and studies of this type improve understanding and explain mixing and trends in water from different sources such as sources of baseflow in the San Pedro River (Gungle et al., *In Review*). A more extensive database would be especially useful in areas such as the San Pedro Basin, where changes in land uses or human activities, for example mining, can alter the quality of water in the region. Studies using stable isotopes in conjunction with other water quality parameters would be very useful for achieving a better understanding of aquifer recharge, groundwater flow directions, the mixture of water from different sources, and long term water availability.

Geophysical and Remote Sensing Methods - Developing binational studies using geophysical methods is recommended to refine the understanding the temporal and spatial distribution of water and the spatial distribution of geologic materials. Considerations for the application of these methods are measure parameter, resolution, instrument availability, expertise, cost, time, and ease of deployment and execution. These methods include magnetics, gravimetry, electromagnetics, and seismic and electrical techniques. They are available in borehole, surficial, and airborne platforms. Nuclear magnetic resonance is a relatively new technique that can be used to estimate hydraulic conductivity and water yield from alluvium. LiDAR, and photogrammetry (terrestrial, drone-based, and fixed-wing) are recommended to provide information on topography and vegetation. These data can be used for estimation of ET and for coupled groundwater-surface-water numerical modeling. Satellite-based methods and products can be used to estimate spatial and temporal variability of geology, vegetation, temperature, snow cover, and soil moisture (Tillman et al., 2012; van der Meer et al., 2012; Schmugge et al., 2002).

Using microgravimetry has been shown in Arizona to be a useful method for measuring changes in water storage in the subsurface. In regions characterized by scarcity or absence of wells, this geophysical technology can contribute information on annual or seasonal changes in the aquifer storage, permitting relatively rapid, and inexpensive regional- and local-scale assessments. At locations with wells, micrgravimetry can be used not only for storage change, but also for estimating groundwater capture and storage properties. Application of this technology applied on both sides of the border in a coordinated manner could be used to evaluate changes in storage and to identify potential causes and effects of changes, for example changes in storage caused by human activities and their potential effects on stream baseflow.

Research Drilling – Drilling provides detailed information on the variability of geologic material within a borehole which is difficult to obtain by other means. It complements geophysical information by providing groundtruthing for the interpretation of geophysical measurements. In fact, all of the aforementioned geophysical methods (and many others) can be carried out in boreholes. In addition, the spatial and temporal variability of water storage and chemistry of the aquifer and unsaturated zone can be studied with techniques such as flow logging, water quality sampling, and in situ monitoring of water levels, pressure head, and chemical constituents. Drill cuttings and cores can be analyzed and tested for a wide variety of parameters including mineralogy, hydraulic and physical properties (density hydraulic conductivity, and particle size distribution), chemical parameters (such as pH and salinity). We suggest drilling at key sites around the BSPB to fill gaps in hydrologic understanding.

Binational Soils Map – Currently no binational soils map exists, because standard methods differ significantly in the two countries. Soil surveys are often time-consuming and expensive, but the decision about whether to choose an existing standard or to develop new or combined standards, and if needed the process of developing new standards will also require time and funding. A logical first step would be to consult the standards of national level bodies in each country that are charged with this responsibility. In the United States, methods development, large-scale surveys, and inventories are typically carried out by NRCS and the Forest Service. In Mexico, the most recent National Census was carried out by the National Forest Commission (CONAFOR).

Database Standardization – Currently binational data standards do not exist for the review and storage of all the different data types noted in this report. Lack of standards is also the case within each country for certain data types. The development of binational data standards related to the review and storage of data would help with ease of data searching, integration, and comparison.

Study Groundwater-Surface Water Interactions - The relationship between surface water and groundwater in this region has been documented in a number of investigations. However, given the continental-scale importance of the riparian and aquatic systems of the San Pedro River, a greater understanding of the evolution of groundwater and surface water interactions through time in the binational regional and alluvial aquifers would permit a deepening understanding by investigators and improve tools available for water management and administration. Numerical models of this study area (see numerical modeling section below) could be designed to include the capability to analyze groundwater-surface-water interactions, further benefiting resource-management decision.

Numerical Modeling - Future research would benefit from building an advanced binational coupled ground- and surface-water model using one of the available codes (GSFLOW (Markstrom et al., 2008), MODFLOW-OWHM (Hanson et al., 2014), HydroGeoSphere (Brunner and Simmons, 2012)) is an important scientific goal for the San Pedro River aquifer. As in Pool and Dickinson (2007), it is recommended that the numerical model of the San Pedro River aquifer cover the entire study area considered in this binational study. The recommended modeling studies require additional quantity and quality data collection beyond what currently exists. It is important to have the technical data and information in order to be properly prepared when undertaking this binational modeling technical effort. The technical recommendations presented in this chapter can contribute to the modeling, but they are not prerequisites for modeling. Modeling can be carried out in “learning mode” as a virtual laboratory even without all the desired information to investigate fundamental questions. One very important way in which models can be used is to identify locations for measurements and monitoring that will maximize hydrologic understanding and minimize uncertainty. This can provide significant cost savings by eliminating sites that would likely provide little insight into processes and questions that have been identified as the most pertinent or important for a particular study.

Similarly, efforts to undertake technical studies should not depend on approval for the binational model. They represent opportunities for continuing the binational cooperation with the goal of improving the understanding of the hydrological systems in the aquifers shared by Arizona and Sonora. The binational team that prepared this report recommends that the significant momentum that was generated during the production of this report not be lost. This technical group believes that it would be appropriate to summarize and assess conditions in the binational San Pedro River aquifer at least every three years starting in 2016 to assess its progress and identify and plan the next steps or studies.

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11. APPENDICES

11.1. Streamgages

Site Number	Streamgage Name	Begin Data	End Date	Decimal Latitude	Decimal Longitude	Horizontal Datum	Altitude (m)	Altitude Datum
9470500	Palominas	5/31/1930	NA	31.38010095	-110.1111882	NAD27	1276	NGVD29
9470520	Greenbush Draw	6/1/2000	9/30/2004	31.38027778	-110.0716667	NAD83	1305	NAVD88
9470700	Banning Creek	2/9/2001	NA	31.50347220	-110.0052778	NAD83	1453	NAVD88
9470750	Ramsey Canyon	5/1/2000	NA	31.44666667	-110.3058333	NAD83	1684	NAVD88
9470800	Garden Canyon	10/1/1959	NA	31.47287518	-110.3478588	NAD27	1646	NAVD88
9471000	Charleston	3/29/1904	NA	31.62592644	-110.1745226	NAD27	1205	NGVD29
9471040	Charleston-Mesquite	10/1/2001	6/3/2002	31.66583333	-110.1786111	NAD83	1186	NGVD29
9471070	Boquillas	11/21/2001	6/3/2002	31.69027778	-110.1847222	NAD83	1210	NGVD29
9471300	Huachuca Canyon	10/1/1961	9/30/1964	31.51120705	-110.3923037	NAD27		
9471310	Huachuca Canyon	5/12/2000	NA	31.51805556	-110.3872222	NAD83	1707	NAVD88
9471380	Upper Babocomari	7/9/2000	NA	31.63500000	-110.4247222	NAD83	1676	NAVD88
9471400	Lower Babocomari	3/18/2000	NA	31.70027778	-110.2263889	NAD83	1213	NAVD88
9471500	Fairbank	10/1/1926	9/30/1928	31.72508990	-110.1922996	NAD27		
9471550	Tombstone	4/18/1967	NA	31.75092240	-110.2011882	NAD27	1152	NGVD29

Table 11.1 Streamgages in the Binational San Pedro Basin. Data are derived from the USGS National Water Information System (http://waterdata.usgs.gov/az/nwis/). NA indicates that data collection is ongoing at the time of publication.

11.2. Soils

Soil classification in the USPSS is based on the physical and chemical properties of the area's soil horizons. A description of the soil units and their subtypes is given below.

Cambisol (Bc+Re/1/G): This soil type is a chromic Cambisol that develops with a subtype of eutric Regosol, coarse textural class and gravelly composition. These are units with a subsurface that to the naked eye is very different in color and texture on the surface layer; it can be dark, and more than 25 cm thick, with poor and occasionally unmeasurable nutrient content. The chromic sub-classification indicates that when moist, it is a dark brown to a dull red color. The eutric Regosol is formed through the physical and chemical breakdown of parent materials; its origin is the result of weathering and erosion of topographically higher rocks. It is very nutrient rich (Ca, Mg, K, and Na). It contains a high percentage of sand in the top 30 cm, and is a soil with a high gravel content in the first 100 cm of depth, that measure from 0.2 to 7.5 cm on their major axes.

Phaeozem (Hh+Re/2/G): This is a haplic Phaeozem soil type and eutric Regosol subtype, medium textural class and gravelly physical phase, which means it has a dark surface layer rich in organic matter and nutrients or bases of Ca, Mg, K, and Na. Regarding eutric Regosol, it seems that this portion is formed from the erosion of acidic and basic igneous rocks, as well as some conglomerates and shales-sandstones, including some colluvial remnants. It is a nutrient-rich soil that locally presents calcium carbonate horizons; it is very similar to the parent material, except it has a yellowish brown or reddish brown superficial layer, which belongs to the ochric A horizon and lacks structure. It is usually very poor in organic matter, containing abundant sand, and is characterized by an exchangeable sodium percentage greater than 15%. Its texture ranges from sandy to sandy loam and high clay content.

Lithosol (I+Re+Rc/1): This type of soil appears as chromic Lithosol with eutric and calcaric Regosol subtypes that have a coarse textural class, which indicates a thickness of less than 10 cm. Regarding eutric Regosol, it seems that this portion is formed from the erosion of acidic and basic igneous rocks, as well as some conglomerates and shales-sandstones, including some alluvial, colluvial, or aeolian remnants. It is a nutrient-rich soil that locally presents calcium carbonate horizons; it is very similar to the parent material, except it has a yellowish brown or reddish brown superficial layer, which belongs to the ochric A horizon and lacks structure. It is usually very poor in organic matter, containing abundant sand, and is characterized by an exchangeable sodium percentage greater than 15%. Its texture ranges from sandy to sandy loam and high clay content. The calcaric Regosol subtype indicates that it is weakly developed; likewise, it has a high sand content, it has a gravelly appearance, and the textures tend to be sandy loam at the surface down to argillaceous loam in the subsurface horizons, composed of a balance of clay, silt, and sand.

Luvisol (Lc+Re/2/L): This type of soil is identified as chromic Luvisol and it comes with a eutric Regosol subtype, medium textural class, and lithic physical phase. This soil is generally fertile with high clay accumulation in the subsurface; its coloring is dark brown to reddish when wet. It contains an argillic B horizon, is slightly acidic, low in organic matter, and potentially rich in minerals. The eutric Regosol was formed by the breakdown of acidic, basic, conglomerate, and shale-sandstone rocks; its origin can be alluvial, colluvial, and even aeolian; it has a balance of clay, silt, and sand in the top 30 cm, with hard rocks at depths of less than 50 cm.

Planosol (We+Xl+Xh/2/n): The eutric Planosol soil type is found in the study area as two Xerosol subtypes, luvic and haplic; it presents a medium textural class and a sodic chemical phase. This soil generally develops in areas of low relief that can become flooded at any time of year; it is fairly deep in most cases, between 50 and 100 cm, and is found mainly in temperate and semi-arid climates. Its natural vegetation is grassland or scrub. It is characterized by having, below the uppermost layer, a relatively thin, infertile layer of a clear material that contains generally less clay than the layers above and below it; and beneath this layer there is a very argillaceous subsurface, or rock, or hardpan, all impervious. It provides moderate yields and is used for cattle, sheep, and goat ranching; it is highly susceptible to erosion, especially in the surface layers and is generally found in topographic depressions. It has a clayey subsurface that decreases drainage considerably and it is very rich in nutrients. The subtypes indicate that, because of a considerable accumulation of clay in the subsurface, there may be traces of limestone or gypsum at greater depths. Usually it contains a balance of sand, silt, and clay in the upper 30 cm and a high enough sodium accumulation to reduce fertility.

