BINATIONAL STUDY OF THE TRANSBOUNDARY SANTA CRUZ AQUIFER

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CONAGUA COMISIÓN NACIONAL DEL AGUA

AUTHORITY

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The binational team also dedicates this study to our friends Roberto Salmon Castelo, former Commissioner, and longtime IBWC representative in Nogales, Sonora, Engineer Jesus Quintanar. †

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AGENCIES

ADEQ	Arizona Department of Environmental Quality
ADWR	Arizona Department of Water Resources
CIAT	Center for Tropical Agriculture, Mexico
CONAGUA	National Water Commission, Mexico
DOE	Department of Energy
EPA	United States Environmental Protection Agency
GAS	Department of Groundwater Management, CONAGUA
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 Department of Agriculture
OOMAPAS	Municipal Operating Organization of Potable Water, Sewage, and Sanitation
SGM	Mexican Geological Service
UA	University of Arizona
WRRC	Water Resources Research Center
UNISON	University of Sonora
USDA	United States Department of Agriculture
USFS	United States Forest Service
USGS	United States Geological Survey
WMO	World Meteorological Organization

KEY TECHNICAL TERMS

AMA	Active Management Area
ARD	Acid Rock Drainage
DMA	Groundwater Availability
DNC	Committed Natural Discharge
COTAS	Technical Groundwater Committee, Mexico
DOF	Official Gazette of the Federation, Mexico
Eh	Redox Potential
ENSO	El Niño-Southern Oscillation
ET	evapotranspiration
FAOCLIM	Food and Agricultural Organization, World Climate Data
GHCN	Global Historical Climatology Network
GIS	Geographic Information System
GWSI	groundwater site inventory
HSIA	Highlands-Sky Islands aquifer
IOI	International Outfall Interceptor
IPCC	Intergovernmental Panel on Climate Change
K	Hydraulic Conductivity
K_h/K_v	Vertical Anisotropy
LAWTP	Los Alisos Wastewater Treatment Plant
LMWL	Modified Local Meteoric Water Line
LULC	Land Use and Land Cover
MCL	Maximum Contaminant Level

M-SEV	Modified Socio-Environmental Vulnerability Index
MODIS	Moderate Resolution Imaging Spectroradiometer
NAM	North American Monsoon
NAS	Nogales aquifer in Sonora as defined by CONAGUA
NED	National Elevation Dataset, United States Geological Survey
NOM	Official Mexican Standard
NIWTP	Nogales International Wastewater Treatment Plant
NWIS	National Water Information System, United States Geological Survey
IOI	International Outfall Interceptor
PDO	Pacific Decadal Oscillation
pH	hydrogen potential
R	Recharge
REPDA	Public Registry of Water Rights, National Water Commission, Mexico
SCAA	Santa Cruz aquifer in Arizona (includes all parts of the study area in Arizona)
SCAMA	Santa Cruz Active Management Area as defined by the ADWR
SCRAS	Santa Cruz River aquifer in Sonora as defined by CONAGUA
SSURGO	Soil Survey Geographic Database
STATSGO	State Soil Geographic Database
S_s	specific storage
S_y	specific yield
TAAP	Transboundary Aquifer Assessment Program
TSCAS	Transboundary Santa Cruz Aquifer System as defined in section 1.2 of this report (the study area)
TDS	Total Dissolved Solids
TEM	Transient Electromagnetic
UTM	Universal Transverse Mercator
VEAS	Groundwater Extraction Volumes
WBM	Water Budget Model
WGS	World Geodetic System

1. INTRODUCTION

1.1. Background

The United States and Mexico share waters from a number of aquifers that cross the international boundary. No treaty exists on the management of the groundwater in these shared aquifers, and most of the scientific work concerning them has been carried out for many years within each country, without full knowledge of the conditions and activities on the other side of the border. A greater scientific understanding of these aquifer systems along and across the common border could be beneficial to both countries.

To address the need for greater understanding of the conditions of aquifers along the U.S.-Mexico border, the Principal Engineers of both the US and Mexican sections 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. The IBWC coordinated the scientific dialogue and the exchange of information to enable the preparation of this U.S.-Mexico Binational Report. This IBWC “Joint Report” serves as the framework for U.S.-Mexico coordination of transboundary aquifer studies. The document clarifies details about the structure and function of the program including background, roles, responsibilities, funding, relevance of the international water treaties, and the use of information collected or compiled as part of the program. Despite asymmetries in binational institutions and differences in culture, language, and legal frameworks, this binational partnership has grown and strengthened since 2009 with success in developing binational datasets and research, as well as binational protocols for cooperation and aquifer classification and assessment (Megdal and Scott, 2011; Callegary et al., 2018, Sanchez and Eckstein, 2020, Tapia-Villaseñor and Megdal, 2021).

Along the Arizona-Sonora portion of the border, the U.S. and Mexican Sections of IBWC agreed to begin with the study of two aquifers: the Transboundary Santa Cruz aquifer and the Transboundary San Pedro aquifer (Figure 1.1). On October 15, 2010, the Mexican Section of the IBWC signed two contracts with the University of Sonora (UNISON) detailing cooperation with respect to the assessment of the two aquifers. The Geology Department of UNISON was designated to perform this technical work. The academic counterparts of UNISON in the United States for this program were the Water Resources Research Center (WRRC) at the University of Arizona (UA). The U.S. Geological Survey (USGS) and the Mexican National Water Commission (Comisión Nacional del Agua/CONAGUA) are the lead federal co-investigators for this binational study which is carried out under the IBWC framework.

This report focuses on the Transboundary Santa Cruz Aquifer System (TSCAS). The Santa Cruz River originates in the San Rafael Valley in Arizona. It flows south towards Sonora, and crosses the international boundary at Lochiel, Arizona and passes through Santa Cruz, Sonora about 12.8 kilometers (km) to the south (Figure 1.2). Around 20 km south of the international boundary, near the community of Miguel Hidalgo (San Lazaro), the river diverts towards the west, then northwest and crosses the international boundary a second time about 7 km east of the largest urban area in the TSCAS—the sister cities of Nogales, Arizona and Nogales, Sonora. Together they are commonly known as “Ambos Nogales” which means “Both Nogales” in English.

TSCAS water is needed for industry, mining, agriculture, and municipal uses, but at the same time it is important ecologically, sustaining the Santa Cruz River and associated aquatic and riparian ecosystems (Norman, 2010). Management of the TSCAS that is grounded in the best available scientific information in both Mexico and the United States to ensure that the Santa Cruz aquifer benefits both countries. As a result, it was agreed to integrate scientific data from both the United States and Mexico through this joint binational study of the Transboundary Santa Cruz Aquifer System.

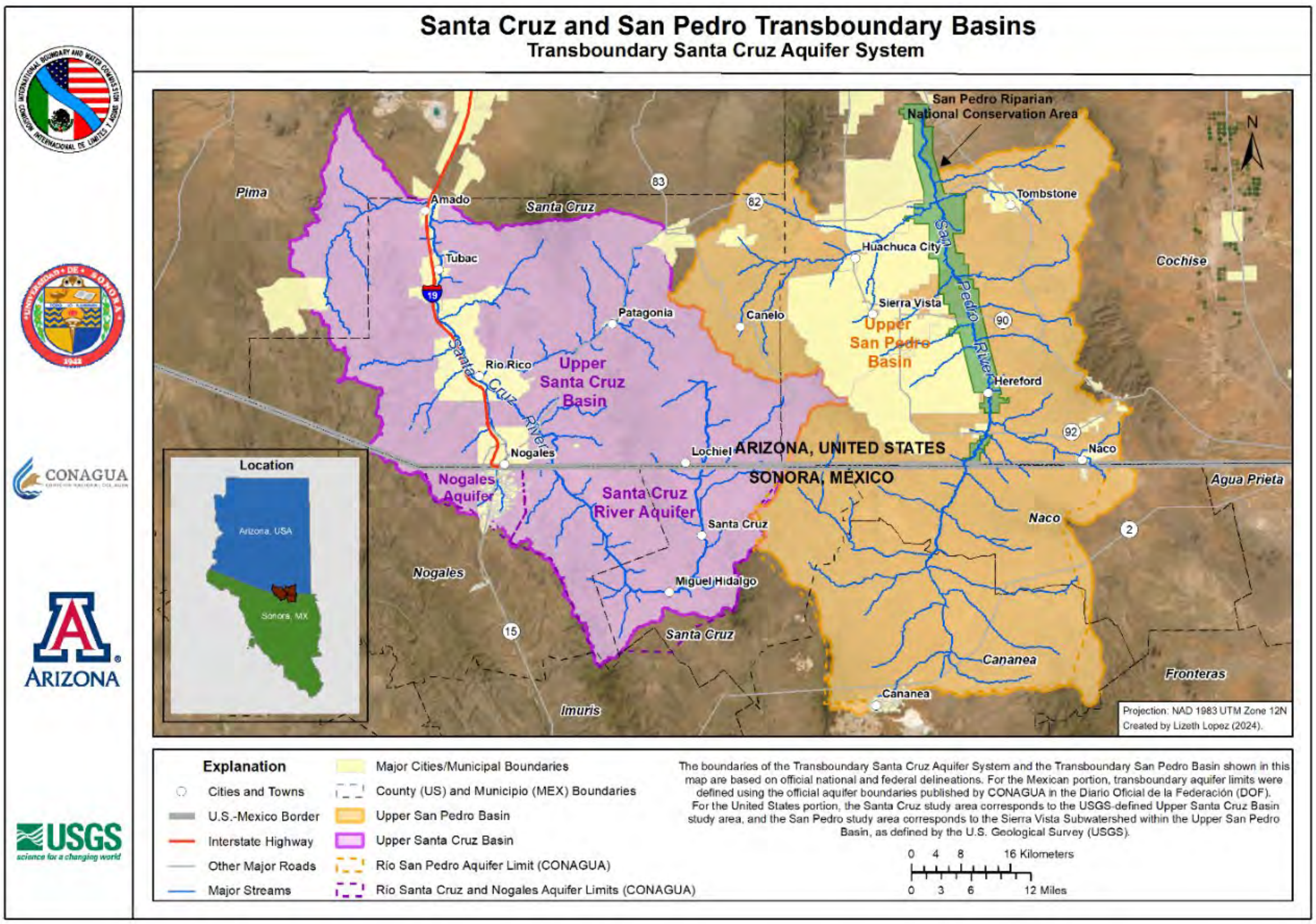

Figure 1.1 Santa Cruz and San Pedro Transboundary Basins (dashed lines indicate county boundaries in the U.S. and municipal boundaries within Mexico).

The cities of Ambos Nogales are located within the Nogales Wash basin. Nogales Wash is the largest transboundary tributary to the Santa Cruz River. It originates in Sonora about 10 km south of the international border and flows northward. The confluence of Nogales Wash with the Santa Cruz River is about 14 km north of the international boundary near the community of Rio Rico, Arizona (Figure 1.2).

Nogales, Arizona, depends on wells located along the Transboundary Santa Cruz River for their water supply. On the other hand, residents of Nogales, Sonora, rely on wells located within the Paredes, Mascareñas, Los Alisos, and Cíbuta regions, along with urban wells from the city (Nogales aquifer) (GAS-CONAGUA, 2024b). Most of the wastewater from the two cities is conveyed by a pipe (known as the International Outfall Interceptor or "IOI") to the Nogales International Wastewater Treatment Plant (NIWTP), located near Rio Rico, Arizona. The treated water is then discharged into the otherwise ephemeral Santa Cruz River channel and flows downstream. The NIWTP was built to handle 645 liters per second (L/s): 211 L/s from Nogales, Arizona, and 434 L/s from Nogales, Sonora. However, a mean of 543 L/s was sent from Nogales, Sonora, during the 2000-2011 period (Tapia-Villaseñor et al., 2020). To treat the excess, construction of a new plant, the Los Alisos Wastewater Treatment Plant (LAWTP), was completed south of Nogales, Sonora, in 2012 with support from the U.S. Environmental Protection Agency (EPA), with the potential to increase capacity (Norman et al., 2013). The reach of the Santa Cruz River from the NIWTP discharge point near Rio Rico to Tubac is largely perennial, with a temporally intermittent reach at the northern end that ceases to flow in summer prior to the onset of the rainy season (USGS gage 09481740, Santa Cruz River at Tubac, AZ). North of Tubac, the river is ephemeral at USGS gage 09482000, Santa Cruz River at Continental, AZ, except for reaches in Tucson that are downstream of the city's two wastewater treatment plants.

1.2. Study Area

The Transboundary Santa Cruz basin is located in the central portion of the international boundary separating the Mexican state of Sonora and the U.S. state of Arizona (Figure 1.2). It is located primarily within the Madrean Archipelago and Sonoran Desert ecoregions of North America (Wiken et al., 2011). To the east is the San Pedro River basin. To the southeast, south, and southwest are the Río Concepción-Arroyo Cocóspera basin (Cuitaca and Cocóspera aquifers) and Río Asunción (Río Alisos aquifer) basin, and to the west is the Cuenca del Río Concepción (Río Altar aquifer). The basins are natural units of the land, defined by the existence of a division of the waters due to the topography (the highest points of the mountains), where all the runoff converges and flows into a common point (SEMARNAT, 2013). An aquifer is a geological formation that stores and transmits groundwater. It consists of permeable materials such as sand, gravel, or rock that allow water to flow through them (Freeze and Cherry, 1979). The Transboundary Santa Cruz basin contains an "aquifer system" which is defined as a group of "aquifers of porous material with various permeabilities that may act as a water-yielding unit of regional scale” (World Meteorological Organization [WMO], 2012). The 2008 Draft Articles on the Law of Transboundary Aquifers (United Nations International Law Commission, 2008) defines a “transboundary aquifer” or “transboundary aquifer system” as “an aquifer or aquifer system, parts of which are situated in different states.” Although the regional alluvial fill aquifers are the principal aquifers in the study area, the terms defined above refer to areas enclosed within the watershed topographic divide, which includes mountain ranges and any bedrock aquifers therein.

In Mexico’s national system, aquifers are typically delineated based on a combination of principal alluvial aquifers and mountains within a topographic divide. This approach aligns with concepts such as “alluvial basins” described by Freethey and Anderson (1986) and the “hydrogeologic areas” of Anning and Knoieczki. For the purposes of this report, aquifer boundaries within Mexican territory are defined by polygons that reflect official designations set forth by CONAGUA's standards (Congreso de los Estados Unidos Mexicanos, 2025). Legally, the Ley de Aguas Nacionales (Law of National Waters [LAN], 1992, latest amendment, 2025) defines an "aquifer" as "any geological formation or group of geological formations that are hydraulically connected, through which groundwater circulates or is stored, [from] which [groundwater] can be extracted for exploitation, use or consumption and whose lateral and vertical boundaries are conventionally defined for the purposes of evaluation, management, and administration of national groundwater resources....". Based on these definitions and given that the alluvial and bedrock aquifers within the Santa Cruz River basin extend continuously across the U.S.-Mexico border, the TSCAS clearly meets the criteria of a transboundary aquifer system.

The TSCAS has an area of about 3,890 km^2 and is subdivided into five distinct areas (Figure 1.3). Several of these areas are statutorily defined including the Santa Cruz Active Management Area (SCAMA) in the United States, and the Santa Cruz and Nogales aquifers in Mexico (Arizona Department of Water Resources [ADWR], 2019a; GAS-CONAGUA, 2024a and 2024b). Because of an intervening mountain range in the Mexican portion of the TSCAS, the Nogales aquifer is considered a distinct administrative region separate from the Santa Cruz River aquifer. The two remaining areas, both in the United States, are the San Rafael Valley and the Upper Sonoita Creek Basin. The administrative limits of the aquifers in Mexican territory are shown in Figure 1.2 and Figure 1.3. A higher resolution aquifer boundary represented by the dotted line in the figure, useful for detailed groundwater and surface water analyses, was defined by a previous binational effort, the Border Environmental Health Initiative (Norman et al., 2010a). Differences in delineation through time also occur on the U.S. side. The unshaded area in Figure 1.3 containing the town of Patagonia has variously been classified as being part of the Empire Ranch Area (Freethey and Anderson, 1986), the Upper Santa Cruz River Basin (Anning and Konieczky, 2005), the Sonoita Creek Basin (Gu et al., 2008), and the Cienega Creek Basin (ADWR, 2019b). Sonoita Creek is one of the major tributaries of the

Santa Cruz River. To the southeast, the adjacent San Rafael Valley contains the headwaters of the Santa Cruz River. To the south, in Mexico, the Santa Cruz River aquifer has an area of about 952 km^2 (GAS-CONAGUA, 2024a) and is identified with the code 2615. To the west, the Nogales aquifer is identified with code 2650 and has an area of about 121 km^2 (GAS-CONAGUA, 2024b). In Arizona, the SCAMA, with a surface area of about 1,791 km^2 (ADWR, 2020), occupies the northwesternmost portion of the TSCAS which includes the watershed outlet.

This report makes use of the following terms:

1. The Santa Cruz River aquifer in Sonora (SCRAS) as defined by CONAGUA.
2. The Nogales aquifer in Sonora (NAS) as defined by CONAGUA.
3. The Santa Cruz aquifer in Arizona (SCAA: includes all parts of the study area in Arizona).
4. The Santa Cruz Active Management Area (SCAMA) as defined by the Arizona Department of Water Resources (ADWR).
5. The Transboundary Santa Cruz Aquifer System (TSCAS) as defined in section 1.2 of this report (the entire study area).
6. The Highlands-Sky Islands aquifer of the southern Santa Rita Mountains and Patagonia Mountains in Arizona, United States, and San Antonio Mountains in Sonora, Mexico (HSIA).

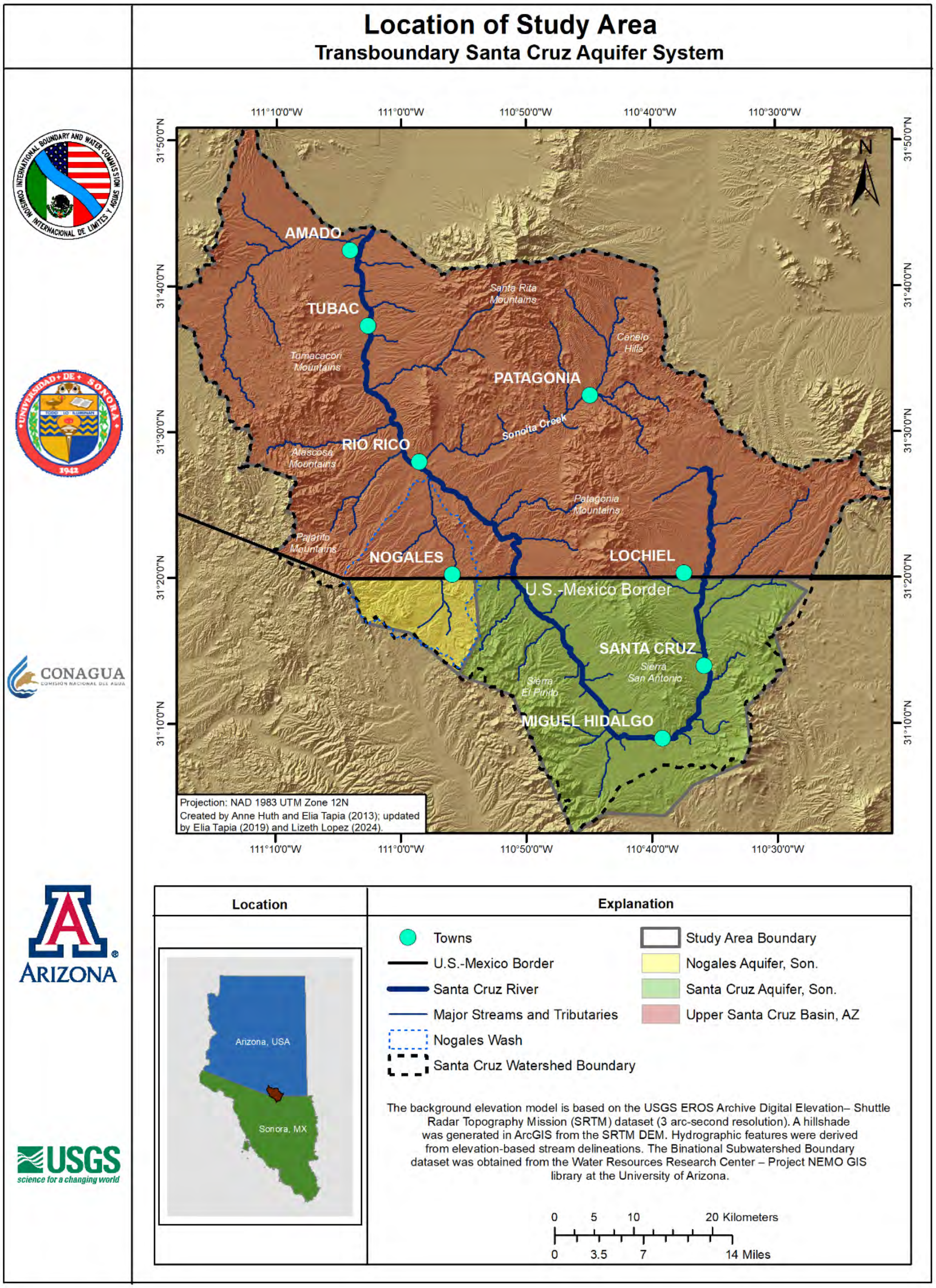

Figure 1.2 Transboundary Santa Cruz Aquifer System.

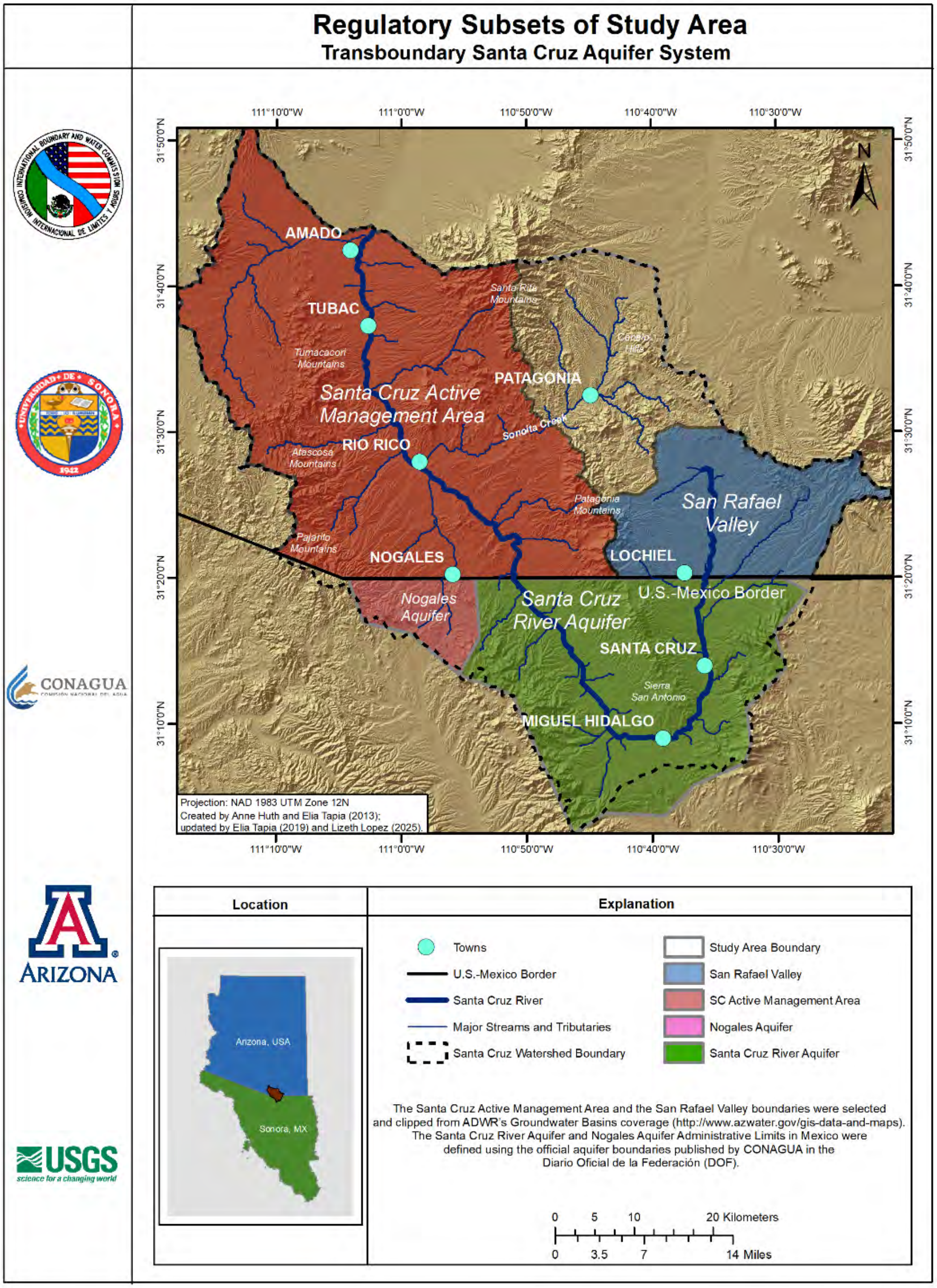

Figure 1.3 Administrative Subdivisions of the Transboundary Santa Cruz Aquifer System.

1.3. Study Objectives

The general objective of this study is to understand the hydrogeological characteristics of the Transboundary Santa Cruz Aquifer System, and to establish a foundation and uniform process for data collection and compilation, review of existing literature, and new analysis.

The specific objectives are as follows:

- Understand the geological and hydrogeological environment of the Transboundary Santa Cruz Aquifer System.
- Compile scientific information from both countries to support the development of a numerical model of the hydrodynamics of the binational aquifer system that includes surface-water and groundwater interactions.
- Whenever feasible, integrate datasets from each country and describe the aquifer system's characteristics in its transboundary context.

1.4. Previous Studies and Ongoing Monitoring

A binational assessment depends on the integration of many studies and publications from both sides of the border. Although the studies will be described in greater detail in the body of the report, here we list some previously published studies, including those that advanced the hydrologic understanding of the TSCAS through measuring, analyzing, or modeling efforts from multiple sources and data types. Numerous U.S. and Mexican studies were catalogued by the University of Arizona (Vandervoet, 2009). A number of hydrological studies have been carried out in the area identified for this binational assessment and, although much of the previous work is detailed, none of it has covered the binational area as a whole and the particular range of topics considered here.

On the Mexican side of the TSCAS, published studies cover stratigraphy, economics, structural geology, hydrogeology, and environmental geology. One article "Santa Cruz, a new copper camp in Sonora, México" (Merrill, 1907), documents prospecting and mining on the southwest bend of the Santa Cruz River near the turn of the 20th century. More recently, the University of Sonora (Rangel et al., 2005) published the report "Groundwater Atlas and Piezometric Monitoring for the State of Sonora" (Atlas de aguas subterráneas y red de monitoreo piezométrico del Estado de Sonora), which documented groundwater monitoring networks in Sonora for the Mexican National Water Commission. Other studies completed in Mexico are the "Actualización de la disponibilidad media anual de agua subterránea, acuífero (2650) Nogales, estado de Sonora" (GAS-CONAGUA, 2024b) and "Actualización de la disponibilidad media anual de agua subterránea, acuífero (2615) Río Santa Cruz, estado de Sonora" (GAS-CONAGUA, 2024a). These reports are part of a series that provides basic information on aquifers throughout Mexico including estimates of water budget components. They are published in Mexico's Official Gazette of the Federation in accordance with NOM-011-CONAGUA-2015 and updated approximately every five years (DOF, 2015). Finally, the study "Actividades Hidrogeológicas en el Acuífero Río

Santa Cruz, en el Estado de Sonora, Primera Etapa" was prepared in 2011 by UNISON (Minjarez et al., 2011) for the Mexican Section of the International Boundary and Water Commission (IBWC). It included climatological, geological, geomorphological, geophysical and geochemical assessments, along with a well survey, pump tests, and piezometric and hydrometric data; the results provided the foundation for this report.

On the U.S. side, ADWR has been the primary institution engaged in studying the groundwater hydrology of the SCAMA. ADWR maintains a groundwater monitoring network (https://gisweb.azwater.gov/waterresourcedata/) and has published several reports, including three based on regional models that simulate groundwater flows in the SCAMA (Nelson, 2007; Erwin, 2007; Hart, 2019). The first model covers the area of the Santa Cruz aquifer from the international border north to the Nogales International Wastewater Treatment Plant located near Rio Rico, Arizona (Erwin, 2007). This model is designed to study the region known locally as the "microbasins" area, which experiences seasonal water-table fluctuations on the order of tens of meters. The second model (Nelson, 2007) covers the area of the SCAMA from NIWTP to the northern boundary of the study area. The third model corresponds to an updated version of Nelson (2007) and represents the main stem of the Santa Cruz River from Rio Rico to Amado, Arizona (Hart, 2019), and the fourth model integrates the previous models (ADWR,2020).

The Arizona Department of Environmental Quality (ADEQ) conducts ongoing water-quality monitoring of both surface water and groundwater in the study area. Water-quality data are available for public water systems as well as surface and groundwater sites (https://waterdata.azdeq.gov/AZWQDB/Pages/Login/?ReturnUrl=%2fAZWQDB%2f; https://www.waterqualitydata.us/portal/). ADEQ publishes reports describing surface-water quality in relation to state standards and designated uses, including a list of impaired surface waters that require development of a Total Maximum Daily Load. Additional studies that have been carried out, for which the data or analysis are of direct benefit to this project, include studies of compounds of emerging concern (Alvarez et al., 2015; Coes et al., 2014), geology and geophysics (Bultman, 2015; Page et al., 2016a, 2016b), surface water hydrology and sediment transport (Niraula et al., 2015, Norman et al., 2012; Norman and Niraula, 2015; Shamir et al., 2007), climate effects (Norman et al., 2010b, Shamir et al., 2015; Tapia-Villaseñor et al., 2020; Shamir et al., 2021; Tapia Villaseñor et al., 2022), and stakeholder engagement (Eden et al., 2016). More recently, Paretti et al. (2019) published an analysis of a three-year study of sources, timing, and distribution of *Escherichia coli* in the upper Santa Cruz River within and upstream of the Tumacácori National Historical Park. These and other studies will be discussed in the subsequent chapters.

1.5. Binational Socioeconomic Environment

In Sonora, the study area includes the municipalities of Santa Cruz and Nogales, whose administrative centers are named Santa Cruz and Nogales, respectively. In Arizona, Nogales is the county seat of Santa Cruz County which covers the majority of the study area in Arizona (Figure 1.1 and Table 1.1). The majority of residents in the study area live in the cities of Nogales, Arizona, and Nogales, Sonora. However, the population of Nogales, Sonora, is ten times greater than Nogales, Arizona (INEGI, 2020; Arizona Office of Economic Opportunity, 2020; Table 1.1). Together, the Arizona and Sonora cities that share the Nogales name form the largest binational community on the Arizona-Sonora border.

Table 1.1 Population in the Main Entities in the Transboundary Santa Cruz Basin.

Community	Estimated Number of Residents (2020) *
Nogales, Sonora	264,782
Nogales, Arizona	19,750
Rio Rico, Arizona	20,549
Tubac, Arizona	1,581
Patagonia, Arizona	804
Santa Cruz, Sonora	1,835
Miguel Hidalgo (San Lázaro), Sonora	599

* Population data from the 2020 INEGI census (INEGI, 2020) and from the Arizona Office of Economic Opportunity (2020), which is based on the 2020 U.S. Census Bureau results.

With respect to education, access to resources, migratory status, housing, and number of dependents, Norman et al. (2012a) used determinants from binational censuses and neighborhood data to develop a Modified Socio-Environmental Vulnerability Index (M-SEVI) of the Santa Cruz watershed. A number of highly socio-environmentally vulnerable neighborhoods were identified in the TSCAS. Some of these are recognized *colonias* as border neighborhoods that typically include inadequate housing and/or infrastructure (Norman et al., 2006, 2004). On the other hand, several communities had very low socio-environmental vulnerability, among them Nogales, Arizona, and Nogales, Sonora. Norman et al. (2012) also identified areas of lower socio-environmental vulnerability on the outskirts of the urban area, in more rural zones.

Ambos Nogales serves as a bridge for international trade between the U.S. and Mexico, with U.S. imports from Mexico through this port of entry far exceeding the value of any other port of entry in Arizona (Eller College of Management, 2024). The CANAMEX Corridor, located in the Santa Cruz Watershed (I-19 in Arizona/I-15 in Sonora), as defined by Congress in the National Highway Systems Designation Act (Public Law 104-95), is a High Priority Corridor (U.S. Congress, 1995). The maquiladora industry (manufacturing largely in Mexico, typically by U.S. companies making products for export to the United States) is an important part of the Ambos Nogales economy. According to the Santa Cruz County Economic

Development Foundation (2019), there are over 100 maquiladoras in Nogales, Sonora, directly employing more than 15% of the population (about 34,000 people). Travel and tourism are also an economic driver in Santa Cruz County. A report for the Arizona Office of Tourism estimated $220,000,000 in visitor spending in Santa Cruz County in 2018 (Dean Runyan Associates, 2019).

Agriculture exists in the study area on both sides of the border, but is relatively small in scale, especially when compared with agriculture in other parts of the two states. There are no irrigation districts in Sonora or Arizona. In the upper part of the watershed, most of the area in the San Rafael Valley (Figure 1.3) was historically managed as one large ranch and is currently one of the few parcels of state land that has not been substantially altered by human contact (Arizona State Parks, 2019). Of the approximately 36,000 hectares in the valley, the U.S. Forest Service manages about 73% of the area (ADWR, 2009). The majority of the remaining land belongs to the state government (categorized as a “natural area”) or is privately owned, but subject to legal restrictions for conservation. These conservation rights, called “conservation easements,” preserve working ranches as open space in perpetuity where no development nor change in land use is allowed. In Sonora there are about 3,000 hectares that are irrigated for agricultural production in the SCRAS (Minjarez et al., 2011). Within the SCAMA, there are about 2,100 hectares that have irrigation rights granted by the State of Arizona (ADWR, 1999). Although there is little agricultural production in the area near Ambos Nogales, it is an important international port of entry for agricultural products and is the largest such port for fruits and vegetables into Arizona and neighboring regions of the U.S. (del Castillo et al., 2007). Tomatoes, cucumbers, bell peppers, zucchini, cantaloupe, watermelon, mangos, and grapes represent more than 75% of the fresh produce that pass through the port. The products originate in Sonora and Sinaloa, the state to the south, as well as from other Mexican states. Almost 200,000 trucks transport these fruits and vegetables annually north from Nogales, Arizona, and to neighboring regions of the U.S. The direct and indirect impacts of this agricultural import/export business to Nogales, Arizona, result in more than 4,000 jobs and $400 annual million U.S. dollars (Santa Cruz County Economic Development Foundation, 2017). This sector is the largest source of employment in the county of Santa Cruz, Arizona.

Behind the importation of agricultural products, mining has been and continues to be the second most important industry in the study area. Indigenous peoples were already mining in the area, prior to the arrival of Europeans (Schrader and Hill, 1915). There are deposits in the mining districts of the Patagonia Mountains of Arizona that have been mined on a relatively small to moderate scale for over a hundred years. There are also deposits of copper and other metals that currently have not been developed for reasons that include depth and degree of mineralization (Lecumberri-Sanchez et al., 2013; Vikre et al., 2014). A number of applications and plans for exploration and mining exist in both Arizona and Sonora (Wilson et al., 2016; Broch, 2012). One of the larger known deposits in Sonora (as of 2025) is "El Pilar", a copper deposit belonging to the Southern Copper Company, a subsidiary of Grupo Mexico. Located near the town of Miguel Hidalgo (San Lazaro) along the southernmost part of the Santa Cruz River, the estimated maximum potential production of El Pilar is 940 million pounds of copper over 16 years (Bennet et al., 2022). Another substantial mining property in Santa Cruz County, Arizona, consists of two deposits, the Hermosa (manganese-silver-zinc) and Taylor (lead-zinc-silver) deposits (Wilson, et al., 2016), which are owned by Australian mining company South32. The deposits, located south of the town of Patagonia in the Patagonia Mountains, will be developed as underground mines.

1.6. Institutional differences in water management in the United States and Mexico

A comparison of water management in Mexico and the U.S. and implications for the Transboundary Aquifer Assessment Program (TAAP) were analyzed in a study by the University of Arizona (Megdal and Scott, 2011). They found that efforts to reconcile differences in legal and institutional frameworks were essential to the development of the TAAP.

In Mexico, part of federal water management relies on thirteen Basin Organizations, which are responsible for preserving the nation's waters and administering CONAGUA's policies and programs (CONAGUA, 2021). The Santa Cruz River and Nogales aquifers are under the jurisdiction of CONAGUA's Northwest Basin Organization. Their territories are subject to the provisions of the "decree establishing prohibition on groundwater extraction for an indefinite period of time in the region called the Santa Cruz River Basin, Municipalities of Nogales and Santa Cruz, State of Sonora", published in the Official Gazette of the Federation (DOF) on January 25, 1961 (DOF, 2015). A small portion of the mountainous areas that delimit the Santa Cruz River aquifer to the east and the west in Sonora, are regulated by the "decree declaring public interest in the conservation of aquifers in the state of Sonora, for better control over pumping, delivery, and beneficial use of the groundwaters in the region", published in the DOF on September 19, 1978 (DOF, 1978). Both decrees are classified as type III, in which the aquifer capacity permits limited extractions for domestic, industrial, irrigation, and other uses (DOF, 1978). According to the 2022 Federal Law on Duties and Taxes, the Río Santa Cruz and arroyo Los Nogales basins are located in water availability zone 7 (DOF, 2025), but within that zone the Rio Santa Cruz aquifer (2615) is considered water availability zone 2, and the Nogales aquifer (2650) is considered water availability zone 1 (GAS-CONAGUA 2024a, 2024b). The main water users are the public-urban and agricultural sectors. Neither the Santa Cruz aquifer nor the Nogales aquifer in Sonora have established a Groundwater Technical Committee (COTAS), and there is no irrigation district.

In the U.S., the states are the primary authority for groundwater management. In Arizona, ADWR regulates the use of groundwater in accordance with the 1980 Arizona Groundwater Management Act. There are eight areas in Arizona designated as Active Management Areas (AMAs), where, because of severe overdraft, the use of groundwater is subject to the highest level of management, which includes rules specific to each AMA (ADWR, 2019a, 2019b and n.d). The Santa Cruz Active Management Area is one such AMA. The following are examples of some of the regulations that the state water agency ADWR applies in this region, with the goals of maintaining a safe-yield condition in the AMA and preventing local water tables from experiencing long-term declines:

1. The expansion of agriculture based on groundwater is prohibited.
2. The conversion of agricultural rights to non-agricultural uses is allowed, but the reverse is not.
3. The potable water utilities must meet state water conservation standards.
4. The industrial sector, which includes thermoelectric plants, copper mines, and sand and gravel mines, among others, must meet specific water conservation standards.
5. There are regulatory incentives to promote wastewater re-use.
6. Development is prohibited without first demonstrating the existence of a guaranteed water supply for one hundred years (water must be guaranteed physically, legally, and financially).
7. The measurement and reporting of groundwater extraction is mandatory for wells equipped with pumps having a 2.2 liters per second capacity or greater, and the extracted volume is subject to an annual tax.

Outside of the AMAs, access to and pumping of groundwater is subject to minimum regulation by the State of Arizona. This includes parts of the study area such as the San Rafael Valley and the Sonoita Creek upper sub-basin. One of the State of Arizona regulations that is most relevant in the areas located outside the AMAs is the requirement to carry out a 100-year water availability study before any development is approved. If, after completing this hydrological, economic, and legal study, it cannot be shown that there is sufficient water supply for a 100-year period, the entity that is selling the property has the obligation to disclose this finding to the buyer before closing the sale.

1.7. Technical Work Undertaken

This report is the product of technical activities undertaken in Sonora and Arizona in a cooperative environment between academic institutions and federal agencies in the U.S. and Mexico. With the coordination of IBWC, the technical work was performed by the Geology Department at the University of Sonora (UNISON), Mexico’s National Water Commission (CONAGUA), WRRC, and the USGS. The University of Sonora was contracted by CILA to perform a technical study on the Santa Cruz River aquifer in Sonora. The Mexican report that UNISON prepared (Minjarez et al., 2011) laid the foundation for hydrologic analysis on the Sonoran side of the border, filling in substantial gaps that made the binational analysis possible. The field activities were carried out during the months of February to March and from May to August 2011. In the first phase of the study, a survey of groundwater wells was undertaken, gathering information such as number and location of existing wells, well type, well use, operational status, equipment characteristics, outlet type, and operating and metering mechanisms. Static water levels and physical and chemical parameters such as electrical conductivity, total dissolved solids, temperature, pH, redox potential (Eh), and salinity were also measured. In addition, ten short-duration aquifer tests (pumping tests) were conducted that were used to estimate the study area's hydraulic parameters. Water samples were also obtained for analysis of major cations and anions (refer to Chapter 7 Hydrogeochemistry). Geophysical studies carried out in Sonora are described in Chapter 4. Within Arizona, the USGS and the University of Arizona carried out a geophysical study in the "microbasins" area to improve understanding of the thickness and permeability of the alluvial aquifer (Culbertson et al., 2010).

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 Mexican portion of the study area were analyzed. Instead of citing the literature that was reviewed and analyzed here, references will be given as needed throughout the report to the relevant publications. The base map and related maps for the current study are based on topographic maps at a 1:50,000 scale, digital elevation models edited by the National Institute of Statistics and Geography (INEGI), geological mining maps, scale 1:250,000, edited by the Mexican Geological Service (SGM), and USGS.

Additionally, the information gathered during the hydrogeological characterization efforts conducted by the University of Sonora (Minjarez et al., 2011) was used. The information collected was modified based on field visits and used to generate the maps included in this report. All data presented in this report have been published previously.

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2. PHYSICAL GEOGRAPHY

2.1. Introduction and Data Sources

This chapter provides a review of information on physiography, soils, vegetation, and land use and land cover (LULC) for the TSCAS. TSCAS refers to areas enclosed within the watershed topographic divide, which includes mountain ranges and any bedrock aquifers therein. Mapping and topographic analyses were performed using a geographic information system (GIS). Physiographic analyses include information on landforms, elevation, and province. Areas in the same province may have similar geology, climate, soils, and vegetation. Because of these similarities, it may be reasonable to assume that these areas have similar characteristics with respect to groundwater such as aquifer type, recharge processes, and water budgets. Soils and vegetation often have a large effect on infiltration and runoff characteristics; an understanding of aquifer behavior thus requires knowledge of the distribution of soils and vegetation. For example, soils with lower permeability such as clays tend to reduce infiltration and recharge and enhance overland runoff. However, if the vegetation type is dense such as in a grassland or forest, runoff may be reduced. LULC datasets consist of classifications of the predominant land use or vegetation type at a given location. Like soil and vegetation information, knowledge of LULC can be used to improve estimates of permeability. For example, highly developed areas will have a greater proportion of impermeable surfaces such as roads and roofs rather than forested areas. Land use and land cover datasets (LULC) can also be used to establish the location and size of agricultural, industrial, and metropolitan areas which can in turn be used to approximate the location and magnitude of water use and areas of potential water quality issues.

2.2. Physiographic Province, Topography, and Landforms

The TSCAS is located in the North American Basin and Range physiographic province (Figure 2.1). Mexico's National Institute of Statistics and Geography (INEGI) uses a different nomenclature for the Mexican portion of the study area, labeling the physiographic province as Sierras y Llanuras del Norte (Northern Mountains and Plains; INEGI, 2001). This province is primarily formed by mountain ranges separated by parallel valleys that are oriented north-south and is underlain by alluvial aquifers delimited by fault-bounded mountain ranges. Acidic volcanic rocks and sedimentary rocks predominate in the mountain regions. Continental sedimentary materials (Tertiary conglomerate, Tertiary and Quaternary alluviums) are abundant in the valleys (refer to Chapter 4 for detailed geological information) (INEGI, 2001). To the east of the TSCAS is the San Pedro basin. To the southeast, south, and southwest is the Arroyo Cocóspera basin (overlying the Cuitaca, Cocóspera, and Rio Alisos aquifers). To the west is the Cuenca del Rio Magdalena (Altar River aquifer).