Regosol (Re+Rc/1/n): Eutric Regosol develops with a calcaric subtype of coarse textural class and sodic chemical phase. This means that it can form from the erosion of acidic and basic igneous rocks, as well as some conglomerates and shales-sandstones, including some alluvial, colluvial, or aeolian remnants. It is a nutrient-rich soil that locally develops calcium carbonate horizons; it is very similar to the parent material, except it has a yellowish brown or reddish brown superficial layer, which belongs to the ochric A horizon and lacks structure. It is usually very poor in organic matter, containing abundant sand, and is characterized by an exchangeable sodium percentage greater than 15%. Its texture ranges from sandy to sandy loam.

Vertisol (Vc/3G): Vertisols are churning heavy clay soils with a high proportion of swelling clays; are characterized by deep, wide cracks that develop during the dry season; they are very clayey, sticky when wet and hard when dry. Overall they have low susceptibility to erosion. Their chromic classification and physical phase indicate the presence of heavy clay with dark color in any layer within the first 50 cm below land surface; in the dry season, as long as there is no irrigation, vertisols have visible cracks extending to depths less than 50 cm.

Xerosol (Xk+Rc/2/G): This is a calcic Xerosol type soil with a subtype of calcaric Regosol, medium textural class, and gravelly physical phase. Xerosol is characteristic of arid regions and has a surface layer called an ochric A horizon; light in color, the percentage of organic matter is very low. In this soil a clay accumulation process occurs in the sub-surface layer, giving rise to a B horizon; when the content of said material is minimal, it is called cambic B, but when it increases, it is called argillic B. In the latter case, there are accumulations of calcium carbonate. The calcaric Regosol subtype is weakly developed; likewise, it has high sand content, it has a gravelly appearance, and the textures tend to be sandy loam at the surface to argillaceous loam in the subsurface horizons, with a balance of clay, silt, and sand.

In the SVSA, the soils were classified by the NRCS (Hendricks et al., 1985). Soils are classified into groups or associations of soil types. There are eight different soil types in the Subwatershed that vary depending on topography, appearance, precipitation, temperature, vegetation, source rock, and other factors. These types are:

MH1 Casto-Martinez-Canelo Association: This association consists of deep soils with very fine texture and deep gravelly soils with fine and moderately fine texture, nearly level to steep on dissected fan surfaces. The soils formed in old alluvium derived from sedimentary and igneous rocks. The slopes range from 2% on the mesas up to 40% on the hillsides and mesas that have a vertical relief between 8 and 60 m. The annual average precipitation ranges between 410 and 510 mm, and the annual average soil temperature varies between 12 and 15°C.

MH2 Lithic Haplustolls-Lithic Argiustolls-Rock Outcrop Association: This association consists of dark soils, shallow and very shallow, gravelly and cobbly, with moderately coarse to fine texture, accumulated on surfaces ranging from slightly to very steep and rocky outcrops on hills and mountains. These soils formed in residuum and colluvium on igneous and sedimentary hills and mountains. The slopes range from 5 to 60%. The annual average precipitation ranges between 410 and 630 mm and the annual average soil temperature varies between 8 and 15°C.

TS2 Torrifluvents Association: This association consists of soils that have textures between moderately coarse and fine, nearly level surfaces to gently sloping on floodplains and alluvial fans. These soils formed in recent mixed alluvium of the San Pedro River and its tributaries. The slopes range from 0 to 3%. The annual average precipitation ranges between 230 and 300 mm and the annual average soil temperature varies between 16 and 22°C.

TS3 Tubac-Sonoita-Grabe Association: This association consists of well-drained soils that have textures between moderately coarse and fine, on nearly level to strongly sloping surfaces of the uplands, drainageways in the valley plains and wide floodplains. The slopes range from 0 to 8%, with some up to 15%. The annual average precipitation ranges between 250 and 400 mm and the annual average soil temperature varies between 16 and 22°C.

TS4 White House-Bernardino-Hathaway Association: This association consists of deep, well-drained soils that have textures between moderately coarse and fine on nearly level surfaces to moderately steep slopes. It is found in alluvial fans, hilly valley plains, dissected old terraces, that formed in old alluvium derived from granitic, volcanic, and sedimentary rocks. The slopes range from 1 to 20%, but up to 50% where there are Hathaway soils. The annual average precipitation ranges between 300 and 460 mm and the annual average soil temperature varies between 15 and 21°C.

TS6 Lithic Torriorthents-Lithic Haplustolls-Rock Outcrop Association: This association consists of shallow, cobbly, and gravelly soils on surfaces between strongly sloping and very steep with rock outcrops. The soils are well-drained on semiarid, mid-elevation hills and mountains. The soils were formed by weathered residuum, originating from granite gneiss, rhyolite, andesite, tuff, limestone, sandstone, and basalt. The slopes normally vary between 20 and 50%, but the full range is from 10 to 70%. The annual average precipitation ranges between 250 and 510 mm and the annual average soil temperature varies between 15 and 22°C.

TS9 Latene-Nickel-Pinaleno Association: This association consists of deep, gravelly, and calcareous soils that have moderately coarse to fine textures on nearly level to very steep surfaces, deposited on deeply dissected alluvial fans and terraces. They formed in an old alluvium derived from granite, gneiss, limestone, and other igneous and sedimentary rocks. Its slopes range from 1 to 60%. The annual average precipitation ranges between 250 and 410 mm and the annual average soil temperature varies between 16 and 22°C.

TS14 Nickel-Latene-Cave Association: This soil association consists of deep and shallow soils, calcareous and gravelly, medium and moderately coarse, on dissected old alluvial fans and also terrace escarpments, ranging from nearly level to very steep. They are mostly found along the San Pedro River, having formed in an old calcareous alluvium derived from igneous and sedimentary rocks. Most of the slopes vary between 5 and 30%, but the full range is from 0 to 60%. The annual average precipitation ranges between 250 and 360 mm and the annual average soil temperature varies between 18 and 22°C.

11.3. Meteorological Data

In order to determine the climate variables within the binational watershed, the WorldClim global climate database was used (http://www.worldclim.org/). Temperature, precipitation, and ET records for the period 1970-2010 were obtained from three weather stations in the area. Two of them are located in Mexico and a single one in the U.S. (Minjárez et al., 2011). This database was obtained from historical records from CONAGUA. Daily climate data from the United States Western Regional Climate Center provided adequate coverage for the northern portion of the aquifer in Sonora. The weather station selection was based on spatial distribution within the watershed, as well as the availability and consistency of data over the period of record. The weather stations analyzed are shown on the table below. All the data records from each weather station were analyzed, including temperature and precipitation. Cumulative annual and monthly mean plots were developed for precipitation. For temperature, only monthly mean and yearly average data were considered.

Table 11.2 Weather stations analyzed

CODE	STATION	STATE	Y	X	Z
26057	NACO	SONORA	3466651	599895	1390
26164	SANTA CRUZ	SONORA	3455165	539047	1350
26013	CANANEA	SONORA	3427602	567796	1600
22140	CORONADO NATL-M	ARIZONA	3468454	571338	1331

Naco Station

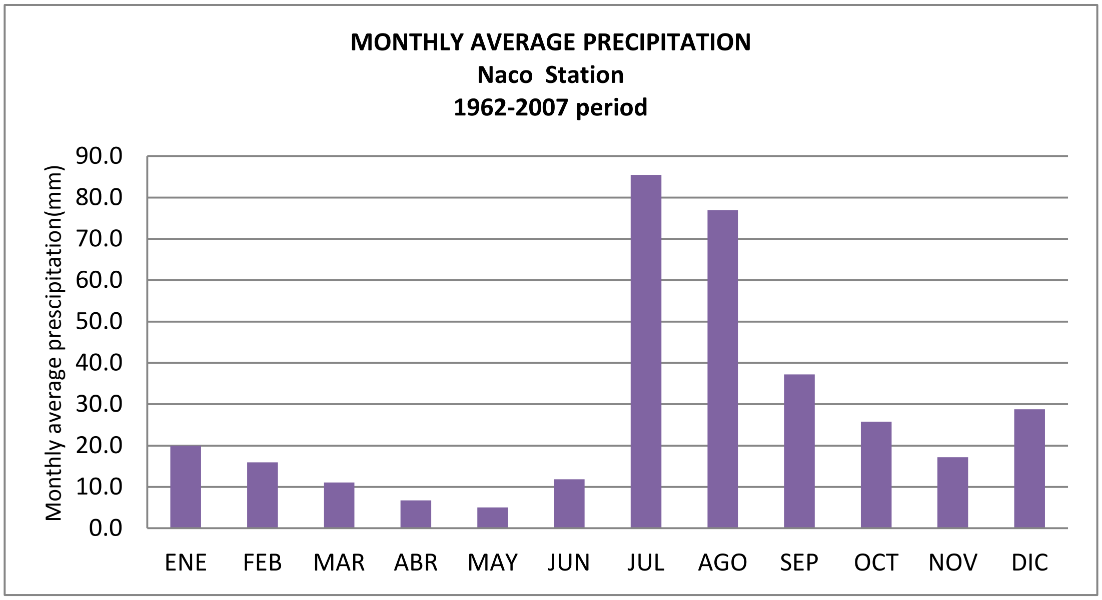

Figure 1. Monthly Average Precipitation Naco Station, 1962-2007 Period.

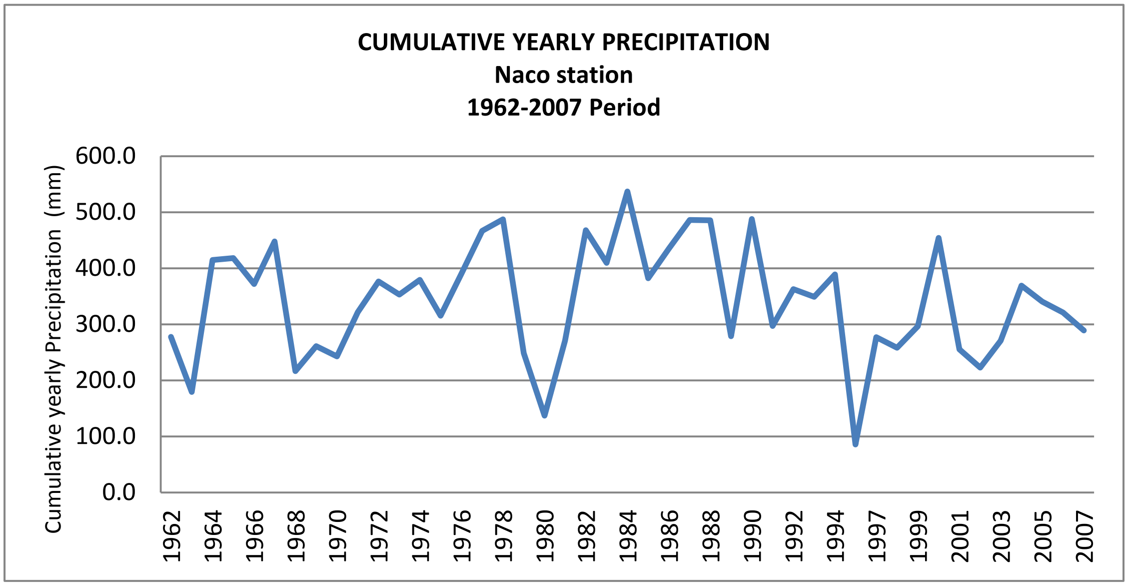

Figure 2. Cumulative Yearly Precipitation, Naco Station, 1962-2007 Period.

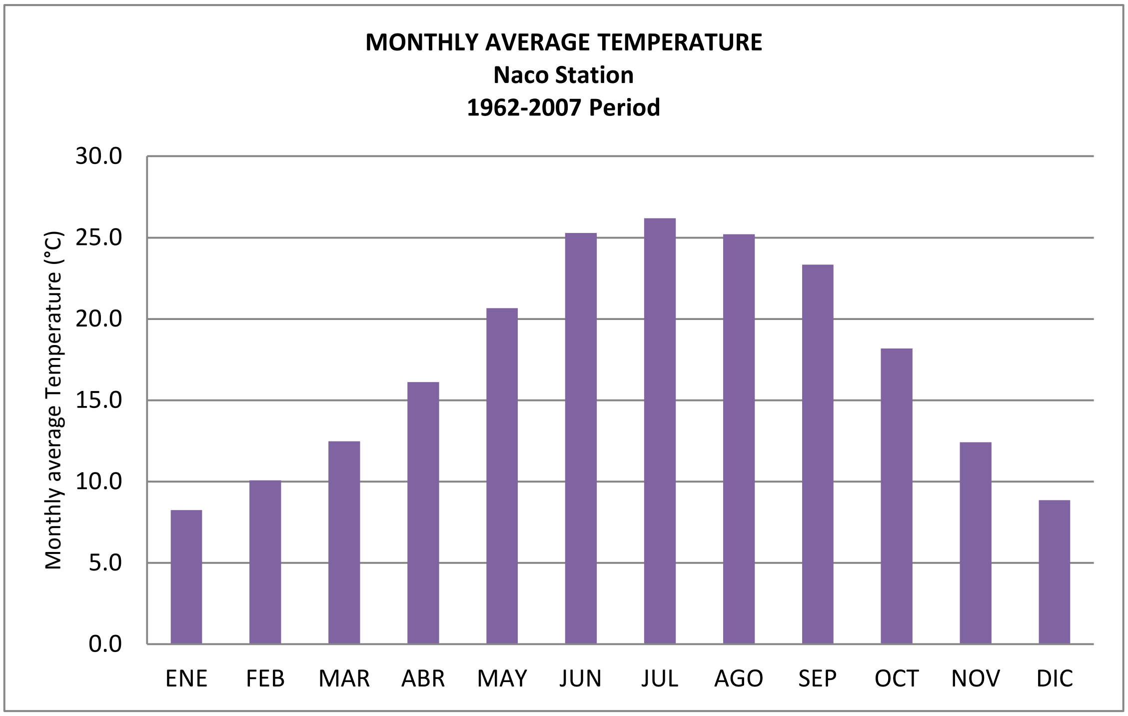

Figure 3. Monthly Average Temperature, Naco Station, 1962-2007 Period.

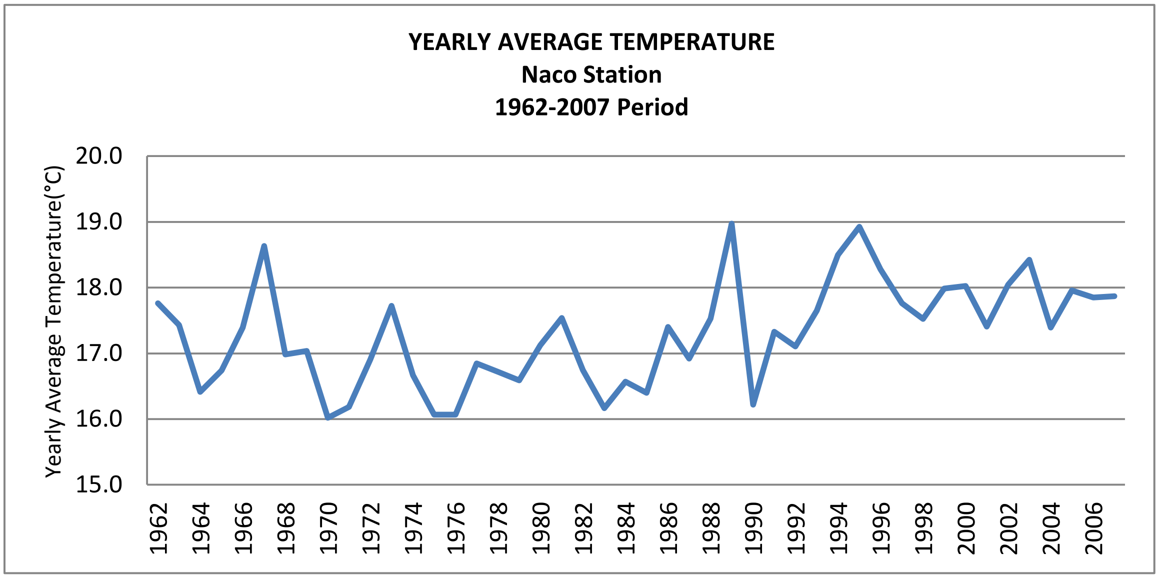

Figure 4. Yearly Average Temperature, Naco Station, 1962-2007 Period.

Santa Cruz Station

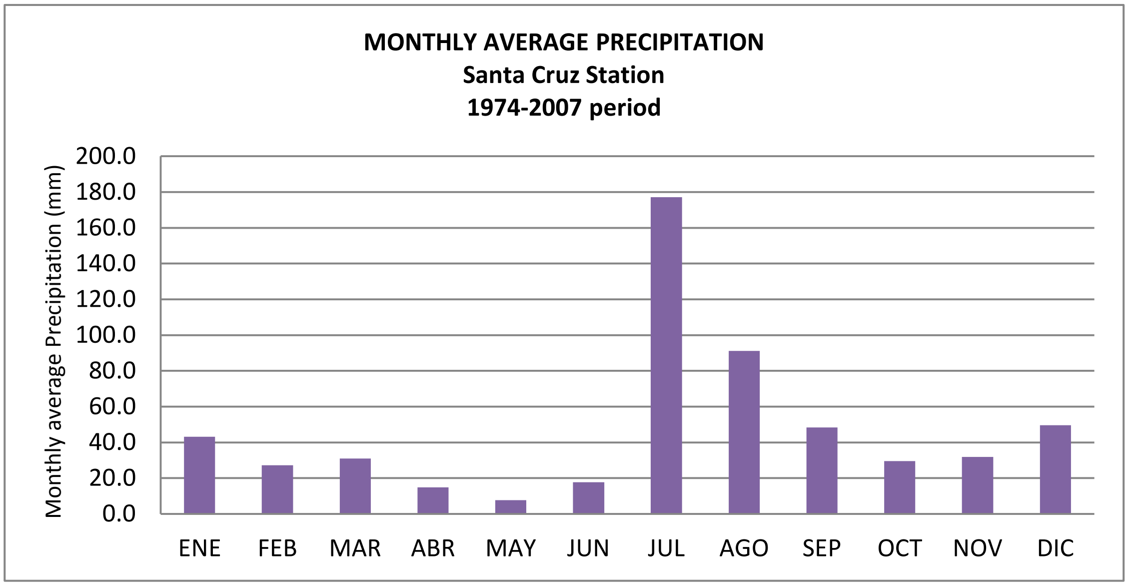

Figure 5. Monthly Average Precipitation, Santa Cruz Station, 1974-2007 Period.

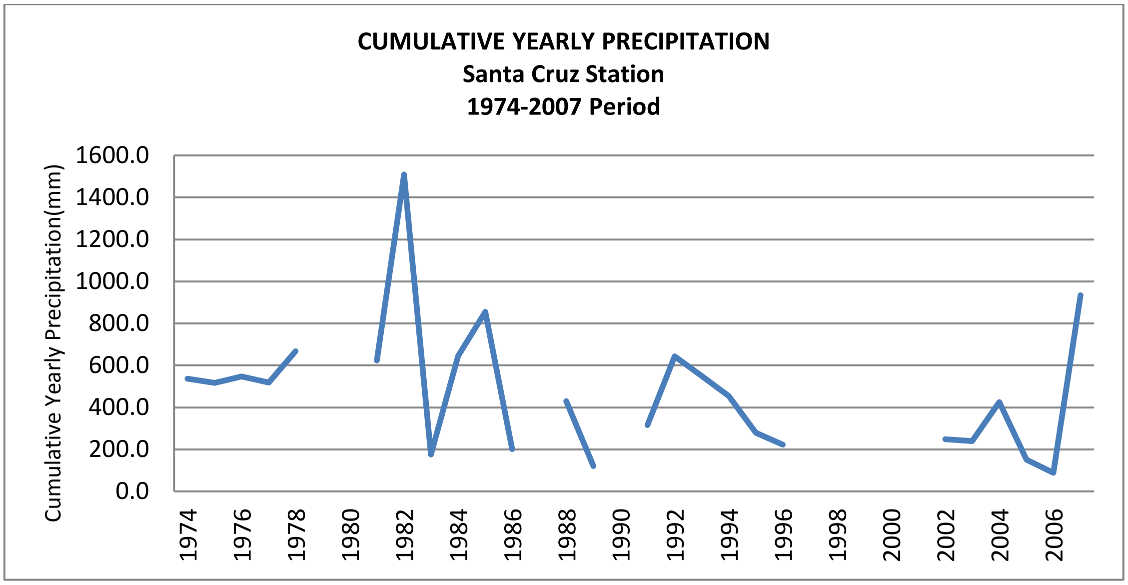

Figure 6. Cumulative Yearly Precipitation, Santa Cruz Station, 1974-2007 Period.

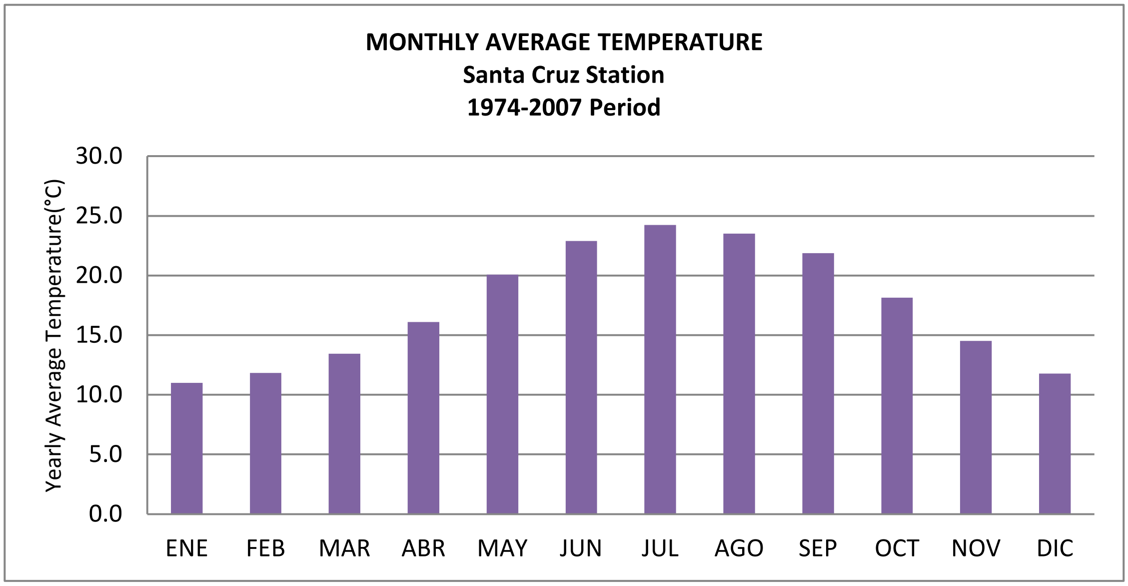

Figure 7. Monthly Average Temperature, Santa Cruz Station, 1974-2007 Period.