The altitude in the TSCAS ranges from about 920 m in the northernmost part of the basin to about 2,880 m in the Santa Rita Mountains located north of Nogales, Arizona (Archuleta et al., 2017; USGS, 2017). South of the Santa Rita Mountains lies a mountain range called the Patagonia Mountains in Arizona and the Sierra San Antonio in Sonora, Mexico, around the southern end of which flows the Santa Cruz River. The northeast boundary of the study area is formed by the Canelo Hills which are a northwest to southeast trending mountain range. The easternmost point of the study area lies in the Huachuca Mountains, and the southeastern boundary is formed by the Sierrita del Alamo and Sierra el Chivato. The Sierra El Pinito forms the southwest boundary of the study area as well as the official boundary between the Santa Cruz and Nogales aquifers in Sonora, Mexico. The northern extent of Sierra El Pinito in Arizona is called Mount Benedict. The western boundary is composed of, from south to north, the Pajarito Mountains, Atascosa Mountains, Tumacácori Mountains, and Cerro Colorado. The Sierrita Mountains comprise the most northeastern portion of the study area.

A GIS and the USGS National Elevation Dataset (USGS, 2012) available for Arizona and Sonora were used to determine the distribution and magnitude of slopes in the study area. Slopes range from 0° to 65°, with the steepest slopes found in Sierra El Pinito, Sierra San Antonio and the Patagonia Mountains. Land cover varies throughout the study area with evergreen and deciduous forest dominant at higher elevations, natural grasslands in the mid-elevation valleys, and shrublands in the low elevation valleys. Low to high intensity development occurs primarily in Nogales, Sonora and in Nogales, Arizona as well as along the lower Santa Cruz River corridor north of Rio Rico, Arizona.

The San Rafael Valley in Arizona is a rural area with cattle ranching and public lands as the primary land use (Arizona Department of Environmental Quality [ADEQ], 2003). The primary land uses in the SCAMA in Arizona are domestic, commercial, industrial, agricultural, and ranching. Over half of the land in the SCAMA is managed by federal and state governments (ADWR, 2009). About 43% of the land in this part of the study area is privately owned and 21% is state owned. These lands are used primarily for private ranching with grazing leases on state trust land. The U.S. Forest Service (USFS) manages 36% of the lands within the SCAMA, mostly in the mountainous area, for recreation, ranching, and natural resources conservation (Villareal et al., 2011). Similar to the SCAMA, lands overlying the Santa Cruz River Aquifer in Sonora (SCRAS) have a mix of domestic, commercial, industrial, and agricultural uses (Minjarez et al., 2011; GAS-CONAGUA, 2024a).

2.3 Soils

An understanding of soil hydraulic properties enhances knowledge of the hydrology and geochemistry of the watershed. The primary natural factors affecting the development of soils are climate, organisms, parent material, topography, and time (USDA, 2019b). These factors can affect the hydraulic properties of the soil. For example, parent material (source rock) from which soil minerals are derived can affect hydraulic conductivity which in turn affects infiltration. For example, soils derived from sandstone rather than siltstone will tend to contain less clay, likely leading to greater permeability. Topography (characterized by slope and aspect) can affect the thickness, texture, and organic matter content of soils (USDA, 2019b). Soils deposited on steep slopes and at higher elevations are thin and gravelly and may contain rock outcrops. The soils deposited on floodplains are generally deeper and have a finer texture.

Organisms can increase soil organic matter content through addition of roots, leaves, and fecal material among other things. They can also increase porosity via burrows or the decay of roots. Climate affects soils through temperature and precipitation. For example, the timing and magnitude of temperature and precipitation control processes such as freeze-thaw, the rate of organic matter decay, and weathering of minerals.

Although information on the spatial distribution of soils supports understanding of hydrologic processes such as infiltration, recharge, and evapotranspiration, a binationally unified soil classification system is currently unavailable. In the U.S., the soil classification system was derived from the Department of Agriculture's (USDA) U.S. General Soil Map (USDA, 2019b). Higher resolution datasets such as the State Soil Geographic Database (STATSGO) and the Soil Survey Geographic Database (SSURGO) are also available (USDA, 2019c). In Mexico, soil surveys are carried out using the methods of the International Society of Soil Science (ISSS) published by the United Nations Food and Agriculture Organization (ISSS Working Group Reference Base, 1998). Binational soil classification compatibility would require binational surveys that incorporate a standard spatial resolution of the study area and common methods for sampling, mapping, and analysis. The time required for the field work would depend on the methods used and map resolution. For this report, both soil classification methods are documented and illustrated (Figure 2.2).

In the SCRAS, six soil types were identified (Minjarez et al., 2011): *Cambisol, Phaeozem, Lithosol, Luvisol, Regosol and Vertisol*, combined with *chromic, haplic, eutric and calcaric*-type subunits (Figure 2.2). A description of the soil units and their subtypes is given below:

Cambisol (Bc+Re/1/G): This soil is a chromic Cambisol that develops with a subtype of eutric Regosol, coarse textural class and a gravelly physical phase. The subsoil is different in color and texture than the surface layer. It tends to be dark, poor in nutrients, and more than 25-cm thick when present. The chromic subclassification indicates that when moist, it is dark brown to dull red. 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 nutrient rich (Ca, Mg, K, and Na), contains a high percentage of sand in the top 30 cm, and a high percentage of gravel in the first 100 cm of depth ranging from 0.2 to 7.5 cm on the long axis.

Phaeozem (Hh+Re/2/G): This soil is a haplic Phaeozem soil type and eutric Regosol subtype. It is gravelly and of medium texture with a dark surface layer rich in organic matter and nutrients or bases of Ca, Mg, K, and Na. Eutric Regosols can form from a variety of sources including the erosion of acidic and basic igneous rocks, as well as conglomerates, shales-sandstones, and colluvium residual. It is a nutrient-rich soil that locally presents calcic horizons. It is similar to the parent material, except it has a yellowish-brown or reddish-brown superficial layer, which belongs to an ochric A horizon and lacks structure. This type of soil is usually poor in organic matter, contains abundant sand, high clay content, and is characterized by an exchangeable sodium percentage greater than 15%. Its texture ranges from sandy to sandy loam.

Lithosol (I+Re+Rc/1): This soil is a chromic Lithosol with eutric and coarse calcaric Regosol subtypes with a thickness of less than 10 cm. Eutric Regosols can form from a variety of sources including the erosion of acidic and basic igneous rocks, as well as conglomerates, shales, sandstones, and colluvium residual. It is a nutrient-rich soil that locally contains a calcic horizon. 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, contains abundant sand, high clay content, and is characterized by an exchangeable sodium percentage greater than 15%. Its texture ranges from sandy to sandy loam. The calcaric Regosol subtype is also little weathered and differentiated from the parent material; it is sandy and gravelly with textures tending to a sandy loam at the surface becoming finer downward to argillaceous loam in the greater horizons.

Luvisol (Lc+Re/2/L): This soil is a chromic Luvisol, of eutric Regosol subtype, medium textural class and lithic physical phase. These are soils with clay accumulation at depth and are generally fertile; color is dark brown to reddish when wet. They contain an argillic B horizon, and are slightly acidic, and low in organic matter. The eutric Regosol is formed by the weathering of acidic and basic rocks, conglomerates and sandy shales; it may have alluvial, colluvial or even eolian origins; it has similar proportions of clay, silt and sand in the top 30 cm, with hard rock at a depth of less than 50 cm.

Regosol (Re+Rc/1/n): Eutric Regosol is a calcaric subtype of coarse textural class with a sodic chemical phase. These soils can form from the erosion of acidic and basic igneous rocks, as well as from conglomerates and sandy shales, or from alluvial, colluvial, or eolian residual material. It is a nutrient-rich soil that locally presents calcic horizons; it is 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. This type of soil is usually poor in organic matter, contains abundant sand, and is characterized by an exchangeable sodium percentage greater than 15%. Its texture ranges from sandy to sandy loam.

Vertisol (Vc/3/G): Vertisol-type soil is characterized by wide and deep cracks that appear during the dry season; it is high in clay, sticky when wet and very hard when dry, with low susceptibility to erosion. It contains a gravelly, dark, heavy clay in any layer within the top 50 cm; in the dry season with no irrigation, it contains visible cracks to depths of less than 50 cm. Surface cracks can also form when it is very wet. It contains gravels typically measuring between 0.2 and 7.5 cm at depths of less than 100 cm that may limit or prevent the use of agricultural machinery.

Figure 2.1 Physiographic Province Designations in the Transboundary Santa Cruz Aquifer System.

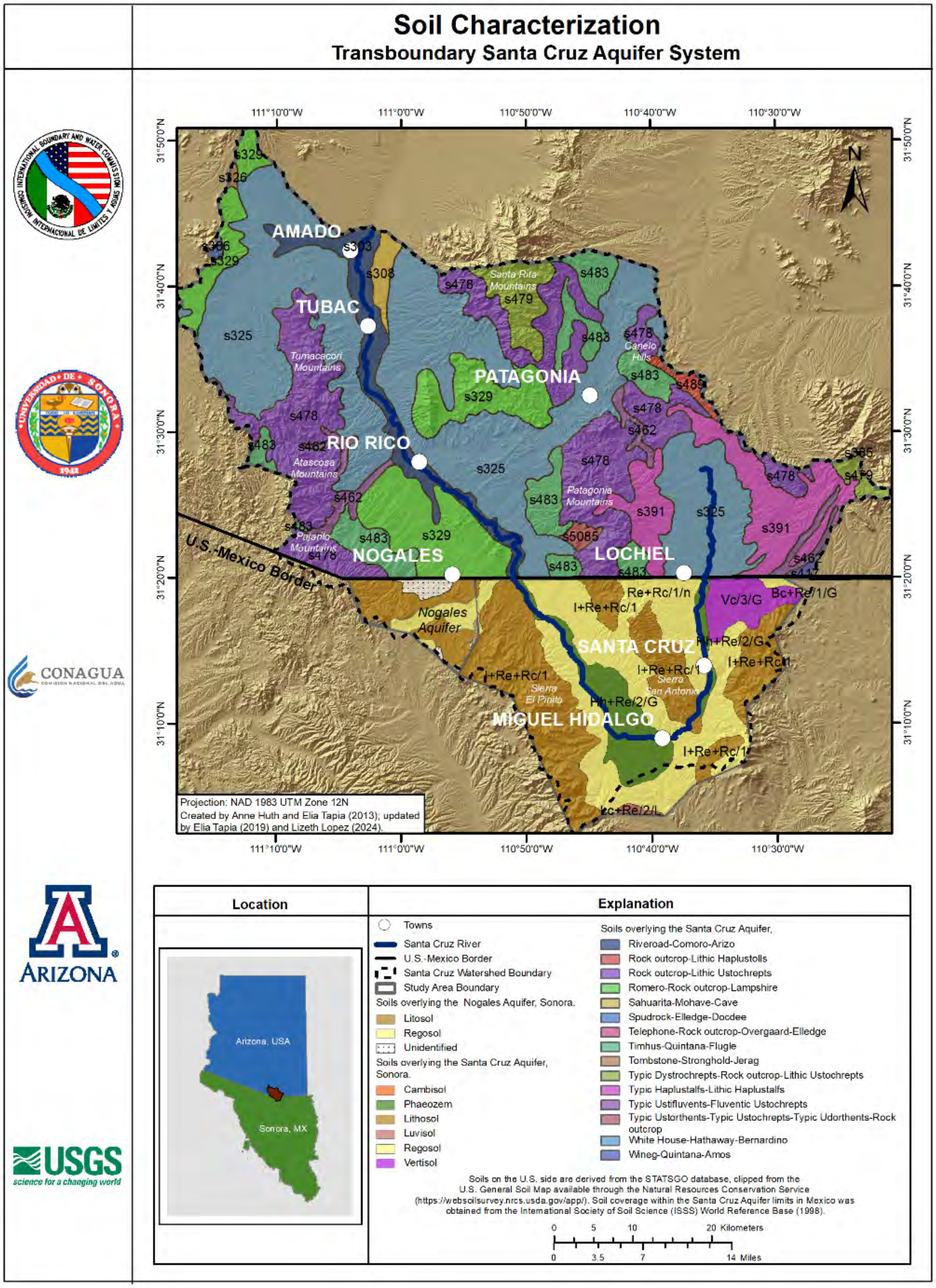

Figure 2.2 Soils overlying the Transboundary Santa Cruz Aquifer System.

In the Santa Cruz Aquifer in Arizona (SCAA), the soils are classified by the Natural Resources Conservation Service (NRCS), which is an agency in the USDA. Soils are classified into groups or associations of soil types. There are fifteen different soil types on the Arizona side of the basin that were determined by variables such as topography, appearance, precipitation, temperature, vegetation, parent rock, and other factors. The following list describes the 10 primary soil types (USDA, 1979; USDA, 2019a):

s303 Riveroad-Comoro-Arizo: This soil association consists of a mix of three series of soils. The Riveroad and Comoro series are very deep soils. They are located on floodplains and alluvial fans and have slopes of 0 to 8%. The annual average precipitation is around 355 mm. Soils in the Riveroad series are formed in stream alluvium from mixed sources. Comoro soils are slightly or excessively drained and are formed by stratified alluvium. The Arizo series also consists of very deep soils formed in mixed alluvium. They are located on recent alluvial fans, inset fans in older fans, fan skirts, stream terraces, and floodplains of intermittent streams and channels. They occur on slopes that range from 0 and 15%, have mean annual precipitation ranging from about 180 to 510 mm, and mean annual air temperature from about 14 to 18°C.

s489 Rock Outcrop-Lithic Haplustolls: This soil association is located on hills and mountains. It consists of 50 to 70% rock outcroppings and between 30 and 50% lithic Haplustolls. Typically, slopes range from 15% to 60%, but some are as low as 5% and as high as 100%. In these soils, the depth to a layer restricting plant roots is greater than 60 cm. The soil is not moist and there is little water available up to depths of 60 cm. It has a low potential for expansion or contraction.

s329 Romero-Rock Outcrop-Lampshire: This soil association consists of a mix of two series of soils with rock outcrops. The Romero series is formed by shallow or very shallow soils that formed in slope alluvium from schist or granite rock. They are found on pediments, hills, and mountains with slopes ranging from 0 to 70%. The Lampshire series consists of very shallow and shallow, well-drained soils that formed in alluvium and colluvium from igneous rocks. They are located on hills and mountains with slopes of 0 to 90%, have mean annual precipitation around 355 mm, and mean annual air temperature of approximately 17°C.

s308 Sahuarita-Mohave-Cave: This soil association consists of three soil series. All of the soils are well drained. Cave series soils are very shallow to shallow with a caliche hardpan, and slopes between 0 and 35%. The Mohave and Sahuarita series are very deep and have slopes of between 0 and 8%. The soils in the Sahuarita series are derived from limestone, schist, granite, and phyllite. Depending on the series, the soils form alluvium on fan terraces, stream terraces, piedmont, and basin floors. The mean annual precipitation of this association ranges between 200 and 280 mm and the mean annual air temperature between 17 and 20°C.

s386 Spudrock-Elledge-Docdee: This soil association consists of a mix of three soil series. All of the soils are well to moderately drained. The soils in the Spudrock and Elledge series are moderately deep. They are located on hills and mountains, forming in mixed slope alluvium. Docdee soils are located on ridge tops and mountain sides, formed by andesite and sandstone. Spudrock series slopes range from 15 to 85%. Slopes of Elledge-type soils vary from 2 to 50%, and slopes of Docdee soils range from 8 to 75%. The mean annual precipitation of this association ranges between 508 and 635 mm, and the mean annual air temperature between 9.4 and 11°C.

s385 Telephone-Rock Outcrop-Overgaard-Elledge: This soil association consists of three soil series and rock outcrops. All of the soils are well to moderately well drained. Telephone soils are located on hills with slopes of between 9 and 60% and are formed from noncalcareous sandstone. Overgaard soils are formed in mixed alluvium, and found on high stream terraces, plateaus, and hillslopes with slopes ranging from 0 and 35%. Elledge soils are formed in slope alluvium and are located on hills and mountains with slopes of 2 to 50%. The mean annual precipitation of this association ranges between 430 and 560 mm, and the mean annual air temperature between 7 and 13°C.

s483 Timhus-Quintana-Flugle: This soil association consists of deep and very deep soils that are well to excessively well drained with moderate or moderately slow permeability. Soils in the Timhus series formed on cinder cones from windblown sediments and have slopes of 20 to 50%. Soils in the Quintana series are found on uplands with slopes of 0 to 20%, and formed from limestone, soft calcareous sandstone, and schist. Soils in the Flugle series were formed in eolian material and fan alluvium, from schists and sandstones, on summits of mesas, dip slopes of hills and ridges, and fan terraces and fan remnants on valley sides. The mean annual precipitation of this association ranges between 355 and 460 mm and the mean annual air temperature between 9 and 11°C.

s326 Tombstone-Stronghold-Jerag: This soil association consists of well-drained to excessively well-drained soils. Tombstone soils (very deep) and Stronghold (deep) formed in fan alluvium on stream terraces and fan terraces with slopes of 0 to 65%. The Jerag series consists of shallow soils with slopes ranging from 0 to 10%, which formed in alluvium mixed with eolian sands on fan piedmonts and fan remnants. The Jerag series is moderately permeable above and below the very low permeability petrocalcic horizon. The mean annual precipitation of this association ranges between 330 and 355 mm, and the mean annual air temperature between 15.5 and 17°C.

s325 White House-Hathaway-Bernardino: This association of three soil series consists of very deep, well-drained soils. It is found on fan terraces with slopes of 0 to 60%. White House and Hathaway soils formed in fan alluvium derived from igneous and sedimentary rock. The mean annual precipitation of this association ranges between 355 and 460 mm, and the mean annual air temperature varies around 16.5°C.

s417 Wineg-Quintana-Amos: This association consists of deep and very deep, well-drained soils with slopes of 0 to 20%. Wineg soils formed in mixed alluvium, derived primarily from granite, basalt, schist and sandstone on alluvial fans and plains. Quintana soils are made from limestone, soft calcareous sandstone, and slate in the uplands. Amos soils are formed by material weathered from slate, siltstone and calcareous sandstone. The mean annual precipitation of this association ranges between 380 and 480 mm, and the mean annual air temperature around 11°C.

2.4. Vegetation and Land Cover

Vegetation and land use and land cover (LULC) data are used for a variety of purposes in hydrologic analysis. Vegetation types can be used to create evapotranspiration parameter estimates for groundwater-flow models (Langevin et al., 2017) and may also be important in surface-water models for estimation of a hydraulic roughness parameter, related to resistance to flow caused by friction of water flowing over land and in channels (U.S. Army Corps of Engineers, 2016). Vegetation density and type can greatly alter roughness and therefore flow velocity and streamflow. Vegetation types tend to be simplified when compared with vegetation maps.

In the TSCAS there are 31 types of vegetation assemblages (Wallace et al., 2011) of which the Apacherian-Chihuahuan Mesquite Upland Scrub, Madrean Encinal, and the Apacherian-Chihuahuan Semi-Desert Piedmont Grassland and Steppe are the predominant types (Figure 2.3). These three types are briefly described below.

The **Apacherian-Chihuahuan Mesquite Upland Scrub** vegetation type occurs as shrublands that are concentrated in the grassland-shrubland transition in foothills and piedmont in the Chihuahuan Desert. The soils are typically derived from alluvium, often gravelly without a well-developed argillic or calcic soil horizon that would limit storage of winter precipitation in deeper soil layers. *Prosopis* spp. and other deep-rooted shrubs exploit this deep soil moisture that is unavailable to grasses and cacti. The amount of grass is typically low. During the last century, the area occupied by this vegetation type has increased through conversion of desert grasslands as a result of drought, overgrazing by livestock, and changes in fire frequency.

The **Madrean Encinal** vegetation type occurs in canyons, and on foothills, bajadas and plateaus in the Sierra Madre Occidental and Sierra Madre Oriental in Mexico, extending north into Texas, southern New Mexico, and Arizona. These woodlands are dominated by Madrean evergreen oaks along a low-slope transition typically lower in elevation than Madrean Pine-Oak Forest and Wood and Madrean Pinyon-Juniper Woodland. Lower elevation groups such as this are typically open woodlands or savannas which transition at lower elevations into desert grasslands, chaparral, or desert scrub. This vegetation type can extend to lower elevations along drainages.

The **Apacherian-Chihuahuan Piedmont Semi-Desert Grassland and Steppe** vegetation type is a broadly defined desert grassland, mixed shrub-succulent, or xeromorphic tree savanna that is typical of the borderlands of Arizona, New Mexico, Sonora, and Chihuahua. Found where frequent fires occur on gently sloping bajadas adjacent to mountains, mesas, and steeper piedmont, it is typically characterized by diverse perennial grasses. Due to intensive grazing and other land uses, many of the historical desert grassland and savanna areas have been converted to Chihuahuan Succulent Desert Scrub.

LULC data includes information on vegetation and intensity of development. In hydrologic analyses and modeling, LULC can be used to estimate roughness as well as surface permeability. Changes in LULC for the binational TSCAS for the period 1979 to 2009 were estimated by Villarreal et al. (2011). Their analysis was performed using calibrated and corrected Landsat imagery followed by the application of Classification and Regression Tree models to derive 14 LULC classes for the TSCAS (Figure 2.4).

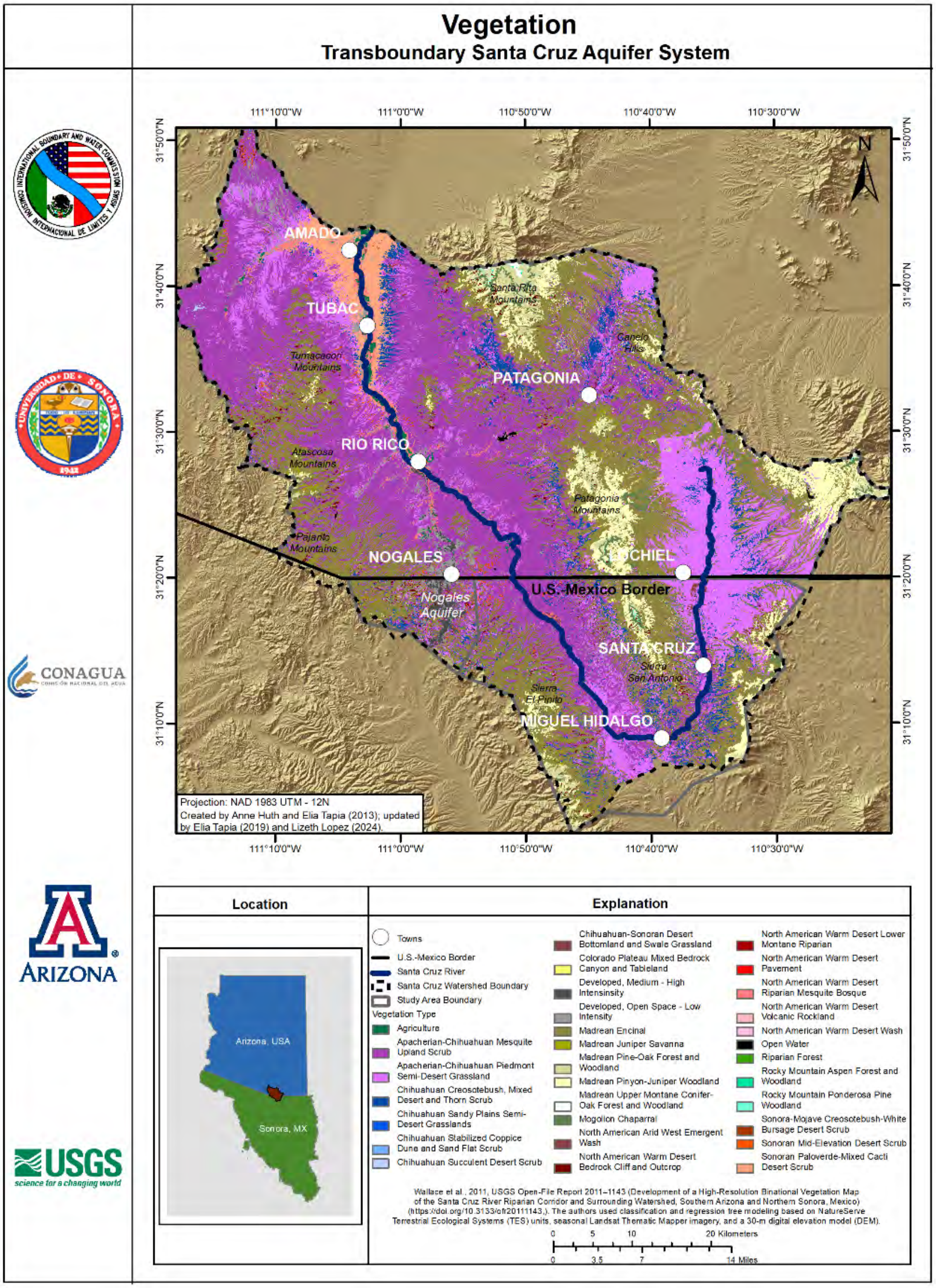

Figure 2.3 Vegetation in the Transboundary Santa Cruz Aquifer System (modified from Wallace et al., 2011).

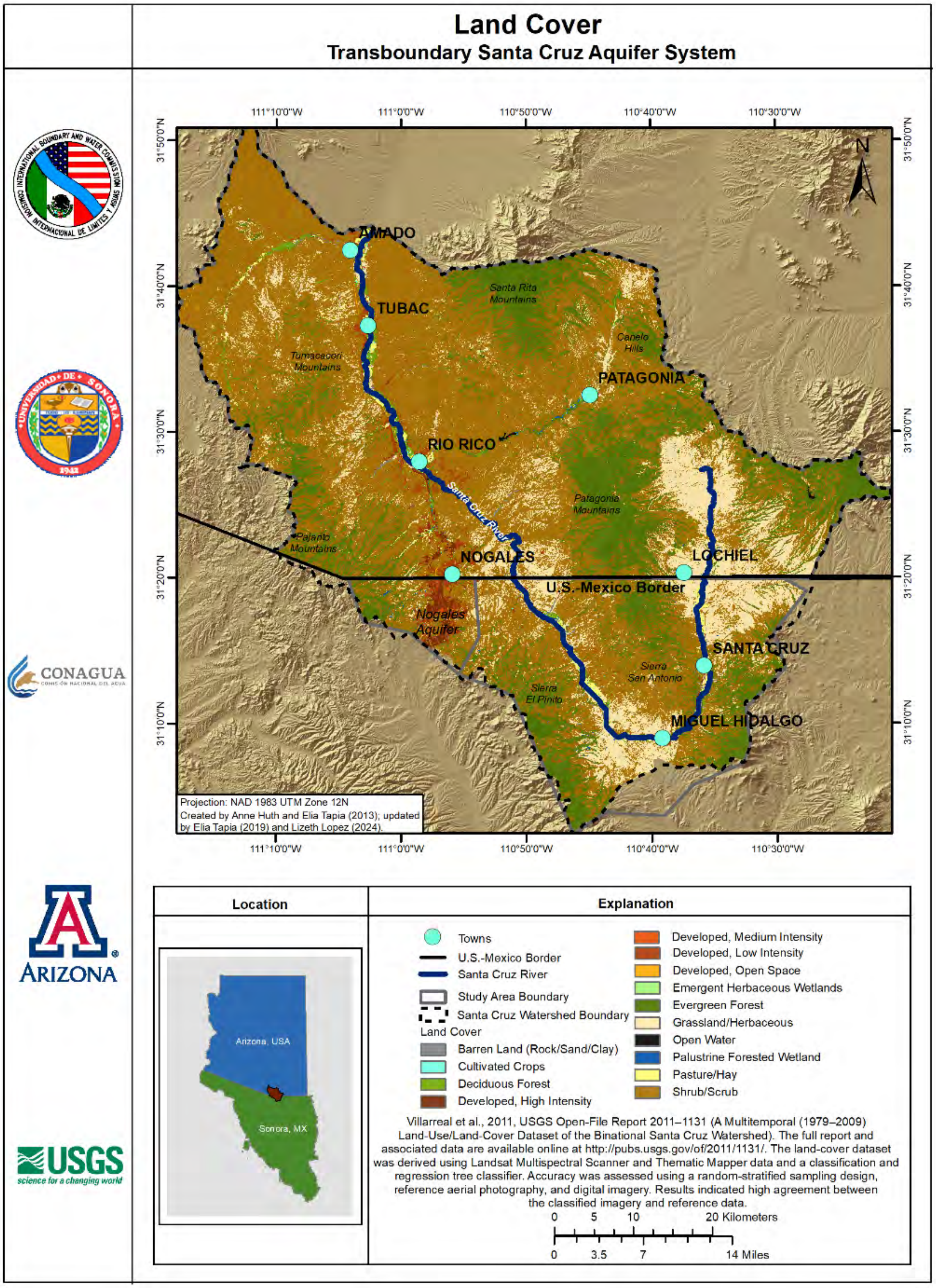

Figure 2.4 Derived land cover in the Transboundary Santa Cruz Aquifer System (modified from Villarreal et al., 2011).

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3. CLIMATE AND SURFACE-WATER HYDROLOGY

3.1. Introduction

A knowledge of climate and the fluxes it controls directly (precipitation, evapotranspiration, direct recharge) or indirectly (recharge and discharge via surface-water bodies) can enhance understanding of aquifer function. Surface-water bodies can act as windows into both climate-driven changes in hydrologic fluxes and also the responses of aquifers to those changes. Because surface water is both visible and accessible, it can be, in some respects, easier and less expensive to study than groundwater. Over the long term, climate is the main driver of the hydrologic cycle, whereas local climate variability is controlled by topography and elevation, and the relation of these features to surface-water bodies. Along with vegetation, soils, and geology, climate controls the quantity of water available for infiltration and, ultimately, for recharge to aquifers. Anthropogenic effects such as climate change and reductions in groundwater discharge to streams caused by groundwater pumping may occur at one or more time scales.

Streamflow varies at various time scales: daily, seasonal, multi-year, and multi-decadal periods. Daily (or “diurnal”) variations can be driven by factors such as evapotranspiration, pumping, and precipitation. Seasonal variations are driven by annual, global-scale changes in insolation which cause shifts in local weather patterns and thus precipitation. Southeast Arizona generally has a bimodal weather pattern with most precipitation falling in winter or summer (Figure 3.1). As a result, certain times of year are typically drier over the TSCAS (for example, the late spring) and other times of year are wetter (the summer monsoon and the winter). Multi-year or decadal droughts and wet periods are driven by other, less well understood factors such as the El Niño-Southern Oscillation, the Pacific Decadal Oscillation, and variations in solar and volcanic radiative forcing (Myhre et al., 2013).

Surface-water has traditionally been studied separately from groundwater, and for certain topics such as flooding and erosion, this approach can be largely valid. Increasingly however, groundwater and surface water are studied as one connected resource. Rivers, streams, and surface-water bodies act both as sources of recharge to aquifers and as locations of aquifer discharge. Although springs result directly from groundwater discharge, they can act as a source of recharge in a stream channel downstream of the source.

In this chapter, we review and analyze information from previous publications related to climate and surface water. We also present and analyze information from climate and surface-water discharge information databases.

3.2. Climate

According to the Koppen-Geiger climate classification system (Peel et al., 2007), the climate in the study area is classified as hot semi-arid. In the Sonoran portion of the study area there are weather stations in Nogales and Santa Cruz, both of which are operated by CONAGUA (Figure 3.1). In the Arizona portion there are stations near Nogales, Rio Rico, and Tubac. Maximum precipitation typically occurs in summer with a second less intense period of precipitation in winter (Figure 3.2). Precipitation is the result of one of three types of weather patterns: mid-latitude frontal systems, which tend to occur during winter months, convective thunderstorms, which predominate during the summer monsoon, and dissipating tropical cyclones, which occur most frequently during the late summer and fall (Wood and Ritchie, 2013; Webb and Betancourt, 1992). Estimates of annual mean precipitation and temperature for the period 1960 to 2018 exhibit several long-term cycles (Figure 3.3). Mean annual temperature in the TSCAS ranges from 9°C to 19 °C. The mean temperature in the coldest month varies between -3.6 and 2.0°C, and in the hottest month between 23 and 37°C (Figure 3.4 through Figure 3.6) (WorldClim Global Climate Data, 2013; Hijmans et al., 2005).

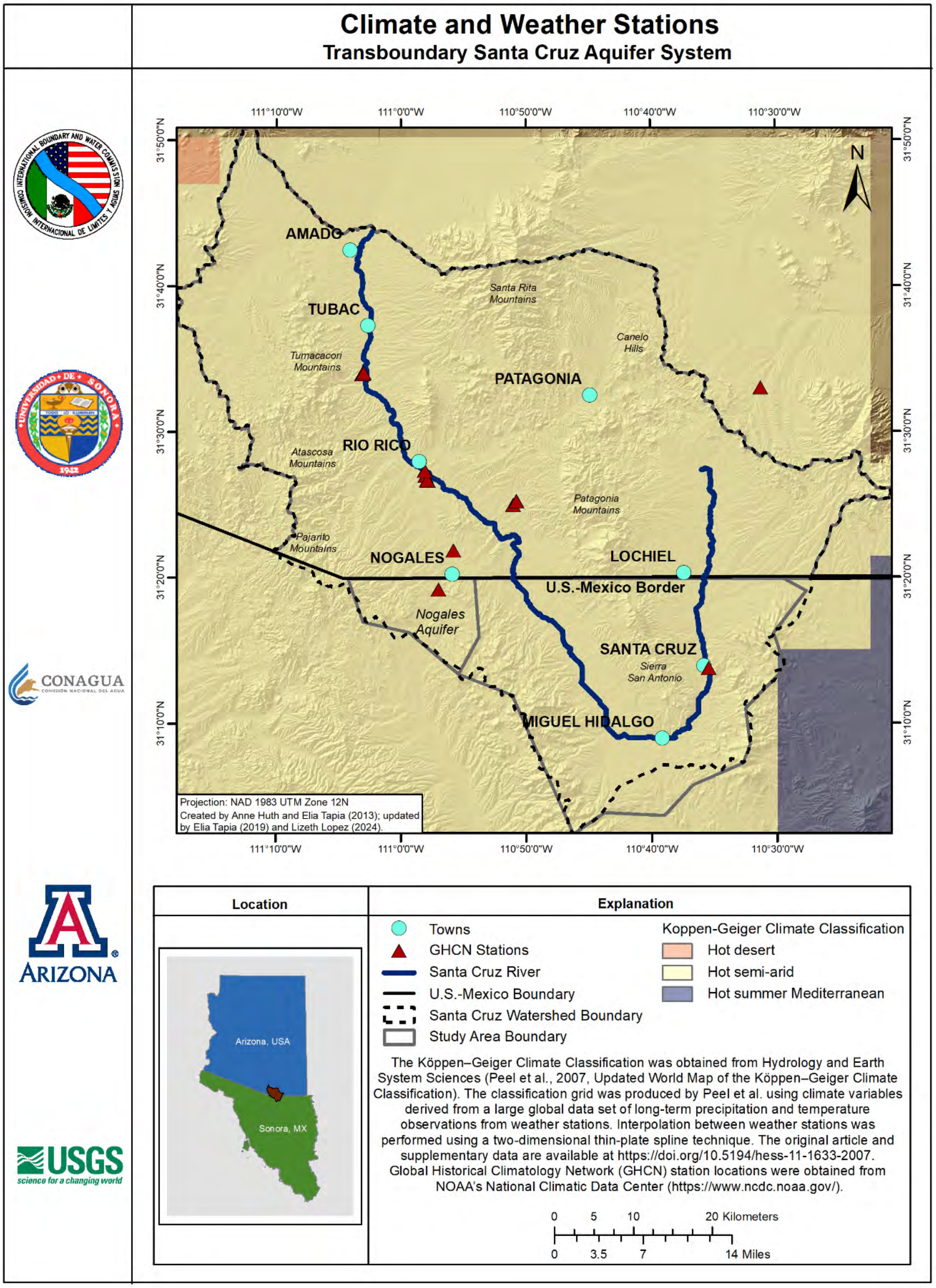

Figure 3.1 Climate and weather stations in the Transboundary Santa Cruz Aquifer System.

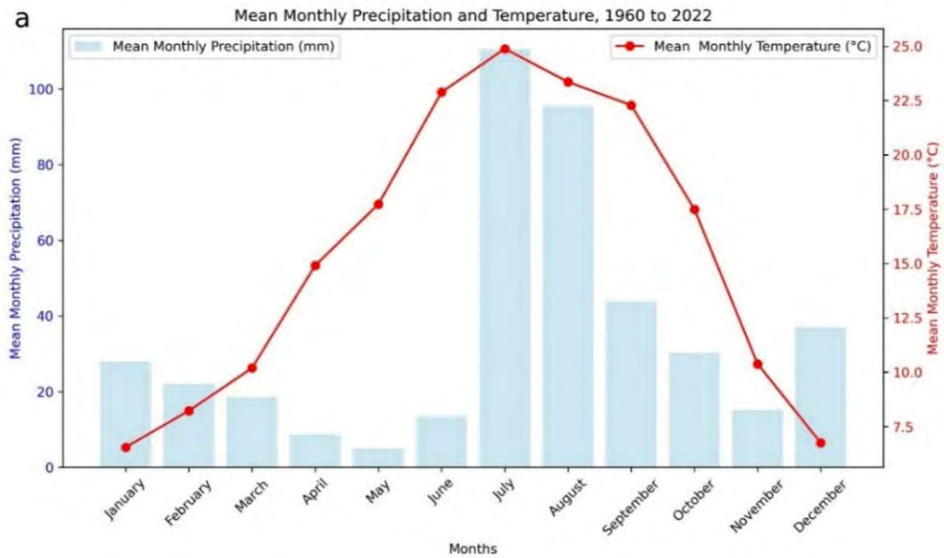

Figure 3.2 Mean monthly precipitation and temperature for the period 1960 to 2022 at NOAA data station NOGALES 6 N, station number USC00025924.

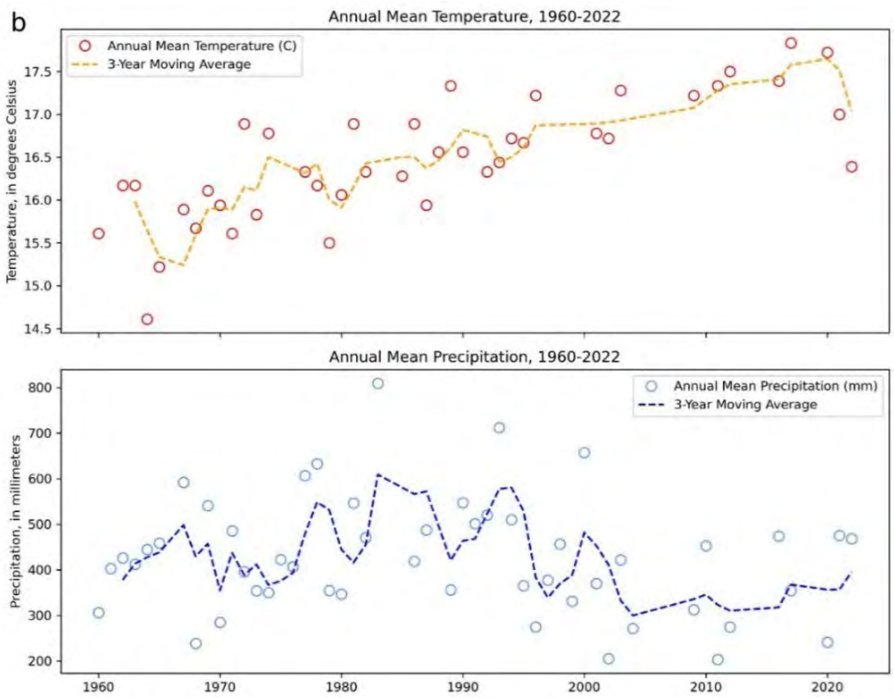

Figure 3.3 Annual mean precipitation and temperature for the period 1960 to 2022 at NOAA data station NOGALES 6 N, station number USC00025924. Data were obtained from NOAA's Climate Data Online web portal (https://www.ncei.noaa.gov/cdo-web/).

Minjarez et al. (2011) presented a climatological analysis for the SCRAS. In the study, the team used two weather stations in Mexico and one in the U.S. to assess climate variables in the area. Data were obtained from CONAGUA and the U.S.-based Western Regional Climate Center. According to Minjarez et al. (2011), precipitation in the SCRAS is variable, but generally bimodal. About 60% of the total rainfall occurs in the summer months (July-August), coinciding with the North American Monsoon and about 50% of the annual precipitation occurs during the winter season (Shamir et al., 2021). Maps of the TSCAS showing mean annual precipitation (Figure 3.7) and mean monthly precipitation for January (Figure 3.8) and for August (Figure 3.9) indicate higher rainfall in the mountains, which are an important source of recharge and runoff. Mean annual precipitation varies between 340 and 840 mm in the study area and includes the summer monsoon and substantial snowfall in winter at high elevations. In January, the mean monthly precipitation varies between 22 and 72 mm, whereas in August the mean monthly precipitation varies between 69 and 150 mm. These ranges are corroborated by PRISM model data (PRISM climate group, 2022) for the period 1995 to 2018, which were selected for a location near where the Santa Cruz River flows north across the international border (Figure 3.1). The date range was selected because it corresponds to the recent drought which began about 1995 and is potentially ongoing. The highest monthly precipitation and temperature generally occur in July with a mean of 108 mm and 26.4ºC (Figure 3.2). The lowest precipitation month is May, estimated at about 3 mm.

Minjarez et al. (2011) calculated annual mean actual evapotranspiration (AET) for three stations: Santa Cruz, Sonora (497 mm); Nogales, Sonora (427 mm); and Nogales, Arizona (472 mm). These were equal to between 90% and 95% of annual mean precipitation. Tillman et al. (2011) used MODIS satellite data to calculate aquifer-derived AET for the period 2000-2007 in the Basin and Range portion of Arizona, which includes the study area. Aquifer-derived AET is water below the water table extracted by roots of riparian and wetland vegetation. For the SCAMA, values ranged from 0.74 hm^3 (cubic hectometers) to 1.85 hm^3. For the San Rafael Valley, values ranged from about 6 hm^3 to 12.6 hm^3.

Several climate studies have been conducted in the study area. Hirschboeck (1985) investigated the link between storm type and flood frequency for the entire Gila River basin, of which the Santa Cruz River watershed is a part, and found that data from different types of weather systems generate flood magnitudes, hydrographs, and frequencies that are distinct from those calculated from the entire dataset. This information could be used to inform surface- and groundwater flow models because these flow characteristics will influence model inputs and outputs such as recharge and discharge. Following on this research, Webb and Betancourt (1992) found that flood magnitudes in the Santa Cruz River increased between 1960 and 1986 because of channelization and changing land use. They also found that there was an increased probability of the joint occurrence of two storm system types (cutoff low-pressure systems and tropical cyclones) during that period, which increased the probability of large floods. With respect to climate cycles, Hanson et al. (2006) carried out spectral and principal component analyses of climate-cycle effects on groundwater levels, streamflow, precipitation, and tree rings in four basins, including the study area. They found that 53% of variability in the data could be explained by the Pacific Decadal Oscillation (PDO), followed by 17% by the El Niño-Southern Oscillation (ENSO). Long-term climate change can affect the magnitude and timing of precipitation and therefore water availability. Scott et al. (2012) used climate scenarios developed by the Intergovernmental Panel on Climate Change (IPCC) to predict the impacts of climate change and population growth on the TSCAS during the 21st century. They found that precipitation projections varied substantially depending on the emissions scenario. Scott et al. (2012) used three specific Special Report on Emissions Scenarios (SRES) scenarios: A2, which assumes high population growth, regionally oriented economic development, and slower technological advancements; B1, which considers more moderate population growth and emphasizes global sustainability and environmental efficiency; and A1B, a balanced scenario with rapid economic growth and technological development that incorporates a mix of fossil fuels and renewable energy sources. All scenarios, however, agreed that temperatures would increase, which would increase removal of water from the system via evapotranspiration. Their results differed from those of a Bureau of Reclamation report which predicted no change in the frequency of wet summers or winters (Gangopadhyay and Pruitt, 2011). In 2015, Shamir et al. used results of dynamically downscaled global climate models to investigate the potential impact of climate change on water resources in the Upper Santa Cruz Basin, which they defined as the study area between the U.S.-Mexico border and the northern boundary of the SCAMA. Their results predict an increase in frequency of dry summers and a decline in non-extreme winter precipitation events.

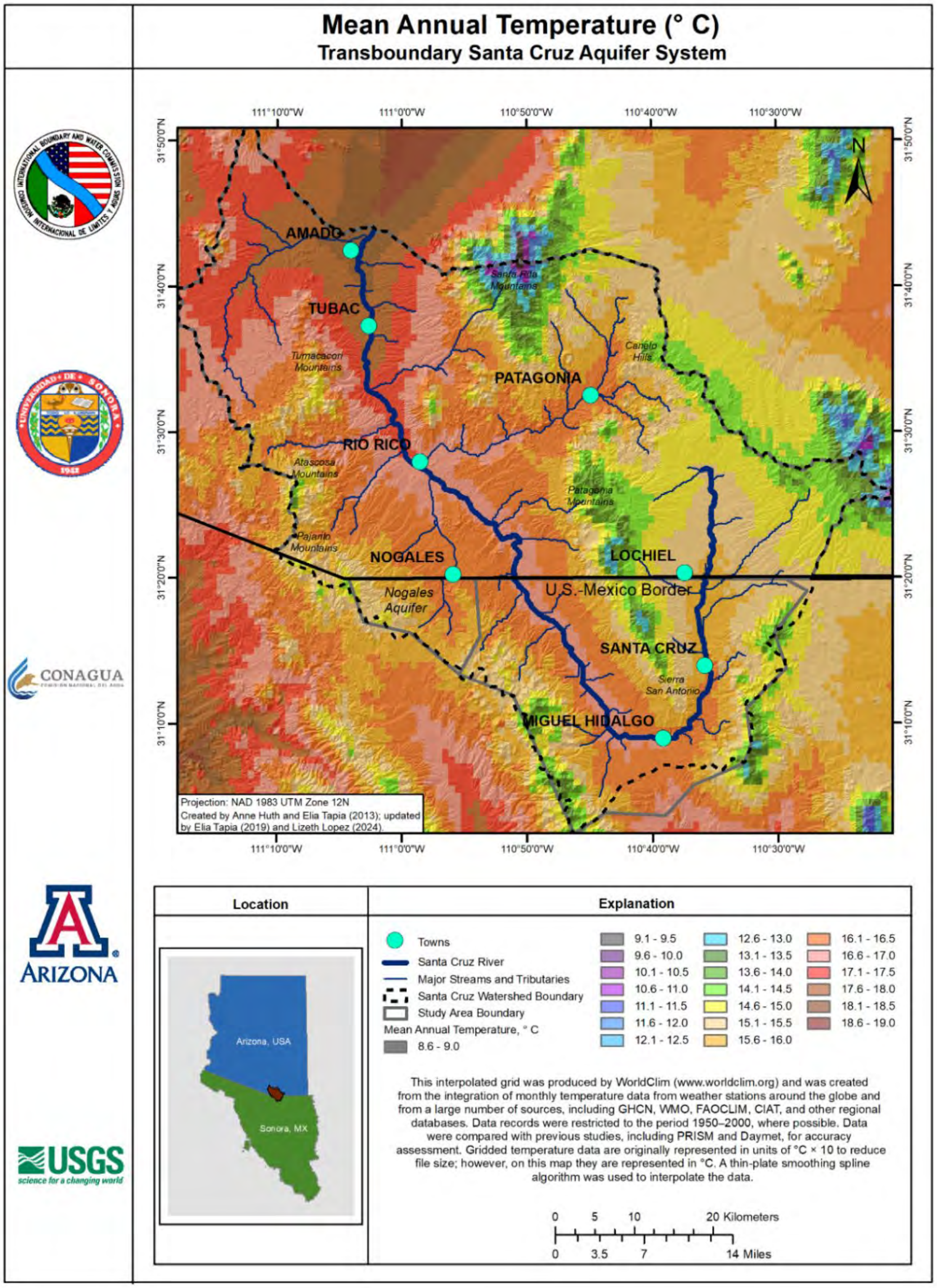

Figure 3.4 Mean annual temperature in the Transboundary Santa Cruz Aquifer System.

For explanation of abbreviations refer to the list of Key Technical Terms at the beginning of chapter 1.

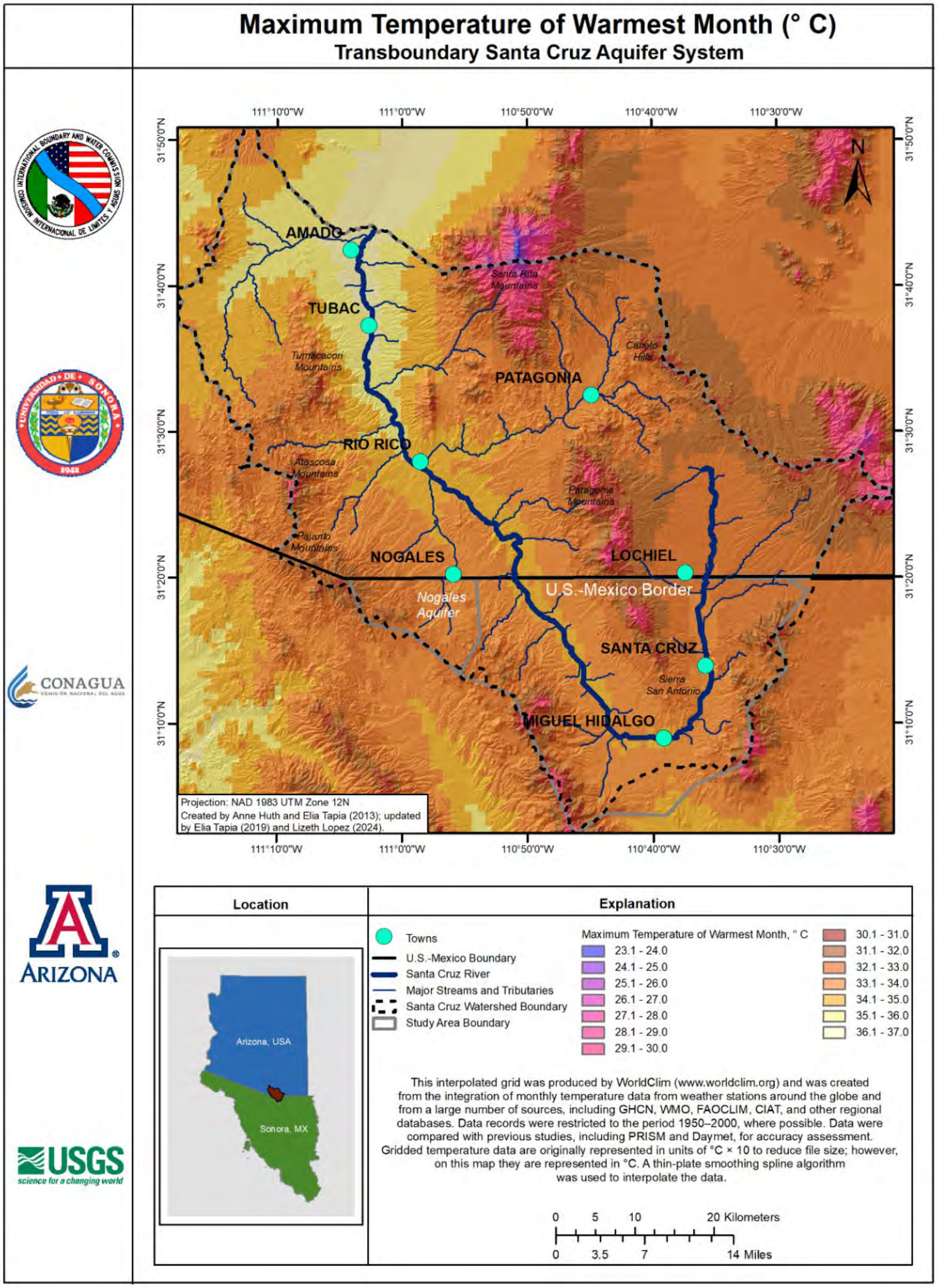

Figure 3.5 Maximum temperature in the warmest month in the Transboundary Santa Cruz Aquifer System.

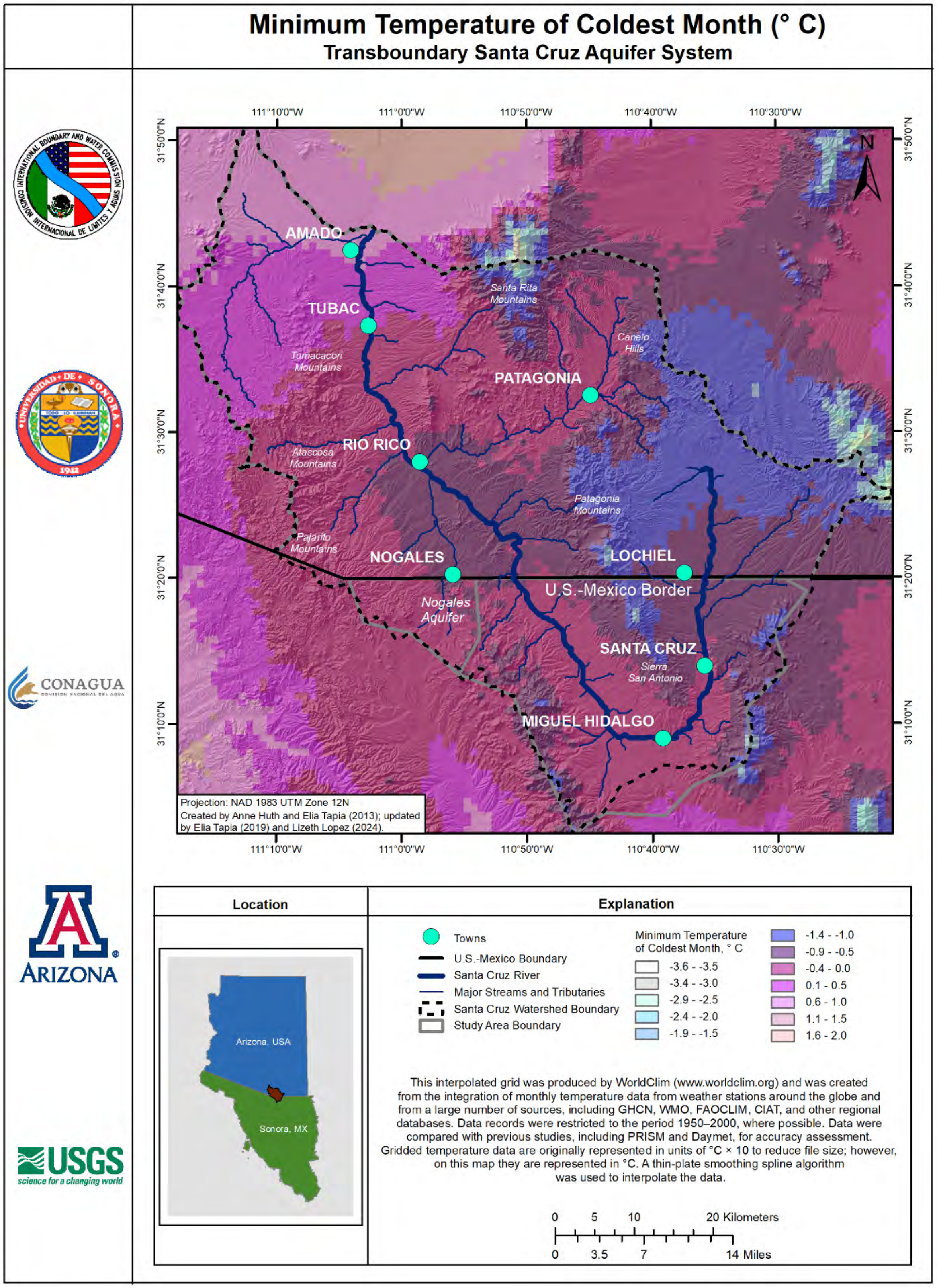

Figure 3.6 Minimum Temperature in the Coldest Month in the Transboundary Santa Cruz Aquifer System.

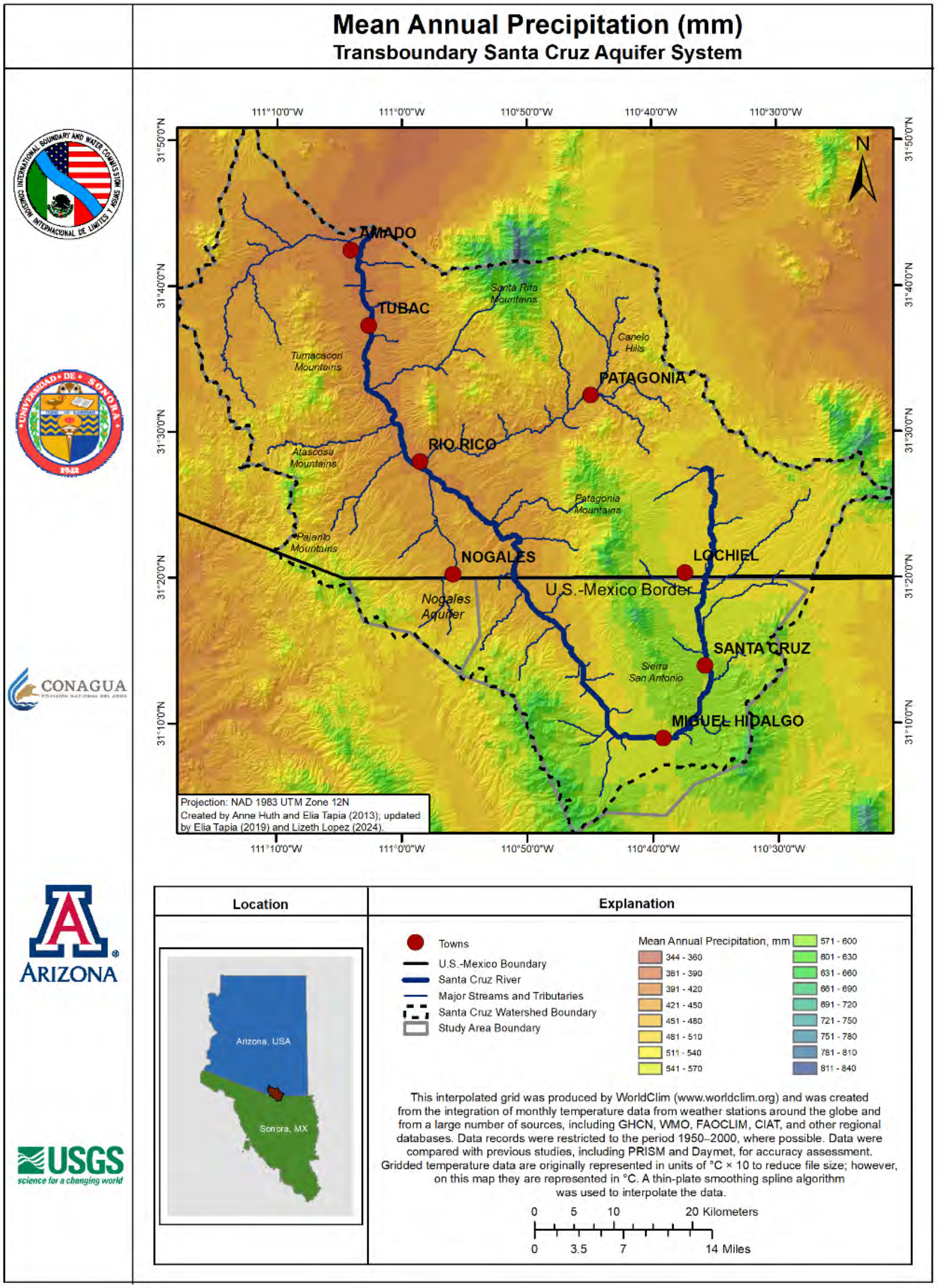

Figure 3.7 Mean annual precipitation in the Transboundary Santa Cruz Aquifer System.

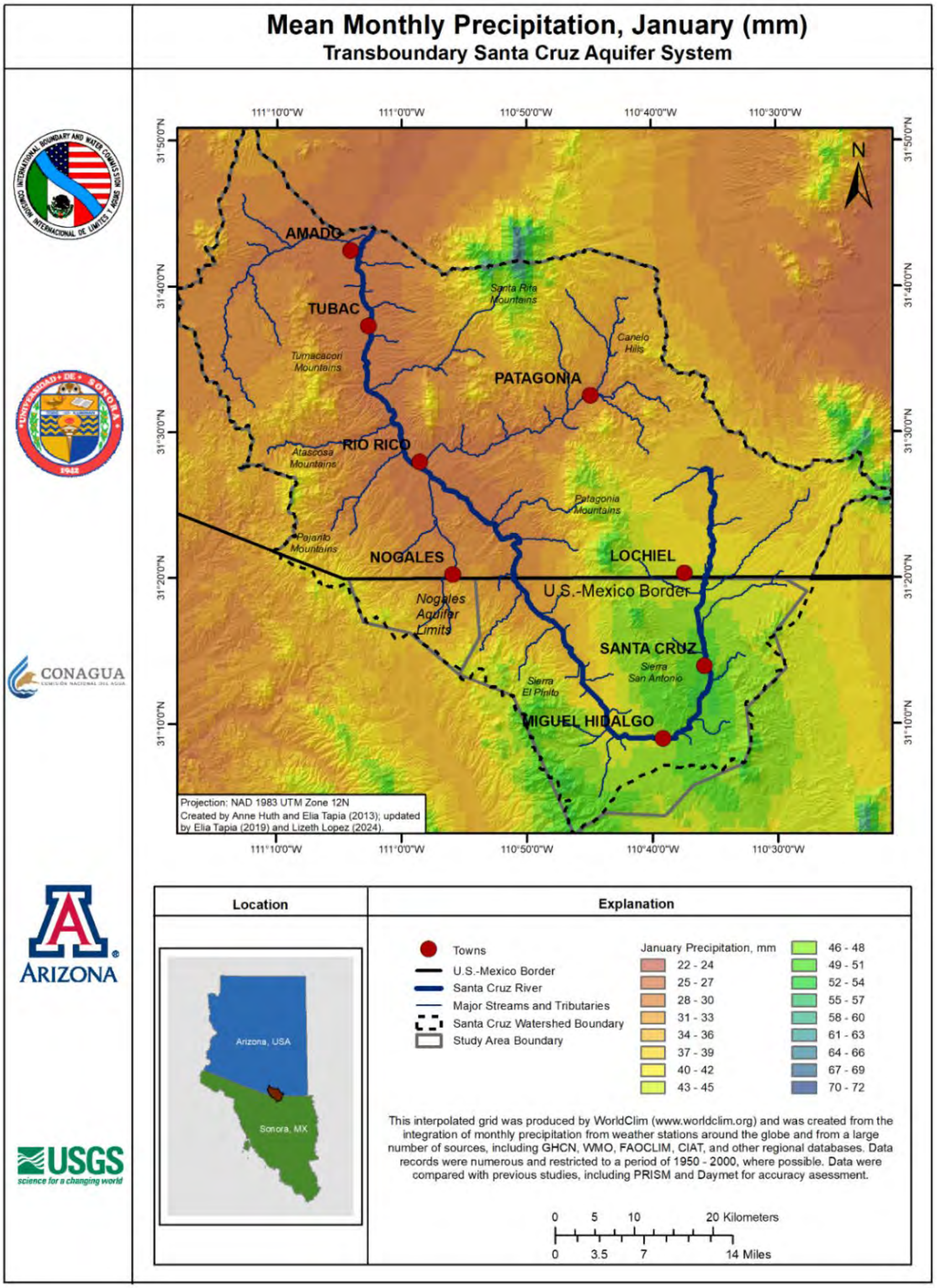

Figure 3.8 Mean monthly precipitation in January in the Transboundary Santa Cruz Aquifer System.

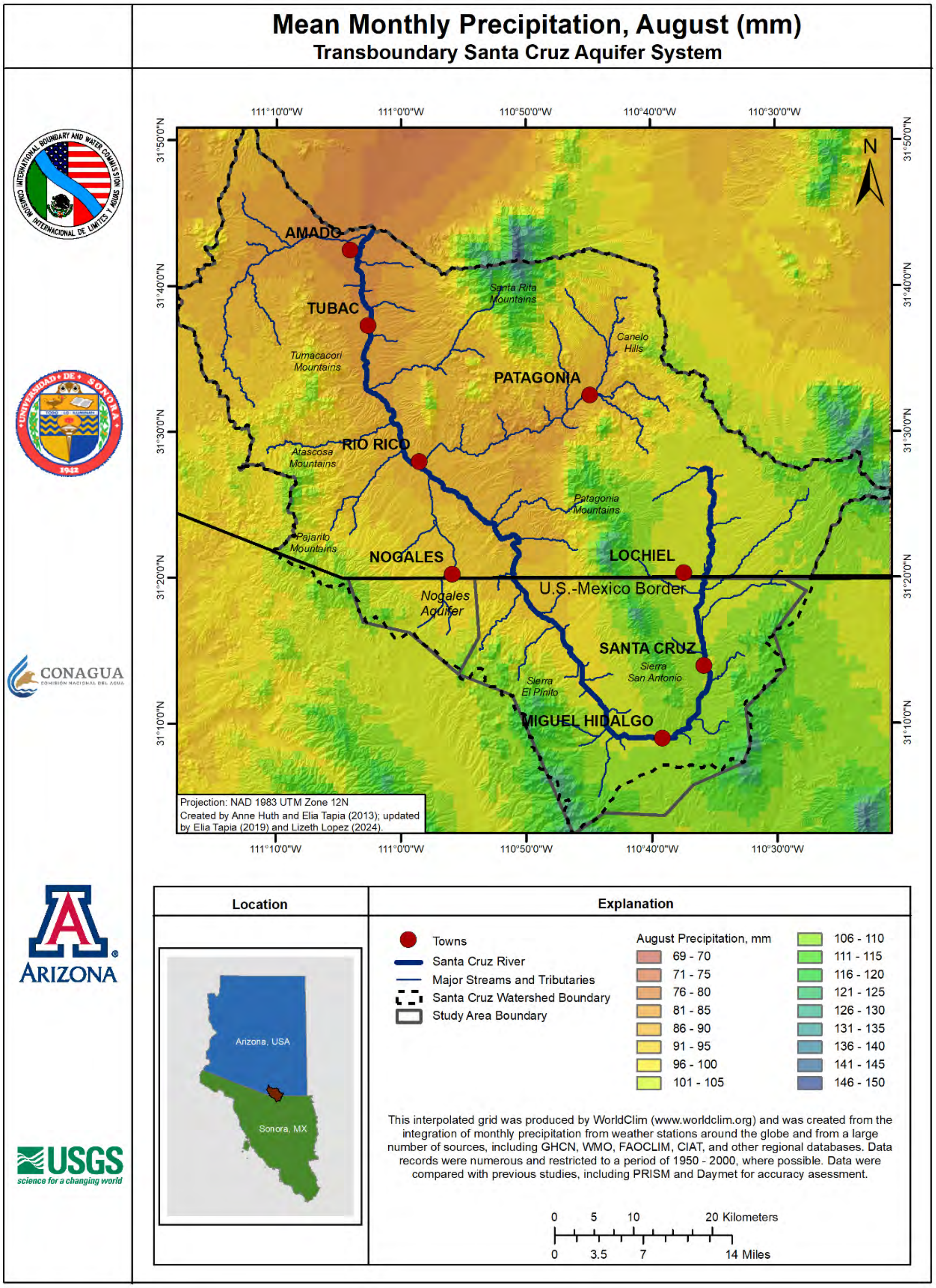

Figure 3.9 Mean monthly precipitation in August in the Transboundary Santa Cruz Aquifer System.

3.3. Surface Hydrologic System

The study area in Mexico falls within Hydrologic Region RH7, Rio Colorado (CONAGUA, 2015). However, because of the manner in which the legal boundaries are drawn in Mexico, the SCRAS is split between two adjacent jurisdictions: the Santa Cruz River subbasin, comprising 93% of the total aquifer area, and the Arroyo Cocospera subbasin, which comprises the remaining 7% (Figure 3.10; Minjarez et al., 2011). The Nogales aquifer has a surface area of around 120 km^2 (GAS-CONAGUA, 2024). The majority of the aquifer is located beneath Sonora. The drainage area of the Santa Cruz River, upstream of the Nogales, Arizona gage (USGS site number 09480500), is 1,400 km^2, of which about 1150 km^2 are in Sonora (Shamir et al., 2015).

The Santa Cruz River originates in the U.S. in the San Rafael Valley and flows south towards Mexico. It crosses the international border near the town of Lochiel, Arizona. In Sonora, the river changes direction approximately 20 km south of the international border and begins to head west just upstream of the town of Miguel Hidalgo (San Lazaro), continuing for about 7 km (Robert, 2006). The river then turns northeast, continuing 27 km until it crosses the international boundary east of Nogales. The river channel continues north, passing through the settlements of Rio Rico, Tumacácori, Tubac, and Amado, Arizona, near the boundary of the study area. North of the study area, streamflow is mostly intermittent as the channel passes through the Tucson area and north toward the Gila River south of Phoenix, Arizona.

Within the study area in Sonora, the major tributaries of the Santa Cruz River are the Arroyos La Zorrilla, Las Pilas, El Pilar, Los Jacalones, Las Abispas, El Bombín, La Capilla, San Luis, and La Calera arroyos (Minjarez et al., 2011) (Figure 3.10). In Arizona, there are four main tributaries to the Santa Cruz River. The most southerly is Nogales Wash, which originates in Nogales, Sonora, and joins the Santa Cruz adjacent to the Nogales International Wastewater Treatment Plant (NIWTP). The main tributaries on the west side of Nogales Wash, in Sonora, are Tecnológico (Chimeneas) and Cementerio (Internacional) arroyos. The remaining three tributaries that join the Santa Cruz River in Arizona are Sonoita Creek, which passes through the town of Patagonia and has its confluence with the river near Rio Rico, Arizona, Josephine Canyon, which drains the southwest portion of the Santa Rita Mountains, and Sopori Wash, located in the northwest corner of the study area.

Streams within the study area fall into three categories: perennial, intermittent, or ephemeral. Perennial streams are those with continuous flow. Intermittent streams flow part of the year, typically in response to seasonally variable sources such as snow melt, springs, or fluctuating groundwater tables (Meinzer, 1923). When a temporally intermittent reach connects two perennial reaches, the stream will become spatially interrupted when seasonal flow ceases. Ephemeral streams flow only in response to precipitation and are disconnected from the water table. In the study area, ephemeral streams and reaches are more numerous and have greater total length than perennial streams. Although this is typical globally, it is more so in arid environments (Acuña et al., 2014; Levick et al., 2008). With respect to spatial distribution of flow, all streams in the study area are normally spatially interrupted (discontinuous) during a portion of the year.

Of the major drainages, the Santa Cruz River, Sonoita Creek, and Nogales Wash all have perennial reaches, although the main reach of the Santa Cruz River is discontinuous for most of the year except during large flood events (Niraula et al., 2012). The reach of the Santa Cruz River between Rio Rico and Tubac, Arizona, is dominated by discharge from the NIWTP. The effluent from this plant comes from wastewater collected on both sides of the border, although the contribution of wastewater from Mexico represents the majority of what is treated at the NIWTP. The effluent helps to maintain surface flows and associated ecosystem services, such as vegetation and habitat for wildlife as well as recharge to groundwater resources for water provisioning downstream of the treatment plant (Norman et al., 2013). About a quarter of the wastewater collected in Nogales, Sonora, is transported to Los Alisos River basin, located immediately south of the Nogales aquifer outside of the study area, where it is treated prior to being discharged into Los Alisos River (Tapia-Villaseñor et al., 2020).

There are currently four operating streamgages located within the study area. The streamgage furthest upstream is the Santa Cruz River near Lochiel (USGS site number 09480000). It is located in the San Rafael Valley about 2.5 km north of the U.S.-Mexico border, first operated between 1949 and 2013 and restarted in 2019. The mean daily streamflow for the most recent 25-year period 10/1/1995 - 9/30/2020 was 0.058 m^3/s, and the median was 0.0093 m^3/s (USGS, 2021). Older data at this streamgage show a period of comparatively lower flows from 1950 through the mid-1960s, and a period of higher flows from the early 1980s to the mid-1990s (Figure 3.11). The pattern in 2020 was similar to other years with little summer flow and reduced winter flow such as occurred in 2002-2003. The next streamgage downstream is located on the Santa Cruz River near Nogales, Arizona (USGS site number 09480500), about 1.3 km downstream (north) of the international boundary and has been operated continuously since October 1985. The mean daily streamflow for the period 10/1/1995 - 9/30/2020 was 0.21 m^3/s, and the median was 0 m^3/s (USGS, 2021). At this streamgage, the streamflow regime began to shift around 1996, with winter flow becoming notably less frequent than in the more recent (2014-2020) portion of the record (Figure 3.11). This coincides with the regional long-term drought which has lasted through 2024 (Arizona State Climate Office, 2025). There were several years of data collected in the early 1930s at the Nogales Wash streamgage at Nogales, Arizona (USGS site number 09481000; Figure 3.12). This streamgage was reactivated in 2010. The mean daily streamflow for the period of 4/23/2010 - 9/30/2020 was 0.27 m^3/s, and the median was 0.10 m^3/s (USGS, 2021). The streamflow record from the early 1930s exhibits low to no flow except in summer. It is possible that this reflects smaller population and less impervious area and industrial activity than at present, but the record is too brief to support firm conclusions. Nogales

Wash is concrete lined for much of its length and experiences few days of no flow, unlike the other gages in the study area. No trends are apparent in the record from the reactivated gage starting in 2010, although annual cycles can be observed including clusters of higher flows during the monsoon months of July, August, and September (Figure 3.13). At the Santa Cruz River at Tubac, Arizona, streamgage (USGS site number 09481740) the mean daily streamflow for the period 10/1/1995 - 9/30/2020, was 0.70 m^3/s, and the median was 0.33 m^3/s (USGS, 2021). With the exception of 2019 and 2020, the record at this gage shows a distinct decline in flow beginning in 2010 with declines most notable in summer (Figure 3.14). The decline coincided with the opening of the upgraded NIWTP and lends support to the hypothesis of Treese and Meixner (2009) that permeability of the streambed has increased. They theorized that the decrease in nutrients in the NIWTP effluent caused disintegration of an impermeable algal mat, which stretched multiple kilometers downstream, resulting in increased streambed infiltration. In addition, in 2013, the river stopped flowing at Tumacácori for an unprecedented nearly four-month period (Sonoran Institute, 2016; USGS, 2021). Table 3.1 and Table 3.2 include information regarding Santa Cruz River streamflow in the Mexican portion of the TSCAS. The information was gathered by the Mexican section of IBWC during the years of 1962-1974 for El Cajón streamgage, located 7 km southwest of Santa Cruz, Sonora, and 50 km southeast of Nogales, Sonora. Mean Santa Cruz River streamflow for the analyzed period is 0.31 m^3/s and the mean surface water volume equals 564 thousand m^3 (IBWC Hydrometric Bulletins, 1962-1974).

Several studies of the surface hydrologic system have been carried out in addition to those mentioned in the climate section of this chapter. The USGS tracked organic and inorganic contaminants and their effects from sources to sinks in sediment, water, plants, and animals using an interdisciplinary and integrative approach (Norman et al., 2010a). The Nogales Wash baseflow is augmented by contributions from perched groundwater as well as leaking potable water and wastewater infrastructure in Nogales, Sonora, exacerbated by increasing population and transportation routes encroaching on the floodplains and drainages (Norman et al., 2010b). The IBWC investigated regulating runoff using a series of detention features in Nogales, Sonora, to increase the effectiveness of detention features by optimizing future locations (Norman et al., 2010c). This study provided insights into the potential benefits of strategic placement and design of detention features, highlighting their role in mitigating flood risks under multiple urbanization scenarios.

Norman et al. (2013) provided a framework for understanding the value of binational effluent, discussed how estimates are developed, and summarized the ecosystem services provided by effluent-driven NIWTP instream flow. A scenario analysis of declining discharges from the binational treatment plant demonstrated the most extreme, visible water declines at an important bird area from 2.5-7.5 months out of the year. This results in a loss of riparian forest and woodlands, habitat for many species, and reverts the riparian zone to conditions prior to the establishment of the treatment plant. Norman et al. (2013) relate losses of habitat and vegetation to losses in property value when homes are no longer situated by a perennial river and identify socio-environmentally vulnerable neighborhoods that might be impacted by these losses.

In the Mexican portion of the TSCAS, hydrometric data from the El Cajón station is limited, with only 14 years of observations between 1962 and 1976 (Table 3.1 and Table 3.2). A water balance model was developed in Tapia-Villaseñor et al. (2022) to quantify water fluxes into and out of the aquifer basin. This model incorporates a hydrologic component that uses precipitation and evapotranspiration data to simulate streamflow, natural recharge, soil moisture, and actual evapotranspiration.

Tapia-Villaseñor et al. (2020), in the Impacts of Variable Climate and Effluent Flows on the Transboundary Santa Cruz Aquifer study, examined the influence of wastewater discharge downstream of the NIWTP, and provided detailed information on the transfer of wastewater from Mexico to the U.S. This study highlights the significance of cross-border wastewater flows and their implications for regional water quality and availability. Norman (2007) focused on evaluating nonpoint source pollution in the border region of Ambos Nogales. This research addressed critical water quality issues related to urban and agricultural runoff in a transboundary watershed context. The study highlighted rapid urbanization in Nogales, Sonora, as a key factor exacerbating pollution issues due to inadequate infrastructure, such as leaking wastewater systems and unmanaged stormwater.

Table 3.1 Mean Monthly Streamflow (m^3/s) in the Rio Santa Cruz in Mexico at the El Cajón Streamgage from 1962-1976 (dash indicates no data exist for that month).

	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
1962	3.17	0.29	0.29	0.17	0.11	0.15	1.90	2.82	0.22	2.68	0.11	0.11
1963	0.10	0.10	0.13	0.01	0.10	0.05	0.48	1.26	-	-	0.19	0.21
1964	0.11	0.11	0.23	0.25	0.24	0.13	0.53	-	-	-	-	-
1965	-	-	-	0.12	0.23	0.23	0.36	0.36	0.34	0.08	0.06	0.38
1966	0.57	0.81	0.40	0.10	0.07	0.07	0.35	1.94	0.76	0.54	0.40	0.33
1967	0.26	0.22	0.24	0.14	0.07	0.14	0.11	0.17	0.14	0.16	0.13	-
1968	-	-	0.41	0.17	0.10	0.06	0.14	0.28	0.10	-	-	-
1969	0.02	0.02	0.02	-	0.01	-	0.13	0.16	0.04	0.03	0.03	0.03
1970	0.34	0.34	0.33	0.34	0.03	0.03	0.07	0.89	0.40	0.18	0.15	0.16
1971	-	0.04	0.03	0.04	-	-	0.15	1.36	0.52	0.25	0.14	-
1972	-	-	-	-	-	-	0.20	0.22	0.29	0.12	0.18	-
1973	0.12	0.21	0.45	0.17	0.06	0.12	0.21	0.14	0.05	0.05	0.07	0.05
1974	0.06	0.06	0.07	0.05	0.05	0.10	-	-	-	-	-	-

Table 3.2 Mean Monthly Volume (thousands of m^3) in the Rio Santa Cruz in Mexico at the El Cajón Streamgauge from 1962-1976 (dash indicates no data exist for that month).

	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
1962	35	28	23	12	4	-	841	1,463	241	76	34	33
1963	258	252	343	289	272	122	1,284	3,382	-	-	499	555
1964	283	279	613	651	631	343	1,432	-	-	-	-	-
1965	-	-	-	321	622	600	966	958	894	214	165	1,025
1966	1,522	1,971	1,097	250	194	190	931	5,207	1,958	1,437	1,034	889
1967	702	537	639	376	194	352	303	460	359	431	344	
1968	-	-	1,092	442	269	149	381	740	245	-	-	-
1969	47	48	45	8	28	9	337	428	110	90	90	69
1970	911	834	886	880	69	86	183	2,386	1,043	486	379	439
1971	-	99	92	94	-	-	389	3,652	1,346	664	373	-
1972	-	-	-	-	-	-	538	598	746	335	465	438
1973	331	510	1,206	429	156	305	559	389	124	127	187	135
1974	168	144	178	128	134	254	-	-	-	-	-	-

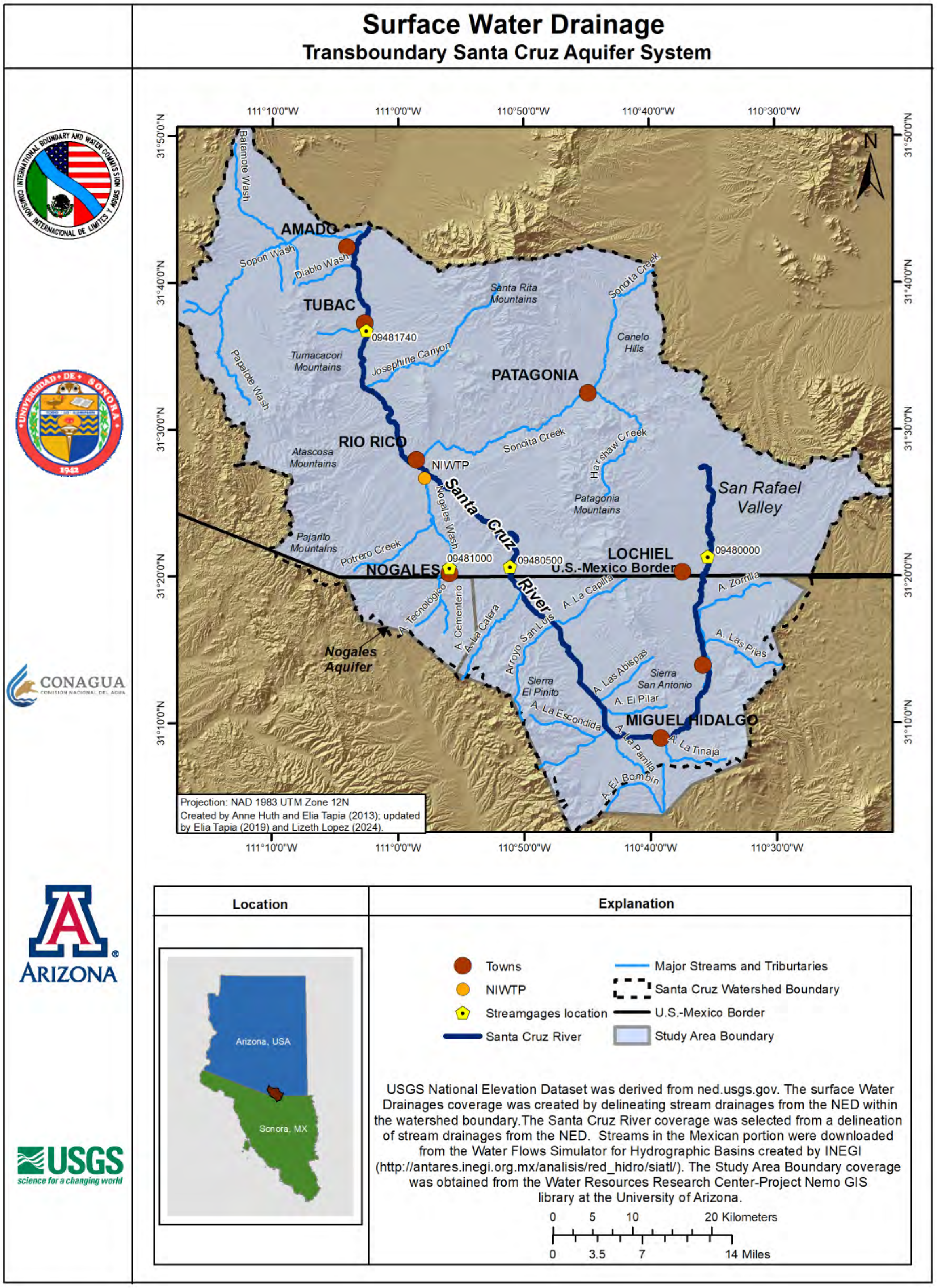

Figure 3.10 Surface-Water Drainage Network in the Transboundary Santa Cruz Aquifer System.

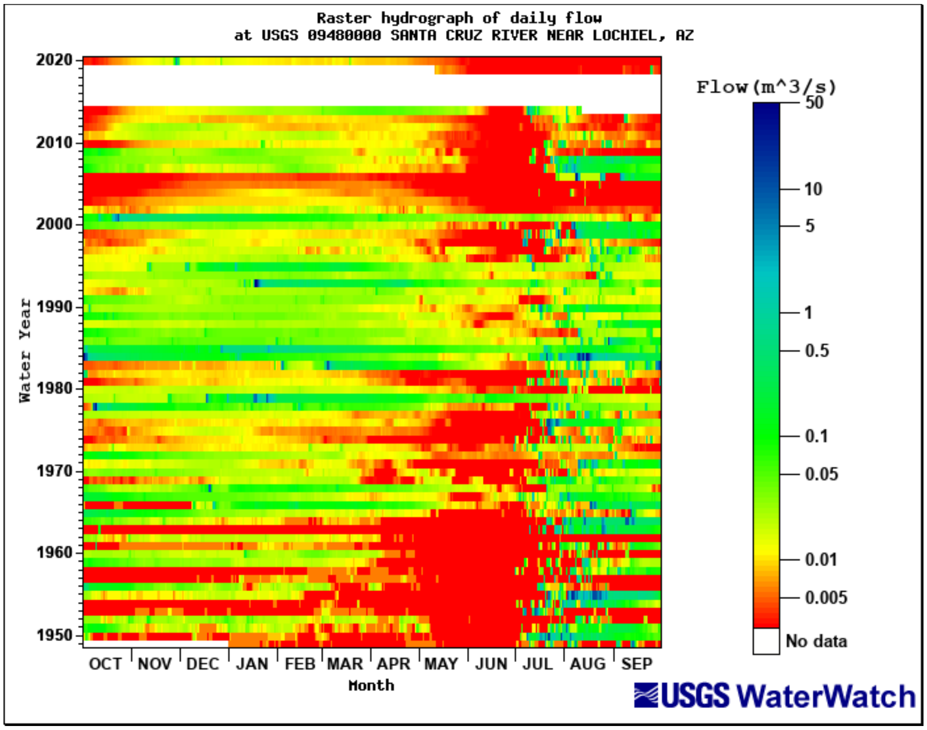

Figure 3.11 Raster hydrograph of daily flow in the Santa Cruz River at Lochiel, Arizona, through the end of the water year 2020.

A water year is the 12-month period from October 1, for any given year through September 30 of the following year. A water year is designated by the calendar year in which it ends. Each pixel represents the mean flow for each day on which flow was measured. The log of the magnitude of the flow is color coded according to the scale bar at the right of the figure, with red indicating low or no flow and blue indicating the highest flows in units of m^3/s (note that scales of raster hydrographs in each figure may differ).

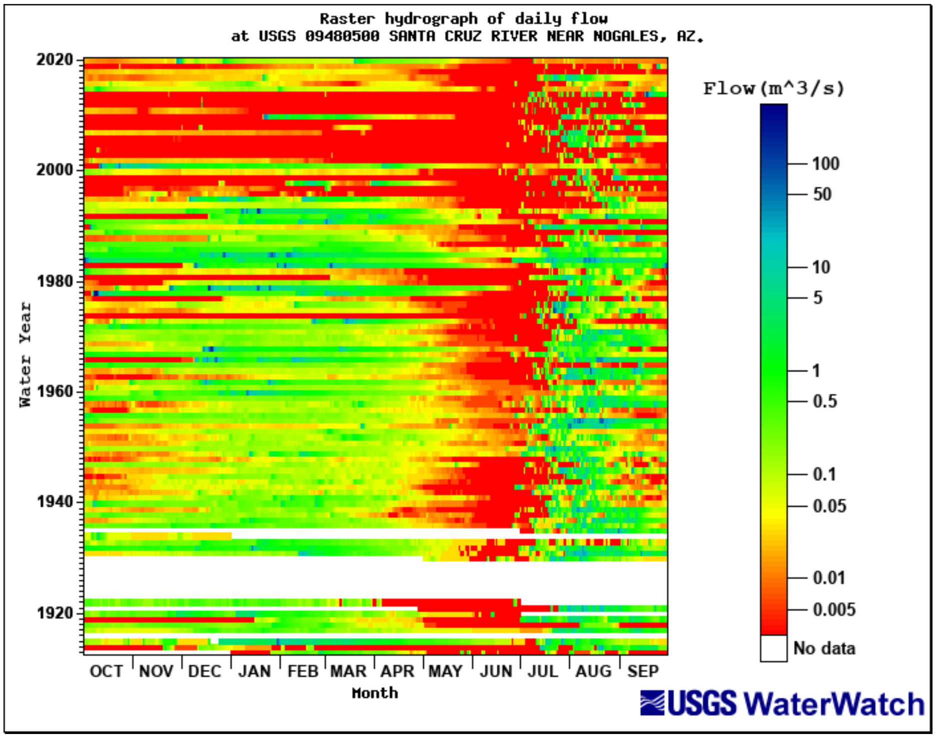

Figure 3.12 Raster hydrograph of daily flow in the Santa Cruz River near Nogales, Arizona, through the end of water year 2020.