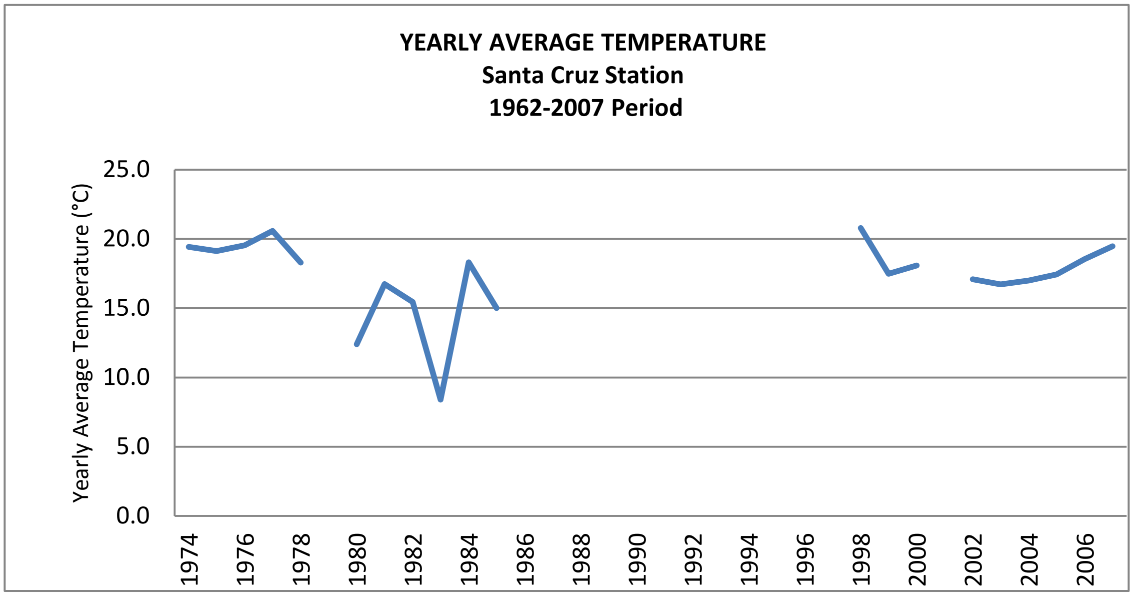

Figure 8. Yearly Average Temperature, Santa Cruz Station, 1974-2007 Period.

Cananea Station

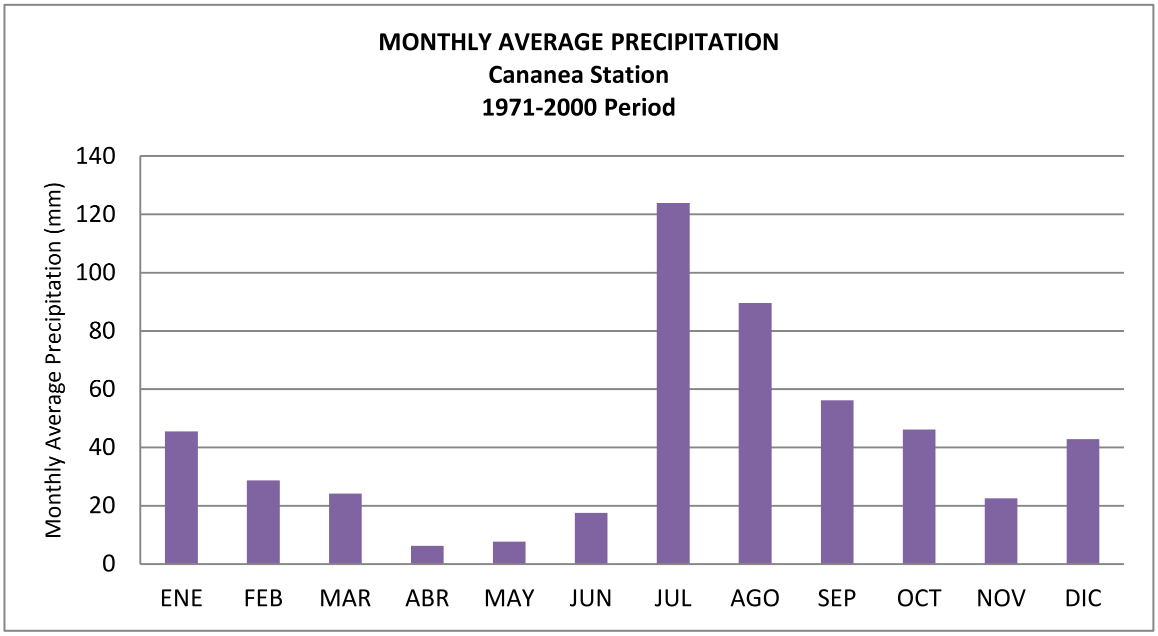

Figure 9. Monthly Average Precipitation, Cananea Station, 1971-2000 Period.

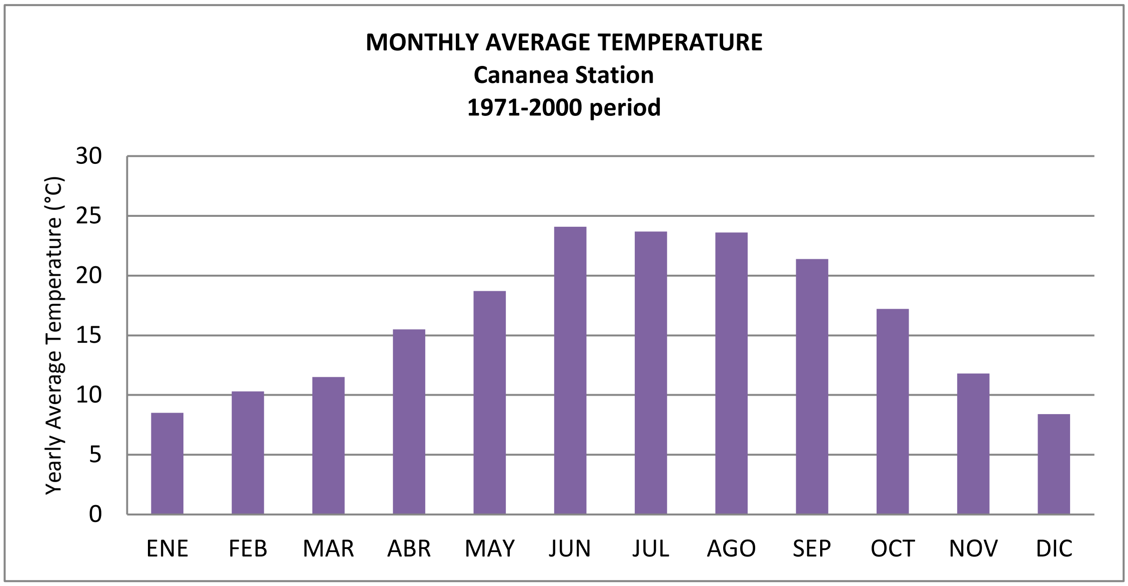

Figure 10. Monthly Average Temperature, Cananea Station, 1971-2000 Period.

Coronado National Monument Station

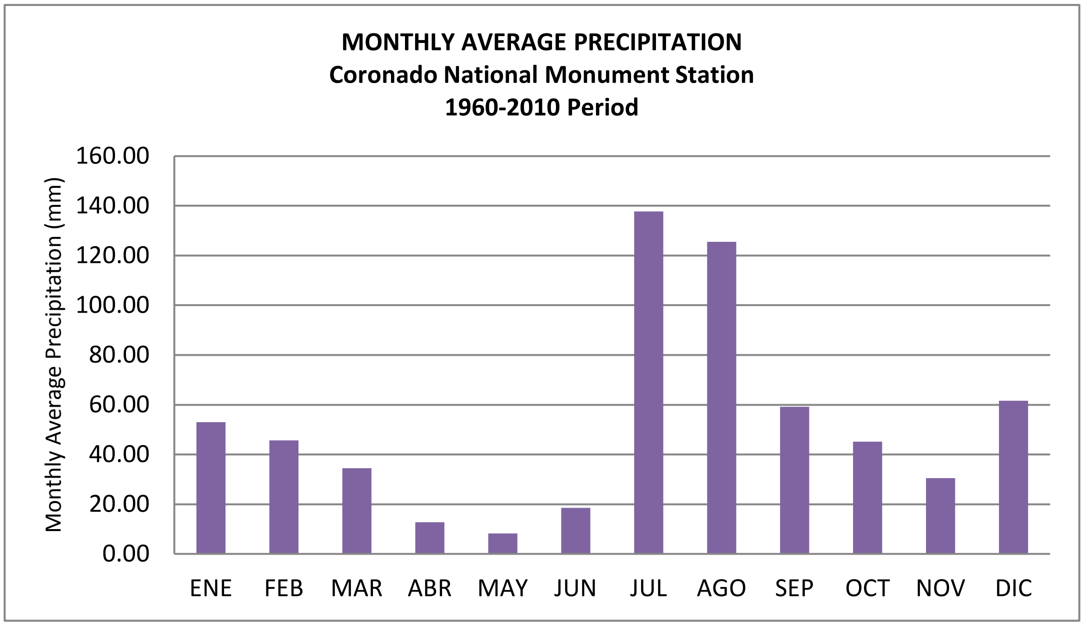

Figure 11. Monthly Average Precipitation, Coronado National Monument Station, 1960-2010 Period.

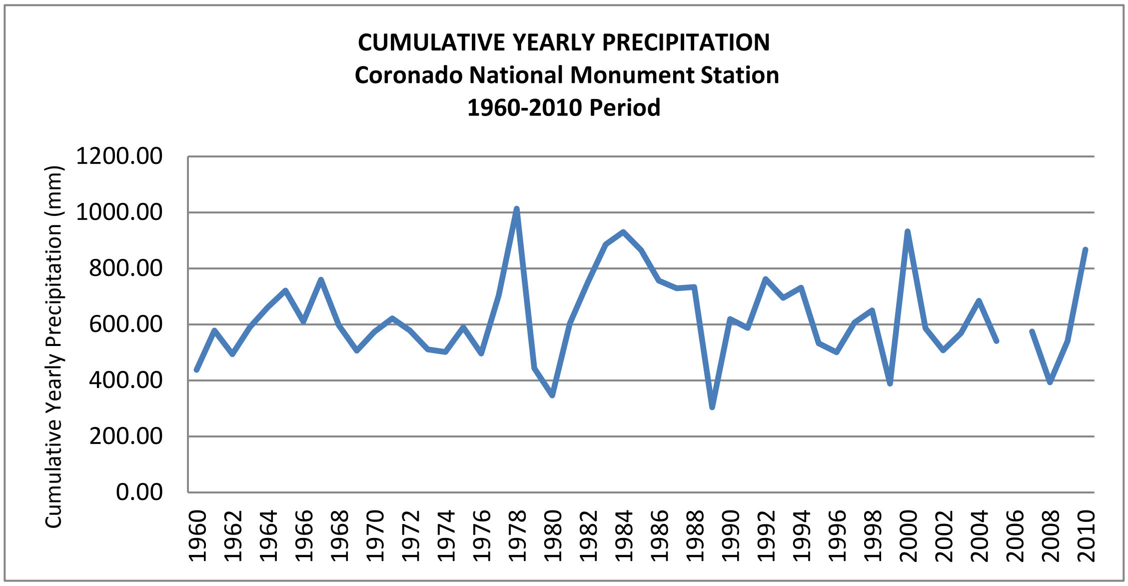

Figure 12. Cumulative Yearly Precipitation, Coronado National Monument Station, 1960-2010 Period.