Each pixel represents the mean flow for each day on which flow was measured. The log of the magnitude of the flow is color coded according to the scale bar at the right of the figure, with red indicating low or no flow and blue indicating the highest flows in units of m^3/s (note that scales of raster hydrographs in each figure may differ).

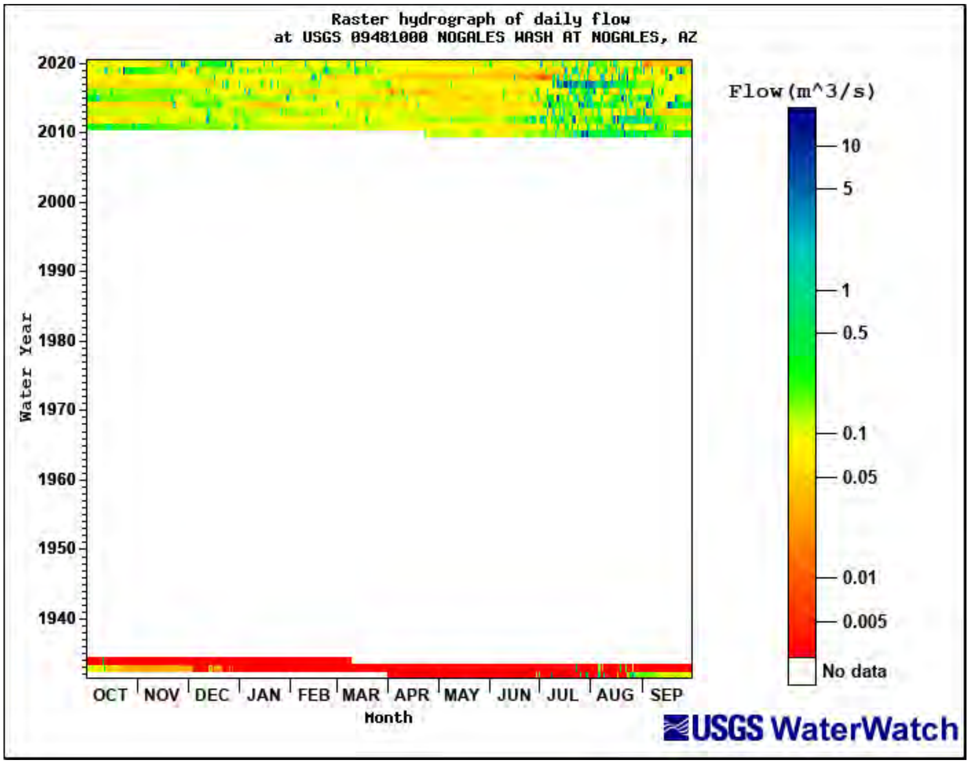

Figure 3.13 Raster hydrograph of daily flow in the Nogales Wash at Nogales, Arizona, through the end of water year 2020.

Each pixel represents the mean flow for each day on which flow was measured. The log of the magnitude of the flow is color coded according to the scale bar at the right of the figure, with red indicating low or no flow and blue indicating the highest flows in units of m^3/s (note that scales of raster hydrographs in each figure may differ).

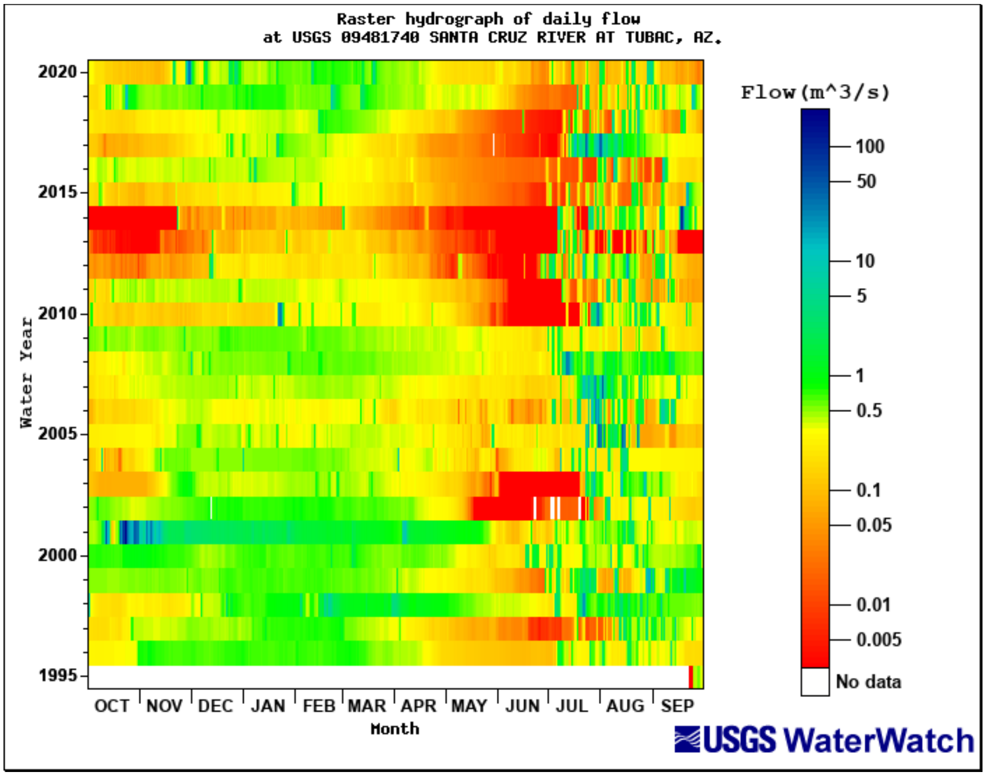

Figure 3.14 Raster hydrograph of daily flow in the Santa Cruz River at Tubac, Arizona, through the end of water year 2020.

Each pixel represents the mean flow for each day on which flow was measured. The log of the magnitude of the flow is color coded according to the scale bar at the right of the figure, with red indicating low or no flow and blue indicating the highest flows in units of m^3s (note that scales of raster hydrographs in each figure may differ).

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4. CONCEPTUAL GEOLOGICAL MODEL

4.1. Regional Geologic Model

The geologic units in the TSCAS are the product of a complex tectonic evolution; the diversity of these tectonic and deformation events produced a region with relatively high geologic complexity. Within the north and northeastern portions of Sonora and the south and southeastern portions of Arizona, the oldest rocks form a Precambrian basement characterized by the Pinal Schist (1,680 million years before present (Ma)) and Mesoproterozoic granitic intrusions. The basement is overlain unconformably by sedimentary platform sequences, mainly carbonate rocks, deposited throughout most of the Paleozoic. These Precambrian-Paleozoic rocks were initially considered part of the basement of the Pinal Schist of Santa Catalina Group by Haxel et al. (1980).

The most widely distributed Mesozoic rocks in this area are a Jurassic-age volcano-sedimentary sequence called El Pinito Formation in Mexico (Gilmont, 1978), and Mount Wrightson Formation (AZ) in part of southern Arizona (Drewes, 1971). The El Pinito Formation is exposed mainly in the mountain range with the same name located west of the town of Santa Cruz (Figure 4.1). The sequence is dominated by rhyolites and rhyolitic lahars that are intercalated with layers of quartz sandstone. The Mount Wrightson Formation is exposed in the Santa Rita Mountains and has similar lithologies as the El Pinito Rhyolites. Tectonically, these rocks represent the development of a continental volcanic arc with deposition of sand dunes during the Jurassic (Riggs and Haxel, 1990). The rocks also correspond to the Papago Formation defined by Haxel et al. (1980) as a region that extends from south-central Arizona to the north-central portion of Sonora.

Cretaceous-Tertiary rocks are widely distributed in both portions of the TSCAS. The opening of the Gulf of Mexico (Gulf of America) 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 affected by the Early Cretaceous marine transgression. This generated the sedimentation represented locally by the detrital-carbonate rocks of the Bisbee Group (Ransome, 1904; Dickinson et al., 1986; Gonzalez-Leon et al., 2008). During the late Cretaceous, this area was also affected by the Laramide orogeny, developing wide folds with axes-oriented northwest-southeast and a series of thrusts. Concurrently, continental sediments of the Cabullona Group (Taliaferro, 1933) and the Fort Crittenden Formation (Epis, 1956) were deposited into these basins. These units mainly comprise a detrital volcano-sedimentary sequence that was deposited in continental fluvial-lacustrine environments (González-Leon and Lawton, 1995).

Synchronously with the deposition of the Cabullona Group, a continental magmatic arc developed farther to the west. This is also known as the “Laramide Arc”, which in this region is represented by a series of granite-granodioritic intrusions that intruded pre-Cenozoic rocks, and by andesitic-dacitic volcanic rocks that are termed the Mesa Formation in Sonora (Valentine, 1936; Valencia et al., 2006). This lithological assemblage also crops out in the Huachuca Mountains and to the west of Grosvenor Hills in Arizona (Drewes, 1980). The magmatic arc subsequently migrated toward the interior of the continent and then retreated toward the Pacific coast. The main effect of this event was increased rhyolitic-dacitic volcanism, commonly ignimbritic, as exemplified in the Sierra Madre Occidental and in southern Arizona during the Oligocene and early Miocene. This chronology of the migration in southwest North American was established by Damon et al. (1983).

Extensional deformation prevailed in north-northeastern Sonora and southern Arizona since the late Paleogene. In Sonora and southern Arizona, early extensional basins were filled with conglomerate and intercalated mafic-intermediate volcanic units. Several formation names are used for units of this age, e.g. Magdalena Formation in Sonora, and Pantano Formation and San Manuel Formation in Arizona (Miranda-Gasca and DeJong, 1992; Dickinson, 1991). Extension since the mid-Miocene developed this part of the Basin and Range physiographic province (Fenneman, 1931; Ferrari et al., 2005; Henry and Aranda-Gómez, 2000), in which normal faulting produced a series of continental basins bounded by bedrock mountain blocks. The basins are filled with thousands of feet of alluvium eroded from adjacent mountain blocks that have undergone progressive uplift. Several formation names are used, including the Baucarit Formation in Sonora and the Nogales Formation, scattered Tinaja beds, as well as the Fort Lowell Formation and Quiburis Formation in Arizona (Miranda-Gasca and DeJong, 1992; Dickinson, 1991).

4.2. Stratigraphy

A variety of stratigraphic names are used for units of comparable age and lithology (Figure 4.1 and Figure 4.2). To simplify the mapping and description of these units in this transboundary study, we propose a series of informal lithostratigraphic and lithodemic units broadly encompassing those that have similar lithology and age. These units are described in order from oldest to youngest. Information about bedrock units were taken from Bultman and Page (2016), the area of Rio Rico and Nogales from Page et al. (2023) and the upper Santa Cruz basin units from Page at al. (2016). The units described in Graybeal and others (2015) were used throughout this section. Information in the following sections were derived from these sources unless otherwise cited.

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

This unit includes outcrops that were originally mapped in southern Arizona (western side of the Patagonia Mountains) by Simons (1974) as an igneous-metamorphic sequence rich in hornblende, to which he assigned a probable Precambrian age. Within the Mexican portion of the TSCAS, there is a restricted outcrop of similar rocks in Sierra San Antonio (north-central area), east of the city of Nogales along the Sonora-Arizona border. In this locality, the unit consists of a green to dark green, phaneritic diorite (**€TmGr)**. The diorite grades locally into fine- to medium-grained schistose metadiorite that is greenish brown and very brittle in weathered outcrops. Primary minerals include mainly hornblende, oligoclase-andesine, augite and quartz, and alteration minerals include chlorite and montmorillonite; the rock is classified as hypabyssal hornblende lamprophyre (Servicio Geológico Mexicano, 2000). Northeast of the Patagonia Mountains and on the west side of the Santa Rita Mountains, the unit consists of granodiorite to quartz monzonite, locally foliated and metamorphosed (**Yg**) and schistose metasedimentary rock (**Xp**) like the Pinal Schist, that is intruded by the Precambrian igneous bodies. In the Patagonia Mountains, this Precambrian complex is intruded by Jurassic granite that contains xenoliths from the Precambrian unit (Greybeal et al., 2015).

Early Paleozoic Sedimentary Unit (Cs)

This unit comprises a dominantly detrital sequence that in the TSCAS only crops out on the U.S. side, where it is termed the Bolsa Quartzite (**Cs**), of Middle Cambrian age (Graybeal et al., 2015). Outcrop is restricted to the east-central portion of the Patagonia Mountains, where it consists of a sequence of light gray quartz sandstone containing local intercalated layers of conglomerate with a light reddish to purple-gray matrix, and shale and limestone.

Late Paleozoic Sedimentary Unit (Ps, Pps, Ph, Mds)

Sequences of mainly Devonian-Permian limestone and sandstone crop out on the main eastern topographic highs of the TSCAS. In the Canelo Hills, Arizona, the sequence includes the Scherrer Formation of Naco Group, Earp Formation of Naco Group and Concha Limestone of Naco Group, which are generally composed of dolomitic and cherty limestone, dolomite, massive sandstone, and reddish siltstone (**Ps**) (Graybeal et al., 2015). The unit also includes the Permian Colina Limestone of Naco Group, consisting of black limestone intercalated with sandstone and shale. This unit is also present in the east-central portion of the Patagonia Mountains, as well as in the northwestern side of the Santa Rita Mountains. In the east-central portion of the Canelo Hills, the Pennsylvanian Horquilla Formation is also present, which includes grayish-blue limestone in thin layers and interbedded reddish shale (**Ph**). On the eastern slopes of the Huachuca Mountains, Devonian-Mississippian formations (**Mds**) are the oldest rocks of this unit. The Devonian Martin Formation consists of dark gray limestone and pinkish gray calcareous shale and the Mississippian Escabrosa Formation is light gray coarse-grain limestone with abundant crinoid fragments (Graybeal et al., 2015).

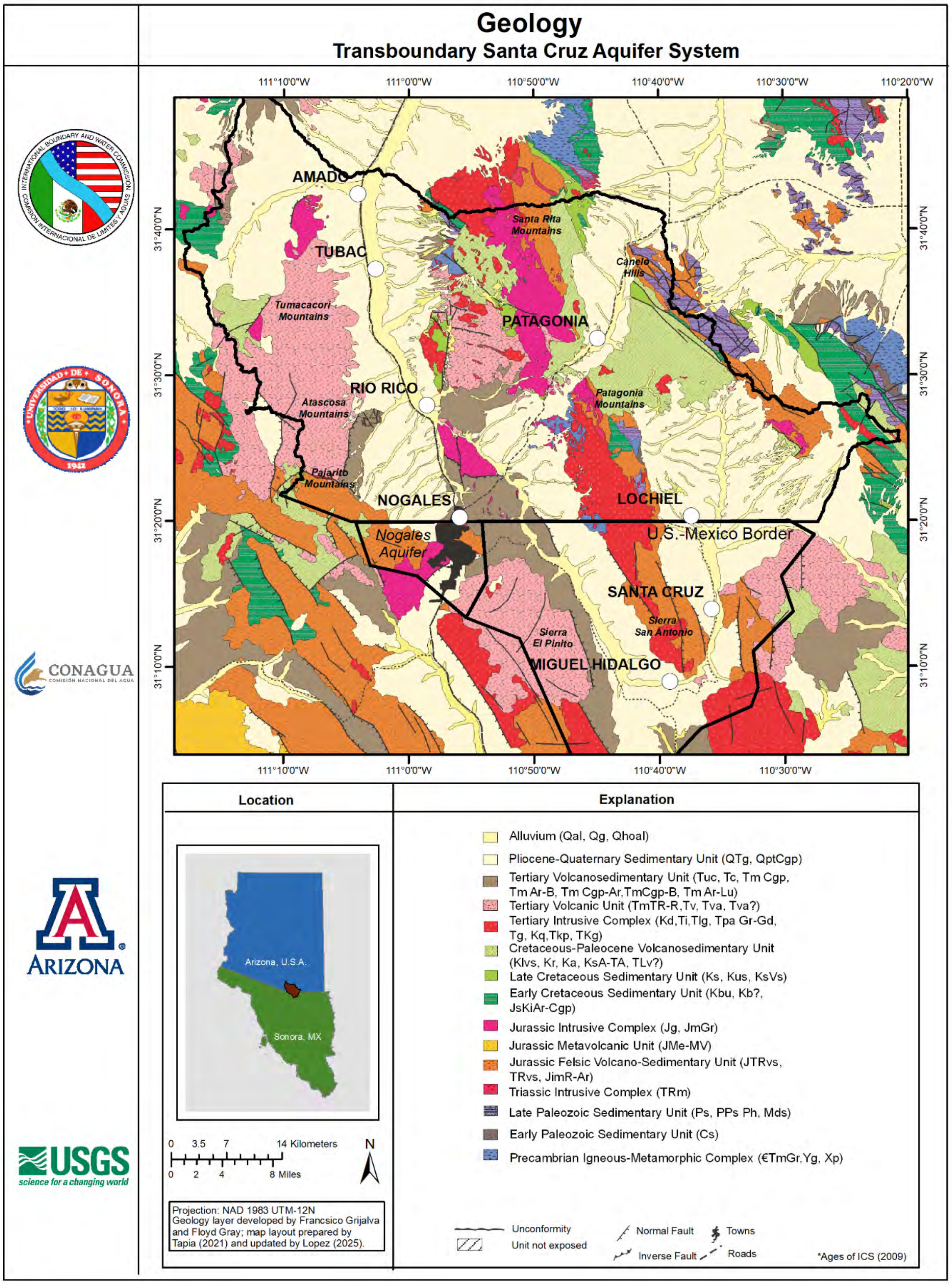

Figure 4.1 Geology of the TSCAS.

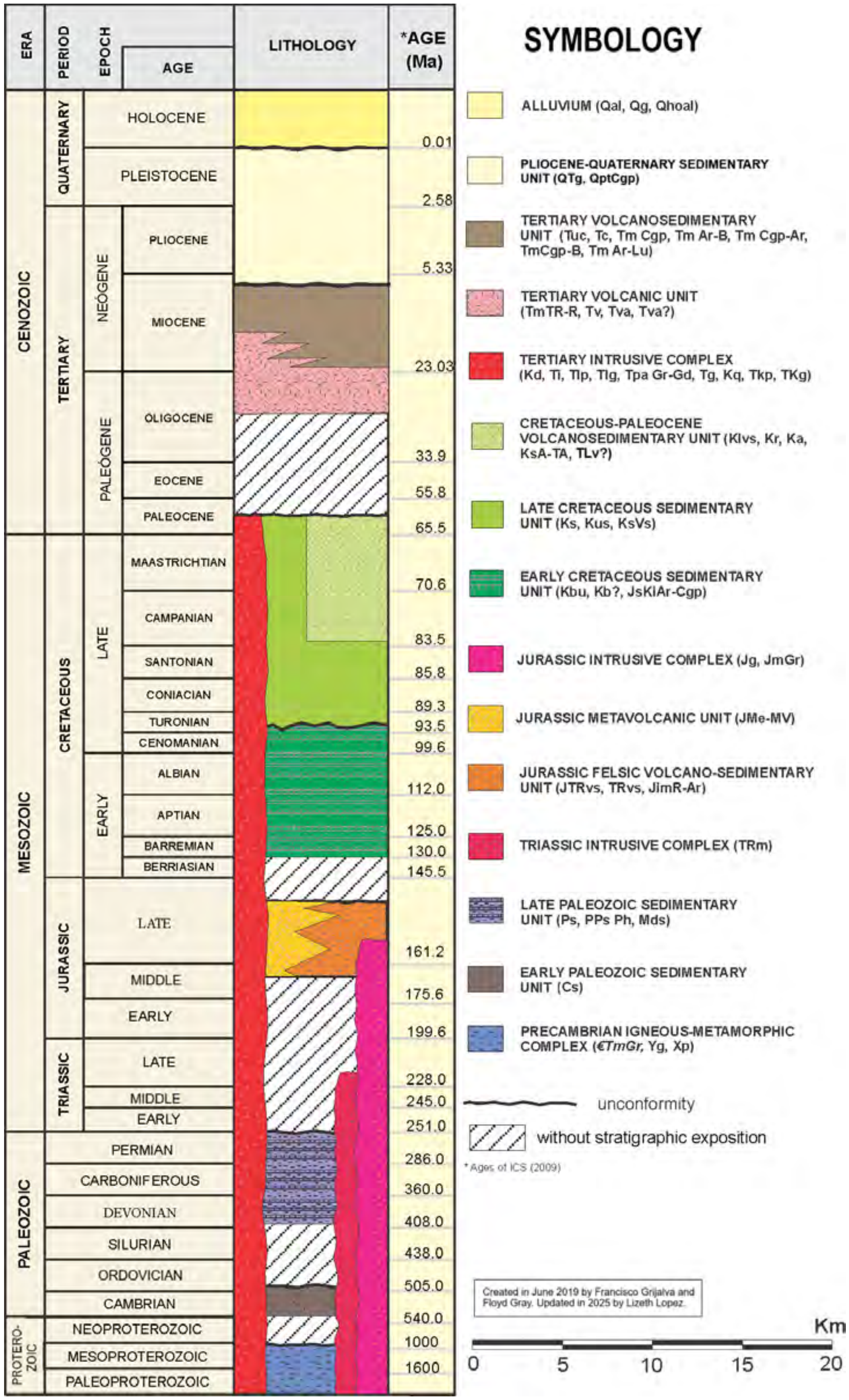

Figure 4.2 Stratigraphy of the TSCAS.

Triassic Intrusive Complex (Trm)

This unit includes several outcrops of Triassic intrusive monzonite to quartz monzonite in the northern Santa Rita Mountains in Arizona. These intrusions (**Trm)** are dated to 184, 190 and 210 Ma (Drewes, 1980).

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

This unit includes mainly Jurassic and likely Triassic volcanic and volcano-sedimentary sequences that are widely distributed in the higher mountain blocks of the TSCAS. In Sierra El Pinito, Sonora, Gilmont (1979) identified a volcano-sedimentary sequence composed of quartz rhyolite, tuff, and sandstone (**Jim R-Ar**). Similar outcrops are present in the Sierra San Antonio, in the northern portion of the Sierra El Chivato and in the Sierra Cibuta, all in Sonora.

The rhyolites are pinkish gray and have various textures, from porphyritic to equigranular and fluidal. Quartz, K-feldspar, and plagioclase are the predominant minerals; the feldspars display a very intense sericitic alteration. One of the main structural characteristics of these rhyolites is that they contain two predominant sets of fractures (140° NE 86° and 50° NW 88°), which form a characteristic cubic shape in outcrop. The tuffs are primarily lithic and gray to pinkish gray in color. Locally, in Sierra El Pinito, there are outcrops of crystal tuffs with a welded textural appearance. The sandstone is mainly medium to fine-grained, medium gray quartz sandstone with a typical "salt and pepper" texture on fresh surfaces, due to an abundance of iron oxides. This sandstone is well sorted arenite with a grain-supported texture and contains eolian cross beds; the mineralogy is dominated by monocrystalline quartz (92%) with wavy extinction; other components are microcline altered to sericite and clay (7%) and felsic volcanic rock fragments (1%). These volcanic rocks have common quartz overgrowths, concave-convex and locally sutured contacts, and heavy minerals (mainly iron oxides). This sequence is assigned to the Jurassic by a U/Pb age of 174 Ma reported by Stewart et al. (1986). The lower contact is not exposed. The sequence is cut by Jurassic and Tertiary felsic intrusions. The upper contact is discordant with the younger volcanic and clastic rocks.

In Arizona, this unit also includes rhyolitic flows and tuffs, andesitic flows, aeolian sandstones and red bed layers (**JTRvs, TRvs**) that occur in Copper Ridge, Gardner Canyon, Mount Wrightson and Pajarito Formations, as well as in the Fresnal Canyon and Artesa sequences in southern and southwestern Arizona. The most extensive outcrops are in the Pajarito and Santa Rita Mountains. The volcanic rocks that are widely distributed in the Canelo Hills are also considered part of this unit.

Jurassic Metavolcanic Unit (Jme-MV)

This unit includes a metavolcanic sequence (**Jme-MV**), known within Mexico as the Coyotillo Group, that crops out locally at the southwestern limit of the study area in Sonora (Sierra Guacomea). The principal lithologies are schist, metarhyolite, metaconglomerate, and metasandstone whose protolith is the El Pinito Formation. That sequence was affected by regional greenschist facies burial metamorphism (Herrera-Urbina y Perez-Segura, 1990), attributed to a Nevadian phase by Morales-Montaño (1984).

Jurassic Intrusive Complex (Jg, JmGr)

This is a proposed unit to group together a series of intrusive bodies of Jurassic age that mainly outcrop on the U.S. side of the TSCAS, and near the city of Nogales in Sonora. In Sonora there are outcrops of Jurassic granitic rocks on the northwest side of the San Antonio Mountains, where they intrude a Precambrian granite (Simons, 1974), as well as in some hills southwest of the city of Nogales. This intrusive rock (**JmGr**) has a reddish-brown and gray color, and phaneritic to porphyritic texture. Quartz and orthoclase are the predominant minerals, and biotite is scarce to absent. In the urban area of Nogales, Arizona, this intrusion has intense fracturing and faulting. Correlative intrusive granitic to granodioritic units in southern Arizona yield K-Ar dates from 160 to 170 Ma (Marvin et al., 1973). Outcrops of these intrusions (**Jg**) on the U.S. side of the TSCAS are north of Nogales, and in the northern portion of the Patagonia and Tumacácori Mountains. These calc-alkaline intrusions are part of the Jurassic continental magmatic arc (Tosdal et al., 1989).

Early Cretaceous Sedimentary Unit (JsKiAr-Cgp, Kbu, Kb?)

This unit includes Early Cretaceous sedimentary rocks correlated with Bisbee Group of southeastern Arizona. In the TSCAS, they occur on both sides of the border. On the Mexican side, they crop out in the Sierra La Esmeralda in the west-central portion of the study area, where conglomerate and reddish sandstone (**JsKiAr-Cgp**) correlative with the Glance Conglomerate of the Bisbee Group is present. On the U.S. side of the TSCAS, this unit crops out extensively north of the Huachuca Mountains, as well as locally on the eastern flanks of the Santa Rita and Patagonia Mountains and the west side of the Canelo Hills. At these localities, several formations of Bisbee Group: the Willow Canyon, Apache Canyon, Shellenberger Canyon, and Turney Ranch Formations are predominantly detrital, and are equivalent to the upper units of the Bisbee Group (**Kbu**). In the Pajarito Mountains, interbedded sequences of shale, siltstone, sandstone, conglomerate and limestone (**Kb**) are also considered part of this unit.

Late Cretaceous Sedimentary Unit (Ks, Kus, KsVs)

The unit crops out at the east limit of the Santa Cruz basin within the Mexican portion of the TSCAS. It consists of interlayered sandstone and shale with local interbedded tuff (**KsVs**). The sandstone and shale are light brown and light gray to green, and weather to a yellowish color. This sequence is correlative to the Cabullona Group, which is present extensively in northeast Sonora. It has been assigned to the Late Campanian-Maastrichtian by paleontological studies. Outcrops in the U.S. portion of the TSCAS are restricted to the western flanks of the Huachuca and Santa Rita Mountains, and to the northeast of the Canelo Hills, where they are mainly detrital sedimentary rocks (**Ks, Kus**) correlative to the Fort Crittenden Formation.

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

The unit consists mainly of volcano-sedimentary strata of intermediate composition and rhyolitic volcanic and volcaniclastic rocks. In the Mexican portion of the TSCAS, the same unit includes the Mesa Formation (Valentine, 1936) exposed on the northeast side of the Sierra El Chivato (**KsA-TA**) where it consists of greenish-gray, porphyritic to aphanitic andesite and minor latite. It also includes aphanitic-porphyritic andesitic tuff, greenish-gray and light gray with purple tones, and greenish-gray andesitic agglomerate with clasts several centimeters in diameter in a tuff matrix. Andesite is dominated by oligoclase-andesine, altered mica, apatite, iron oxide, and secondary epidote, argillaceous (clay-dominant) minerals, sericite, chlorite, hematite, and calcite. Oxidized pyrite is disseminated in fractures. Associated sedimentary rocks include gray to greenish-brown polymictic conglomerate containing subangular to sub-rounded clasts of light gray to tan limestone, andesitic tuff, andesite, and porphyritic rhyolite in a sandy matrix. The clasts are well-sorted and vary in size from pebbles to cobbles. The matrix consists of purplish-gray to yellowish-brown fine-to medium-grained sand.

The Mesa Formation overlies older Mesozoic and pre-Mesozoic units and is overlain by Tertiary sediments and volcanic rocks, with both contacts being unconformities. The unit is intruded by plutons from the Laramide magmatic arc. The formation's chronostratigraphic position is consistent with a radiometric Ar/Ar age of 69 ± 0.2 Ma (Wodzicki, 1995). This phase of intermediate volcanism is related to the subduction of the Farrallon plate under North America between Late Cretaceous to Early Paleogene time. The outcrops of this unit on the U.S. side of the TSCAS primarily form NW-SE-trending belts in the northeastern Santa Rita Mountains and in the southwestern Canelo Hills. These rocks consist of andesitic to rhyolitic volcanic rocks intercalated with conglomerate and sandstone (**Klvs**). In the western Canelo Hills and the Santa Rita Mountains, Cretaceous rhyodacitic tuffs (**Kr**) with andesitic-dacitic volcanic breccia (**Ka**) predominate. Outcrops of intercalated rhyolitic to andesitic flows, pyroclastic and some clastic rocks near Patagonia, Arizona, (**Tlv?**) probably correspond to this volcanic phase.

Tertiary Intrusive Complex (Kd, Ti, Tlp, Tlg, Tpa Gr-Gd, Tg, Kq, Tkp, TKg)

This unit includes a series of intrusive felsic bodies of Late Cretaceous to Eocene age, present on both sides of the TSCAS. In Mexico, such intrusions (**Tpa Gr-Gd**) are widely distributed, mainly on the west side of the Sierra Mariquita, and in the El Chivato and San Antonio Mountains, as well as the eastern portion of the Sierra El Pinito. These igneous rocks are medium-grained phaneritic and porphyritic granite-granodiorite and vary in color from light gray-white to gray-green and pink. They consist of K-feldspar, albite-oligoclase, quartz, biotite, and secondary sericite, chlorite and hematite. Damon et al. (1983) considered these intrusions to form part of the Sonoran Laramide Batholith (90-40 Ma), a series of felsic intrusions of Late Cretaceous to Eocene age, and the main expression of the Mesozoic-Paleogene magmatic arc in Sonora. Component bodies of the batholith have been dated by several researchers, yielding ages of 64 Ma using U/Pb, Rb/Sr and Sm/Nd methods (Wodzicki, 1995), and a U/Pb age of 64 ± 3 and 69 ± 1 Ma (Anderson and Silver, 1977) in outcrops from the Cuitaca-Cananea region. In the U.S. portion of the TSCAS, this unit is mainly represented by granitic intrusions in the Patagonia Mountains (**Tlg**), as well as diorites and quartz diorites in the central Santa Rita Mountains (**Kd**), where this unit also includes a series of porphyritic and aplitic felsic intrusions (**TKp**) and rhyolitic to rhyodacitic intrusions (**Ti**). Also included in this lithodemic unit are granodiorite (**Kg**) and quartz-monzonite (Kq) in the northern Santa Rita Mountains, and Late Cretaceous to Eocene granite to monzonite, granodiorite and diorite (**TKg)** from west of the Atascosa, and latite porphyry (**Tlp**) from south of Patagonia, Arizona. The youngest rocks in the unit are granitic stocks (**Tg**) that intrude the Cretaceous-Paleocene volcano-sedimentary unit (**Tlv**) between the Patagonia Mountains and the Canelo Hills. This unit, along with co-eval early Tertiary volcanic units (described below) host and/or are the source rocks of extensive Laramide-age mineralization in the TSCAS which includes most of the Patagonia, southern Santa Rita Mountain.

Tertiary Volcanic Unit (TmTR-R, Tv, Tva, Tva?)

This unit includes Paleogene rhyolitic outcrops that are widely exposed in both portions of the TSCAS. In Mexico, the unit is exposed on the north side of the El Pinito and El Chivato Mountains where it consists of pseudostratified rhyolitic tuff that is light gray with cream and light gray tones. It contains quartz, feldspar, plagioclase, biotite crystals, and volcanic lithic fragments in a vitreous-crystalline matrix. Locally, it is intercalated with tuff breccia and agglomerate. It also includes gray, flow-banded rhyolite consisting of quartz, glass, feldspars and iron oxides in a glassy-spherulitic matrix (**TmTR-R**). An Ar/Ar age of 28 Ma (Floyd Gray, U.S. Geological Survey, oral communication, 2012) combined with stratigraphic position suggest that it corresponds with the latest Oligocene to the Early Miocene. On the U.S. side of the TSCAS, similar outcrops occur in the Tumacácori and Atascosa Mountains. Typical rocks of this unit are exposed in the Grosvenor Hills, where they consist of pale red to pink rhyolite and rhyodacitic tuff, vitric lithic tuff, agglomerate, flow breccia, and latite. Page et al. (2016) reported Ar/Ar ages for this unit from 27 to 23 Ma (**Tv**). In the Tumacácori Mountains, the unit includes flows, pyroclastic rocks and intrusive porphyries of andesitic-dacitic composition, and volcanic porphyries with the same composition (**Tva, Tva?**), with ages between 24 and 39 Ma.

Tertiary Volcano-sedimentary Unit (TmCgp-Ar, Tm Ar-Lu, Tm Ar-B, TmCgp-B, Tm Cgp, Tuc, Tc)

The Paleogene volcano-sedimentary sequence of the Nogales Formation in the U.S., and those units considered part of the Baucarit Formation on the Mexican side, were combined in this work as part of the Tertiary volcano-sedimentary unit. For the hydrogeological purpose of this study, this unit is considered as part of the bedrock, given that it is variably lithified, tilted by a late Tertiary extensional event, and faulted. This unit is overlain by Pliocene-Quaternary unconsolidated sediments that make up the TSCAS regional alluvial aquifer.

The unit includes a sequence of continental rocks dominated by conglomerates with intercalations of sandstone, lutite, tuff, and basalt, which are predominantly present in the central TSCAS. On the Mexican side, this unit consists of conglomerate with intercalations of sandstone (**TmCgp-Ar**) and is exposed south of Ejido Miguel Hidalgo and west of the Sierra El Chivato. The conglomerate is light brown, well-consolidated, with subangular and subrounded variable-sized clasts of rhyolite, granite, andesite and andesitic tuff, within a sandy tuffaceous matrix. The sandstone lenses and strata are the same light brown color. It is also represented by polymictic conglomerate with intercalations of basalt (**TmCgp-B**), on the left bank of the Santa Cruz River southeast of Nogales and to the northeast of the Sierra El Chivato. In these localities, the conglomerate occurs as light brown, well-consolidated medium strata containing subangular clasts of rhyolite, rhyolitic tuff, granite and quartzite in a sandy matrix. Locally, the matrix is mainly tuffaceous, with sandstone layers and lenses. This unit also includes basalt flows containing olivine and calcite-filled vesicles that appear interstratified with the polymictic conglomerate. These rocks are considered part of the Baucarit Formation in Sonora (Dumble, 1900; King, 1939), which formed from the sedimentary basin fill of extensional basins generated during the Miocene. In the southeastern portion of the Sierra El Pinito, this unit includes a fine- to medium-grained, thinly bedded clastic sedimentary sequence consisting of alternating sandstone and shale with local tuffaceous and conglomeratic members and layers of fibrous gypsum (**Tm Ar-Lu**). The sandstone is light gray to reddish-brown and contains carbonate. The shale is light gray to yellowish-brown and includes minor thin beds of limestone and locally it has intraformational folds. A detrital sequence with intercalated basalts (**Tm Cgp** and **Tm Ar-B**) immediately southeast of Nogales is also included in this unit.

In the U.S. portion of the basin located in the Nogales, Arizona area, outcrops of the Tertiary volcano-sedimentary unit near Nogales are dominated by conglomerate and sandstone with volcanic and pyroclastic rocks (**Tuc**). In the northern Huachuca Mountains, the unit is represented by conglomerate with sub-rounded clasts (**Tc**), with minor debris flow deposits and bodies of porphyritic tuff and andesite. Simons (1974) defined these units as the Nogales Formation. Houser et al. (2004) reported $^{40}Ar/^{39}Ar$ dates for the formation to range between 13.23 and 17.38 Ma. Page et al. (2016) divided the Nogales Formation in the Rio Rico and Nogales quadrangles into three informal members, from base to top: A) Proto Canyon member: moderately to weakly consolidated volcaniclastic conglomerate and sandstone, arkosic sandy and clayey conglomerate, and gravelly claystone; B) Nogales Wash member: pervasively fractured, moderately consolidated volcaniclastic sandstone and conglomerate with abundant pumice fragments; and

C) Mariposa member: moderately to weakly consolidated calcareous, volcaniclastic sandstone and conglomerate, siltstone, claystone, with basalt flows dated at 11.67 Ma. Nogales Formation sediments were deposited by streams and debris flows on alluvial fans flanking the upper Santa Cruz basin and in playas in axial parts of the basin (Page et al., 2023).

Pliocene-Quaternary Sedimentary Unit (QTg, QptCgp)

This unit includes a series of coarse and fine unconsolidated sediments that crop out widely in the center portion of the TSCAS. They are continental sediments that consist of gravel, sand and silt that are poorly stratified or appear as a single mass. These sediments fill the Basin and Range valleys with northwest-southeast and north-south orientations and crop out along the flanking foothills. They overlay all older formations unconformably and in some locations they cover a normal fault.

Alluvium (Qal, Qg, Qhoal)

The unit includes Quaternary fluvial sediments deposited in channels and floodplains of rivers and major tributaries, which consist of unconsolidated gravel, sand, silt and clay.

4.3. Structural Geology

Compressional structures (thrust faults and folds) formed during the early and middle Phanerozoic era (Drewes, 1980) were followed by the generation of larger, more pervasive normal faults. The modern geomorphology of the TSCAS resulted from Cenozoic activity, with normal faulting the most typical structural driver. The resulting systems of faults could be important for the hydrogeology of the TSCAS because of the potential for mountain-to-basin groundwater connections.

The extensional structures within the TSCAS appear as sets of faults with two preferential orientations (Drewes, 1972 and 1980). The first is an NNW-SSE system of faults with the greatest longitudinal continuity (up to 30 km). In the Mexican portion of the TSCAS, these faults represent the boundary between the Santa Cruz basin and topographic highs in the Sierras of San Antonio and El Pinito. In the U.S., the faults bound the Santa Rita and Atascosa mountains, and the west flank of the Canelo Hills (Figure 4.1). The second family of structures has a preferential NW-SE orientation and mainly occurs in the Canelo Hills in Arizona.

Aeromagnetic and gravimetric data indicate that the Mt. Benedict fault, which controls the location of the Santa Cruz River east of Nogales, continues north below the sedimentary fill north of the Nogales International Wastewater Treatment Plant (NIWTP) (Page et al., 2016). This fault also controls the direction and location of the river in the northern portion of the basin (Gettings and Houser, 1997). A third set of NE-SW Miocene age basin and range structures prominently define the Sonoita Creek basin and alluvial channel. Sub-parallel fault and fracture zones are observed south-southeast interior to the main Patagonia fault in Pre-Cenozoic rocks (Page et al., 2016; Page et al., 2023; Menges, 1981). These faults/fractures were not mapped on larger scale regional maps but are important in their ability to transport groundwater into the interior lowlands of the crystalline mountain range. In addition, less penetrative faults and fracturing occur as a result of magma and hot late-stage fluid injection during hydrothermal mineralization events related to the Laramide orogeny. These events result in localized fracturing and/or chemical alteration that allows metal-rich fluids and gases to deposit abundant ores through the central and northern Patagonia Mountains highlands and southern Santa Rita Mountains in the TSCAS area.

4.3.1 Review of Geophysical Studies in the Arizona Portion of the TSCAS

One of the principal objectives of a hydrogeological investigative study is development of a subsurface geologic model. To create the model, subsurface information is required from wells drilled within the study area, as well as indirect information obtained from airborne and terrestrial geophysical methods. The interpretation of the data enhances understanding and enables estimates of the fundamental elements needed to develop the conceptual model including: 1) basin geometry, extent, and boundaries, defining the hydrogeological units, and the structures that affect the basin, including faults that can act either as flow conduits or as barriers; and 2) the characteristics of the sedimentary basin fill, including thickness, grain-size, lateral variations and hydraulic properties which can be interpreted as lateral and vertical flow barriers/boundaries such as the hydrogeological basement.

A series of geophysical studies in the U.S. portion of the TSCAS have helped to determine the structural configuration of the Santa Cruz basin. Lysonski et al. (1981) presented a map of the residual gravity anomaly in Arizona. Richard et al. (2007) estimated depth to bedrock in Basin and Range alluvium, based on studies of Oppenheimer and Sumner (1980, 1981). Both studies also extend over the TSCAS in Arizona. Baldyga (2001) conducted a study of gravimetry and magnetometry on the western flank of the Santa Rita Mountains. Bultman (1999) estimated the subsurface structure and geometry of the San Rafael Valley.

In the residual anomaly map of the U.S. portion of the TSCAS (Lysonski et al., 1981), at least four major negative anomalies (-40 milligal [mGal]) are identified. The anomalies probably represent the areas of greatest depth to bedrock within the basin. Two of these anomalies are oriented north-south along the present course of the Santa Cruz River, and another is present along the western flank of the Santa Rita Mountains. The fourth anomaly with a similar gravimetric response is found west of the Atascosa Mountains, in a small, isolated area between Tertiary volcanic rocks north of Bear Valley. To the east, three concentrations of anomalies between -34 and -36 mGal are found in the San Rafael Valley and north of Patagonia whereas other anomalies less than -20 mGal are located east of Nogales and northeast of the Canelo Hills.

The USGS and Mexico’s Minerals Resources Council jointly undertook one of the first binational studies in 1977. The product of this cooperation was a preliminary map of the simple Bouguer gravity anomaly of this region (Consejo de Recursos Minerales [Mexico] and USGS [1977]). In the portion coinciding with the TSCAS, the negative Bouguer anomalies in Arizona are assumed to correspond to major depressions in the basin and correspond to similar features defined by Lysonski et al. (1981). A zone with an anomaly of -160 mGal is located beneath the Santa Cruz River in Sonora. However, it is important to note that the distribution of gravimetric stations taken to generate the map in plate 3 of Gettings and Houser (1997) is concentrated in U.S. territory, with few stations on the Mexican side.

Later studies updated and expanded these results. For the San Rafael Valley, Bultman (1999, 2013) reported a maximum depth to bedrock of about 1 km near the center of the basin with shallow sediments on the north and west sides of the basin. For the unconsolidated Pliocene-Quaternary sediments representing the alluvial aquifer, Bultman (1999) reported a thickness of up to 300 m. The San Rafael Valley is a half-graben with the primary displacement along the fault to the east. On the western flank of the Santa Rita Mountains, Baldyga (2001) carried out a gravimetric and magnetometric study in the area of Cottonwood Canyon, estimating a thickness of 200 m of sediment that increases in depth toward the west, overlying normal-faulted bedrock. Gettings and Houser (1997) used the residual gravity anomaly field to calculate the depth to bedrock in the central portion of the TSCAS (plate 3 in Gettings and Houser, 1997). They delineated areas where sediments are thicker than 500 m in Amado, Tubac, Rio Rico, and Nogales sub-basins. Richard et al. (2007) concluded that some basins in the TSCAS have depths on the order of 490 m, although the depth of the Santa Cruz basin near Amado probably exceeds 950 m. More recently, Bultman and Page (2016) used previously published aeromagnetic and gravity data, Bouguer gravity anomalies, and conductivity-depth transformed from a transient electromagnetic survey to interpret the bedrock morphology and structure of the upper Santa Cruz Basin between Rio Rico and Nogales, Arizona. Their estimates of depth to bedrock were consistent with those from previous studies.

4.4. Geophysical Modeling and Analysis of Basin Structure in the Sonoran portion of the TSCAS

Efforts to determine the structure and depth of the Santa Cruz Basin in Sonora have been limited. For the Mexican portion of the TSCAS, the study "Actividades Hidrogeológicas en el Acuífero Santa Cruz, Estado de Sonora, Primera Etapa" (Hydrogeological Activities in the Santa Cruz River Aquifer, State of Sonora, Phase I), prepared in 2011 by UNISON (Minjarez et al., 2011), included geophysical assessments. This section of the chapter presents the gravity modeling used to generate a generalized view of basement geometry. The model was based on gravimetric profiles from a ground survey made along the Santa Cruz River. In the Sonoran portion of the study area, gravity surveys were conducted along the eastern, southern, and western reaches of the Santa Cruz River (Figure 4.3). Gravity models were created and evaluated separately for each of these three reaches. The gravimetric profile located on the east side of the Sierra San Antonio is oriented N-S and consists of 10 stations (Figure 4.4). In the southern half of the residual anomaly map (Figure 4.4), there is a gravimetric low at the southern limit of the profile, bounded to the north by a pronounced high; this behavior is interpreted as the product of a normal fault, with depth to bedrock in the downfaulted block to the south reaching about 800 m. The northern half of the profile corresponds to a basin with a shallower irregular basement affected by buried structures. Model results predict a maximum depth to bedrock of 450 m between stations 36 and 46, and at station 32 (Figure 4.4). Along the western reach of the river, a thirteen-station profile with NNW-SSE orientation was modeled (Figure 4.5). The residual anomalies indicate depths to bedrock up to 400 m in the center of the profile, and similar to the previous survey, a gravimetric high next to a gravimetric low in the southeastern part, interpreted as a depth to bedrock of 600 m south of a buried structural high (Minjarez et al., 2011)

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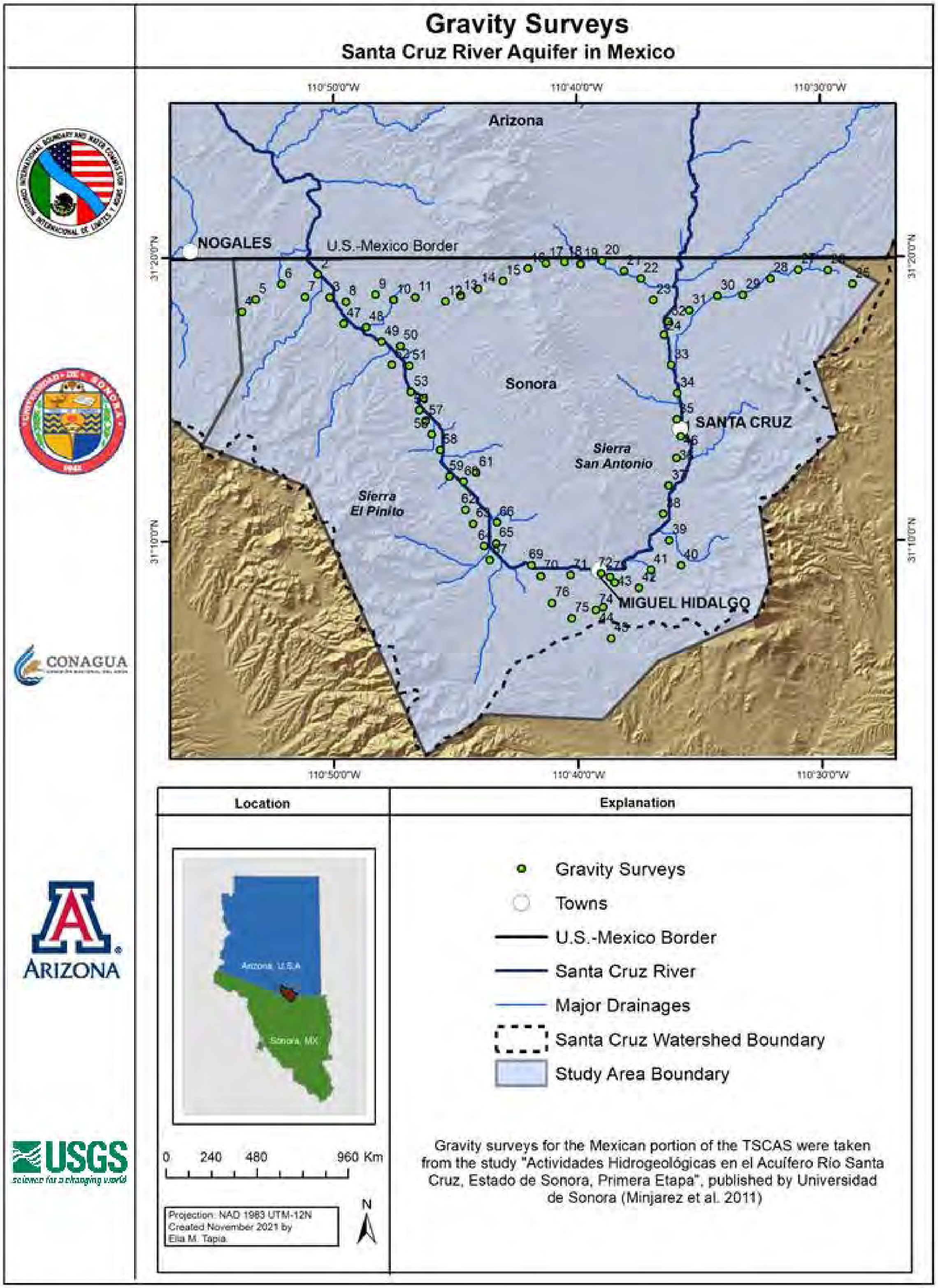

Figure 4.3 Gravity Surveys in the Santa Cruz River Aquifer in Mexico.

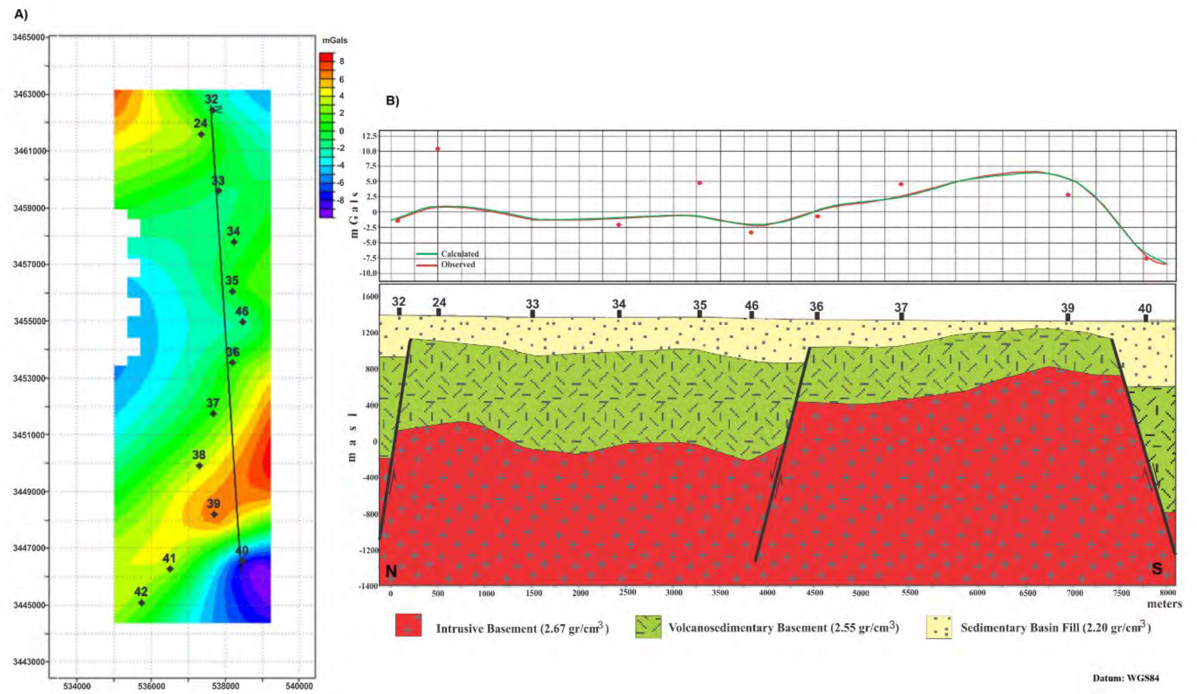

Figure 4.4 Map and cross section of residual anomaly (A) and gravimetric N-S profile (B) along the Santa Cruz River on the east side of the Sonoran portion of the TSCAS.

The east-west oriented gravimetric profile along the southern reach of the river includes 6 stations (Figure 4.6). The negative residual anomaly at station 40 (Figure 4.6) corresponds to the negative anomaly identified at the southern end of the eastern profile (Figure 4.4). The modeled depth to bedrock is around 450 m at station 71, increasing to more than 700 m towards the eastern end of the profile at station 40.

The horst and graben system is well defined in the Sonoran part of the TSCAS, where uplifted tectonic blocks correspond to the Sierra El Pinito and Sierra San Antonio. These mountain ranges consist of Mesozoic volcanic rocks, and Tertiary volcanic and intrusive rocks. They are bounded by regional normal faults and separated by elongated valleys filled mainly with Tertiary and Quaternary sediments which represent semi-graben and graben-type extensional basins. These features have been preliminarily mapped by the Servicio Geológico Mexicano (2000). The system of northeast-southwest lineaments and faults is expressed primarily in the rectilinear layout of the major rivers and streams. Based on the gravimetric analysis, depth to basement increases from the border north into Arizona (refer to Section 4.3), as well as from this boundary south into the Mexican portion.

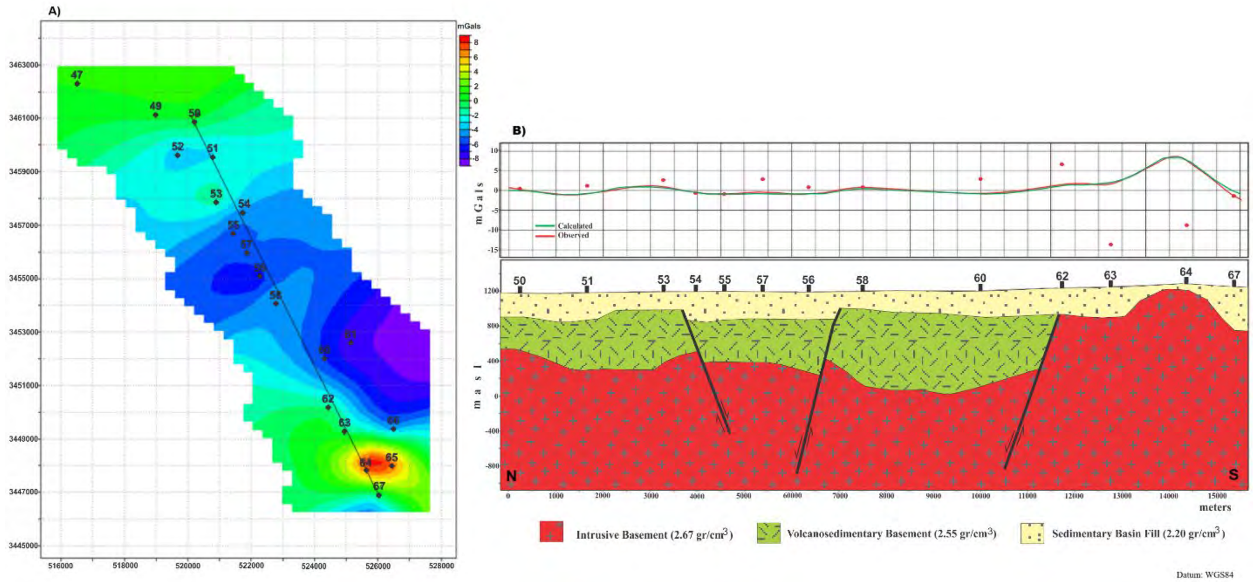

Figure 4.5 Map and cross section of residual anomaly (A) and gravimetric N-S profile (B) along the Santa Cruz River on the west side of the Sonoran portion of the TSCAS.

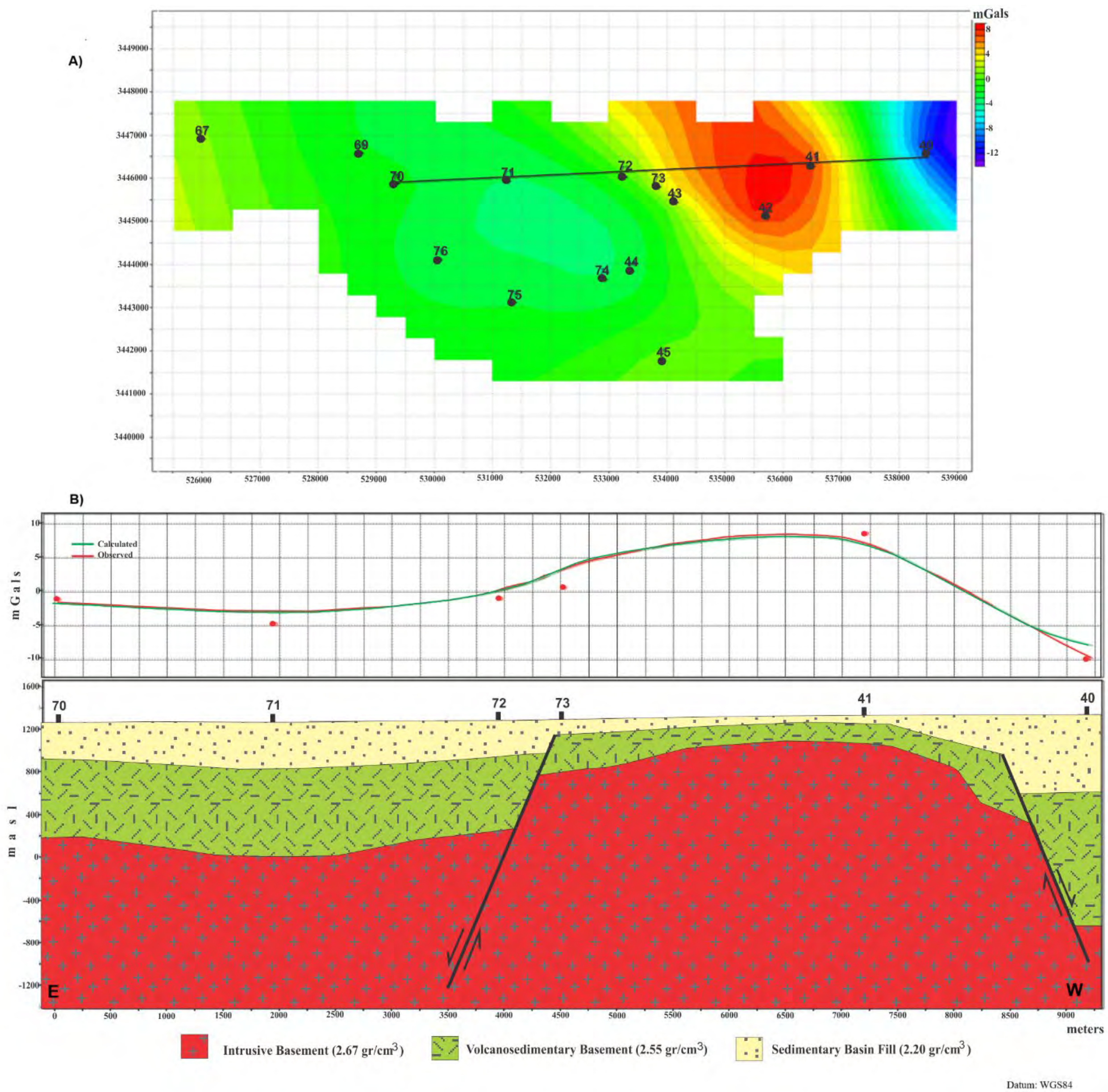

Figure 4.6 Map and cross section of residual anomaly (A) and gravimetric E-W profile (B) along the Santa Cruz River on the south side of the Sonoran portion of the TSCAS.

4.5. Characteristics of the Sedimentary Fill

In the Arizona portion of the TSCAS, the Nogales Formation (refer to Section 4.1) is a Miocene conglomeratic sequence that represents early stages of sedimentation in Tertiary extensional basins of the region. In the TSCAS, its thickness ranges from 900-1000 m in the deepest part (Amado sub-basin, north of Tubac) to 240 m between the Tubac and Rio Rico sub-basins (Gettings and Houser, 1997; Nelson, 2007). The Pliocene-Quaternary Sedimentary Unit (refer to Section 4.2), ***(QTg, QptCgp)*** consists primarily of Pliocene to Pleistocene sand and gravel deposits with moderate to poor consolidation. It has a thickness of up to 60 m along the reach of the Santa Cruz River located between the border and the NIWTP, with distribution and thickness increasing to the north, reaching a maximum of between 260 and 365 m (Gettings and Houser, 1997; Nelson, 2007). Above this unit and along the river channel, the younger alluvium ***(Qal, Qg, Qhoal)*** is composed of Quaternary sediments with little silt or clay, and with a typical thickness of between 10 and 45 m. The regional aquifer is contained within these two units and has been used for crop irrigation and mining since the early twentieth century (Nelson, 2007).

In the San Rafael Valley, the unconsolidated sedimentary basin-fill is thin with a thickness of approximately 100 m coming off the slopes of the Patagonia Mountains in the west, which increases to 300 m towards the center and east side of the valley. The gravity model presented by Bultman (1999) indicates a maximum thickness of almost 1 km for the combined Nogales Formation and upper sedimentary basin fill.

The basement rock in the Sonoita Creek basin consists of Precambrian and Mesozoic rock overlain by Paleogene sedimentary and volcanic rocks. The overlying sedimentary basin fill consists of detrital, alluvial and fluvial deposits, Quaternary alluvium with a thickness of up to 27 m of unconsolidated gravel, sand and silt.

In the Sonoran portion of the TSCAS, the Baucarit Formation (Tertiary volcano-sedimentary unit) is partly equivalent in age to the Nogales Formation in Arizona. However, the unconsolidated Pliocene-Quaternary sedimentary fill has not been specifically correlated with the units in the U.S. portion. A transient electromagnetic (TEM) survey is summarized for the Sonoran portion of the Santa Cruz Basin to aid in the characterization of the sedimentary fill. Variations in resistivity can be related to changes in the sediment grain size, especially if additional lithological information is available from drill cores for comparison (Minjarez et al., 2011).

A 10 km-long E-W resistivity profile located in the southern portion of the basin along the Santa Cruz River was modeled using five TEM soundings (Figure 4.7). The sedimentary fill is characterized by resistivities between 6 and 36 Ω-m, and material with resistivity over 40 Ω-m is interpreted to be bedrock. These resistivity values and the different divisions outlined in Figure 4.7 and Figure 4.8 are from Minjarez et al. (2011). We propose that resistive unit U1, as defined in the profiles on the Sonoran side (Figure 4.7 and Figure 4.8), corresponds to younger alluvium composed of unconsolidated, non-saturated material such as gravel, sand, and mud. In contrast, resistive unit U2 and its subdivisions (U2a, U2b, and

U2c) correspond to sediments of the older alluvium, including clay, sandy gravel, and conglomerate. Finally, U3 represents low-permeability rock materials: U3a includes volcanic rocks ranging from non-fractured, high-resistivity zones to slightly fractured, lower-resistivity zones, whereas U3b comprises low-permeability, non-fractured intrusive rocks (bedrock). In general, the bedrock (U3b) is deeper in the western portion of the profile, in which coarser sediments, probably gravels, are found in the basal portion, with resistivities between 30 and 36 Ω-m (U2c). This unit may also contain portions of the Baucarit Formation. A substantial portion of this sedimentary fill is likely to be predominantly sandy, based on a range of resistivity between 10 and 30 Ω-m (U2b).

In TEM SC-13, at 200-m depth, the presence of a fine-grained sediment (probably lacustrine deposits) was identified by resistivities lower than 10 Ω-m (U2a). The maximum interpreted thickness of the sedimentary fill in this resistivity profile was over 400 m, which is consistent with the depth to basement defined in the gravimetric profile for this portion of the basin. Figure 4.8 shows a resistivity profile that was oriented perpendicular to the previous profile. It is based on an analysis of three TEM soundings and has a north-south orientation. In this profile, a maximum thickness of 300 m was interpreted for the sedimentary fill, with a grain-size distribution similar to the profile in Figure 4.7.

In the Ambos Nogales area on the Sonoran side, the aquifer is identified as a 100-m thick unit consisting of unconsolidated gravel, sands, and clays. The average thickness of the alluvium near Nogales Wash and other main channels is approximately 30 m. These sediments are considered part of the older and younger alluvium found on top of fractured Tertiary continental and volcanic deposits (GAS-CONAGUA, 2024).

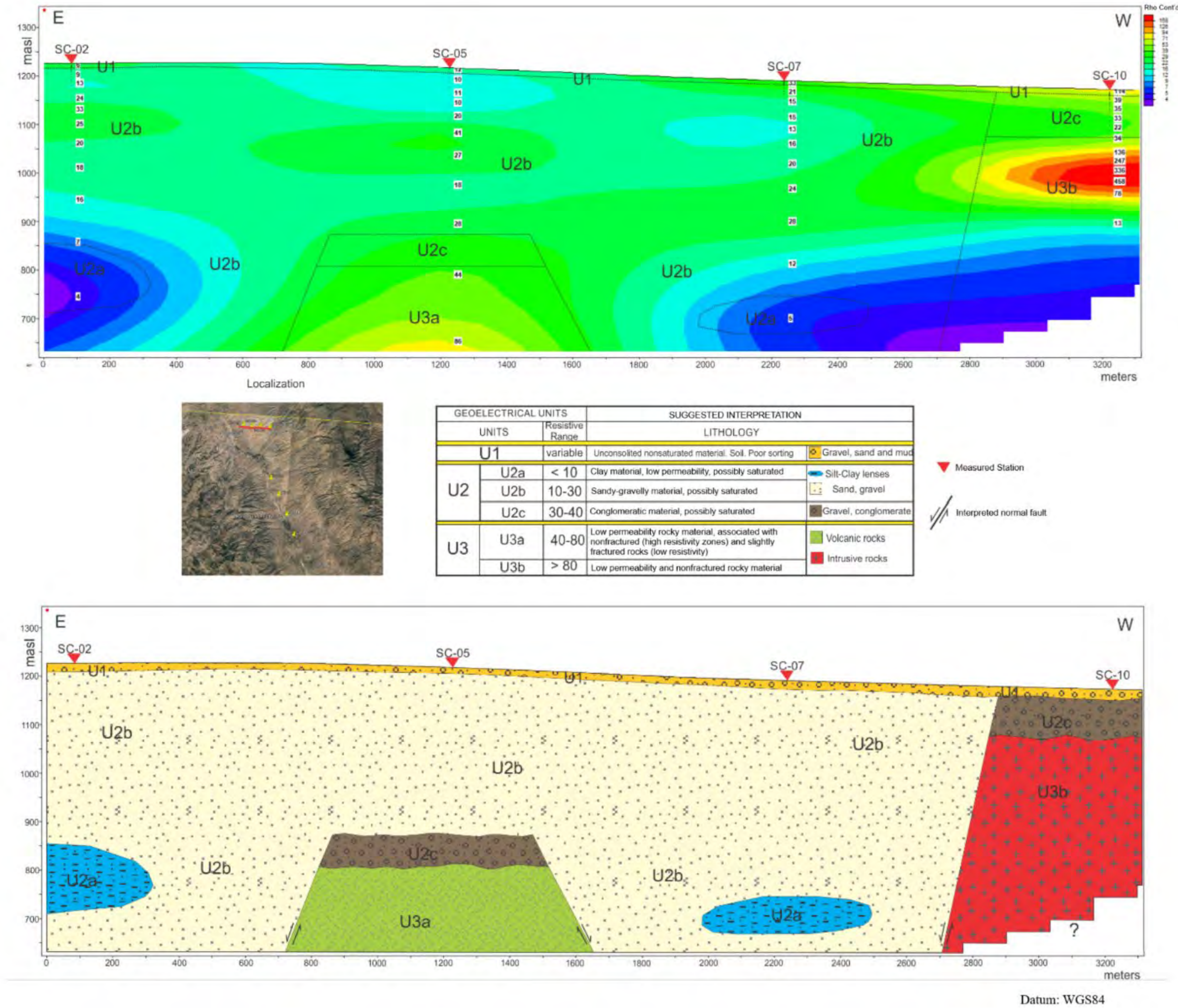

Figure 4.7 TEM-based resistivity E-W profile located in the Sonoran portion of the study area along the Santa Cruz River.

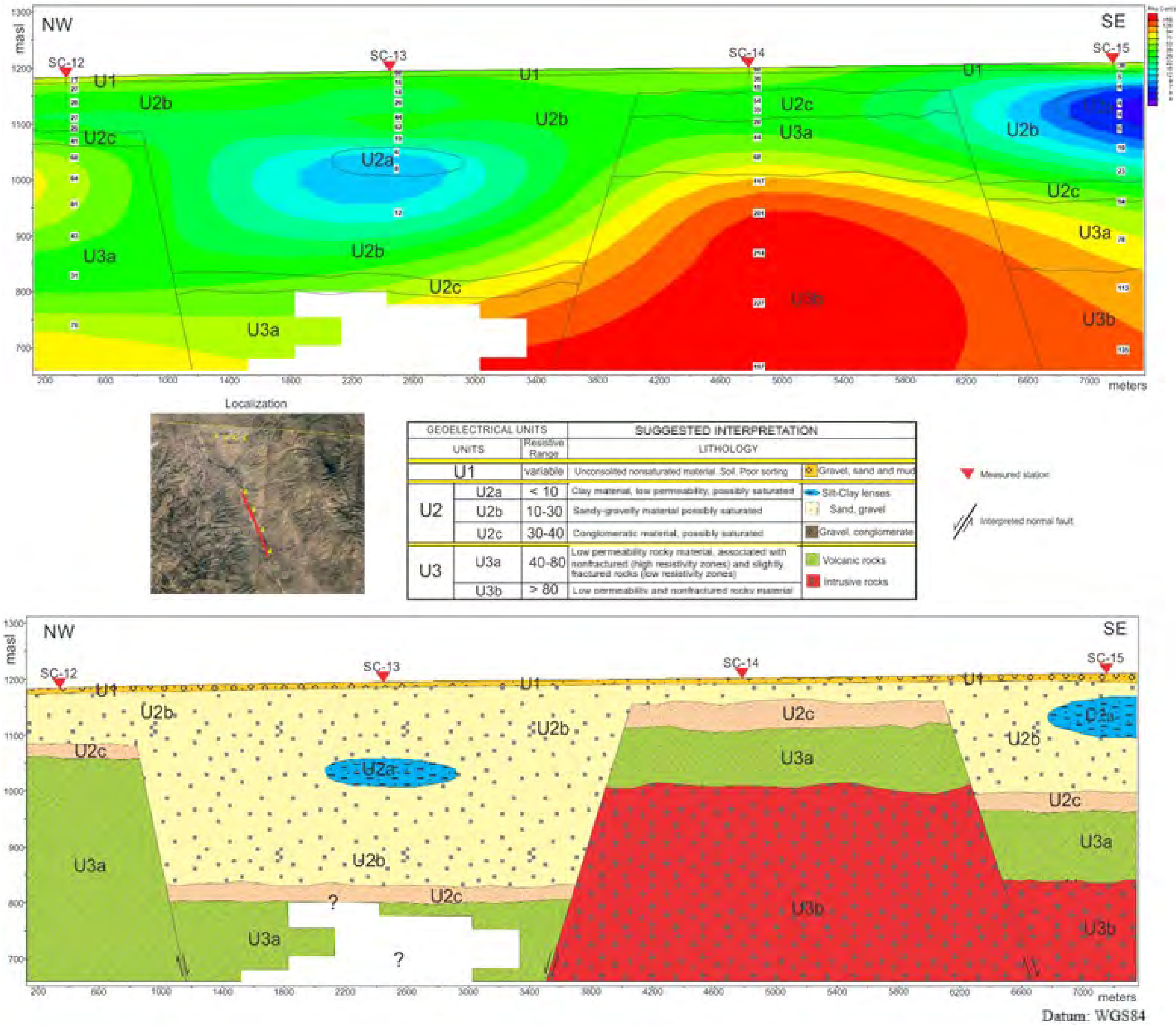

Figure 4.8 TEM-based resistivity profile located in the Sonoran portion of the study area.

4.6. Conclusions

The geology of the TSCAS area resulted from a complicated tectonic and sedimentary basin evolution in a region with great geological complexity. To simplify the mapping and description of the lithologic units on both sides of the border, a series of informal lithostratigraphic and lithodemic units are proposed.

Within the north-central portion of Sonora and the south-central portion of Arizona, the oldest rocks are part of a Precambrian basement mainly characterized by felsitic to intermediate intrusions, as well as metasedimentary rocks in Patagonia Mountains, correlated with the Pinal Schist (1,680 Ma). These rocks are covered mainly by carbonate rocks that represent shallow-water marine deposits during middle to late Paleozoic.

Triassic and Jurassic rocks within this region suggest a broad period of magmatic activity. The Triassic-Jurassic intrusive rocks of the Santa Rita, Patagonia and Tumacácori Mountains, and a Jurassic volcano-sedimentary sequence, which is exposed mainly in Pajarito and Santa Rita Mountains in Arizona and in El Pinito Mountains in Sonora, are representative of this Mesozoic event. Cretaceous rocks are mainly distributed in the northern portion of the TSCAS area and are represented by sedimentary sequences of Late Cretaceous age that outcrop to the northeast and southwest of Patagonia. Cenozoic rocks are widely distributed in both portions of the TSCAS, and include an intrusive complex, volcanic and volcano-sedimentary units of Tertiary age, as well as a Pliocene-Quaternary unit represented by clastic sediments.

The modern geomorphology of the TSCAS areas resulted from Cenozoic extensional activity including extensional high-angle normal faulting. This extensional event resulted in normal faults with two preferential orientations, NNW-SSE and NW-SE. The NW-SE trending feature represents the most recent basin and range faulting in the region.

Geophysical studies in the U.S. portion of the TSCAS area suggest a thickness of 200 to 500 m for the unconsolidated Pliocene-Quaternary units, whereas for the Sonoran portion of TSCAS a maximum thickness of 450 m is estimated for these sediments.

Planning and coordinating binational studies that use geophysical methods could refine the understanding of the temporal and spatial distribution of water and the spatial distribution of geologic materials.

Disclaimer: Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. or Mexican Government.

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5. HYDROGEOLOGY

5.1. Introduction

Geologic formations, stratigraphy, and geologic structure form the physical foundation of an aquifer. In order to conduct a hydrologic analysis of aquifers, geologic information must also be interpreted with respect to the hydraulic properties of the sediments, rocks, and strata at both local and regional scales. In this case, hydraulic properties are the characteristics of geologic units that influence groundwater flow and storage.

Features that affect flow and storage on the regional or local level include rock and sediment thickness and porosity, degree of consolidation, fracturing, lithologic continuity and homogeneity**,** and the thickness and three-dimensional configuration of rock strata and basin-fill alluvial layers. This section summarizes a compilation of what is known about the TSCAS based on previous work that defines hydrogeologic basement and hydrostratigraphy in the study area. These characteristics are embedded in a general interpretation of hydrogeology, beginning with a discussion of the bedrock, which bounds and underlies valley sediments. This is followed by the division of alluvial sediments into three hydrostratigraphic units (U1, U2 and U3), which are laterally extensive zones of similar permeability. The methods and information on depth to bedrock (or more commonly "depth to basement") and the distribution of rocks and sediments that fill the alluvial basins are discussed in Chapter 4.

5.2. Hydrogeologic Basement

The TSCAS is included in the Basin and Range Physiographic Province composed of generally north-south trending valleys separated by block-faulted mountains which act as watershed boundaries (Fenneman, 1931). In Mexican literature, the TSCAS is within two physiographic provinces: the Northern Mountains and Plains and the Sierra Madre Occidental. The rock that comprises these mountains also underlies the alluvium that fills the valleys, and it forms hydrogeologic basement underlying the primary alluvial aquifers (refer to Figure 5.1).

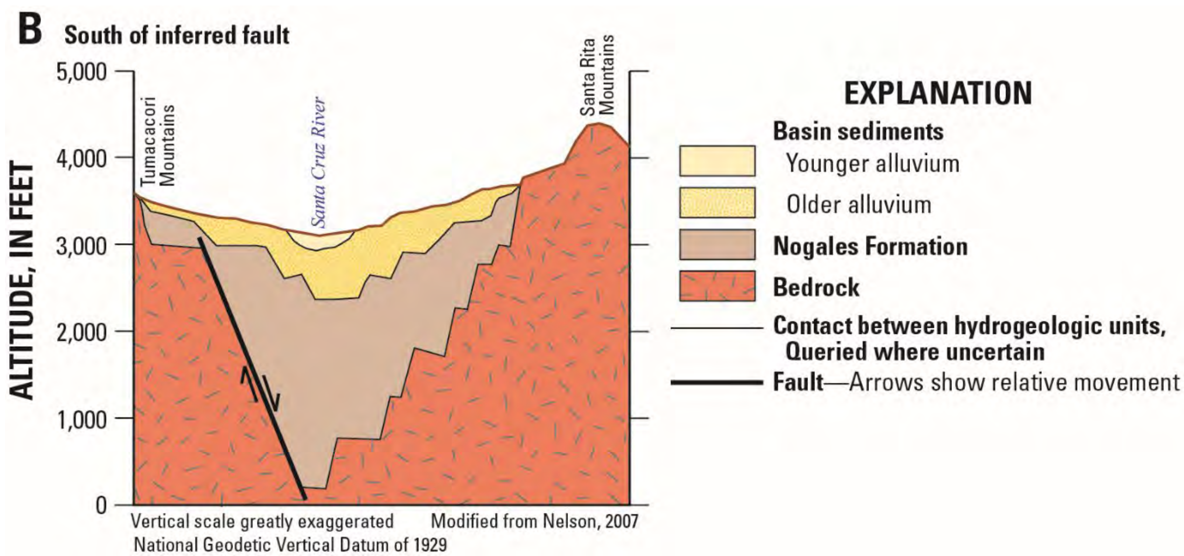

Figure 5.1 Generalized cross-section of the Upper Santa Cruz River and underlying hydrogeologic units near the northern boundary of the TSCAS within Arizona, from profile B-B' in figure 3 of Anning and Leenhouts (2010), modified from Nelson (2007).

Hydrogeologic basement in the TSCAS is generally composed of Paleozoic to Mesozoic volcano-sedimentary and sedimentary rocks, overlain and intruded by Jurassic and Tertiary granites and other younger volcanic rocks; these rocks are typically of low porosity and permeability with fracturing that locally increases their capacity to store and transmit water (Davidson, 1973). The potential for groundwater flow and storage in these rocks has not been evaluated, but the productivity of fractured-rock aquifers depends primarily on their extent (local or regional), ability to transmit water, source of recharge, and physical characteristics such as the size, connectedness, and number of fractures per unit area. Page et al. (2018) described a "Lower Basement Confining Unit" in the Ambos Nogales area. It consists of Jurassic monzonite, as well as Cretaceous sedimentary, volcanic and plutonic rocks, and Tertiary (Paleocene and Oligocene) volcanic and plutonic rocks. An example of Tertiary volcano-sedimentary sequences as part of the "Lower Basement Confining Unit" occurs in the Grosvenor Hills volcanics on the east side of the basin, which display scarce fracturing and are not highly transmissive. However, Page et al. (2018) point out that Tertiary (Oligocene) volcanic rocks, for example in Peck Canyon, can be highly fractured due to range front faulting and are observed to transmit groundwater from the highlands of Tumacácori Mountains to the basin sediments. These volcanic units of the Lower Basement Confining Unit may play an important role in the movement of groundwater through their hydraulic connection with the basin-fill aquifers. Thus, in the present study they are classified among the hydrostratigraphic units in the basin and include the Nogales Formation in the

U.S. portion of the TSCAS (Page et al., 2016a, b), and various strata associated with the Baucarit Formation in the Mexican portion of the study region.

5.3. Hydrostratigraphic Units

Hydrostratigraphic units as described by Maxey (1964) are laterally extensive bodies of rock (or alluvium) that function as aquifers and are differentiated from more indurated, crystalline units with low permeability by having distinct hydraulic properties.

Although traditionally described as aquifer units, hydrostratigraphic units are now broadly defined based on their hydraulic properties and may also include materials of low permeability. The division of an aquifer into hydrostratigraphic units supports the development of conceptual and numerical models of groundwater flow.

Anning and Leenhouts (2010) and Coes et al. (2000) indicated that the regional basin-fill aquifer in the U.S. portion of the TSCAS is composed mainly of unconsolidated sedimentary fill units. These are also the most important units in the Mexican portion of the aquifer (GAS-CONAGUA, 2024a and 2024b). They correspond to those units defined in Chapter 4 as part of the Plio-Quaternary Sedimentary Unit. In addition, fractured sedimentary and volcanic rocks function locally as important sources of groundwater in the TSCAS. Hydraulic interaction between fractured crystalline rocks and unconsolidated materials occurs primarily along fault zones and mountain-front areas, where fractures can locally transmit groundwater into the sedimentary aquifers. This includes the Oligocene volcanics mentioned above as well as in the variably consolidated and fractured rocks of the Nogales Formation.

For this study, the hydrostratigraphic units described below (Figure 5.2) were defined based on:

a) Previous hydrogeologic studies in Arizona and Sonora.
b) Their electrical properties derived from transient electromagnetic (TEM) surveys on the Mexican side (IDEAS, 2008; and refer to Chapter 4) and previously estimated hydraulic parameters on the U.S. side (refer to Chapter 6 for detailed discussion).
c) The correlation with hydrogeologic characteristics of neighboring aquifers in the Agua Prieta, San Pedro, and Bacanuchi, on the Mexican side (Minjarez et al., 2011).

Hydrostratigraphic Unit 1: This unit corresponds to coarse material (gravelly sands and sandy gravels) that is unconsolidated, poorly to moderately bedded, and moderately to well sorted. It is confined to the major stream channels in the study area and corresponds to the younger alluvium unit of Nelson (2007). This unit has the highest hydraulic conductivities in the study area. Nelson (2007) suggested a hydraulic conductivity greater than about 35 m/day for sediments in this unit in the Arizona portion of the TSCAS.

Hydrostratigraphic Unit 2: In the U.S. portion of the TSCAS, this unit corresponds to the older alluvium unit of Nelson (2007), the Miocene to early Pleistocene basin-fill deposits of Page et al. (2018), and both upper and lower basin-fill mentioned by Pool and Dickinson (2007) in the San Pedro basin. This unit is composed of unconsolidated to weakly consolidated interstratified gravels, and sandy gravel to gravelly sand. Nelson (2007) mentioned a moderate to high hydraulic conductivity for these sediments, although this likely declines with depth owing to compaction. This hydrostratigraphic unit also includes fine sediments (silt and clay) with low hydraulic conductivity that are primarily present in the form of lenticular bodies. These may create locally confined conditions in the aquifer. For example, in the Mexican portion, IDEAS (2008) identified these as low electrical-resistivity zones classified as deposits of silt and clay. In the U.S. portion of the study area, Culberston et al. (2010) identified a low electrical-resistivity zone in the Santa Cruz River reach west of Nogales, which may also be composed of fine sediments. Locally, this unit may act as a confining layer and is visible in some of the hydrogeologic sections created from resistivity profiles (Figure 5.3).

Hydrostratigraphic Unit 3: Included in this unit are fractured-rock aquifers, among which are the clastic sequences of the Nogales and Baucarit Formations. Also included are rocks that lie below these formations, such as fractured or weathered Tertiary felsic and older volcanic and intrusive rocks that could possibly contain groundwater. Hydrogeologic and stratigraphic studies of the Nogales Formation in Arizona (Page et al., 2016a, 2016b 2018) indicate that parts of the formation may provide deeper sources of groundwater for the TSCAS.

5.4. Definition of the Aquifer System

When defining an aquifer system, factors controlling the movement of groundwater need to be considered. Anning and Leenhouts (2010) found that groundwater flow into the TSCAS is similar to other Basin and Range systems in southern Arizona. For example, variations in water-level altitudes in the basin-fill aquifer tend to broadly mimic variations in land-surface elevation, such that groundwater typically flows from the basin margins toward stream channels. Often, as groundwater moves toward the stream channel and drains the valley, the direction changes so that flow converges at the stream channel, intersecting it at an acute angle with flowlines pointing downgradient toward the basin outlet.

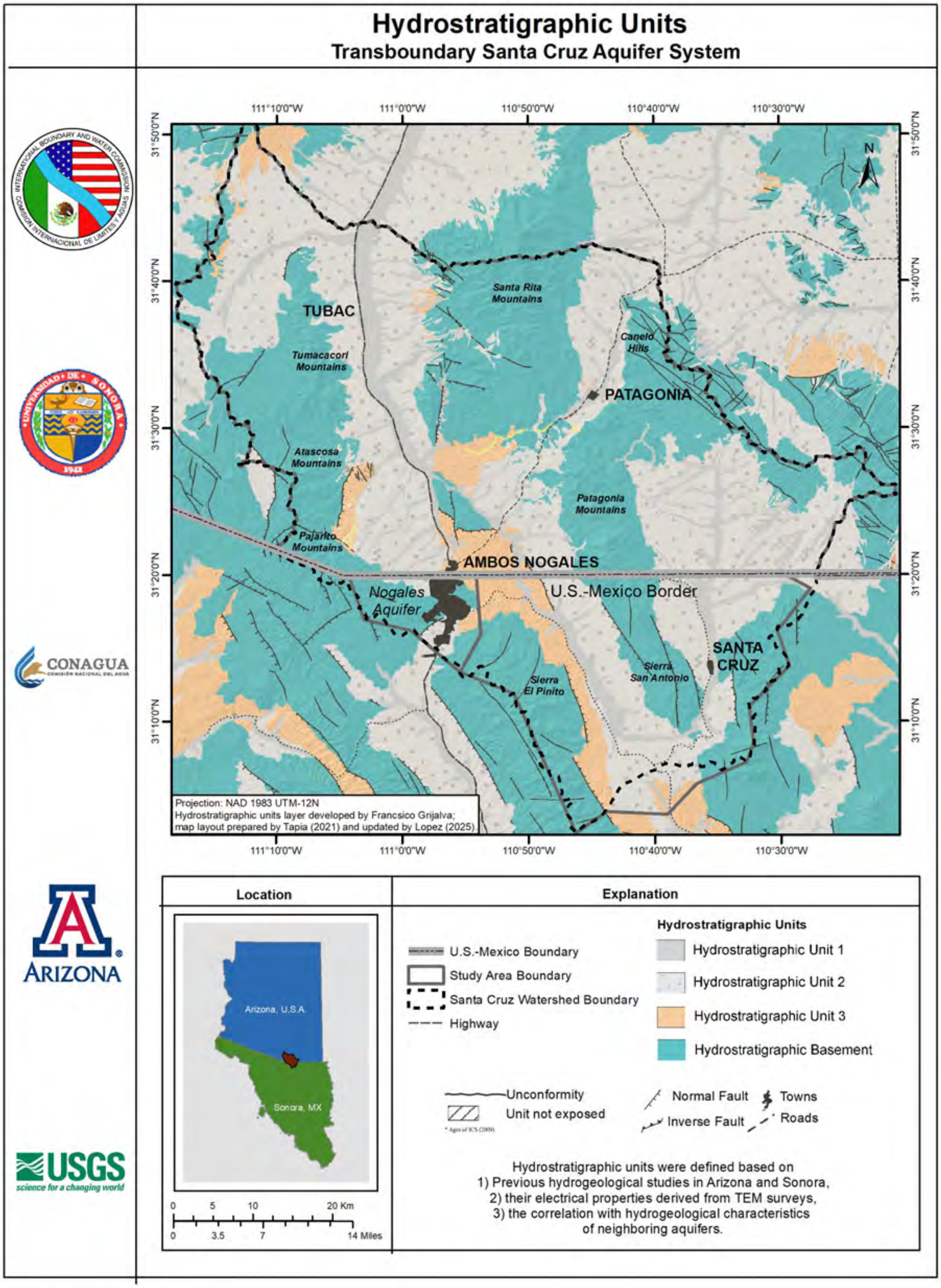

Figure 5.2 Hydrostratigraphic Units in the TSCAS.