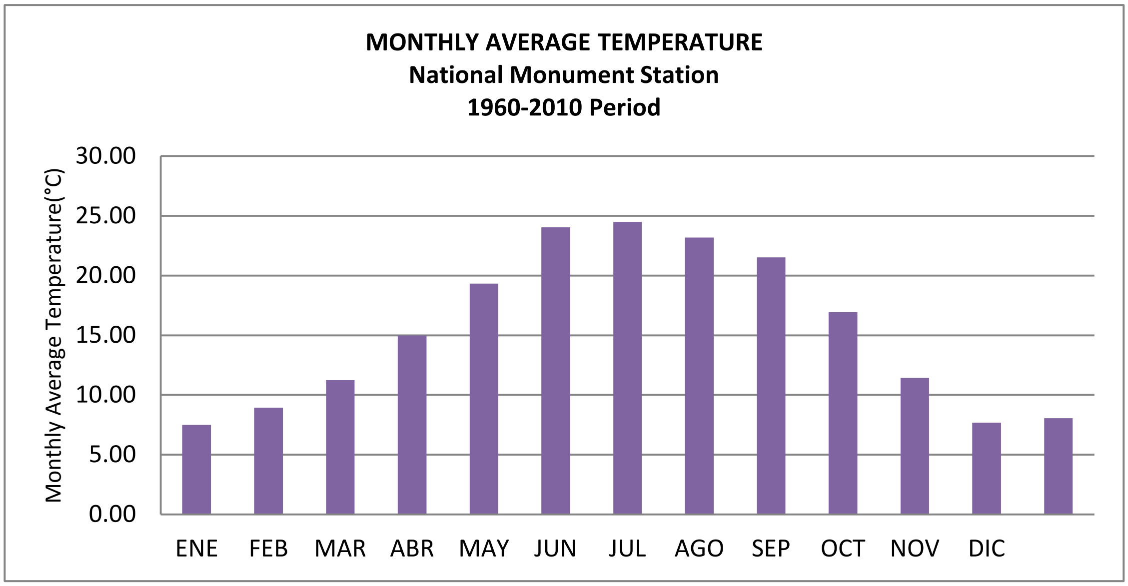

Figure 13. Monthly Average Temperature, Coronado National Monument Station, 1960-2010 Period.

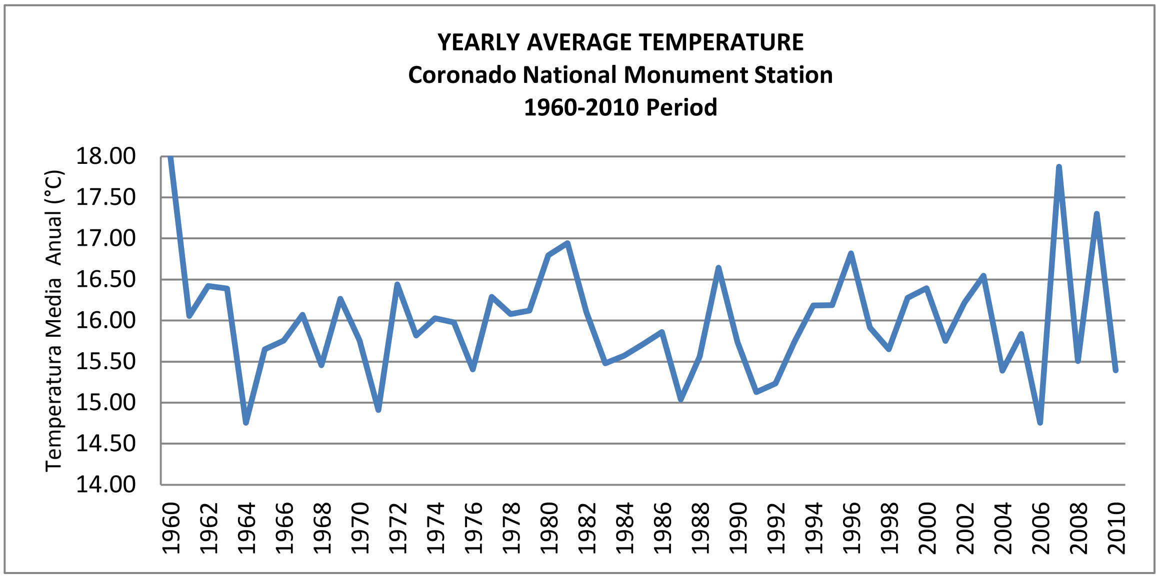

Figure 14. Yearly Average Temperature, Coronado National Monument Station, 1960-2007 Period.

11.4. Vegetation Classes and Descriptions

SPCode	**SWReGAP Code**	**Vegetation Class (**Boykin et al., 2014)	**Description (**Modified from Southwest Regional Gap Analysis Project (U.S. Geological Survey, 2004)	**Percentage (%)**
1	N80	Agriculture	Combination of N81 (Pasture/Hay) and N82 (Cultivated Crops). N81: Areas of grasses, legumes, or grass-legume mixtures planted for livestock grazing or the production of seed or hay crops, typically on a perennial cycle. N82: Areas used for the production of annual crops, such as corn, soybeans, vegetables, tobacco, and cotton, and also perennial woody crops such as orchards and vineyards. Includes all land being actively tilled. Pasture/hay and/or crop vegetation accounts for greater than 20 percent of total vegetation.	0.201%
2	N21	Developed, Open Space - Low Intensity	Open space: Includes areas with a mixture of some construction materials, but mostly vegetation in the form of lawn grasses. Impervious surfaces account for less than 20 percent of total cover. These areas mostly include large-lot single-family housing units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes.	1.286%
3	N22	Developed, Medium - High Intensity	Includes areas with a mixture of constructed materials and vegetation. Impervious surface accounts for 50-79 percent of the total cover. These areas most commonly include single-family housing units.	1.294%
4	N11	Open Water		0.023%
10	S010	Colorado Plateau Mixed Bedrock Canyon and Tableland	The distribution of this ecological system is centered on the Colorado Plateau where it is comprised of barren and sparsely vegetated landscapes (generally <10% plant cover) of steep cliff faces, narrow canyons, and open tablelands of predominantly sedimentary rocks, such as sandstone, shale, and limestone. Common species includes *Pinus edulis*, *Pinus ponderosa*, *Juniperus* spp., *Cercocarpus intricatus*, and other short-shrub and herbaceous species, utilizing moisture from cracks and pockets where soil accumulates.	0.015%
16	S016	North American Warm Desert Bedrock Cliff and Outcrop	This ecological system is found from subalpine to foothill elevations and includes barren and sparsely vegetated landscapes (generally <10% plant cover) of steep cliff faces, narrow canyons, and smaller rock outcrops of various igneous, sedimentary, and metamorphic bedrock types. Also included are unstable scree and talus slopes that typically occur bellow cliff faces. Species present are diverse and may include *Bursera microphylla*, *Fouquieria splendens*, *Nolina bigelovii*, *Opuntia bigelovii*, and other desert species, especially succulents.	0.798%
19	S019	North American Warm Desert Volcanic Rockland	This ecological system occurs across the warm deserts of North America and is restricted to barren and sparsely vegetated (<10% plant cover) volcanic substrates such as basalt lava (malpais) and tuff. Vegetation is variable and includes a variety of species depending on local environmental conditions, e.g., elevation, age and type of substrate. Typically scattered *Larrea tridentata*, *Atriplex hymenelytra*, or other desert shrubs are present.	0.022%
20	S020	North American Warm Desert Wash	This ecological system is restricted to intermittently flooded washes or arroyos that dissect bajadas, mesas, plains and basin floors throughout the warm deserts of North America. Although often dry, the intermittent fluvial processes define this system, which are often associated with rapid sheet and gully flow. The woody	0.252%

			layer is typically intermittent to open and may be dominated by shrubs and small trees such as *Acacia greggii, Brickellia laciniata, Baccharis sarothroides, Chilopsis linearis, Fallugia paradoxa, Hymenoclea salsola, Hymenoclea monogyra, Juglans microcarpa, Prosopis* spp., *Psorothamnus spinosus, Prunus fasciculata, Rhus microphylla, Salazaria mexicana*, or *Sarcobatus vermiculatus*.	
21	S021	North American Warm Desert Pavement	This ecological system occurs throughout much of the warm deserts of North America and is composed of unvegetated to very sparsely vegetated (<2% plant cover) landscapes, typically flat basins where extreme temperature and wind develop ground surfaces of fine to medium gravel coated with "desert varnish." Very low cover of desert scrub species such as *Larrea tridentata* or *Eriogonum fasciculatum* is usually present.	0.020%
23	S023	Rocky Mountain Aspen Forest and Woodland	This widespread ecological system is more common in the southern and central Rocky Mountains, but occurs throughout much of the western U.S. and north into Canada, in the montane and subalpine zones. Elevations generally range from 1525 to 3050 m (5000-10,000 feet), but occurrences can be found at lower elevations in some regions. These are upland forests and woodlands dominated by *Populus tremuloides* without a significant conifer component (<25% relative tree cover).	0.014%
35	S035	Madrean Pine-Oak Forest and Woodland	This system occurs on mountains and plateaus in the Sierra Madre Occidentale and Sierra Madre Orientale in Mexico, Trans-Pecos Texas, southern New Mexico and southern and central Arizona, from the the Mogollon Rim southeastward to the Sky Islands. These forests and woodlands are composed of Madrean pines (*Pinus arizonica*, *Pinus engelmannii*, *Pinus leiophylla* or *Pinus strobiformis*) and evergreen oaks (*Quercus arizonica, Quercus emoryi*, or *Quercus grisea*) intermingled with patchy shrublands on most mid-elevation slopes (1500-2300 m elevation).	0.372%
36	S036	Rocky Mountain Ponderosa Pine Woodland	This very widespread ecological system is most common throughout the cordillera of the Rocky Mountains. It is also found in the Colorado Plateau region, west into scattered locations in the Great Basin, and north into southern British Columbia. These woodlands occur at the lower treeline/ecotone between grassland or shrubland and more mesic coniferous forests typically in warm, dry, exposed sites. Elevations range from less than 500 m in British Columbia to 2800 m in the New Mexico mountains.	0.019%
38	S038	Southern Rocky Mountain Pinyon-Juniper Woodland	This southern Rocky Mountain ecological system occurs on dry mountains and foothills in southern Colorado, in mountains and plateaus of northern New Mexico and Arizona, and extends out onto limestone breaks in the Great Plains. Soils supporting this system vary in texture ranging from stony, cobbly, gravelly sandy loams to clay loam or clay. *Pinus edulis* and/or *Juniperus monosperma* dominate the tree canopy. *Juniperus scopulorum* may codominate or replace *Juniperus monosperma* at higher elevations.	0.018%
51	S051	Madrean Encinal	Madrean Encinal occurs on foothills, canyons, bajadas and plateaus in the Sierra Madre Occidentale and Sierra Madre Orientale in Mexico, extending north into Trans-Pecos Texas, southern New Mexico and sub-Mogollon Arizona. These woodlands are dominated by Madrean evergreen oaks along a low-slope transition below Madrean Pine-Oak Forest and Woodland (CES305.796) and Madrean	10.007%