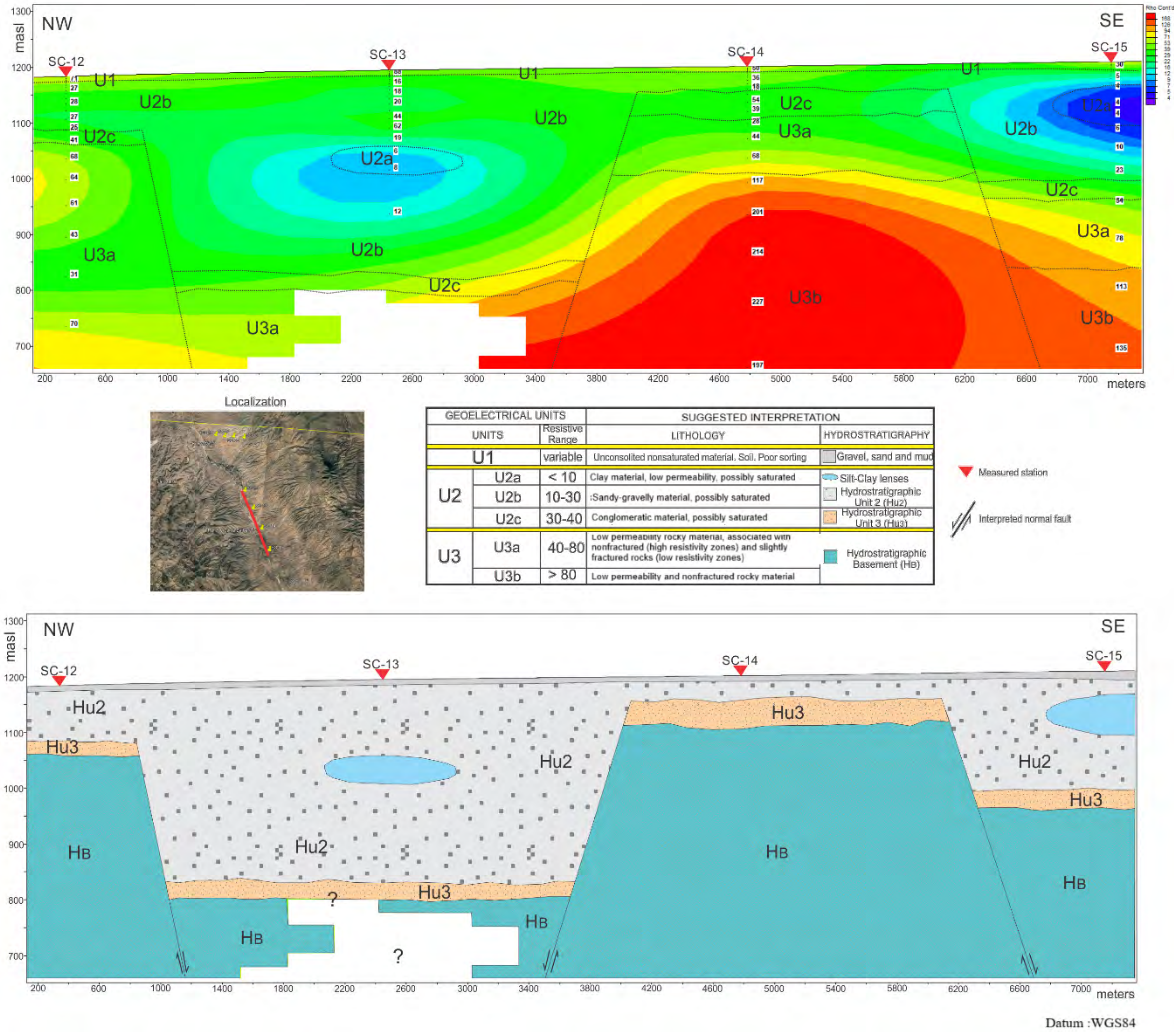

Figure 5.3 Interpreted hydrostratigraphic profile (bottom) from the resistivity profile (top) from the southwestern edge of the Sierra San Antonio on the Mexican side of the TSCAS (this was interpreted based on the data in Figure 4.7).

Groundwater, stream channels, and surface water can interact in many ways, and in the case of disconnected streams they may interact little or not at all (Winter et al., 1998). Typical interactions between groundwater and surface water, where they occur, include gaining reaches, sections along the stream channel where groundwater discharges to the river, and losing reaches, sections of the stream channel where surface water infiltrates into the aquifer. Such patterns can be affected by spatial variability of aquifer characteristics, or the presence of irrigation, recharge basins, and pumping or irrigation wells, as well as long-term climatic conditions. It is also important to understand other processes by which water enters and exits aquifers. Recharge is the process in which water from the surface moves into an aquifer and may be quantified on local or regional scales. Most recharge to regional aquifers within arid and semiarid mountainous regions occurs at the mountain-front or, more speculatively, within the mountain-block (Wilson and Guan, 2004). However, mountain-block recharge requires sufficiently active faulting, fracturing, and or shearing to be present and aligned to deliver water into the basin-fill capture zones. Removal of water from an aquifer, via processes such as evapotranspiration, discharge to downgradient basins, and pumping are all dependent to a greater or lesser extent on geology. Crystalline rocks and pre-Tertiary sedimentary and volcanic rocks in the study area are not major sources of groundwater; although they can be locally important for mining and, on a larger scale, for transporting groundwater to primary sedimentary (basin fill) aquifers in the basin.

The main aquifers in the TSCAS are unconfined, and groundwater primarily flows through unconsolidated layers of coarse sediments (hydrostratigraphic unit 2) and in the Plio-Quaternary surface deposits associated with terraces and alluvial deposits (hydrostratigraphic unit 1). These unconfined alluvial aquifers are located mainly in upper basin-fill sediments associated primarily with distal and middle alluvial fan facies. In contrast, aquifers situated in lower basin-fill sediments, which have greater thickness towards the center of the basin, are confined by zones of fine sediments of variable thickness (within hydrostratigraphic unit 2). These clay and silt rich zones strongly affect the flow of groundwater in the subsurface, including the hydrologic communication between the surface water in the Santa Cruz River and the regional aquifers, and are responsible for semi-confined or confined aquifer conditions in some parts of the TSCAS.

Tertiary conglomerates in the U.S. portion of the TSCAS are locally important as a source of groundwater (hydrostratigraphic unit 3). Some wells draw water from this unit, but they are generally low production with minimal flow. Although not often used for production wells, fracture zones in this unit may locally transport substantial quantities of water. This occurs, for example, in the micro-basins area where fractures are an important sink for water recharging the river's alluvium (ADWR, 2020).

5.5. Structural Geology

The tectonic history from the Phanerozoic to Cenozoic and to a lesser extent the late Mesozoic to Cenozoic magmatic history in the TSCAS has resulted in substantial faulting and fracturing of hydrogeologic units that are important drivers of groundwater movement (Drewes, 1980; Bultman and Page, 2016; Page et al., 2016a, 2016b, 2018). These structures of the TSCAS have the potential for internal mountain controls of groundwater in crystalline or otherwise highly impermeable basement/bedrock areas and semi-consolidated older basin-fill sediments. They regionally penetrate all hydrogeologic units except areas of latest Neogene to Quaternary deposition. Major faulting-fracturing epochs appear to occur from oldest to youngest in discrete orientations: 1) NNW-SSE system with the greatest longitudinal continuity, 2) NW-SE orientation occurring most prominently in the Canelo Hills and outcropping in the central TSCAS as the Mt. Benedict fault, and 3) NE-SW Miocene age basin and range structures, which prominently define the Sonoita Creek basin and alluvial channel (Drewes, 1980). Less penetrative faults and fracturing occur as a result of magma and hot late-stage fluid injection during Laramidic hydrothermal mineralization events. These events result in localized fracturing that allows metal rich fluids and gases to deposit abundant ores through the central and northern Patagonia Mountains highlands and southern Santa Rita Mountains in the TSCAS area. These structural features may also influence groundwater movement by creating preferential pathways or barriers within the hydrostratigraphic units.

5.6. Conclusions

This study describes the hydrogeologic setting of the TSCAS based on previous hydrogeologic and geophysical studies for the states of Arizona and Sonora, along with information available for the neighboring aquifers. For this study, we define and separate three hydrostratigraphic units: Unit 1 (~ 10–45 m thickness) consists of unconsolidated materials such as gravel, sand and mud; Unit 2 (~ 250–350 m thickness) is formed by clay, sandy-gravel, and conglomerate; also includes lenticular bodies (silt and clay) that can create locally confined conditions, and Unit 3 (thickness not defined), which contains fractured-rock aquifers that include the Nogales and Baucarit Formations. Beneath the three hydrogeologic units is a low permeability crystalline complex made up of Paleozoic to Mesozoic volcano-sedimentary and sedimentary rocks, overlain and intruded by Jurassic and Tertiary granitic and other younger volcanic rocks categorized as the hydrostratigraphic basement. Further binational geophysical studies could enhance and refine the understanding of the temporal and spatial distribution of water and the geologic materials that compose the hydrogeologic units. Additionally, hydrogeochemical and isotopic studies could help analyze the origin of the water, understanding its composition and age, as well as potentially identifying specific water-rock interactions and groundwater flow paths on different scales. These analyses could aid in determining the locations of recharge to and discharge from the aquifer. Additional studies of the Baucarit Formation (part of hydrostratigraphic unit 3) could identify areas of persistent fractures that might favor groundwater circulation and connectivity between the alluvial and rocky aquifers.

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6. PIEZOMETRIC AND HYDRAULIC PARAMETERS

6.1. Introduction and Methods

The goal of this chapter is to review existing information and publications related to piezometric data (water levels or water pressure) and hydraulic parameters (transmissivity, hydraulic conductivity, or storage coefficient) in order to understand the groundwater behavior of the TSCAS. Piezometric data and hydraulic parameters are used to calculate estimates of groundwater storage and flow. These represent the next stage of hydrologic analysis after hydrogeologic interpretation (refer to Chapter 5). Groundwater flow (or more precisely, flux) can be estimated in a variety of ways, depending on the type of flux, but all except for pumping and rainfall, require information on water-pressure gradients and transmissivity or hydraulic conductivity. This chapter presents information regarding groundwater levels and groundwater withdrawals in both the U.S. and Mexico. It describes the piezometric behavior of the TSCAS and includes a summary of hydraulic parameters for the region, such as transmissivity and hydraulic conductivity.

In Mexico, the Law of the Nation's Waters (LAN) establishes the allocation and use of water (Cruz-Ayala and Megdal, 2020). The LAN ordains that "the exploitation, use, or non-consumptive use of the nation's water resources should be carried out through a concession or asignación granted by the Federal Executive Branch or Basin Councils" (LAN, 1992, last amendment 2025). A concession is the official authorization granted by the National Water Commission (CONAGUA) to individuals or legal entities, which allows the use of groundwater up to the specified maximum concession volume for a defined purpose and period of time. Asignación is the legal term the Mexican legislation establishes for water appropriation granted primarily to public entities for public use purposes, including urban and domestic water supply. Unlike concessions, asignaciones cannot be transferred to other users (Cruz-Ayala and Tortajada, 2022). The concessions and asignaciones are registered in the Public Registry of Water Rights (CONAGUA-REPDA, 2022).

A portion of the Santa Cruz River Aquifer in Sonora (SCRAS) is subject to certain prohibitions regarding the development of new wells for an indefinite time. The prohibition is part of a decree published in the Mexican Federal Official Gazette (DOF) in 1961 stating "Resolution establishing restricted water rights for an indefinite period of time with regard to the delivery of groundwater in the region called the Santa Cruz River Basin, Municipalities of Nogales and Santa Cruz, State of Sonora", (DOF, 2015). Another portion of the aquifer is governed by the 1978 decree "Meridiano 110", that established conservation and management of groundwater resources in Sonoran aquifers for the public good (DOF, 1978). Both decrees allow limited extractions for domestic, industrial, and irrigation purposes (Minjarez et al., 2011). The Santa Cruz Active Management Area (SCAMA) is an ADWR-regulated area with an established goal of maintaining safe-yield conditions and preventing local water tables from experiencing long-term declines (ADWR, 2021).

6.2. Well Inventory and Groundwater-Level Data

The TSCAS contains approximately 522 wells with at least one depth to groundwater recorded in recent decades, from multiple data sources (Figure 6.1). In the Arizona portion, there are around 960 total wells in the ADWR Groundwater Site Inventory (GWSI), of which 401 included at least one groundwater level observation since 2000. In the Mexican portion, the REPDA database includes 276 registered wells, of which 226 are located in the Santa Cruz River Aquifer and 50 in the Nogales Aquifer. However, groundwater level data are available only for 71 wells, including 26 wells measured by Minjarez et al. (2011) and 45 wells with measurements made by CONAGUA. The distribution of these wells is shown in Figure 6.1.

In the U.S. portion, the majority of wells are located along the basin's primary rivers and streams: the Santa Cruz River, Sonoita Creek, Nogales Wash, and Sopori Wash. Many of these wells have published records (ADWR, 2025a) containing information on total depth, casing material, and depth to the screened interval, as well as a database of groundwater level measurements (ADWR, 2025b). Within the Santa Cruz Aquifer in Arizona (SCAA), the availability of lithological records varies by administrative region, ranging between 20 and 50 percent of the wells. The ADWR GWSI database contains groundwater level data collected by multiple entities, including data from ADWR "index wells", which are often instrumented with continuous dataloggers. In the Mexican portion, the CONAGUA-REPDA report (2022) indicates there were 248 registered wells as of 2022, primarily distributed along the Santa Cruz River channel (Figure 6.1). The report also includes information on 53 wells within the Nogales Aquifer System (NAS).

Figure 6.2 shows the location of the wells used to create hydrographs of the groundwater levels in the SCAMA and the SCRAS. Wells used to create the hydrographs in Figure 6.3 were selected to capture spatial and temporal trends throughout the SCAMA and the SCRAS. All wells reported for the U.S. portion of the TSCAS were taken from the GWSI database (ADWR, 2025a). Well information for the SCRAS and NAS were obtained from CONAGUA-REPDA (2024). In Mexico, it is known that the actual volume of groundwater withdrawal is often not monitored by CONAGUA and may therefore deviate from REPDA's permitted concession or asignaciones volumes (Tapia-Villaseñor et al., 2022).

For the SCRAS and NAS, we found seven uses registered: domestic, municipal supply (public-urban in Mexico), stock, agricultural irrigation services, undetermined/unknown and industrial. Although there are similarities between domestic and urban-public supply use, there are notable differences between them. Domestic use is defined by water used for watering plants, households and private residences, and self-consumption farms. Generally, it is authorized for rural communities lacking the infrastructure to provide potable water. Urban-public supply use is defined as water used to provide water supply to cities or other population centers.

For the SCAMA, we present water use information for municipal supply, domestic wells, industrial, and agricultural irrigation. Municipal includes a city, town, private water company, or irrigation district that supplies water for non-irrigation use. Domestic wells are small non-irrigation wells, typically used to provide water for domestic purposes for households not reached by municipal supply lines.

6.3. Groundwater Withdrawals

The withdrawal of water from the TSCAS began in the early 1900s, but data are limited and insufficient to adequately reconstruct the pumping history of the first half of the century. However, Nelson (2007) estimated that the maximum pumping rate in the SCAMA during the middle part of the twentieth century from all wells combined was around 25 million cubic meters per year (Mm^3/yr). The pumping rate in low-capacity wells was reported to be around 18.5 Mm^3/yr with 60% for agricultural use. There are also historical data on withdrawals from the Santa Cruz River alluvium reported by the City of Nogales, Arizona, to ADWR (Nelson, 2007). These data start in 1941 with a pumping rate of approximately 0.62 Mm^3/yr, increasing to more than 3.0 Mm^3/yr between 1977 and 1983 (Nelson, 2007). In the higher elevation portions of the SCAA, the San Rafael Valley and the upper basin of Sonoita Creek (Figure 6.3), data regarding changes in and magnitudes of groundwater pumping are sparse, but it is likely that annual pumping volumes have had minimal effect on groundwater levels and surface-water capture.

Water use in the SCAMA for the 1985-2017 period was dominated by municipal and agricultural irrigation uses. Agricultural consumption has increased through time, from approximately 1 Mm^3/yr in 1997 to approximately 9 Mm^3/yr by 2020 (Figure 6.4; ADWR 2012). Industrial uses also began in 2011, increasing the overall groundwater extraction volumes along with agricultural uses. Nelson (2007) surveyed the 1997-2002 annual reports of the region's non-exempt wells to estimate an average yearly withdrawal of 19.49 Mm^3/yr. Non-exempt wells in the SCAMA account for about 95% of the region's withdrawals. About 60% of the withdrawals occur during the summer (May-September) and 40% in the winter (October-April). ADWR (2012) projected that groundwater demand in the study area will gradually increase from ~20.97 Mm^3/yr in 2006 to ~28.37 Mm^3/yr in 2025, mainly due to an increase in municipal demand. Groundwater extractions in 2023, as reported by ADWR (2024), reached 17.059 Mm^3/yr (Table 6.1).

Table 6.1 Annual Extractions from the SCAMA for the year 2023, in Mm^3 (ADWR, 2024).

Use	Groundwater Extraction (2023)
Municipal	7.581
Industrial	1.259
Agricultural irrigation	8.219
Total	17.059

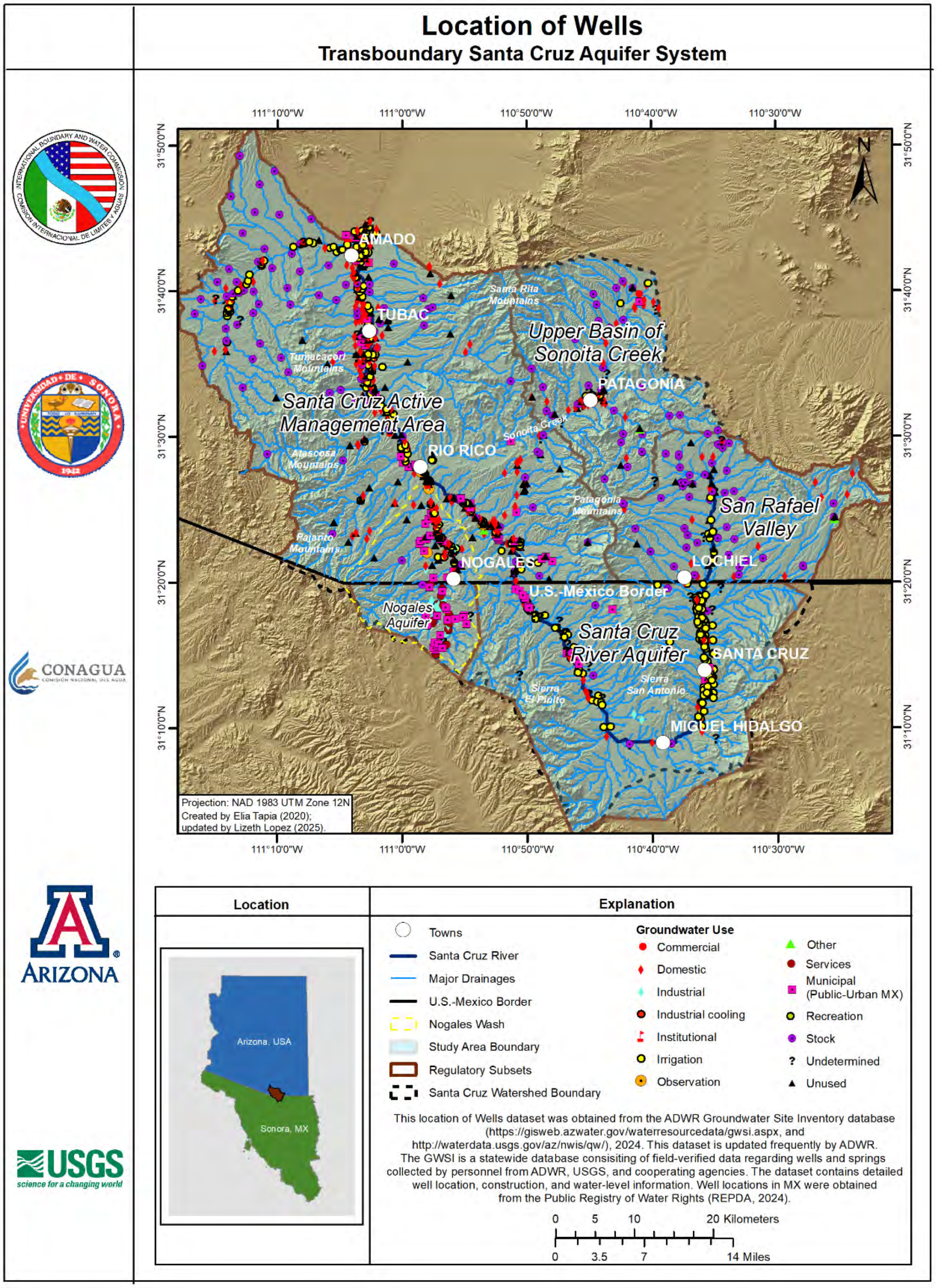


Figure 6.1 Location of wells in the TSCAS.

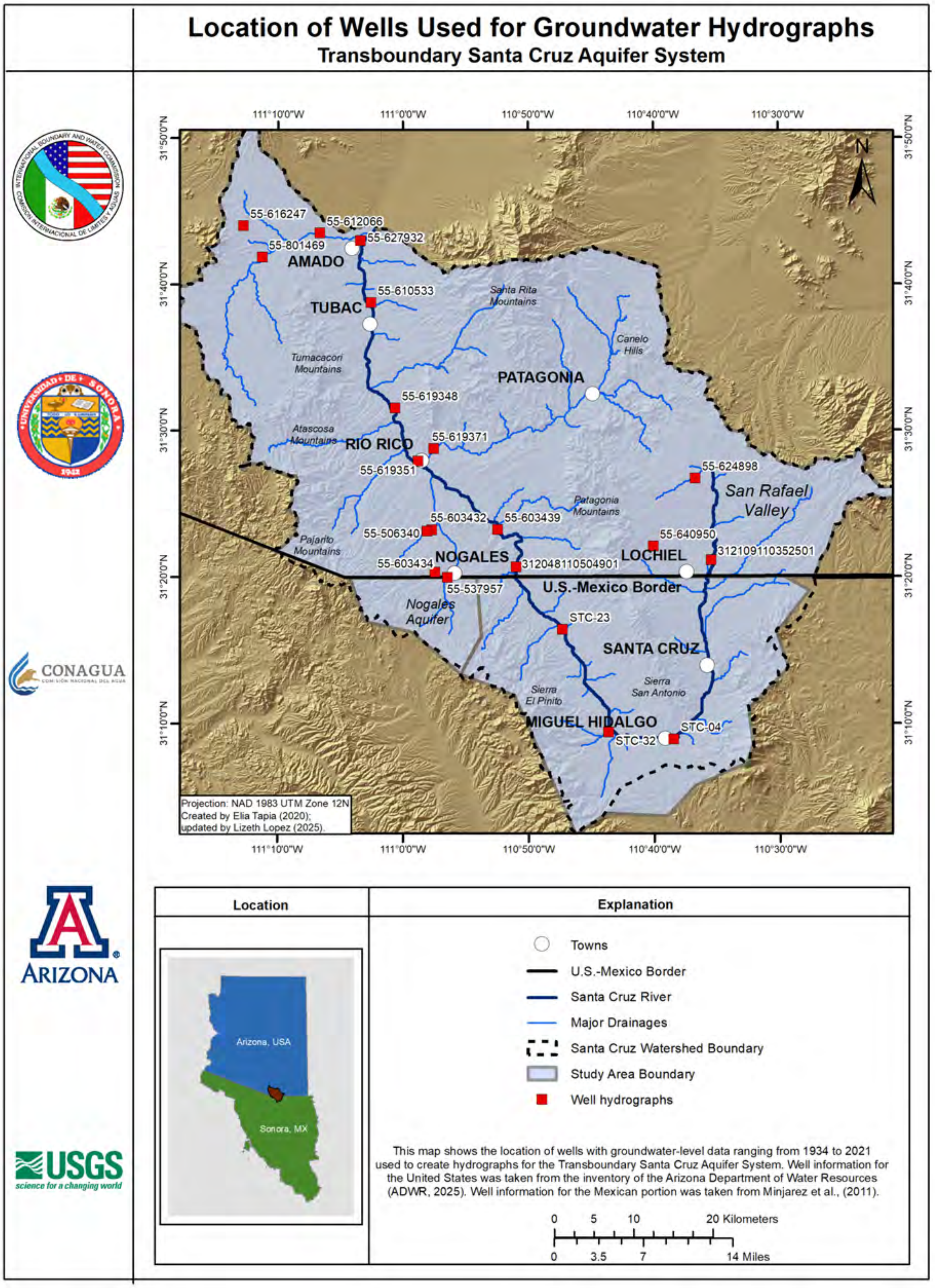
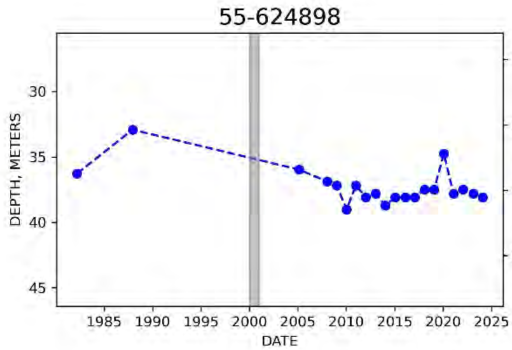


Figure 6.2 Location of wells used for groundwater hydrographs in the TSCAS.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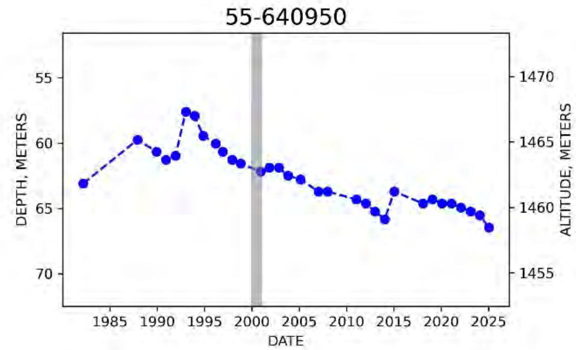
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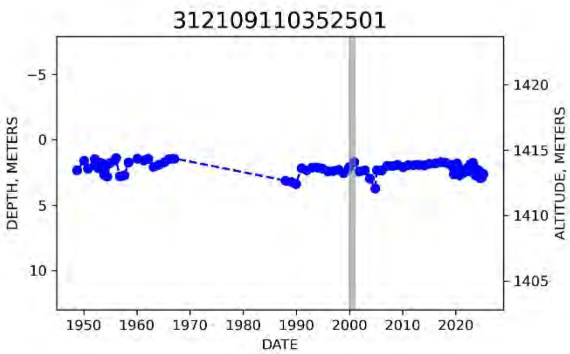
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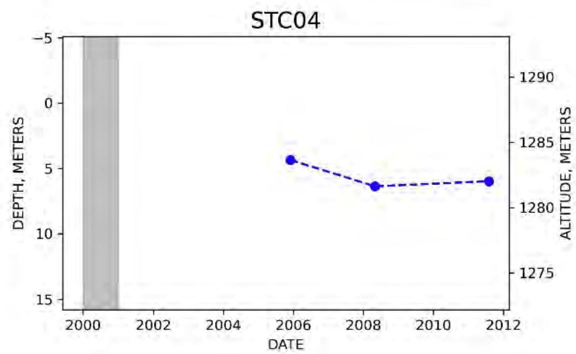
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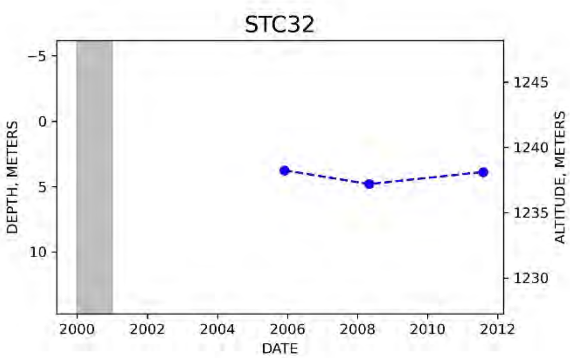
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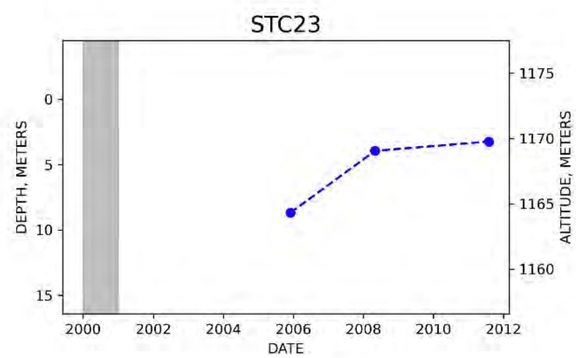
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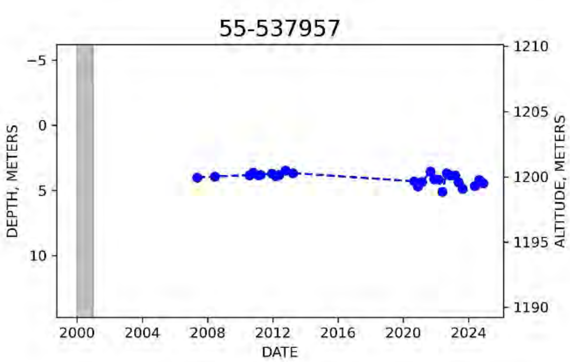
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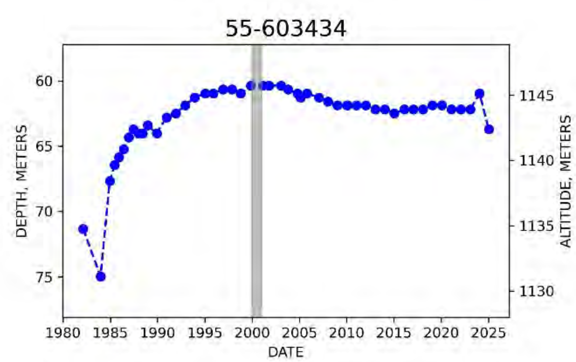
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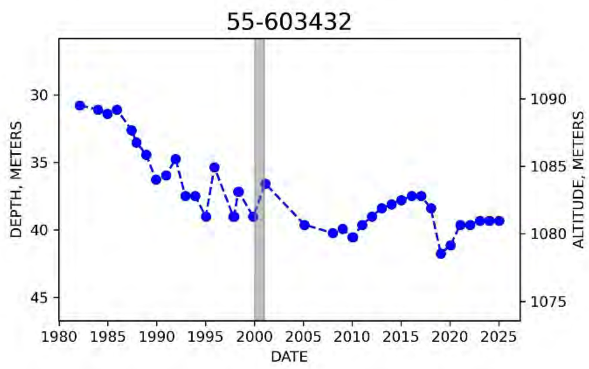
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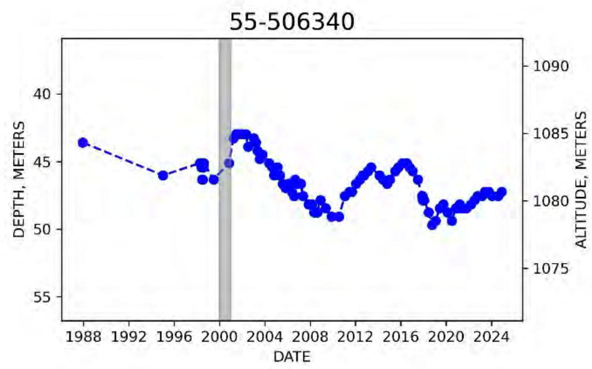
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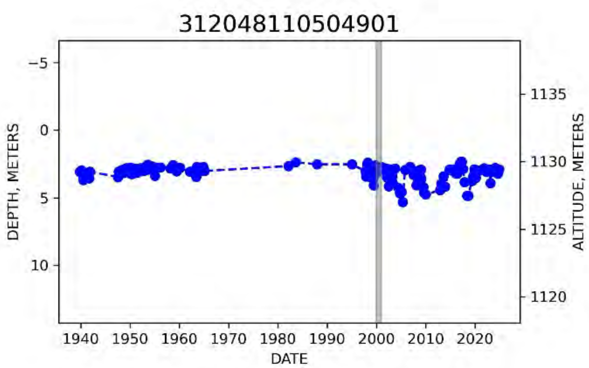
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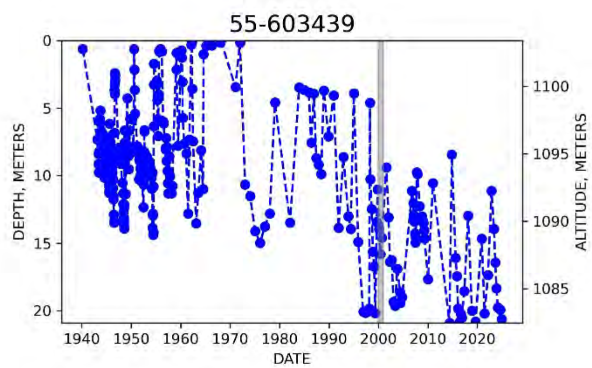
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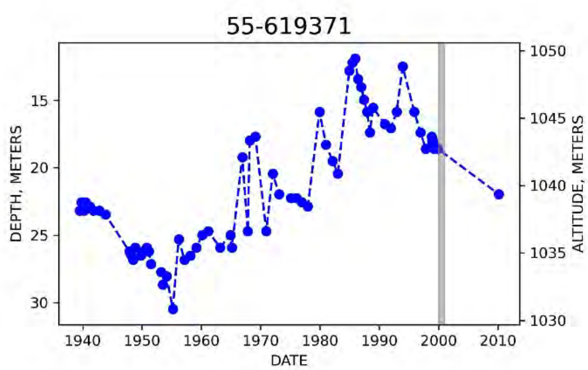
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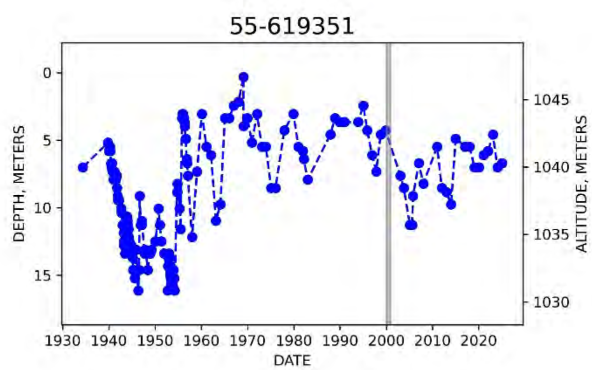
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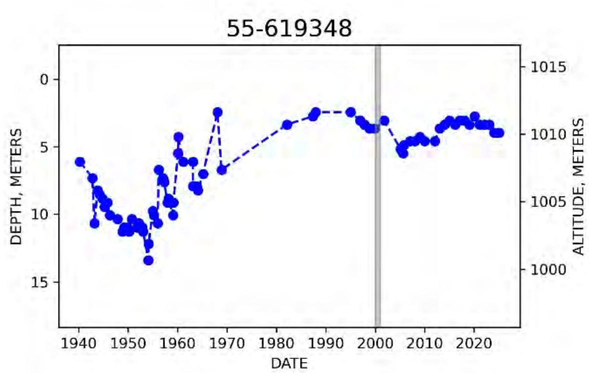
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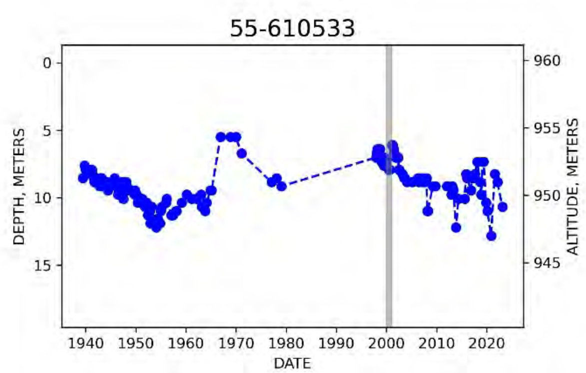
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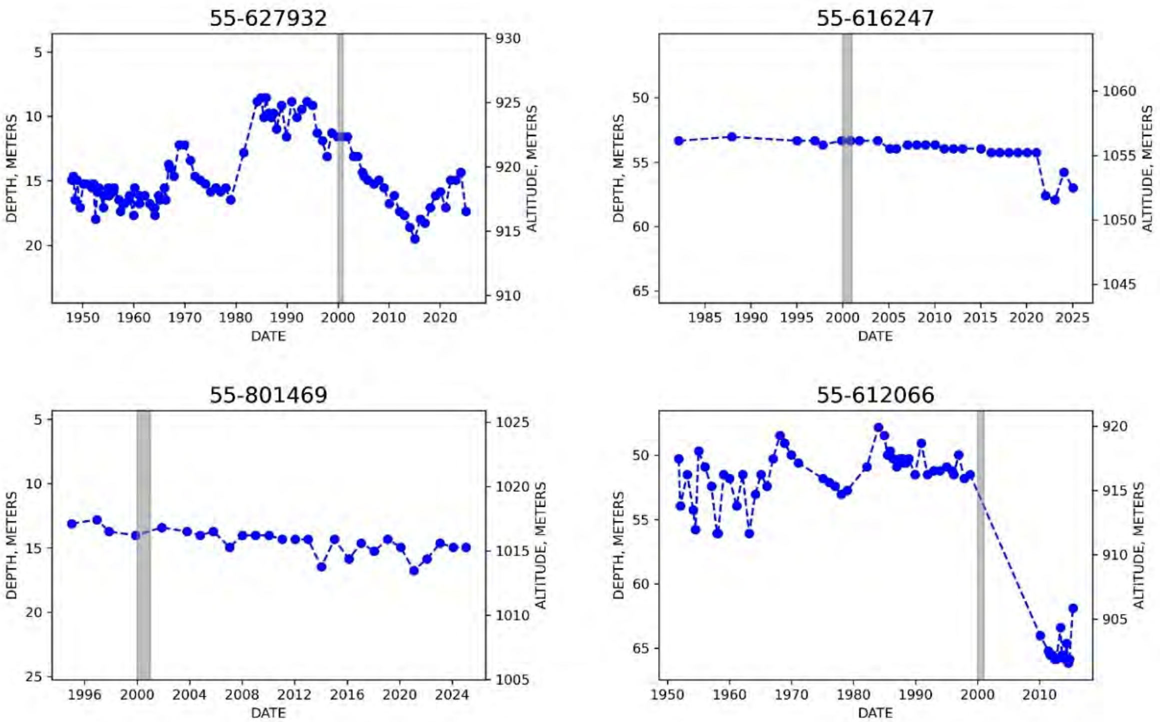

Figure 6.3 Hydrographs for selected wells in the TSCAS, showing depth to groundwater in meters on the left y-axis, and altitude in meters (NAD27) on the right y-axis (ADWR, 2025a; Minjarez et al., 2011).

The gray bar indicates the calendar year 2000, to give a sense of timescale, and y-axes encompass an identical magnitude of change across all plots (20 m). Plots for U.S. wells are titled by their ADWR Well 55 number if they have one, or by their 15-digit ADWR GWSI number if they do not. Dashed lines indicate periods without data and should not be used to interpolate or estimate actual values.

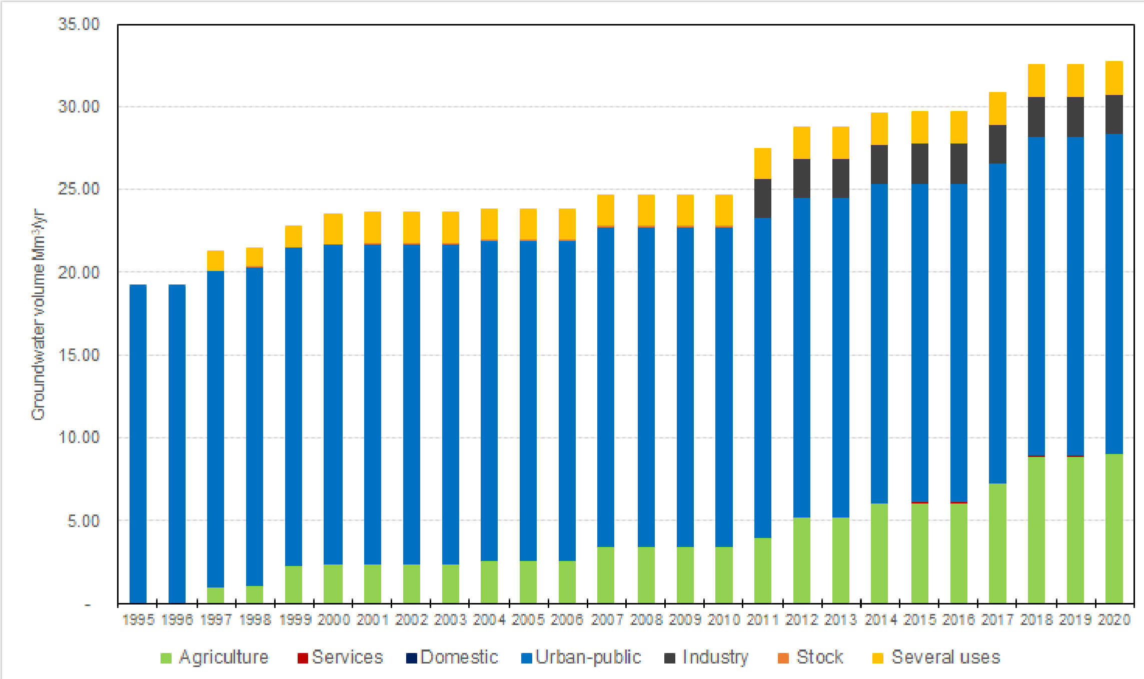

Figure 6.4 Annual groundwater extractions between 1995 and 2020 in the SCAMA (ADWR, 2020).

On the Mexican portion of the study area, there are two primary sources of groundwater information: The REPDA and the Municipal Operating Organization of Potable Water, Sewage, and Sanitation in Nogales, Sonora (OOMAPAS). Volumes and percentages of groundwater withdrawals were obtained by analyzing the available REPDA wells using GIS.

The SCRAS has an annual availability of about 2.20 Mm^3/yr, (GAS-CONAGUA, 2024a) whereas for the NAS there is a deficit of -0.86 Mm^3/yr, so there is no volume available to grant new concessions (GAS-CONAGUA, 2024b). In the SCRAS, the groundwater extraction volume has increased from 19.2 Mm^3/yr in 1995 to 33.9 Mm^3/yr in 2020 (Figure 6.5). This increase is mainly attributed to increases in concessions for agriculture from 0 in 1995 to about 8.13 Mm^3/yr in 2020. The volume of groundwater extraction in the NAS reported by REPDA is 2.4 Mm^3/yr (GAS-CONAGUA 2024b), and the volumes over time are shown in Figure 6.6; Figure 6.7 shows the combined demand in the TSCAS. Table 6.2 and Table 6.3 present a summary of the SCRAS and the NAS, respectively. Only wells that intercepted the SCRAS and the NAS were considered. Withdrawals for municipal supply (public-urban) purposes represent the primary groundwater use in the SCRAS (about 68.5% of the total concession volumes), followed by agricultural irrigation (30.8%) and stock (0.53%). In the NAS, the primary use is industrial (89% of the total concession volumes), followed by services (5.4%), stock (3.7%), different uses (1.2%), and other minor uses.

Table 6.2 Concession and asignaciones volumes for calendar year 2022, from the SCRAS in Mm^3 (GAS-CONAGUA, 2024a).

Groundwater Use	Concession Volume (Mm^3)
Agricultural irrigation	8.13
Domestic	0.04
Stock	0.14
Municipal (Public-urban)	18.09
Total	26.4

Table 6.3 Concession and asignaciones volumes for calendar year 2022, from the NAS in Mm^3 (GAS-CONAGUA, 2024b).

Groundwater Use	Concession Volume (Mm^3)
Different Uses	0.01
Domestic	0.00007
Industrial	0.73
Municipal (Public-urban)	0.008
Stock	0.03
Services	0.044
Total	0.82

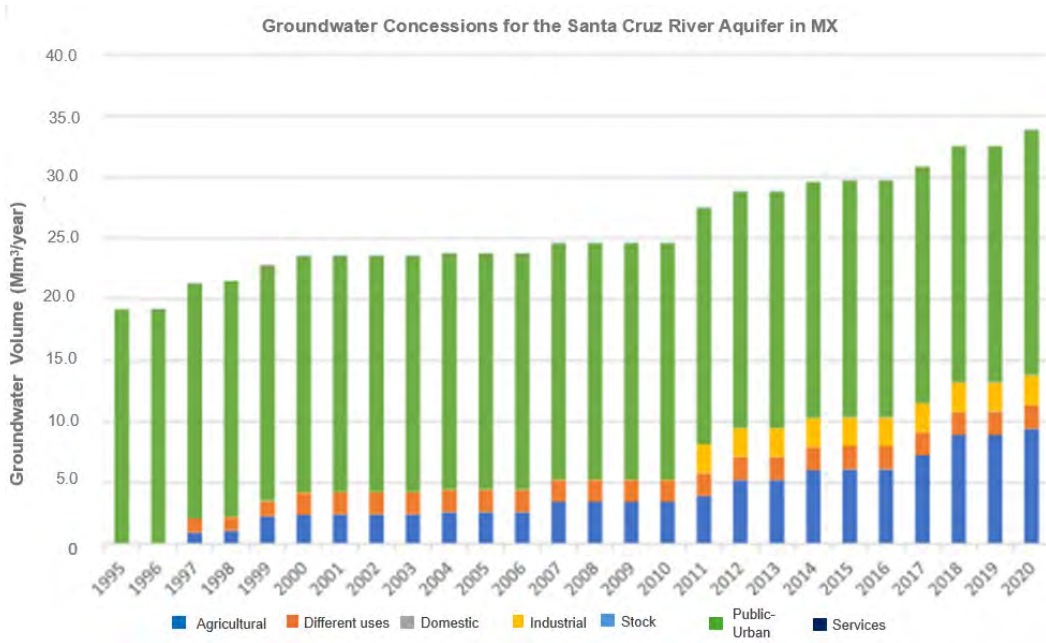

Figure 6.5 Annual groundwater concessions and asignaciones between 1995 and 2020 in the SCRAS in Mexico (CONAGUA-REPDA, 2022; Tapia-Villaseñor et al., 2022).