			Pinyon-Juniper Woodland (CES305.797). Common evergreen oak species include *Quercus arizonica, Quercus emoryi, Quercus intricata, Quercus grisea, Quercus oblongifolia*, *Quercus toumeyi* and in Mexico, *Quercus chihuahuaensis* and *Quercus albocincta*.	
57	S057	Mogollon Chaparral	This ecological system occurs across central Arizona (Mogollon Rim), western New Mexico and southwestern Utah and southeast Nevada. It often dominants along the mid-elevation transition from the Mojave, Sonoran, and northern Chihuahuan deserts into mountains (1000-2200 m). Stands are often associated with more xeric and coarse-textured substrates such as limestone, basalt or alluvium, especially in transition areas with more mesic woodlands. The moderate to dense shrub canopy includes species such as *Quercus turbinella, Quercus toumeyi*, *Cercocarpus montanus*, *Canotia holacantha*, *Ceanothus greggii*, *Forestiera pubescens (= Forestiera neomexicana), Garrya wrightii, Juniperus deppeana, Purshia stansburiana, Rhus ovata, Rhus trilobata*, and *Arctostaphylos pungens* and *Arctostaphylos pringlei* at higher elevations.	2.218%
58	S058	Apacherian-Chihuahuan Mesquite Upland Scrub	This ecological system occurs as upland shrublands that are concentrated in the extensive grassland- shrubland transition in foothills and piedmont in the Chihuahuan Desert. It extends into the Sky Island region to the west, and the Edwards Plateau to the east. Substrates are typically derived from alluvium without a well-developed argillic or calcic soil horizon that would limit infiltration and storage of winter precipitation in deeper soil layers. Vegetation is typically dominated by *Prosopis glandulosa* or *Prosopis velutina* and succulents.	16.739%
61	S061	Chihuahuan Succulent Desert Scrub	This ecological system is found in the Chihuahuan Desert on colluvial slopes, upper bajadas, sideslopes and mesas. The vegetation is characterized by the relatively high cover of succulent species such as *Agave lechuguilla, Euphorbia antisyphilitica, Fouquieria splendens, Opuntia engelmannii, Opuntia imbricata*, *Opuntia spinosior*, *Yucca baccata*, *Yucca elata* and *many others*. The abundance of succulents is diagnostic of this desert scrub system, but desert shrubs are usually present.	0.216%
63	S063	Sonoran Paloverde-Mixed Cacti Desert Scrub	This ecological system occurs on hillsides, mesas and upper bajadas in southern Arizona and extreme southeastern California. The vegetation is characterized by a diagnostic sparse, emergent tree layer of *Carnegia gigantea* (3-16 m tall) and/or a sparse to moderately dense canopy codominated by xeromorphic deciduous and evergreen tall shrubs *Parkinsonia microphylla* and *Larrea tridentata* with *Prosopis* sp., *Olneya tesota*, and *Fouquieria splendens* less prominent. Other common shrubs and dwarf-shrubs include *Acacia greggii*, *Ambrosia deltoidea*, *Ambrosia dumosa* (in drier sites), *Calliandra eriophylla*, *Jatropha cardiophylla*, *Krameria erecta*, *Lycium* spp., *Menodora scabra*, *Simmondsia chinensis*, and many cacti including *Ferocactus* spp., *Echinocereus* spp., and *Opuntia* spp. (both cholla and prickly pear).	0.002%
67	S067	Chihuahuan Creosotebush, Mixed Desert	This ecological system is limited to extremely xeric, lower elevation broad basins in the Chihuahuan Desert. Substrates are gravelly, non-saline and typically covered by desert pavement. The vegetation is an open shrubland dominated by *Larrea tridentata* without codominant thornscrub or succulent species that are	11.381%

		and Thorn Scrub	common on the piedmont and alluvial fans. *Parthenium incanum* or *Tiquilia hispidissima* may be codominate.	
68	S068	Chihuahuan Stabilized Coppice Dune and Sand Flat Scrub	This ecological system includes the open shrublands of vegetated coppice dunes and sandsheets found in the Chihuahuan Desert. Usually dominated by *Prosopis glandulosa* but includes *Atriplex canescens, Ephedra torreyana, Ephedra trifurca, Poliomintha incana*, and *Rhus microphylla* coppice sand scrub with 10-30% total vegetation cover. *Yucca elata, Gutierrezia sarothrae*, and *Sporobolus flexuosus* are commonly present.	1.372%
69	S069	Sonora-Mojave Creosotebush-White Bursage Desert Scrub	This ecological system forms the vegetation matrix in broad valleys, lower bajadas, plains and low hills in the Mojave and lower Sonoran deserts. This desert scrub is characterized by a sparse to moderately dense layer (2-50% cover) of xeromorphic microphyllous and broad-leaved shrubs. *Larrea tridentata* and *Ambrosia dumosa* are typically dominants, but many different shrubs, dwarf-shrubs, and cacti may codominate or form typically sparse understories.	0.015%
77	S077	Apacherian-Chihuahuan Piedmont Semi-Desert Grassland and Steppe	This ecological system is a broadly defined desert grassland, mixed shrub-succulent or xeromorphic tree savanna that is typical of the Borderlands of Arizona, New Mexico and northern Mexico [Apacherian region], but extends to the Sonoran Desert and throughout much of the Chihuahuan Desert. Common grass species include *Bouteloua eriopoda, Bouteloua hirsuta, Eragrostis intermedia, Muhlenbergia porteri, Muhlenbergia setifolia, Pleuraphis jamesii, Pleuraphis mutica*, and *Sporobolus airoides*, succulent species of *Agave, Dasylirion*, and *Yucca*, and tall shrub/short tree species of *Prosopis* and various oaks (e.g., *Quercus grisea, Quercus emoryi, Quercus arizonica*).	28.992%
94	S094	North American Warm Desert Lower Montane Riparian Woodland and Shrubland	This ecological system occurs in canyons and valleys of southern Arizona and New Mexico, and adjacent Mexico and consists of mid- to low-elevation (1100-1800 m) riparian corridors along perennial and seasonally intermittent streams. Dominant trees include *Populus angustifolia, Populus deltoides ssp. wislizeni, Populus fremontii, Platanus wrightii, Juglans major, Fraxinus velutina*, and *Sapindus saponaria*. Shrub dominants include *Salix exigua, Prunus* spp., *Alnus oblongifolia*, and *Baccharis salicifolia*.	0.094%
97	S097	North American Warm Desert Riparian Woodland and Shrubland	This ecological system consists of low-elevation (<1200 m) riparian corridors along medium to large perennial streams throughout canyons and the desert valleys of the southwestern United States and adjacent Mexico. The vegetation is a mix of riparian woodlands and shrublands. Dominant trees include *Acer negundo, Fraxinus velutina, Populus fremontii, Salix gooddingii, Salix lasiolepis, Celtis laevigata var. reticulata*, and *Juglans major*. Shrub dominants include *Salix geyeriana, Shepherdia argentea*, and *Salix exigua*.	0.001%
98	S098	North American Warm Desert Riparian Mesquite Bosque	This ecological system consists of low-elevation (<1100 m) riparian corridors along intermittent streams in valleys of southern Arizona and New Mexico, and adjacent Mexico. Dominant trees include *Prosopis glandulosa* and *Prosopis velutina*. Shrub dominants include *Baccharis salicifolia, Pluchea sericea*, and *Salix exigua*. Vegetation, especially the mesquites, tap groundwater below the streambed when surface flows stop.	0.269%

100	S100	North American Arid West Emergent Marsh	This widespread ecological system occurs throughout much of the arid and semi-arid regions of western North America. Natural marshes may occur in depressions in the landscape (ponds, kettle ponds), as fringes around lakes, and along slow-flowing streams and rivers (such riparian marshes are also referred to as sloughs). Soils have characteristics that result from long periods of anaerobic conditions in the soils (e.g., gleyed soils, high organic content, redoximorphic features). Common emergent and floating vegetation includes species of *Scirpus* and/or *Schoenoplectus, Typha, Juncus, Potamogeton, Polygonum, Nuphar*, and *Phalaris*.	0.004%
109	S109	Chihuahuan-Sonoran Desert Bottomland and Swale Grassland	This ecological system occurs throughout the northern Chihuahuan Desert and adjacent Sky Islands and Sonoran Desert, as well as limited areas of the southern Great Plains and Edwards Plateau in depressions on broad mesas and plains, and valley bottoms that receive runoff from adjacent areas. Vegetation is typically dominated by *Pleuraphis mutica* (tobosa swales) or other mesic graminoids such as *Pascopyrum smithii, Panicum obtusum, Sporobolus airoides*, or *Sporobolus wrightii*.	13.521%
111	S111	Madrean Upper Montane Conifer-Oak Forest and Woodland	This system occurs at the upper elevations in the Sierra Madre Occidentale and Sierra Madre Orientale. In the U.S., it is restricted to north and east aspects at high elevations (1980-2440 m) in the Sky Islands (Chiricahua, Huachuca, Pinaleno, Santa Catalina, and Santa Rita mountains) and along the Nantanes Rim. The vegetation is characterized by large- and small-patch forests and woodlands dominated by *Pseudotsuga menziesii, Abies coahuilensis*, or *Abies concolor* and Madrean oaks such as *Quercus hypoleucoides* and *Quercus rugosa*.	0.460%
112	S112	Madrean Pinyon-Juniper Woodland	This system occurs on foothills, mountains and plateaus in the Sierra Madre Occidentale and Sierra Madre Orientale in Mexico, Trans-Pecos Texas, southern New Mexico and in southern and central Arizona, from the Mogollon Rim south to the Sky Islands. Substrates are variable, but soils are generally dry and rocky. The presence of *Pinus cembroides, Pinus discolor*, or other Madrean trees and shrubs is diagnostic of this woodland system.	7.031%
113	S113	Chihuahuan Sandy Plains Semi-Desert Grassland	This ecological system occurs across the Chihuahuan Desert and extends into the southern Great Plains where soils have a high sand content. These dry grasslands or steppe are found on sandy plains and sandstone mesas. The graminoid layer is dominated or codominated by *Achnatherum hymenoides, Bouteloua eriopoda, Bouteloua hirsuta, Hesperostipa neomexicana, Pleuraphis jamesii, Sporobolus cryptandrus*, or *Sporobolus flexuosus*.	0.025%
115	S115	Madrean Juniper Savanna	This Madrean ecological system occurs in lower foothills and plains of southeastern Arizona, southern New Mexico extending into west Texas and Mexico. These savannas have widely spaced mature juniper trees and moderate to high cover of graminoids (>25% cover). The presence of Madrean *Juniperus* spp. such as *Juniperus coahuilensis, Juniperus pinchotii*, and/or *Juniperus deppeana* is diagnostic.	0.050%
116	S116	Chihuahuan Mixed Salt Desert Scrub	This system includes extensive open-canopied shrublands of typically saline basins in the Chihuahuan Desert. Stands often occur on alluvial flats and around playas. Substrates are generally fine-textured, saline soils. Vegetation is typically composed of one or more *Atriplex* species such as *Atriplex canescens, Atriplex*	2.619%

			obovata, or *Atriplex polycarpa* along with species of *Allenrolfea, Flourensia, Salicornia, Suaeda*, or other halophytic plants.	
129	S129	Sonoran Mid-Elevation Desert Scrub	This transitional desert scrub system occurs along the northern edge of the Sonoran Desert in an elevational band along the lower slopes of the Mogollon Rim/Central Highlands region between 750-1300 m. Stands occur in the Bradshaw, Hualapai, and Superstition mountains among other desert ranges and are found above Sonoran Paloverde- Mixed Cacti Desert Scrub (CES302.761) and below Mogollon Chaparral (CES302.741).	-

11.5. Location of Wells in Mexico and Arizona (Piezometric Survey).

Well	State	X	Y	Depth	Elev.	Well	State	X	Y	Depth	Elev.
28	Son.	583963	3442773	50.37	1394.63	D-18-21 06AAB2	Ar.	572414.1	3529958.8	11.9	1092.0
30	Son.	574871	3432033	41.20	1418.80	D-23-21 06CCC2	Ar.	570680.6	3479867.5	7.4	1467.7
35	Son.	576304	3432214	44.25	1395.75	D-22-18 15CBD	Ar.	546601.4	3486917.8	12.5	1551.1
36	Son.	577159	3432617	49.11	1380.89	D-16-20 34ACB	Ar.	567300.6	3540623.8	25.2	1051.6
42	Son.	576318	3434093	28.33	1421.67	D-18-21 28DAA	Ar.	575990.6	3522665.7	24.2	1117.2
43	Son.	576936	3434161	58.86	1385.14	D-22-21 23CBA	Ar.	577182.7	3485437.1	41.0	1275.7
46	Son.	583024	3437531	63.76	1412.04	D-21-22 27BCD	Ar.	585240.0	3493437.6	37.2	1236.9
55	Son.	581243	3438226	72.36	1367.64	D-21-17 14ACC	Ar.	539260.0	3496973.4	15.9	1530.0
56	Son.	570854	3432305	45.73	1448.95	D-20-18 03CAA	Ar.	547899.1	3509703.7	42.2	1449.7
57	Son.	571623	3432795	42.95	1437.05	D-23-22 32DDD2	Ar.	583395.8	3471869.9	11.9	1282.8
58	Son.	572202	3433427	36.86	1433.84	D-18-19 25DCC	Ar.	560917.7	3522098.9	22.4	1409.9
61	Son.	573810	3434823	29.90	1429.48	D-21-21 33CBB1	Ar.	573781.5	3491878.1	58.0	1260.8
62	Son.	571892	3433079	40.45	1439.55	D-23-22 07DCC	Ar.	581102.5	3478373.0	32.7	1286.1
63	Son.	572191	3433425	34.58	1436.09	D-19-21 12DBB2	Ar.	580287.7	3517713.3	67.2	1165.7
66	Son.	573519	3434620	31.33	1428.67	D-24-22 20BBA	Ar.	582305.0	3466799.2	12.3	1296.7
67	Son.	570721	3437079	33.37	1436.63	D-23-21 26ADC	Ar.	578268.0	3474040.9	72.1	1290.9
68	Son.	571114	3437734	39.34	1429.48	D-23-21 08DDD	Ar.	573660.1	3478441.0	44.4	1375.9
70	Son.	584485	3438056	63.44	1426.56	D-22-20 35CDC	Ar.	567856.7	3481440.5	12.3	1513.2
71	Son.	585954	3440075	51.41	1428.59	D-22-22 03CBA	Ar.	585384.2	3490325.6	56.0	1240.9
72	Son.	585490	3440665	9.93	1460.07	D-19-23 35ACD	Ar.	598108.1	3511715.4	89.4	1398.0
73	Son.	585116	3441027	49.78	1420.22	D-21-18 24BBB	Ar.	549625.2	3496057.3	38.4	1432.8
278	Son.	579624	3461395	7.08	1316.92	D-23-22 25BBC	Ar.	588398.7	3474722.1	54.7	1280.3
286	Son.	589796	3451534	3.27	1509.33	D-18-20 06BDD	Ar.	562179.0	3529365.1	80.7	1272.5
291	Son.	595510	3448998	11.33	1508.67	D-18-21 01DCA	Ar.	580380.1	3528755.7	103.6	1164.3
295	Son.	599355	3442691	24.42	1520.38	D-18-19 36ADC	Ar.	560986.5	3521345.5	74.8	1358.5
297	Son.	597707	3437503	6.13	1674.37	D-22-21 34ACC	Ar.	576170.6	3482418.4	63.0	1281.1
298	Son.	596287	3436350	2.51	1617.49	D-21-20S05ABC	Ar.	563425.0	3500553.7	69.8	1251.5
299	Son.	598252	3435411	6.18	1653.82	D-21-20 23AAB	Ar.	568584.2	3495959.0	93.0	1260.3
312	Son.	582615	3432174	48.49	1414.51	D-17-21 32BAB	Ar.	573185.4	3531565.5	18.6	1108.2
316	Son.	579953	3433567	48.06	1290.48	D-17-22 17DAA	Ar.	583904.2	3535678.3	158.7	1162.5
332	Son.	579287	3438608	27.72	1380.37	D-21-21 27CAA	Ar.	576138.4	3493305.3	20.6	1274.8
338	Son.	577505	3441791	36.80	1353.20	D-22-20 36ABB	Ar.	569830.7	3483023.7	132.1	1318.7
360	Son.	573424	3453716	10.02	1359.98	D-20-22 11ADB	Ar.	588642.0	3508670.7	128.5	1258.3
372	Son.	575785	3452871	5.20	1354.80	D-21-21 31BDC	Ar.	571070.6	3491933.2	94.0	1259.2
376	Son.	575767	3455303	7.23	1366.77	D-17-20 14CCC	Ar.	567975.8	3534978.2	4.4	1086.7
379	Son.	577000	3456759	4.23	1335.77	D-21-20 35CDD	Ar.	568335.9	3491237.1	136.5	1253.3
383	Son.	578663	3460835	6.23	1314.77	D-22-21 18DCD	Ar.	571676.1	3486321.4	116.5	1270.0
384	Son.	577779	3460683	14.32	1322.88	D-17-19 14ACA	Ar.	559299.2	3535863.3	168.3	1105.7
390	Son.	570759	3448618	6.12	1376.88	D-21-20 34AAA	Ar.	567258.8	3492671.3	136.4	1255.3
401	Son.	563097	3451120	54.13	1423.31	D-22-20 24AAA2	Ar.	570471.1	3486245.4	130.1	1273.5
403	Son.	561794	3447114	6.41	1433.59	D-23-22 16BDD	Ar.	584209.4	3477436.9	18.2	1271.1
406	Son.	558841	3458956	4.35	1462.25	D-22-20 24DBB	Ar.	569817.6	3485357.4	138.9	1276.8
423	Son.	578968	3462976	14.03	1316.97	D-22-20 10ABB	Ar.	566567.7	3489449.5	171.4	1254.1
426	Son.	575287	3453017	8.03	1349.97	D-21-20 16AAC1	Ar.	565447.7	3497202.7	90.9	1259.3
S/N	Son.	581072	3464166	8.37	1308.63	D-21-20 10BBC	Ar.	565856.8	3498838.6	72.1	1255.3
S/N	Son.	580057	3462514	7.11	1312.89	D-22-22 17CDB UNSURV	Ar.	582343.8	3486652.8	1.2	1247.5
S/N	Son.	582313	3466521	20.05	1299.95	D-21-20 11BCD	Ar.	567656.2	3498437.6	71.1	1253.2
S/N	Son.	579197	3438816	15.67	1384.33	D-22-20 01DCD	Ar.	570058.7	3489515.5	117.1	1254.4
S/N	Son.	586042	3446950	27.67	1399.33	D-21-20 33ACC UNSURV	Ar.	564996.6	3491890.3	164.3	1246.8

11.6. Location of Wells in Mexico (Geochemistry Survey)

Well	Owner	Location	Y (UTM)	X (UTM)
29	Minera de Cananea	Patos Norte	577514	3433792
30	Minera de Cananea	Patos Sur	574864	3432016
31	Minera de Cananea	Patos Sur	575545	3432103
35	Minera de Cananea	Patos Sur	576305	3432215
38	Minera de Cananea	Patos Sur	576018	3432826
40	Minera de Cananea		577984	3433384
41	Minera de Cananea	Patos Norte	576646	3433430
43	Minera de Cananea	Patos Norte	576943	3434156
47			582486	3438029
50	Ej. Emiliano Zapata	Patos Norte	577562	3436186
51			581651	3435705
53			581090	3437265
70	Minera de Cananea	Zona Zaragoza	584482	3438052
71	Minera de Cananea	Zona Arroyo Claro	585956	3440072
75			584313	3442400
383	Ej. José M. Morelos	Galera del Pedregón 10	578663	3460835
418	Ejido San Pedro	La Milpona	575389	3453883
483			573483	3453902
Barrilito			572713	3431248
El Texano			574409	3464479

11.7. GIS Metadata

Figure	Layers on Map	Source of Original Shapefile or Coverage
Location of Study Area	Hillshade NED	Hans Huth, ADEQ
	San Pedro River	Hans Huth, ADEQ
	Nearby Towns (>Pop. 1000)	WRRC/Project NEMO files
	Cananea	Hans Huth, ADEQ
	Study Area Boundary	WRRC/Project NEMO files and UNISON
	San Pedro Riparian National Conservation Area	WRRC/Project NEMO files
	Physiographic Province	INEGI, 2005 for Mexico; U.S. province labeled according to Fenneman, 1931.
Surface Water Drainages	Hillshade NED	Hans Huth, ADEQ
	San Pedro River	Hans Huth, ADEQ
	Nearby Towns (>Pop. 1000)	WRRC/Project NEMO files
	Cananea	Hans Huth, ADEQ
	Study Area Boundary	WRRC/Project NEMO files and UNISON
	Surface Water Drainages	Hans Huth, ADEQ
Climate and Weather Stations	Hillshade NED	Hans Huth, ADEQ
	Koppen-Geiger Climate Classification	Peel et al. 2007
	San Pedro River	Hans Huth, ADEQ
	Study Area Boundary	WRRC/Project NEMO files and Minjárez, 2011 (UNISON)
	Nearby Towns (>Pop. 1000)	WRRC/Project NEMO files
	Cananea	Hans Huth, ADEQ

Soil Characterization	Hillshade NED	Hans Huth, ADEQ
	San Pedro River	Hans Huth, ADEQ
	Study Area Boundary	WRRC/Project NEMO files and Minjárez, 2011 (UNISON)
	Nearby Towns (>Pop. 1000)	WRRC/Project NEMO files
	Cananea	Hans Huth, ADEQ
	Soil Classes, AZ	www.epa.gov/nerlesd1/land-sci/san_pedro
	Soil Classes, MX	Ismael Minjárez (UNISON); mael@geologia.uson.mx
Natural Vegetation	Hillshade NED	Hans Huth, ADEQ
	San Pedro River	Hans Huth, ADEQ
	Nearby Towns (>Pop. 1000)	WRRC/Project NEMO files
	Cananea	Hans Huth, ADEQ
	Study Area Boundary	WRRC/Project NEMO files and Minjárez, 2011 (UNISON)
	Natural Vegetation	EPA San Pedro River Basin Browser (http://case.nmsu.edu/CASE/SanPedro/gisdata.htm)
Mean Annual Temperature ©	Hillshade NED	Hans Huth, ADEQ
	San Pedro River	Hans Huth, ADEQ
	Nearby Towns (>Pop. 1000)	WRRC/Project NEMO files
	Cananea	Hans Huth, ADEQ
	Study Area Boundary	WRRC/Project NEMO files and Minjárez, 2011 (UNISON)
	Mean Annual Temperature	www.worldclim.org
Minimum Temperature of Coldest Month ©	Hillshade NED	Hans Huth, ADEQ
	San Pedro River	Hans Huth, ADEQ
	Nearby Towns (>Pop. 1000)	WRRC/Project NEMO files
	Cananea	Hans Huth, ADEQ
	Study Area Boundary	WRRC/Project NEMO files and Minjárez, 2011 (UNISON)
	Minimum Temperature of Coldest Month	www.worldclim.org
Maximum Temperature of Warmest Month ©	Hillshade NED	Hans Huth, ADEQ
	San Pedro River	Hans Huth, ADEQ
	Nearby Towns (>Pop. 1000)	WRRC/Project NEMO files
	Cananea	Hans Huth, ADEQ
	Study Area Boundary	WRRC/Project NEMO files and Minjárez, 2011 (UNISON)
	Maximum Temperature of Warmest Month	www.worldclim.org
Mean Annual Precipitation (mm)	Hillshade NED	Hans Huth, ADEQ
	San Pedro River	Hans Huth, ADEQ
	Study Area Boundary	WRRC/Project NEMO files and Minjárez, 2011 (UNISON)
	Nearby Towns (>Pop. 1000)	WRRC/Project NEMO files
	Cananea	Hans Huth, ADEQ
	Mean Annual Precipitation	www.worldclim.org
Mean Monthly Precipitation, January (mm)	Hillshade NED	Hans Huth, ADEQ
	San Pedro River	Hans Huth, ADEQ
	Nearby Towns (>Pop. 1000)	WRRC/Project NEMO files
	Cananea	Hans Huth, ADEQ
	Study Area Boundary	WRRC/Project NEMO files and Minjárez, 2011 (UNISON)
	January Precipitation	www.worldclim.org
Mean Monthly Precipitation, August (mm)	Hillshade NED	Hans Huth, ADEQ
	San Pedro River	Hans Huth, ADEQ
	Nearby Towns (>Pop. 1000)	WRRC/Project NEMO files
	Cananea	Hans Huth, ADEQ
	Study Area Boundary	WRRC/Project NEMO files and UNISON
	August Precipitation	www.worldclim.org