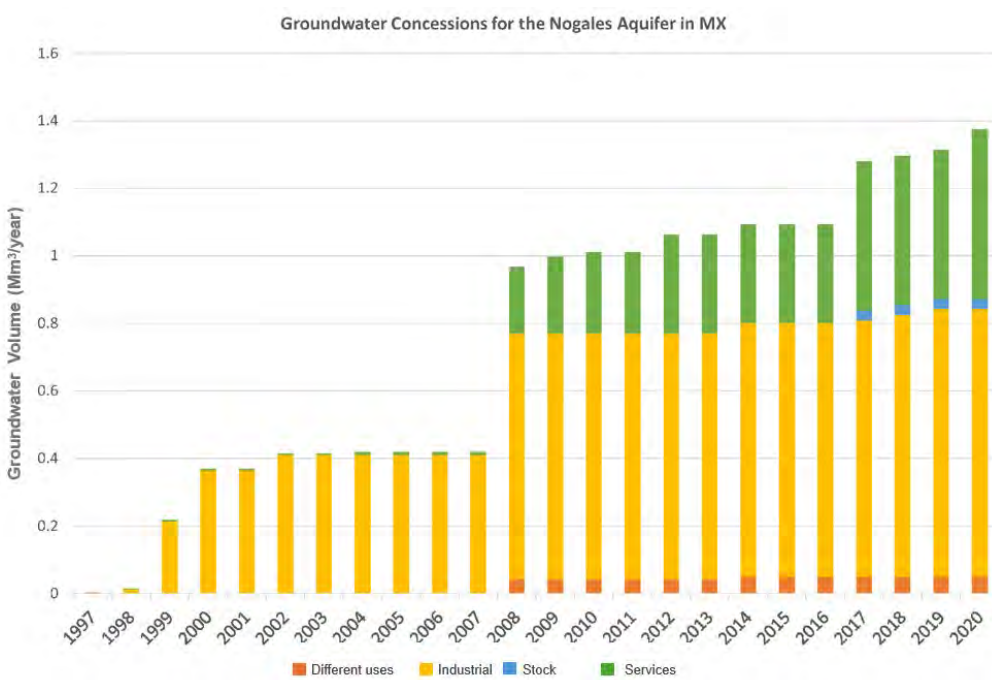

Figure 6.6 Annual groundwater concessions and asignaciones between 1997 and 2020 in the NAS in Mexico (CONAGUA-REPDA, 2022; Tapia-Villaseñor et al., 2022).

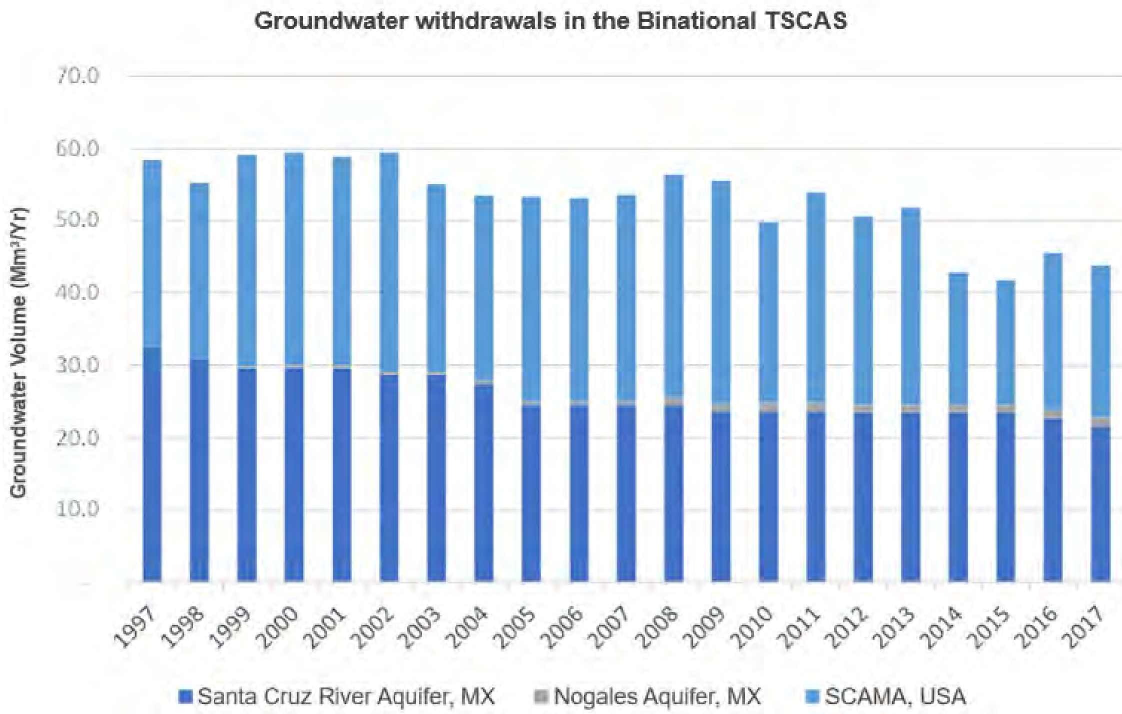

Figure 6.7 Annual groundwater withdrawals in the TSCAS in Mexico and the U.S.

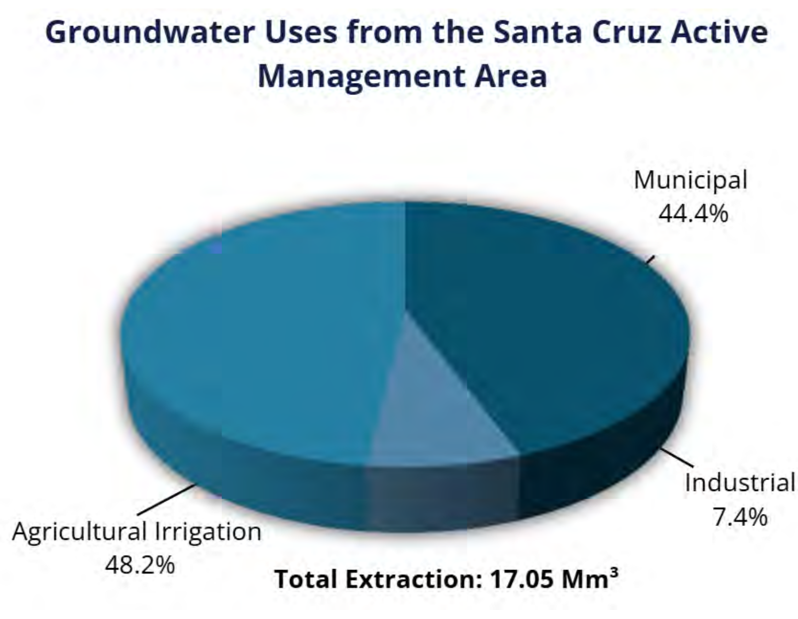

Figure 6.8 Groundwater extraction and uses from the SCAMA in the U.S. for calendar year 2023 (ADWR, 2024).

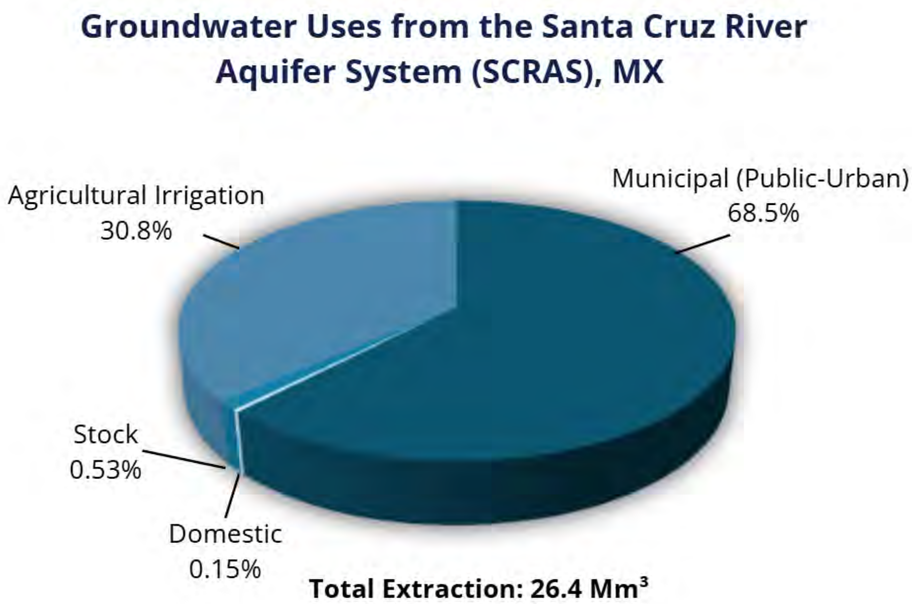

Figure 6.9 Groundwater extraction and uses from the SCRAS in Mexico for calendar year 2022 (GAS-CONAGUA, 2024).

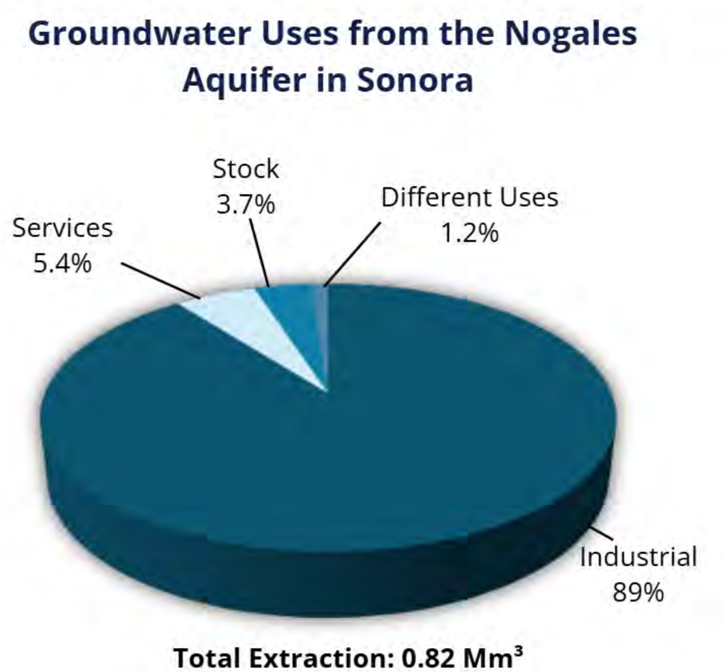

Figure 6.10 Groundwater extraction and uses from the NAS in Mexico for calendar year 2022 (CONAGUA-REPDA, 2024).

The city of Nogales, Sonora, relies on physical water and wastewater transfers from both Los Alisos Aquifer and the SCRAS. These transfers come from three different aquifers and are needed to sustain groundwater demand (Tapia-Villaseñor et al., 2020). According to OOMAPAS (written communication, 2025), the total water extraction supporting the city of Nogales is derived from three primary sources: the Santa Cruz River Aquifer (8.86 Mm³/yr), the City of Nogales well field (7.88 Mm³/yr), and Los Alisos Aquifer (9.78 Mm³/yr) (Table 6.4). Wastewater generated in Ambos Nogales is transferred to treatment plants in Los Alisos, Mexico and the SCAMA in the U.S., where is treated and discharged into existing stream channels, which contributes to groundwater recharge in the region. However, the volume, timing, and reliability of wastewater transfers are influenced by Mexican water governance structures and binational agreements between the U.S. and Mexico (Tapia-Villaseñor et al., 2020). Infrastructure conditions also affect water and wastewater transfers. For example, in 2018, a failure at the Mexican wastewater pumping station (Cárcamo de Bombeo) reduced inflows to the Los Alisos Wastewater Treatment Plant (LAWTP), with the remaining wastewater being diverted to the NIWTP in the SCAMA (OOMAPAS, 2018, oral communication; Tapia-Villaseñor et al., 2020).

Table 6.4 Physical water and wastewater transfer in Nogales, Sonora (OOMAPAS, 2025, written communication).

Source	**Amount**
Santa Cruz River Aquifer	8.86 Mm³/yr (281 liters per second [L/s])
Nogales City (Nogales Aquifer)	7.88 Mm³/yr (250 L/s)
Los Alisos Aquifer	9.78 Mm³/yr (310 L/s)
Total	26.52 Mm³/yr (841 L/s)

6.4. Analysis of Piezometric Behavior

There is little information on the behavior of the groundwater system in the San Rafael Valley and the upper basin of Sonoita Creek, but the ADWR index wells in those locations indicate slow declines over recent decades (ADWR, 2022b). In Nogales, Sonora, CONAGUA (2024b) reported changes in depth to groundwater in 17 wells between 1994 and 2005, and found that groundwater levels in most of those wells only changed by about one meter. Over this period, depth to groundwater increased by more than 5 m at only two wells, one located in the northwestern part of the city where the depth to groundwater increased ~7 m, and the other located in south central Nogales, Sonora, where depth to groundwater increased ~19 m.

A selection of wells across the SCAMA (Figure 6.3) were chosen to illustrate the groundwater-level trends in space and time (Figure 6.2). The hydrographs in Figure 6.3 are shown roughly by well location, from upstream to downstream. Looking at the hydrographs, there are a few patterns to notice. First that, as expected, depth to groundwater typically increases away from the Santa Cruz River channel, even when wells are located along tributaries. One exception is well 55-537957, located just north of the border and along Nogales Wash, which may be affected by infrastructure leakage or recharge to the aquifer from sewage or wastewater discharged into Nogales Wash. Of the wells located along the Santa Cruz River (Figure 6.2), some exhibit a relatively stable depth to groundwater (312109110352501, ST32, 312048110504901), whereas others show relatively greater fluctuations (55-603439, 55-619351) or have increasing or decreasing trends across different time periods. Factors that can influence these observed differences could include differences in well construction, local geology, nearby pumping, and proximity to the river channel.

Hydrographs from wells along tributaries that exhibit increasing depth to groundwater include two wells along tributaries in the headwaters of the Santa Cruz River (55-624898, 55-640950). In both cases, the decline over this period is relatively small, but there is an overall increase in depth to groundwater from the first measurements to the last measurements at each well. The wells along tributaries at the far downstream end of the SCAMA also exhibit relatively small increases in depth to groundwater (55-616247, 55-801469). Wells 55-603432 and 55-506340, both located along Potrero Creek, also show a trend of increasing depth to groundwater over the period of data collected but exhibit a temporary increase in groundwater levels from approximately 2010 to 2018. This could be related to large precipitation events, for example the increase shown around 2014 is likely a result of Hurricane Odile, which was a substantial source of recharge in southeastern Arizona (Uhlman et al., 2020). Similar responses from 2010 to 2018 are not in hydrographs of the other wells shown in Figure 6.3.

The greatest magnitude of variability is shown in 55-603439, which is approximately 10 kilometers downstream of 312048110504901, a well exhibiting relatively stable groundwater levels. However, the downstream well is closer to the river channel and was drilled within the transmissive river sediments, and the relatively large (up to 15 m) seasonal fluctuations at this well fit the pattern observed in the southern three Santa Cruz River microbasins (Erwin, 2007). This well (55-603439) also exhibits an overall increase in depth to groundwater through time, with the period from approximately 2000 to present particularly apparent. This last period is also visible in wells further downstream (55-619351, 55-619348, 55-610533), though the magnitude of increasing depth to groundwater is less, and groundwater levels recover in 55-619348. Closer to the northern SCAMA border, wells 55-627932 and 55-612066 exhibit an overall large increase in depth to groundwater over the period of record, with some recovery beginning in approximately 2015. It is possible that groundwater pumping in the Tucson AMA may affect groundwater levels at the northern end of the SCAMA near the Santa Cruz River channel.

The ADWR drought monitor indicates that Arizona entered a drought in January of 2000 and has been consistently within various stages of drought since January 2002 to present (ADWR, 2025c). The effect of this drought on depth to groundwater is apparent in the hydrographs of many of the wells. Comparing well logs, local geology, and patterns of groundwater pumping in space and time could enhance understanding of wells that did not respond to drought effects.

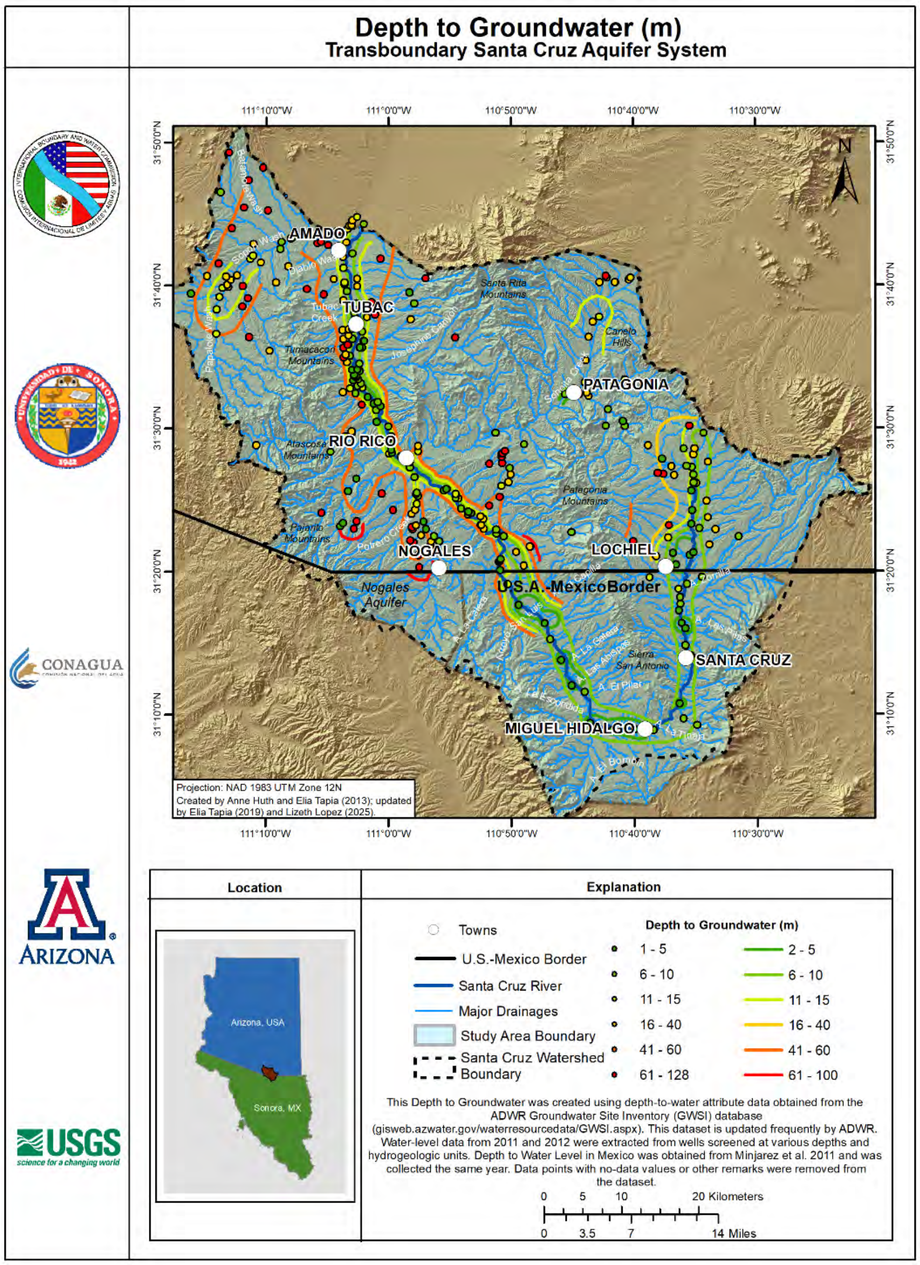

Figure 6.11 Depth to groundwater in the TSCAS for the year 2011, with some 2012 data included in the GWSI dataset.

Contours were developed using Inverse Distance Weighting interpolation in ArcGIS) and were manually corrected in no-flow areas such as mountains or non-permeable geologic units.

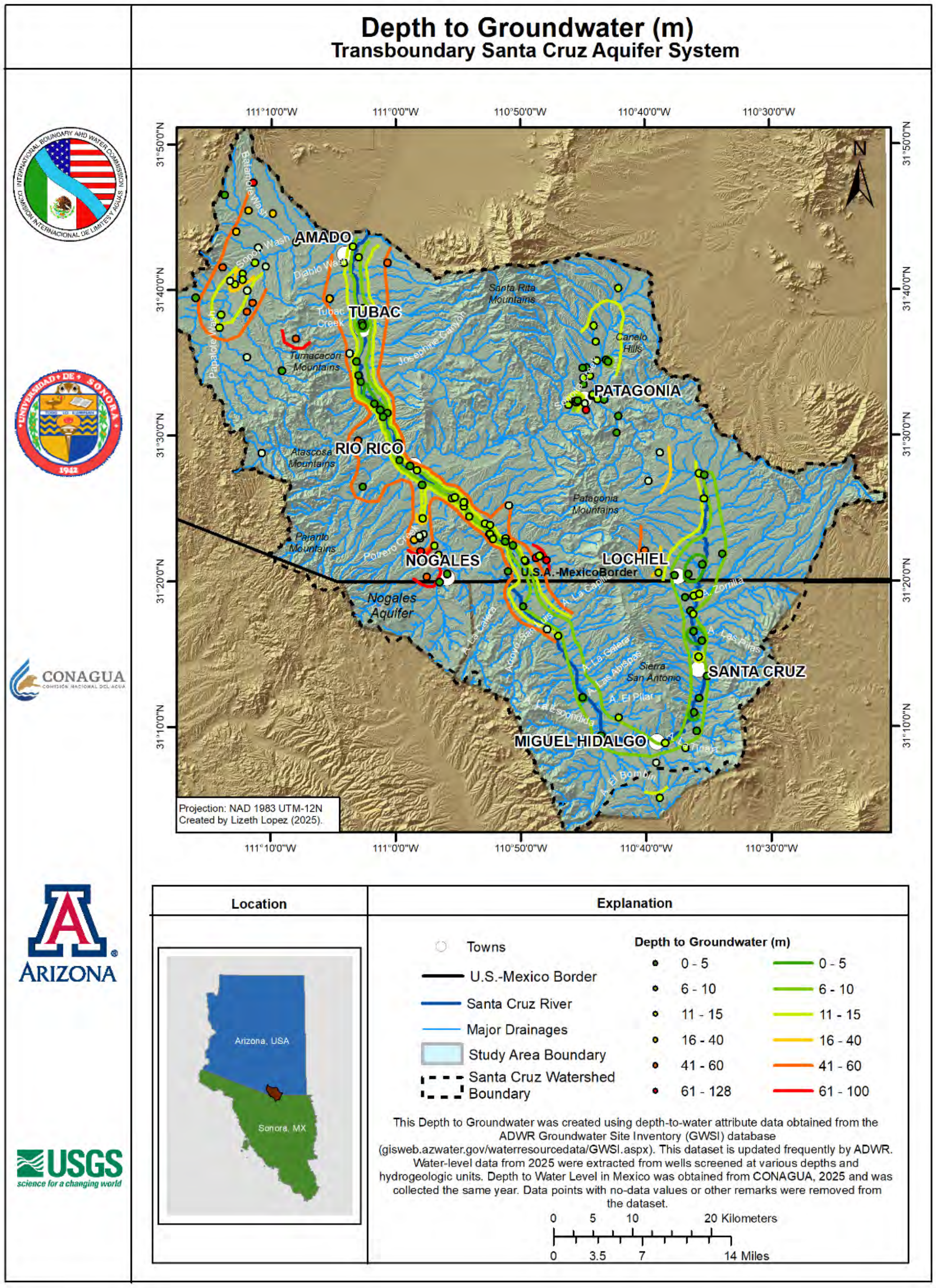

Figure 6.12 Depth to groundwater in the TSCAS for the year 2025.

Contours were developed using Inverse Distance Weighting interpolation in ArcGIS) and were manually corrected in no-flow areas such as mountains or non-permeable geologic units.

6.5. Hydraulic Parameters

Data to estimate hydraulic parameters were scarce or difficult to find in some parts of the TSCAS. They appear to be unavailable for the San Rafael Valley or the upper basin of Sonoita Creek, and there were a limited number of tests for the Nogales basin.

Within the SCRAS, aquifer tests were completed by Minjarez et al. (2011) (Figure 6.13) for estimation of transmissivity (T) and hydraulic conductivity (K). T values of the aquifer were high for all the tests, which supports findings in Chapters 4 and 5 that the primary aquifer unit corresponds to more permeable sediments such as sands with occasional clay lenses. The T values varied between $1.78x10^{-2}$ m^2/s and 9.27^{-3} m^2/s. K values varied between $1.92x10^{-3}$ m/s and $6.85x10^{-4}$ m/s (Table 6.5). The minimum K value was found in well STC-05. The greatest K value was found in well STC-12. The K values corresponded to the percentage of sand present in the unit where K values decreased with the presence of clays (a percent reduction in sand). In the NAS, there was one estimate for an unsaturated K value of $3.33x10^{-8}$ m/s with a water content of 20 percent (GAS-CONAGUA, 2024b).

Table 6.5 Transmissivity and hydraulic conductivity values derived from aquifer tests in the SCRAS (Minjarez et al., 2011).

Well Name	Coord. X	Coord. Y	Elevation	T (m^2/min)	T (m^2/s)	K (m/min)	K (m/s)
STC-05	534,382	3,446,200	1,288	$5.03x10^{-1}$	$8.38\ x10^{-3}$	$1.18\ x10^{-2}$	$1.97\ x10^{-4}$
STC-12	538,332	3,457,091	1,380	$5.56\ x10^{-1}$	$9.27\ x10^{-3}$	$3.39\ x10^{-1}$	$5.65\ x10^{-3}$
STC-16	538,069	3,461,390	1,388	$3.77\ x10^{-1}$	$6.28\ x10^{-3}$	$4.11\ x10^{-2}$	$6.85\ x10^{-4}$
STC-26	525,361	3,451,086	1,226	$1.07\ x10^{0}$	$1.78\ x10^{-2}$	$1.15\ x10^{-1}$	$1.92\ x10^{-3}$
STC-50	518,140	3,462,096	1,167	$1.60\ x10^{0}$	$3.68\ x10^{-2}$	$2.30\ x10^{-2}$	$3.83\ x10^{-4}$

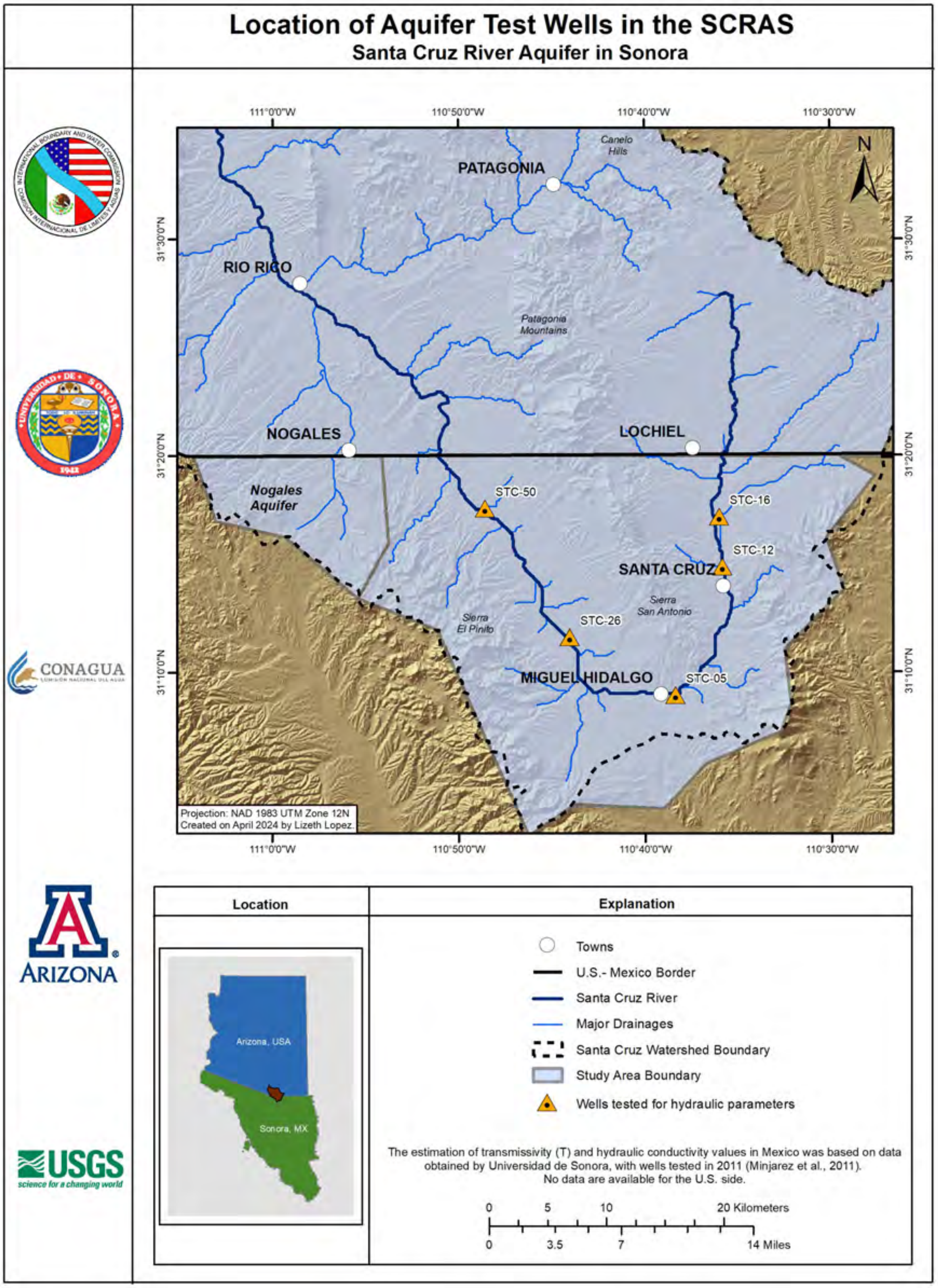

Figure 6.13 Location of aquifer test wells along the SCRAS.

In the SCAMA, a number of pumping tests were documented by Nelson (2007) and Erwin (2007). Additional estimates of hydraulic parameters come from estimates generated by numerical groundwater flow models. Two regional groundwater flow models were developed by the ADWR to facilitate the management of regional water resources in the SCAMA (Nelson, 2007; Erwin, 2007). In this section, we discuss these models with respect to hydraulic parameters, but additional details are discussed in Chapter 8. The groundwater-flow model documented in ADWR Modeling Report No. 15, developed by Erwin (2007), addresses the area within the U.S.-Mexico border and the NIWTP, an area that is sometimes referred to as the microbasins. The model simulated hydrologic conditions from October 1997 to September 2002 within a domain of about 100 km^2. The model is composed of three layers and 2,500 active model cells, with surficial dimensions of 200 by 200 m. The model simulated the hydraulic connections between the Santa Cruz River and the groundwater system with bi-seasonal precipitation forcing (Erwin, 2007).

The model-estimated T values in the SCAMA varied considerably depending on the geologic formation. In the area of the microbasins in the younger alluvium, aquifer tests indicated T values between 540 and 1,540 m^2/d with storage coefficients (S) from 0.14 to 2 (Erwin, 2007). In the older alluvium, Erwin (2007) reported a single T value of 7 m^2/d with a specific storage (S) value equal to $1.4x10^{-3}$ and an estimated K value of $1.1x10^{-6}$ m/s. In the microbasins, there was only one measurement that included the Nogales Formation, but the well screen was located in the older alluvium as well as the Nogales Formation. Thus, the reported T, S, and K values represented a mixture of the properties of the two aquifers.

Erwin (2007) reported two values for each property that depended on the method used for the analysis. The difference in the magnitude of the values was insubstantial. For this reason, the results analyzed using the Theis method are reported: T = 26 m^2/d, S = $1.25x10^{-6}$, and K = $1.8x10^{-6}$ m/s. The Salero Formation outcrops in two locations in the microbasins area, a few kilometers south of Sonoita Creek. The T values in three wells in the Salero Formation varied from 19 to 68 m^2/d, and the S values ranged between 0.1 and 0.15. Also, in some locations, crystalline rock can function as an aquifer. In the southern part of the microbasins, T values of 11 m^2/d, S =$1.1x10^{-4}$, and K = $3.5x10^{-6}$ m/s were recorded in a well where the water-productive zone was granodiorite. For groundwater modeling, depending on the area, Erwin (2007) used calibrated values for K between $1.2x10^{-3}$ and $3.4x10^{-3}$ m/s, with S values ranging between 0.14 and 0.20 for the younger alluvium. In the older alluvium, values of between $6.7x10^{-7}$ and $3.9x10^{-6}$ m/s were used with a specific yield (Sy) value of 0.025. For the Salero Formation, a K value of $1.1x10^{-5}$ was used and Sy of 0.15.

The groundwater-flow model documented in ADWR Modeling Report No. 14, developed by Nelson (2007), analyzed the reach of the effluent-dominated Santa Cruz River located between the NIWTP and Elephant Head Bridge. The model simulates hydraulic heads, flows, and water budgets for steady state and transient conditions for the 1997 and 2002 period. The model considers three basin fill units: the younger alluvium, older alluvium, and the Nogales Formation (Nelson, 2007). Nelson (2007) summarized the information about the hydraulic properties in the SCAMA area between the NIWTP and Amado, Arizona. There were a number of pumping tests, and only the T-derived K values are reported here. The vertical hydraulic conductivity (Kv) values in this part of the aquifer were assumed to be one tenth of the horizontal hydraulic conductivity (Kh) value, and Kh was assumed to be isotropic. For the younger alluvium near Rio Rico, Arizona, Nelson (2007) reported large K values that varied from $1.8x10^{-4}$ to $6.8x10^{-3}$ m/s, with a Sy of 0.19 and S values of 0.0001 up to 0.0098. In the area of Tubac and Amado, K values varied between $1.8x10^{-4}$ and $2.2x10^{-3}$ m/s with S values between $7.7x10^{-4}$ and $8.7x10^{-4}$.

For the older alluvium, which is less permeable than the younger alluvium and, in some places, consolidated, Nelson (2007) reported K values near Tubac and Amado of between $3.5x10^{-6}$ and $5.7x10^{-4}$ m/s, with S values of $6x10^{-4}$ and $4x10^{-3}$. East of Tubac, the K values are lower and less variable; K values varied between $3.5x10^{-6}$ and $4.4x10^{-5}$ m/s. Near Rio Rico, the observed K values were between $7.1x10^{-6}$ and $1.7x10^{-4}$ m/s with S values of $1x10^{-4}$ and $2x10^{-4}$. In the Nogales Formation for this part of the basin, there were only three wells with T measurements and K values. The Nogales Formation has a tendency to be more lithified than the older alluvium. Thus, K values are lower, varying between $6.14x10^{-7}$ and $5.96x10^{-6}$ m/s with an S value of $1.1x10^{-4}$.

For the groundwater modeling, Nelson (2007) simulated two cases, a base case for the years 1997-2002 and a pre-development case. The calibrated K values for the two cases were similar, so only the values for the base case are given here. In the model, the younger alluvium was divided into two areas: North and Rio Rico. The hydraulic conductivity in the northern part was $3.88x10^{-4}$ m/s, and in the Rio Rico area was $2.48x10^{-4}$ m/s. The older alluvium was divided into four areas with K values varying between $1.27x10^{-7}$ m/s and $1.02x10^{-4}$ m/s. The Nogales Formation was modeled as a homogeneous unit (Knog, K = $3.56x10^{-7}$ m/s) except for an area near the Sopori Wash tributary (Knog_Sopori, K = $1.89x10^{-5}$ m/s).

There have been several discussions about temporal changes in Kv of the bed sediments of the Santa Cruz River (Treese et al., 2009; Nelson, 2007). It has been proposed that these variations occurred prior to the upgrade of the NIWTP in 2009 because of the seasonal decrease in permeability caused by the growth of algae and other microorganisms in the pores of the sediments forming a kind of biological seal. Algal growth was caused by high concentrations of ammonia in the water discharged from the NIWTP and lack of disturbance in the riverbed during discharge (Treese et al., 2009). For this reason, Nelson (2007) assigned K values in the model that varied from one stress period to another depending on the streamflow, from a minimum of $3.5x10^{-7}$ to a maximum of $1.1x10^{-5}$ m/s. In 2009, the NIWTP was upgraded from secondary to tertiary treatment level (Tapia-Villaseñor et al., 2020). Nitrogen concentrations in treated effluent were reduced after the upgrade. With this reduction, the formation of the biological seal was impeded leading to an increase in streambed permeability (Treese et al., 2009; Tapia-Villaseñor et al., 2020).

6.6. Conclusions

Groundwater monitoring analysis for the TSCAS shows an overall increase in total groundwater demand for both the U.S. and Mexico, which is dominated by use for irrigation, and over the last couple of years by industrial users in Mexico. A high density of wells has been identified in urban areas such as Nogales and Tubac, reflecting greater pressure on water resources in these zones because of domestic, agricultural, and industrial activities. Depth to groundwater level is variable in the TSCAS, with greater depths to groundwater away from the Santa Cruz River. The analysis of groundwater use and piezometric behavior supports understanding of the status of current groundwater demand in the region and can inform decision making regarding over-exploited areas. Information on hydraulic parameters can be used to develop conceptual and numerical flow models. Generally, the highest values of T and K are found in the younger alluvium associated with the Santa Cruz River. Values tend to increase downstream, but they can vary two to three orders of magnitude over distances of one to two kilometers. The older alluvium and Nogales Formation have lower values of T and K that depend largely on degree of consolidation and fracturing respectively.

To further enhance understanding of the binational aquifer system, additional efforts could focus on regular monitoring of depth to groundwater, to better characterize changes in water storage and the evolution of the piezometric surface over time. Aquifer testing and geophysical investigations would help refine estimates of aquifer properties in areas where hydrogeologic data remain limited. In addition, integrating information from multiple data sources, such as CONAGUA and OOMAPAS, would support a more comprehensive and coordinated assessment of groundwater conditions across the binational system. Collectively, these efforts would strengthen the technical foundation for future evaluations and support informed, science-based decision making related to groundwater resources within the TSCAS.

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7. HYDROGEOCHEMISTRY

7.1. Introduction and methods

This chapter describes the U.S. and Mexican collaborative efforts towards improving the understanding of the geochemical characteristics of the TSCAS. Major factors influencing groundwater in the TSCAS are bedrock geology, land use, and water use. Population growth, naturally occurring mineralized rocks with related acid rock drainage, historical mining and acid mine drainage, as well as industrial and wastewater treatment activities have all affected the water quality of the entire TSCAS since the early evolution of the landscape to recent decades.

This chapter describes available information on the geologic substrate (mineralogy-geology), hydrochemical sampling, water-quality data, and stable isotope data for the study region. We distinguish between water quality sampling (assessing the suitability of water for particular uses) and hydrochemical sampling, which is sampling with the goal of understanding environmental and geologic processes. Though isotope sampling is a type of hydrochemical sampling, we mention it because there is a separate section of the chapter devoted to using isotope data to develop a hydrologic model of the study area. This chapter also incorporates the results of water-quality studies and well surveys in the TSCAS.

Available geochemical data include major ions in groundwater and surface water, field parameters, trace elements (in parts per billion) and stable isotopes of source materials. These data are used to understand the hydrochemistry of the system. Groundwater chemistry is largely a function of rock-water interaction. Solid phases, mainly inorganic mineral species, are the primary sources and sinks of dissolved constituents of groundwater. As groundwater moves through rock, a range of chemical reactions (weathering effects) occur depending on the chemical nature of the water, availability of elements in the various geologic formations, and total residence time of groundwater. These processes include dissolution/precipitation, ion exchange, and oxidation/reduction. The lowland basin-fill alluvial aquifer of the upper Santa Cruz River basin is the primary water-bearing aquifer and is considered here as separate from the highland crystalline-rock aquifers of the mountain blocks (“Sky Islands”) within the TSCAS area (Figure 7.1)

A primary concern in the mountain blocks is the release of dissolved metals during weathering of mineralized rock and associated alteration zones. Interaction of groundwater with acid-consuming minerals, for instance in carbonate rocks, may modify groundwater chemistry. The chemical composition of groundwater in such systems, with low water-rock ratios, results from the combined effects of these processes (Plumlee, 1999; Elango and Kannan, 2007). Mountain ranges potentially provide mountain front, mountain block or overland surface water recharge, and erosional materials to the lowland alluvial aquifer. The mountain-block and alluvial aquifers differ greatly in hydrologic characteristics (permeability, porosity, water storage capacity) and in their potential for water-rock chemical interaction.

In this chapter, we 1) list sources of data and explain how they have been used, 2) review geochemical data for groundwater in the highlands hard-rock aquifers in the context of the geology of the aquifer systems, 3) review groundwater and surface water geochemistry in the lowlands basin-fill aquifer, and 4) review stable isotope data for both aquifer types and surface water in and around the Patagonia Mountains.

7.2. Methods

The hydrogeochemistry, geologic substrate including mineral deposits, and water quality of the TSCAS have been assessed by combining the results of three phases of study: 1) literature review of previous water quality surveys, reports, and peer-reviewed articles, 2) reviews of relevant data derived from geologic maps, including faults and related structures, subsurface 3-dimensional profile data, and mineralogical analyses along with rock and soil chemistry, and 3) compilation and examination of available data in a consistent way.

To develop a consistent approach, we needed: 1) a binational Arizona-Sonora TAAP technical team consensus on the scope of the study, specifically which parameters to include and to the extent possible, a common interval of time, 2) data availability with a preference for binational datasets, 3) consensus on mapping presentation, 4) consistent binational descriptions, and 5) consensus on acceptable sampling and analytical methods. Selected parameters included major ions, physical parameters, stable isotopes, and trace element chemistry of rock, soil, and water. Data on the U.S. portion of the TSCAS were obtained from the Arizona Department of Environmental Quality (ADEQ), USGS published data (Coes et al., 2000; Wanty et al., 2001; Gray et al., 2000 and 2004). For the Mexican portion, information was obtained from data and analysis published in Minjarez et al. (2011) (Table 7.1). An additional framework for interpreting the data on hydrochemical processes in alluvial basins was provided in Robertson (1991) who described the evolution of groundwater chemistry in terms of a 13-component reaction system. The study detailed major reactions as 1) dissolution and precipitation of calcite and dolomite, 2) the weathering of feldspars and ferromagnesian minerals, 3) the formation of montmorillonite, iron oxyhydroxides, silica, and to a lesser extent 4) ion exchange.

7.3. Water Quality Standards

Compiled acceptable data were compared with the Maximum Contaminant Levels (MCLs) established in the Official Mexican Standard (NOM) NOM-127-SSA1-2021 for human use and consumption, and the U.S. Environmental Protection Agency (EPA) standards (Table 7.1). Recommendations from Custodio and Llamas (1996) were considered if there were no applicable MCLs listed for Mexico and the U.S. Table 7.2 presents the maximum permissible limits of pollutants in wastewater discharged into national waters and public areas, as established by NOM-001-SEMARNAT-2021. This information is particularly relevant given the wastewater transfers between the U.S. and Mexico discussed in Chapters 6 and 7. In addition, Table 7.3 provides a list of NOMs used to analyze water samples in the Mexican portion of the TSCAS, serving as a reference for quality control purposes. The table includes the standards in effect at the time the samples were analyzed, as well as updated standards to account for potential methodological changes.

Table 7.1 Comparison of Mexican (NOM-127-SSA1-2021) and U.S. (EPA, 2016) drinking water standards for selected compounds.