Surface Water Drainages, Orders 1 - 7	Hillshade NED	Hans Huth, ADEQ
	San Pedro River	Hans Huth, ADEQ
	Nearby Towns (>Pop. 1000)	WRRC/Project NEMO files
	Cananea	Hans Huth, ADEQ
	Study Area Boundary	WRRC/Project NEMO files and Minjárez, 2011 (UNISON)
	Major Drainages, Orders 4 - 7	Hans Huth, ADEQ
Percent Slope (%)	Hillshade NED	Hans Huth, ADEQ
	San Pedro River	Hans Huth, ADEQ
	Study Area Boundary	WRRC/Project NEMO files and Minjárez, 2011 (UNISON)
	Nearby Towns (>Pop. 1000)	WRRC/Project NEMO files
	Cananea	Hans Huth, ADEQ
	Percent Slope (%)	ned.usgs.gov (slope transformation on original NED in ArcMap)
Land Cover	Hillshade NED	Hans Huth, ADEQ
	Study Area Boundary	WRRC/Project NEMO files and Minjárez, 2011 (UNISON)
	Nearby Towns (>Pop. 1000)	WRRC/Project NEMO files
	Cananea	Hans Huth, ADEQ
	Land Cover	fws-case-12.nmsu.edu/SanPedro/data/SPCART_Landcover2.htm
Land Ownership	Hillshade NED	Hans Huth, ADEQ
	Study Area Boundary	WRRC/Project NEMO files and UNISON
	Nearby Towns (>Pop. 1000)	WRRC/Project NEMO files
	Cananea	Hans Huth, ADEQ
	Land Ownership	For U.S.: Arizona State Land Dept, Arizona Land Resource Information System For Mex: Ismael Minjárez, UNISON
Geology	Geology	Francisco Grijalva, Floyd Gray, Ismael Minjárez and Rogelio Monreal
	Study Area Boundary	WRRC/Project NEMO files and UNISON
	Nearby Towns (>Pop. 1000)	WRRC/Project NEMO files
Depth to Bedrock (km)	Hillshade NED	Hans Huth, ADEQ
	San Pedro River	Hans Huth, ADEQ
	Study Area Boundary	WRRC/Project NEMO files and Minjárez, 2011 (UNISON)
	Nearby Towns (>Pop. 1000)	WRRC/Project NEMO files
	Depth to Bedrock (km)	USGS Open-File Report 2000-138 by Gettings and Houser
Residual	Residual	Francisco Grijalva, UNISON
	Study Area Boundary	WRRC/Project NEMO files and Minjárez, 2011 (UNISON)
	Nearby Towns (>Pop. 1000)	WRRC/Project NEMO files
	Hillshade NED	Hans Huth, ADEQ
Resistivity Maps at Different Elevations	Resistivity Maps at Different Elevations	Francisco Grijalva, UNISON
	Study Area Boundary	WRRC/Project NEMO files and Minjárez, 2011 (UNISON)
	Nearby Towns (>Pop. 1000)	WRRC/Project NEMO files
	Hillshade NED	Hans Huth, ADEQ
Location of Wells	Hillshade NED	Hans Huth, ADEQ
	San Pedro River	Hans Huth, ADEQ
	Study Area Boundary	WRRC/Project NEMO files and Minjárez, 2011 (UNISON)
	Nearby Towns (>Pop. 1000)	WRRC/Project NEMO files
	Cananea	Hans Huth, ADEQ
	Wells	Minjárez, 2011 (UNISON); ADWR Groundwater Site Inventory and USGS National Water Information System
Hydrographs	Hillshade NED	Hans Huth, ADEQ
	San Pedro River	Hans Huth, ADEQ
	Study Area Boundary	WRRC/Project NEMO files and Minjárez, 2011 (UNISON)
	Nearby Towns (>Pop. 1000)	WRRC/Project NEMO files
	Cananea	Hans Huth, ADEQ

	Hydrographs	Minjárez, 2011 (UNISON); ADWR Groundwater Site Inventory and USGS National Water Information System
Depth to Water Level (m)	Hillshade NED	Hans Huth, ADEQ
	San Pedro River	Hans Huth, ADEQ
	Study Area Boundary	WRRC/Project NEMO files and Minjárez, 2011 (UNISON)
	Nearby Towns (>Pop. 1000)	WRRC/Project NEMO files
	Cananea	Hans Huth, ADEQ
	Depth to Water (m)	gisweb.azwater.gov/waterresourcedata/GWSI.aspx
	Depth to Water (m), MX	Minjárez, 2011 (UNISON)
	Depth to water contours	Elia M. Tapia (UNISON)
Static Water Level Elevation (m)	Hillshade NED	Hans Huth, ADEQ
	San Pedro River	Hans Huth, ADEQ
	Study Area Boundary	WRRC/Project NEMO files and UNISON
	Nearby Towns (>Pop. 1000)	WRRC/Project NEMO files
	Cananea	Hans Huth, ADEQ
	Water elevation (m)	gisweb.azwater.gov/waterresourcedata/GWSI.aspx
	Water elevation (m), MX	Minjárez, 2011 (UNISON)
	Water elevation contours	Elia M. Tapia (UNISON)
Specific capacity tests	Hillshade NED	Hans Huth, ADEQ
	San Pedro River	Hans Huth, ADEQ
	Study Area Boundary	WRRC/Project NEMO files and Minjárez, 2011 (UNISON)
	Nearby Towns (>Pop. 1000)	WRRC/Project NEMO files
	Cananea	Hans Huth, ADEQ
	Specific capacity tests	Brown et al., 1966
Transmissivity	Hillshade NED	Hans Huth, ADEQ
	San Pedro River	Hans Huth, ADEQ
	Study Area Boundary	WRRC/Project NEMO files and Minjárez, 2011 (UNISON)
	Nearby Towns (>Pop. 1000)	WRRC/Project NEMO files
	Cananea	Hans Huth, ADEQ
	Transmissivity	Digitized by UNISON. Taken from Pool and Dickinson, 2007.
Geochemistry Surveys	Hillshade NED	Hans Huth, ADEQ
	San Pedro River	Hans Huth, ADEQ
	Study Area Boundary	WRRC/Project NEMO files and Minjárez, 2011 (UNISON)
	Nearby Towns (>Pop. 1000)	WRRC/Project NEMO files
	Cananea	Hans Huth, ADEQ
	Geochemistry surveys	GWSI WQ reports; gisweb.azwater.gov/waterresourcedata/GWSI.aspx; Minjárez, 2011 (UNISON)
Temperature of Groundwater	Hillshade NED	Hans Huth, ADEQ
	San Pedro River	Hans Huth, ADEQ
	Study Area Boundary	WRRC/Project NEMO files and UNISON
	Nearby Towns (>Pop. 1000)	WRRC/Project NEMO files
	Cananea	Hans Huth, ADEQ
	Major Drainages	Hans Huth, ADEQ
	Well Site, Temperature ©	GWSI WQ reports; gisweb.azwater.gov/waterresourcedata/GWSI.aspx; Minjárez, 2011 (UNISON)
pH of Groundwater	Hillshade NED	Hans Huth, ADEQ
	San Pedro River	Hans Huth, ADEQ
	Study Area Boundary	WRRC/Project NEMO files and UNISON
	Nearby Towns (>Pop. 1000)	WRRC/Project NEMO files
	Cananea	Hans Huth, ADEQ
	Major Drainages	Hans Huth, ADEQ
	Well Site, pH	GWSI WQ reports; gisweb.azwater.gov/waterresourcedata/GWSI.aspx; Minjárez, 2011 (UNISON)

Alkalinity of Groundwater	Hillshade NED	Hans Huth, ADEQ
	San Pedro River	Hans Huth, ADEQ
	Study Area Boundary	WRRC/Project NEMO files and UNISON
	Nearby Towns (>Pop. 1000)	WRRC/Project NEMO files
	Cananea	Hans Huth, ADEQ
	Major Drainages	Hans Huth, ADEQ
	Well Site, Alkalinity (mg/L CaCO3)	GWSI WQ reports; gisweb.azwater.gov/waterresourcedata/GWSI.aspx; Minjárez, 2011 (UNISON)
Specific Conductance	Hillshade NED	Hans Huth, ADEQ
	San Pedro River	Hans Huth, ADEQ
	Study Area Boundary	WRRC/Project NEMO files and UNISON
	Nearby Towns (>Pop. 1000)	WRRC/Project NEMO files
	Cananea	Hans Huth, ADEQ
	Major Drainages	Hans Huth, ADEQ
	Well Site, Specific Conductance (uS/cm)	GWSI WQ reports; gisweb.azwater.gov/waterresourcedata/GWSI.aspx; Minjárez, 2011 (UNISON)
Na Concentration	Hillshade NED	Hans Huth, ADEQ
	San Pedro River	Hans Huth, ADEQ
	Study Area Boundary	WRRC/Project NEMO files and UNISON
	Nearby Towns (>Pop. 1000)	WRRC/Project NEMO files
	Cananea	Hans Huth, ADEQ
	Major Drainages	Hans Huth, ADEQ
	Well Site, Na Concentrations	GWSI WQ reports; gisweb.azwater.gov/waterresourcedata/GWSI.aspx; Minjárez, 2011 (UNISON)
Ca Concentration	Hillshade NED	Hans Huth, ADEQ
	San Pedro River	Hans Huth, ADEQ
	Study Area Boundary	WRRC/Project NEMO files and UNISON
	Nearby Towns (>Pop. 1000)	WRRC/Project NEMO files
	Cananea	Hans Huth, ADEQ
	Major Drainages	Hans Huth, ADEQ
	Well Site, Ca Concentration	GWSI WQ reports; gisweb.azwater.gov/waterresourcedata/GWSI.aspx; Minjárez, 2011 (UNISON)
Mg Concentration	Hillshade NED	Hans Huth, ADEQ
	San Pedro River	Hans Huth, ADEQ
	Study Area Boundary	WRRC/Project NEMO files and UNISON
	Nearby Towns (>Pop. 1000)	WRRC/Project NEMO files
	Cananea	Hans Huth, ADEQ
	Major Drainages	Hans Huth, ADEQ
	Well Site, Mg Concentration	GWSI WQ reports; gisweb.azwater.gov/waterresourcedata/GWSI.aspx; Minjárez, 2011 (UNISON)
K Concentration	Hillshade NED	Hans Huth, ADEQ
	San Pedro River	Hans Huth, ADEQ
	Study Area Boundary	WRRC/Project NEMO files and UNISON
	Nearby Towns (>Pop. 1000)	WRRC/Project NEMO files
	Cananea	Hans Huth, ADEQ
	Major Drainages	Hans Huth, ADEQ
	Well Site, K Concentration	GWSI WQ reports; gisweb.azwater.gov/waterresourcedata/GWSI.aspx; Minjárez, 2011 (UNISON)
Cl Concentration	Hillshade NED	Hans Huth, ADEQ
	San Pedro River	Hans Huth, ADEQ
	Study Area Boundary	WRRC/Project NEMO files and UNISON
	Nearby Towns (>Pop. 1000)	WRRC/Project NEMO files
	Cananea	Hans Huth, ADEQ
	Major Drainages	Hans Huth, ADEQ
	Well Site, Cl Concentration	GWSI WQ reports; gisweb.azwater.gov/waterresourcedata/GWSI.aspx; Minjárez, 2011 (UNISON)

SO4 Concentration	Hillshade NED	Hans Huth, ADEQ
	San Pedro River	Hans Huth, ADEQ
	Study Area Boundary	WRRC/Project NEMO files and UNISON
	Nearby Towns (>Pop. 1000)	WRRC/Project NEMO files
	Cananea	Hans Huth, ADEQ
	Major Drainages	Hans Huth, ADEQ
	Well Site, SO4 Concentration	GWSI WQ reports; gisweb.azwater.gov/waterresourcedata/GWSI.aspx; Minjárez, 2011 (UNISON)
HCO3 Concentration	Hillshade NED	Hans Huth, ADEQ
	San Pedro River	Hans Huth, ADEQ
	Study Area Boundary	WRRC/Project NEMO files and UNISON
	Nearby Towns (>Pop. 1000)	WRRC/Project NEMO files
	Cananea	Hans Huth, ADEQ
	Major Drainages	Hans Huth, ADEQ
	Well Site, HCO3 Concentration	GWSI WQ reports; gisweb.azwater.gov/waterresourcedata/GWSI.aspx;Minjárez, 2011 (UNISON)