Contaminant	NOM-127-SSA1-2021 (mg/L)	EPA Guidelines (MCLs) (mg/L)
Aluminum	0.20	**0.05** to 0.2**
Arsenic	0.025	0.010 Zero MCLG
Barium	**1.3**	2
Benzene	0.01	**0.005** Zero MCLG
Cadmium	**0.005**	**0.005**
Cyanide (CN^-)	**0.07**	0.2
Chloride (as Cl^-)	**250**	**250****
Copper	2.0	**1.3***
Chromium (Total)	**0.05**	0.1
Fluoride (as F^-)	**1.50**	4.0
Iron	**0.3**	**0.3**
Lead	**0.010**	0.015*
Manganese	0.15	**0.05****
Methoxychlor	**0.02**	0.04
Mercury	0.006	**0.002**
Nitrate (measured as N)	11	**10**
Nitrite (measured as N)	**0.9**	1.0
Pesticides: Aldrin and dieldrin +	**0.00003**	0.001 0.002
Sulfate (as SO_4^{2-})	400	**250**
Toluene	**0.7**	1
Total Trihalomethanes ***	0.20	**0.080**
Xylene	0.5 (three isomers)	10 (Total)
Zinc	**5.0**	**5.0****
2,4-dichlorophenoxyacetic acid (2,4, D)	**0.03**	0.07

Values shown in bold indicate the most restrictive (lowest) standard between the two regulatory frameworks.

*Copper action level 1.3 mg/L; lead action level 0.015 mg/L

**These contaminants are listed in the National Secondary Drinking Water Regulation (they are non-enforceable).

+ Aldrin and dieldrin from https://www.atsdr.cdc.gov/toxfaqs/tf.asp?id=316&tid=56. From the 1950s until 1970, aldrin and dieldrin were widely used pesticides for crops like corn and cotton. Because of concerns about damage to the environment and potentially to human health, the EPA banned all uses of aldrin and dieldrin in 1974, except to control termites. In 1987, EPA banned all uses.

Maximum Contaminant Level Goal (MCLG) - The level of a contaminant in drinking water below which there is no known or expected risk to health. MCLGs allow for a margin of safety and are non-enforceable public health goals.

Maximum Contaminant Level (MCL) - The highest level of a contaminant that is allowed in drinking water. MCLs are set as close to MCLGs as feasible using the best available treatment technology and taking cost into consideration. MCLs are enforceable standards.

*** Although there is no collective MCLG for this contaminant group, there are MCLGs for some of the individual contaminants: Trihalomethanes: bromodichloromethane (zero); bromoform (zero); dibromochloromethane (0.06 mg/L); chloroform (0.07 mg/L). Haloacetic acids: dichloroacetic acid (zero); trichloroacetic acid (0.02 mg/L); monochloroacetic acid (0.07mg/L). Bromoacetic acid and dibromoacetic acid are regulated with this group but have no MCLGs.

Table 7.2 NOM-001-SEMARNAT-2021 maximum permissible limits of pollutants in the wastewater discharged into national waters and public areas.

Parameters	Rivers				Soils		Natural wetlands	
	Agricultural use Monthly average	Agricultural use Daily average	Aquatic life Monthly average	Aquatic life Daily average	Agriculture Monthly average	Agriculture Daily average	Monthly average	Daily average
Temperature (Celsius)	-	-	35	35	-	-	35	35
Grease and oils (mg/L)	15	18	15	18	15	18	15	18
Arsenic (mg/L)	0.2	0.3	0.2	0.3	0.2	0.3	0.1	0.15
Cadmium (mg/L)	0.2	0.3	0.2	0.3	0.05	0.075	0.1	0.15
Cyanide (mg/L)	1.0	2.0	1.5	2.0	2.0	2.5	1.0	1.5
Copper (mg/L)	4.0	5.0	4.0	5.0	4.0	5.0	4.0	5.0
Chromium (mg/L)	1.0	1.25	1.0	1.25	0.5	0.75	0.5	0.75
Mercury (mg/L)	0.01	0.015	0.01	0.015	0.005	0.008	0.005	0.008
Nickel (mg/L)	2.0	3.0	2.0	3.0	2.0	3.0	2.0	4.0
Lead (mg/L)	0.2	0.3	0.5	0.75	0.5	0.75	0.2	0.3
Zinc (mg/L)	10	15	10	15	10	15	10	15

Table 7.3 List of Official Mexican Standard methods used to analyze water samples in Minjarez et al. (2011).

Test Method	Reference
Determination of Temperature in Natural Waters, Wastewaters and Treated Wastewaters - Test Method	NMX – AA – 007 –SCFI – 2013
Determination of pH - Test Method	NMX – AA – 008 – SCFI – 2011 (Now updated to NMX – AA – 008 – SCFI – 2016)
Measurement of Salts and Solids Dissolved in Natural Waters, Wastewaters and Treated Wastewaters - Test Method	NMX – AA – 034 – SCFI – 2001 (Now updated to NMX – AA – 034 – SCFI – 2015)
Determination of Acidity and Alkalinity Total in Natural Waters, and Treated Wastewaters	NMX – AA – 036 – SCFI – 2001
Determination of Turbidity in Natural Waters, Wastewaters and Treated Wastewaters - Test Method	NMX – AA – 038 – SCFI – 2001
Determination of Total Chlorine in Natural Waters, Wastewaters and Treated Wastewaters - Test Method	NMX – AA – 073 – SCFI – 2001
Determination of Total Hardness in Natural Waters, Wastewaters and Treated Wastewaters - Test Method	NMX – AA – 072 – SCFI – 2001
Determination of Electrical Conductivity - Test Method	NMX – AA – 093 – SCFI – 2000 (Now updated to NMX – AA – 093 – SCFI – 2018)
Determination of Sulfide	NMX – AA – 084 – 1982
Determination of Total Phosphorus in Natural Waters, Wastewaters and Treated Wastewaters - Test Method	NMX – AA – 029 – SCFI – 2001
Determination of Sulfate Ion	NMX – AA – 074 – 1981 (Now updated to NMX – AA – 074 – SCFI – 2014
Determination of Fluoride in Natural Waters, Wastewaters and Treated Wastewaters - Test Method	NMX – AA – 077 – SCFI – 2001
Determination of Nitrate in Natural and Drinking Waters, Wastewaters and Treated Wastewaters - Test Method	NMX – AA – 079 – SCFI – 2001
Determination of Metals by Atomic Absorption in Natural and Drinking Waters, Wastewaters and Treated Wastewaters - Test Method	NMX – AA – 051 – SCFI – 2001 (Now updated to NMX – AA – 051 – SCFI – 2016)

7.4. Quality Assurance/Quality Control

Quality Assurance/Quality Control (QA/QC) information has been reviewed for each report or database if it is available. Little or no QA/QC information was available for several data sources. Data from these sources have been accepted in the following cases: 1) they are the oldest published data, 2) the data helped to fill a significant gap where few data were otherwise available for a parameter/analyte. Such data have been accepted if they fall within the ranges of data with adequate QA/QC. Data falling outside the ranges of data with adequate QA/QC have in some cases been accepted if there is a plausible reason for a difference (e.g., effects of mining, geology, climate change, industry, etc.). However, this QA/QC review is not strictly necessary, as all reports used for this study have already been published.

7.5. Highland Aquifers of the TSCAS

7.5.1. Introduction

This section describes the hydrologic and hydrogeochemical conditions inside the most documented mountain range hard-rock aquifers in the study area, and their relation, if any, to the adjacent alluvial aquifers. Potential uses of this information include groundwater and geochemical modeling. By specifying appropriate boundary conditions in groundwater models, hydrogeologists can simulate and predict the behavior of groundwater flow and contaminant transport within aquifer systems, helping to better understand and manage groundwater resources and understand potential environmental impacts. In modelling alluvial aquifers of the Basin and Range province, specified flow (i.e. constant flow value), or no-flow boundary conditions (i.e. no flow across relatively impermeable boundaries such as unfractured bedrock or clay), are commonly assumed. While it is clear that the water budget of an alluvial basin includes water flowing overland into the basin, there can be a lack of recognition that in arid lands a significant proportion of recharge may occur via hard rock mountain aquifer systems (Eastoe and Towne, 2018). An understanding of the hydrology of the mountain ranges of the study area is critical to an understanding of the entire study area.

The example considered here is the Patagonia Mountains, in the center of the TSCAS study area (Figure 1.2), which is host to some of the most intensely mineralized bedrock in southern Arizona's Basin and Range Province. The Patagonia Mountains are in the core of what is commonly referred to as the "Great Cluster" of porphyry copper and associated deposits of Arizona, Sonora, and New Mexico, and is one of the most important copper provinces on Earth (Keith and Swan, 1996). The Patagonia Mountains and the Sierra de San Antonio (the Mexican portion of the mountain range) extend approximately 70 linear kilometers from the town of Patagonia and the San Rafael Valley in Arizona to the bend of the Santa Cruz River near Santa Cruz, Sonora. Because the Patagonia Mountains have been the subject of intensive mineral exploration, detailed geological data are available for the range.

The appropriate groundwater boundary conditions for the fragmented, variable hard rock of the Patagonia Mountains are unclear due to multiple overlaid or overlapping hydrothermal mineralization episodes that occurred within the range. Developing groundwater models that can simulate the geological and geochemical complexity caused by the multiple mineralization sequences in the mountain is beyond the scope of this report. However, the information presented here will provide a foundation for future models designed to enhance understanding of the processes governing the major acid-generating and acid-buffering groundwaters that interact in the mountain's groundwater flow regime.

7.5.2. Background

Although the mountain ranges surrounding the Santa Cruz River basin contain typical, low-yielding hard-rock aquifers, they are important to the understanding of hydrology and water quality in the study area. Mountain ranges in Arizona typically receive higher annual rainfall than basin floors (Eastoe and Towne, 2018) and are therefore the principal source of water in the lowland alluvial aquifers. In the TSCAS, the mountain ranges host numerous hydrothermal base-metal and precious-metal deposits, some of which have been mined for centuries. Mining operations use significant amounts of water that can affect groundwater levels. This can impact both stream- and spring-flow; both of which may be important in sustaining mountain ecosystems and mountain-block and mountain-front recharge. Weathering of mineralized rocks, either natural or enhanced in mine workings, releases potential contaminants into groundwater and surface water.

Unfractured or unaltered hard-rock aquifers typically yield less water than unconsolidated or semi-consolidated sediments and carbonate rocks (the term hard-rock aquifer, for purposes of this discussion, implies silicate and carbonate rocks as described in Chapters 4 and 5 of this volume). This is due to the relatively scarce groundwater resources in hard rocks, enhanced mineral content, low capacity of wells, strong variations and abrupt discontinuities in aquifer properties, and difficulties in exploration and quantitative assessment of the resource (Limaye, 2010). Given these challenges, data for groundwater in highland (mountain range) aquifers are generally scarce because wells are few. Much of the information on highland groundwater comes from springs and spring/seep related baseflow sampling (i.e. landscape geochemistry methods).

7.5.3. Chemical, Structural, and Mineralogic Controls on Permeability

The interaction of groundwater with aquifer matrix minerals plays a significant role in controlling water quality, water flow, and water availability in hard-rock aquifers. Water quality (or the chemical character of the water) in bedrock aquifers is a result of the residence time and flow paths of the water that allow it to react with and ultimately reflect the geochemical composition of the lithology. The upper portion of the aquifer can also be affected locally by land use and geomorphology. Specific controls include weathering extent, solubilities of mineral species, and porosity and permeability of host lithologies. In the Patagonia Mountains, the primary control on groundwater quality is exerted by acid-generating and acid-consuming minerals in the bedrock. Groundwater recharge into hard rock takes place through secondary porosity (fracturing, weathering, hydrothermal activity), developed after the formation of the rock. Unlike sedimentary rocks, which often have primary porosity (pore spaces formed during deposition), crystalline rocks such as granite, basalt, and gneiss typically have very low primary porosity due to their crystalline and interlocking nature (Anderson, 2015).

Understanding the mechanisms and characteristics of secondary porosity in crystalline rocks is crucial for geological studies and resource exploration. The most significant result of secondary porosity in the central TSCAS is multiple epochs of mineralization and the introduction of base metals via hydrothermal fracturing and the circulation of metal-enriched fluids. Post-hydrothermal secondary mineralization enhances fluid migration, mineral sulfide oxidation, and groundwater storage in crystalline rocks such as those of the Patagonia Mountains. Secondary porosity can develop through various geological processes, including:

1. Fracturing: Crystalline rocks can undergo tectonic stresses that cause them to fracture and develop networks of interconnected fractures and joints. Over time, dissolution, and other processes can widen these fractures, creating secondary pore spaces. Other processes, such as subsidence, renewed tectonic activity, and mineral deposition can narrow or even close fractures.

2. Weathering: Chemical and physical weathering processes can alter the mineral composition of crystalline rocks, leading to the formation of secondary pores. For example, dissolution of minerals such as feldspar can create pore spaces within the rock. Weathering of reactive sulfides can also create opportunities for groundwater infiltration and circulation.

3. Hydrothermal activity: Hydrothermal phenomena may include formation of stockworks and breccias around mineralizing intrusions, formation of alteration minerals in large volumes of rock around heat sources, and dissolution or precipitation of minerals. To the extent that open space remains after the deposition of vein-filling minerals, secondary porosity may persist after the cessation of hydrothermal activity.

Low primary permeability and hydraulic conductivity characterize unfractured igneous rocks that occur throughout the mountain ranges of the TSCAS. These characteristics, however, can vary over many orders of magnitude given the effects of secondary porosity and permeability generated by fractures, joints, and faulting. Carbonate rocks such as limestones, found extensively in the TSCAS, can have low to moderate primary porosity and permeability. However, limestones and dolomites can have high hydraulic conductivities with extensive chemical dissolution such as found in karst landscapes and when extensively fractured and faulted. More detailed discussions of porosity and permeability of multiple rock types can be found in Domenico and Schwartz (1990) and Freeze and Cherry (1979).

7.5.4. Weathering Geochemistry

The weathering of mineralized rock leads to decomposition of igneous and secondary silicate minerals and sulfides. The weathering process leads to aqueous and particulate transport of major rock-forming elements (Si, Al, Na, K, Ca, Mg) along with base metals (Cu, Fe, Zn, Pb, Cd, As, Sb). Hypogene sulfide minerals (formed at great depths and exposed at the surface through uplift/erosion) are unstable in the presence of air and water in the weathering environment (Rakovan, 2003). In the Patagonia Mountains, the most abundant sulfide species are pyrite (FeS_2), chalcopyrite ($CuFeS_2$), and sphalerite (ZnS).

Here are some reactions that may take place:

1. Oxidation

Reactions in and immediately below the weathering zone are complex. Simple base-metal sulfides are oxidized to sulfates, (e.g., $ZnS + 2O_{2(aq)} \rightarrow ZnSO_4$). Soluble sulfates may be transported in groundwater, except where insoluble salts are formed, particularly in the presence of dissolved CO_2 or silica, e.g., smithsonite ($ZnCO_3$), malachite ($Cu_2CO_3(OH)_2$), azurite ($Cu_3(CO_3)_2(OH)_2$), chrysocolla ($Cu_2H_2Si_2O_5(OH)_4$), and Fe oxyhydroxides. The oxidation of FeS_2 and chalcopyrite ($CuFeS_2$) is more complex. For FeS_2, two reactions are possible:

$FeS_2 + 7/2O_{2(aq)} + H_2O \rightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+$ (1)

$FeS_2 + 14Fe^{3+} + 8H_2O \rightarrow 15Fe^{2+} + 2SO_4^{2-} + 16H^+$ (2)

(Stumm and Morgan, 1970). Reaction 2 is limited by the availability of dissolved Fe^{3+}, which is enhanced by bacterial oxidation of Fe^{2+} in subaqueous environments, according to the reaction:

$Fe^{2+} + 1/4O_{2(aq)} + H^{+} \rightarrow Fe^{3+} + 1/2H_2O$ (3)

Reaction 2 appears dominant in southern Arizona, according to typical near-zero values of $\delta^{18}O$ in supergene sulfate (Gu and Eastoe, 2021). This reaction produces abundant acid. Acid may also be produced by hydrolysis of dissolved sulfate salts.

2. Supergene sulfide formation

Sulfate reduction may also occur in and at the water table, leading to the formation of supergene sulfide minerals such as chalcocite (Cu_2S) and covellite (CuS). Enders (2000) presented evidence that the sulfate reduction at Morenci, Arizona, is brought about by bacteria. Where a water table is present beneath the weathering zone, bacterial sulfate reduction in the presence of dissolved $CuSO_4$ may lead to the deposition of supergene Cu sulfides like covellite and chalcocite (Enders, 2000).

Essentially, the oxidation and weathering of base-metal sulfide minerals can release base-metal ions into the surrounding environment. These metals can be leached into soil and water, leading to potential contamination and adverse effects on ecosystems and human health. The formation of sulfuric acid from the oxidation of sulfide minerals can contribute to the generation of acid rock drainage (ARD). ARD can have significant environmental impacts, including the acidification of water bodies and the mobilization of metals as part of natural weathering processes.

7.5.5. Geology and Geochemistry of the Patagonia Mountains

To understand the hydrology and hydrochemistry of the mountain blocks, it is necessary to review data related to geology including structure, geologic history, and mineral distribution. The geology of the Patagonia Mountains is dominated by a composite Laramide granodiorite batholith (Vikre et al., 2014) (Figure 7.1). The batholith is about 8 km wide at the international border and extends 19 km north of the border where it narrows and terminates against intrusion breccias. These breccias are composed of Mesozoic granitic and volcanic rocks and formed during assembly of the batholith. The oldest wall rocks, into which the granodiorite pluton was emplaced, include Precambrian biotite quartz monzonite and hornblende diorite, on the east side of the range, along with Precambrian biotite-hornblende, quartz monzonite, and hornblende gabbro along the west side. Paleozoic sedimentary rocks ranging in age from Middle Cambrian to early Permian are present in two areas on the east side of the range. These rocks represent near shore marine environments. Mesozoic rocks, principally Triassic to Jurassic silicic volcanics, unconformably overlie Paleozoic units.

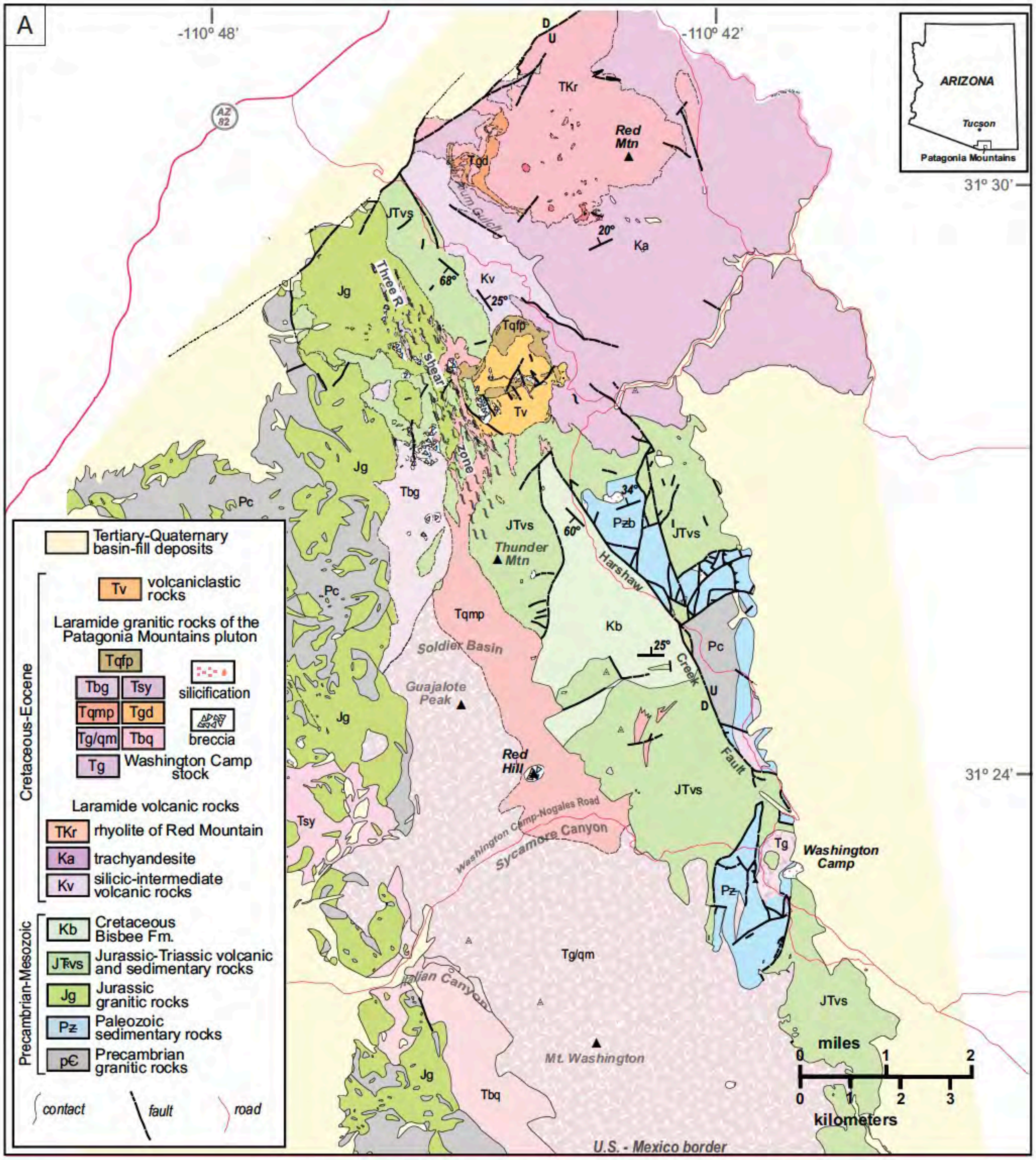

Figure 7.1 Geology of the Patagonia Mountains from Vikre et al. (2014).

Geologic map of the Patagonia Mountains, Santa Cruz County, Arizona. Laramide granitic rocks include Tqfp (quartz feldspar porphyry) at Sunnyside, Tbg (biotite granodiorite), Tsy (syenodiorite), Tqmp (quartz monzonite and quartz monzonite porphyry), Tgd (granodiorite) of Red Mountain, Tg (granodiorite) of Washington Camp, which also includes porphyritic biotite granodiorite, and Tbq (biotite quartz monzonite porphyry). Laramide volcanic rocks include TKr (rhyolite) of Red Mountain, Ka (trachyandesite), and Kv (silicic intermediate volcanic rocks including biotite latite).

Later Mesozoic rocks are predominantly igneous and include intermediate to felsic volcanic tuffs and flows and intrusive rocks (Vikre et al., 2014). Widespread deposition of volcanic rocks with lesser sedimentary rocks occurred in Late Cretaceous time. Volcanism continued into the early Tertiary (Paleocene) with deposition of andesitic to rhyolitic lava and tuff, and volcaniclastic conglomerate. Much of the mineralization seen in the Patagonia and southern Santa Rita Mountains to the north occurred during the Late Cretaceous–early Tertiary magmatism such as is found at Red Mountain (Figure 7.1). The occurrence of a thick section of Cretaceous to Tertiary sedimentary and volcanic rocks at the north end of the Patagonia Mountains and the greater width of the exposed intrusion south along the U.S.-Mexico border suggests that the southern area may be more deeply eroded than exposures farther north. Uplift, accompanied and followed by deposition of fanglomerate, conglomerate, and extensive alluvium characterized the Basin and Range orogeny and resulted in the present-day landscape. From the eastern border of the study area to the town of Patagonia, the Sonoita Creek valley is underlain by predominantly Pleistocene to Pliocene age alluvium (Drewes, 1980) that consists of poorly consolidated boulders, gravel, sand, silt, and clay. This unit is commonly referred to as "basin fill". Southwest of Patagonia, the valley lies within a southwest-trending graben-like structure with moderately consolidated sediments of Pleistocene to Miocene age underlain by a mixture of Tertiary to Cretaceous volcanic flows, tuffs, and volcaniclastic sediments ranging in composition from andesite to rhyodacite and rhyolite. Recent alluvial material, mainly sands and gravel, is exposed within the active streambed.

In the lowermost elevations between the Patagonia and Santa Rita Mountains, bedrock is overlain by and locally interspersed with alluvial sand and gravel deposits. These basin-fill sediments skirt the area, typically in depositional contact with bedrock but locally are faulted directly against older bedrock units such as at the foot of the Patagonia Mountains south of the town of Patagonia (Drewes, 1972a, b). Younger poorly consolidated, finer textured deposits consisting of interbedded pebbly, silty sandstone and sandy pebble gravels form the dominant exposures in the main basin of Sonoita Creek. In deeper portions of the basin, sediments are typically medium grained (pebble-cobble) sandy conglomerate with locally interbedded pebbly sandstone and may be moderately consolidated at the base. Local cementation and red staining of the alluvial deposits increase with proximity to the Patagonia fault zone and appear to represent iron-oxide-related diagenetic alteration.

Structural interpretations and geophysical data suggest that the Sonoita Creek basin is a narrow complex-graben system that is bounded to the north and south by steeply dipping normal faults (Menges, 1981). Menges (1981) presented a compilation of regional geophysics and detailed structural data on the basin and range setting of the Sonoita Creek valley around Patagonia. The interpretations of the Patagonia fault geometry by Menges (1981) were particularly useful in identifying some of the principal features causing structural controls on bedrock hydrology. On the south side of the basin system, the Patagonia Fault forms the steep boundary between basin sediments and igneous rocks of the main mountain system (Menges, 1981). At this contact, basin sediments are exposed as high as 210 m above the valley floor. To the north on the Santa Rita side of the graben, bedrock appears abruptly along concealed fault structures along the banks of Sonoita Creek at the valley's lowest elevations. This geologic basin margin configuration has implications on the controls of the geochemistry of waters in the groundwater system.

Hydrothermal mineralization and geochemical exploration

Studies that have been particularly useful for this investigation include the early geologic and mineral deposit compilation by Schrader (1915). Chatman (1994) and Keith (1975) also published extensive summaries of mine workings in the area. Modern geologic information and interpretations include Drewes (1971; 1972 a, b; 1980), Simon (1971; 1974) and du Bray, (1996). Mineral-related information relevant to this investigation, published by Corn (1975), outlined the alteration and mineralization present within the Red Mountain porphyry deposit (Chaffee, 2020). Other studies of local porphyry deposits and related systems include Graybeal (1984) and Graybeal (1996). Chaffee et al. (1981) broadly defined the geochemical expression of rocks within the porphyry systems of the area, using geochemical analyses of stream sediments. The USGS conducted a comprehensive mineral resource assessment of the Coronado National Forest (du Bray, 1996) that included the Patagonia Mountains and Harshaw Creek watershed. The assessment was provided to help the U.S. Forest Service comply with requirements of title 36, chapter 2, and part 219.22, Code of Federal Regulations, which requires the U.S. Forest Service to provide information and interpretations so that mineral resources can be considered with other types of resources in land-use planning. Graybeal et al. (2015) and Vikre et al. (2014) presented a chronology of multiple mineralization episodes important to understanding chemical overprinting on the host geology within this portion of the TSCAS crystalline highlands and hard-rock aquifers.

In addition to the many interpretive geochemical studies of selected areas in and near Coronado National Forest, a broad regional interpretive geochemical study was carried out by the USGS (Chaffee, 1990). This study was part of a preliminary mineral resource assessment of the Tucson and Nogales 1° x 2° quadrangles (Peterson, 1990) and is based entirely on a compilation of geochemical data obtained from other studies. In 1996, the USGS published a study evaluating the mineral resource of areas in the Coronado National Forest of southeastern Arizona, which includes much of the Patagonia Mountains (duBray, 1996). Compilations of geologic, geochemical, and geophysical data were examined to determine high, moderate, and low mineral resource potential for future land management planning and objectives. Lecumberri-Sanchez et al. (2013) provided a detailed

3-dimensional temporal and spatial distribution of mineralization and alteration at Red Mountain in the northern Patagonia Mountains. The most recent publications, and possibly most relevant to the present study, are those of Chaffee (2020) and Horton et al. (2020), which reported results of geochemical analyses of greater than 1,000 samples of various types including drill core, rock, soils, and several plant species. The samples were collected on and around Red Mountain, an unmined porphyry copper-molybdenum deposit (Cu-Mo deposit). These latter studies used drill cores to profile the deep subsurface rock chemistry and mineralogy of the mountain range.

Relevant lessons from these previous studies in the Patagonia Mountains and surrounding areas include: 1) hydrothermal fluids associated with the emplacement of granitoid magmas have deposited concentrations of base-metal sulfides (veins, replacements, and disseminations) within a broad envelope of hydrothermally-altered wallrock that also bears disseminated base-metals (e.g., iron, nickel, lead, zinc, copper) and sulfide minerals, 2) the altered wallrock may strongly influence groundwater flow because alteration modifies the hydraulic properties of the rock, and 3) the wallrock influences water chemistry and quality by acting as a large-volume source of potential contaminants.

7.5.6. Hydrology and Ecology: Previous work

Only a small collection of studies directly pertain to geochemical, environmental, and hydrologic aspects of the area (Gray et al., 1998; Brady et al., 2001; Gray et al., 2004; Balistrieri et al., 2007; Norman et al., 2008; Eddleman, 2012). The results of these studies, however, shed light on the nature of the 3-dimensional geochemistry of the subsurface that hosts extensive but poorly known highland aquifer systems. These studies help to understand the controls that mineral deposit geology exerts on groundwater quality and surface drainage.

Studies that include water-quality analyses and environmental characterization of stream quality and ecology in the Patagonia Mountains include those by Dean (1982) and Hyde (1995). Gray et al. (2000) presented the results of analysis of the relationship between the geohydrologic setting and metals distribution and compared seasonal storm events with fluxes of metal concentrations within the region. Brady et al. (2000) discussed the criteria for a GIS-based analysis of soil erosion and presented models of the geochemical effects of eroding mine waste upon several watersheds in the area. Gu (2005) and Gu et al. (2008) discussed the use of stable isotopes in understanding the sources of water quality inputs to various watersheds in the Patagonia Mountains, specifically in Harshaw Creek and Alum Gulch. Eddleman (2012) investigated aqueous plant and soil chemical relations in mine-impacted streams in the study area and evaluated levels of bio-uptake of metals caused by acid drainage in the area. An understanding of metals sources and pathways in mineralized ecosystems including the Patagonia Mountains and southern Santa Rita Mountains is discussed in Balistrieri et al. (2007). The most significant landscape scale interaction observed in shallow to deep groundwater and related surface water is the buffering of acidity where groundwater flows from intensely mineralized acid-generating silicate rocks in the center of the Patagonia Mountains across the Harshaw Creek fault into acid-absorbing Paleozoic carbonate.

7.6. Lowland Geochemistry: Lowland Data Summary and Review

In the following section we present a summary of the selected water-quality information (physio-chemical parameters and major ions) primarily for the lowland aquifers of the TSCAS. Selected sites with relevant water-quality data can be found in Figure 7.2. Additional review is provided of selected data and publications regarding the NIWTP, microbiology, and organic compounds.

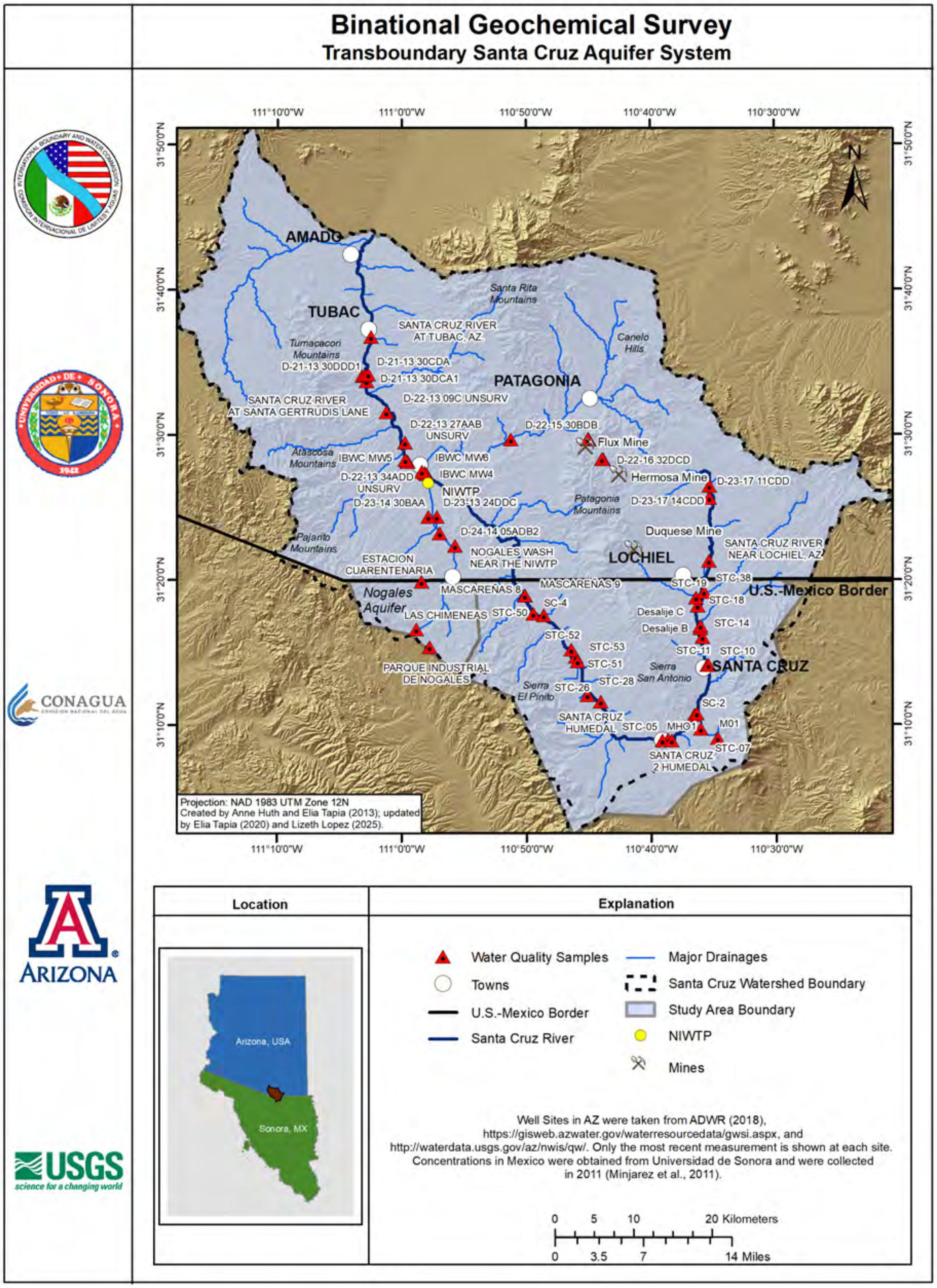

Figure 7.2 Binational Geochemical Survey in the TSCAS.

7.6.1. Temperature

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. The Basin and Range province has relatively high geothermal gradients with temperature values in groundwater wells ranging from 0.47 to 0.6°C per 30 m (Keys, 1990). The temperature of water in shallow wells in the Basin and Range province in southwestern Arizona have shown abnormally high geothermal gradients. In Santa Cruz County, one such gradient was observed to be 66°C per km (Giardina and Conley, 1978). Near the surface, the geothermal gradient may be modified by infiltration of surface water, which may represent seasonal temperature signals (Dowman et al., 2003). Temperature also affects the rate of chemical reactions and biological processes. For this and other reasons, it is a common parameter measured in ground- and surface-water. Figure 7.3 shows spatial variability of groundwater and surface-water temperatures in the TSCAS. As shown in the figure, groundwater temperature ranges from 16 to 28°C.

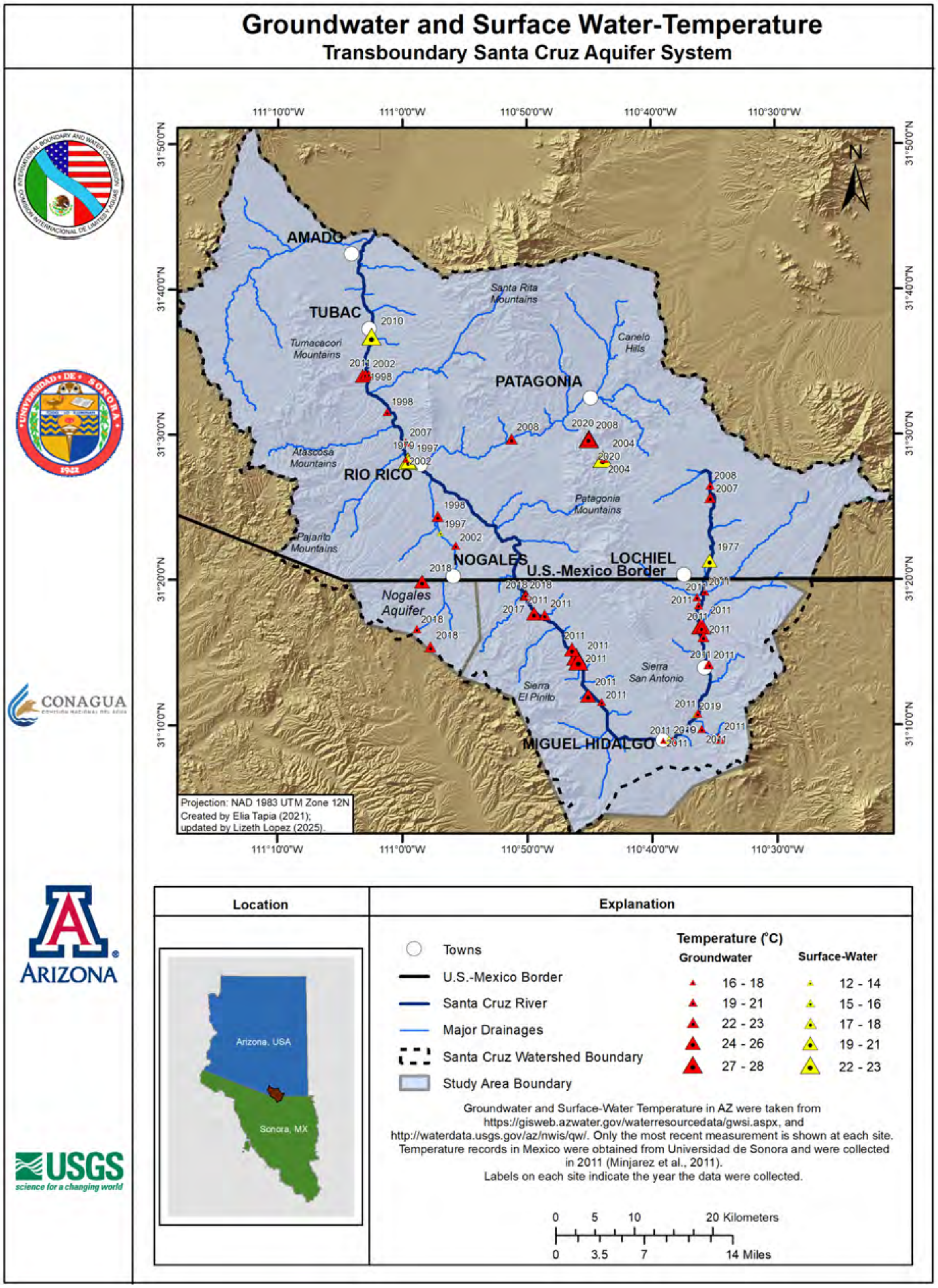

Figure 7.3 Groundwater and Surface-Water Temperature in the TSCAS.

7.6.2. pH

The pH of a solution indicates the effective concentration of hydrogen ions. It is typically determined in the field, because time, exposure to air, and temperature change after collection can change the pH of the sample. pH is both determined and influenced by multiple chemical processes such as water-rock interaction and biogeochemical cycling of nutrients. It is thus an important parameter to measure because it influences water chemistry, governing the presence and concentration of different components in a solution. A pH of 7.0 is neutral; values above or below this are considered to indicate acidic (less than 7) or alkaline (greater than 7) conditions. Both the U.S. Environmental Protection Agency (USEPA) and the Mexican Ministry of Health regulate drinking water pH to be in the range 6.5-8.5 (USEPA, 2024; NOM-127-SSA1-2021). Under this criterion, acidic water is considered to be less than 6.5 and alkaline water to be greater than 8.5. In the U.S values in groundwater, typically range from 6.5 to 8.5 (Hem, 1985). Figure 7.4 shows spatial variability of groundwater and surface-water pH in the TSCAS, which ranges from 2.7 to 8.7. The well with the highest pH is Nogales Wash near the NIWTP, located north of the U.S.-Mexico border, whereas the well with the lowest pH is D-22-16 30ACB1 [REEF MINE SEEP], located in the Patagonia Mountains, south of Patagonia.

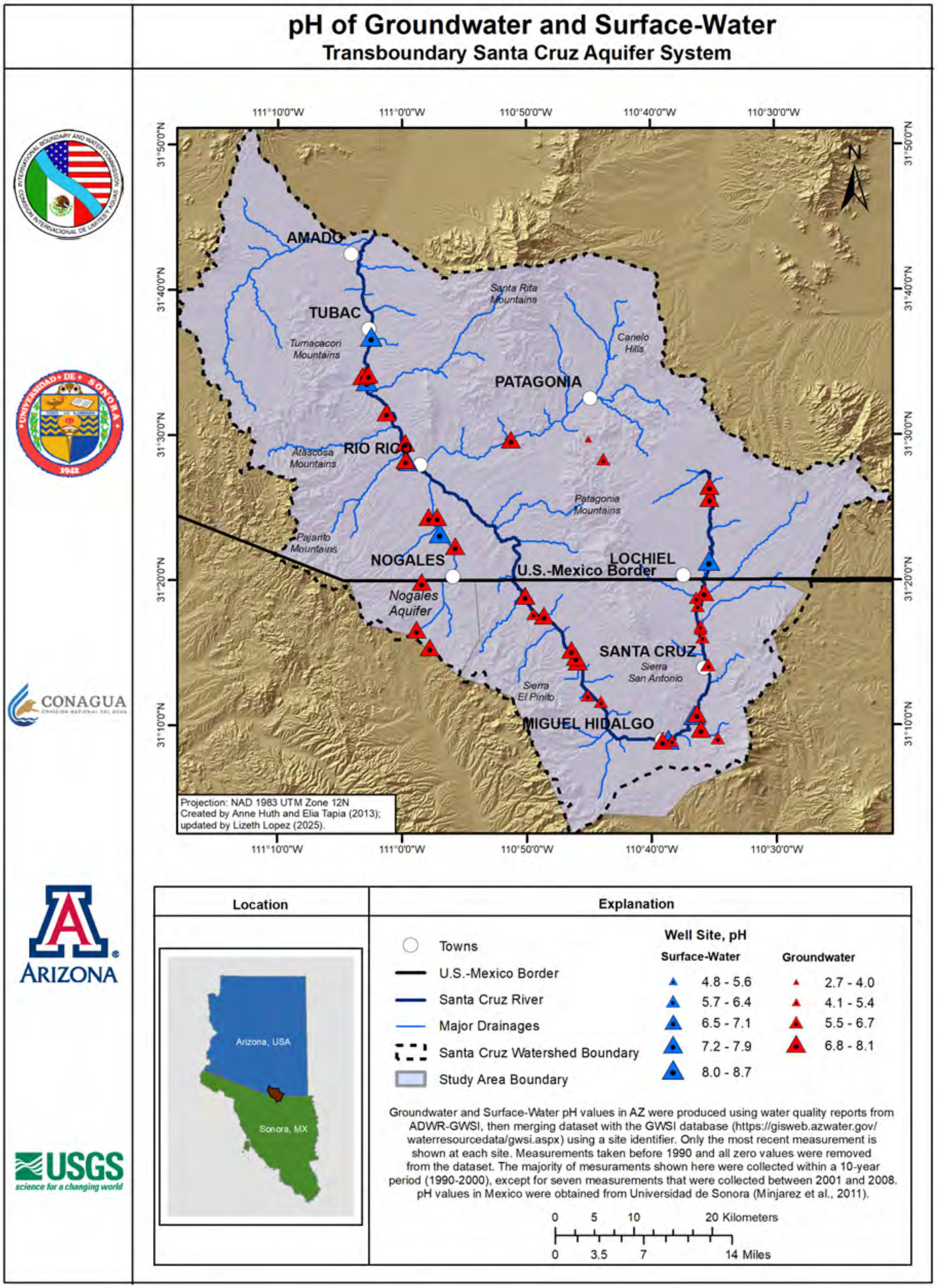

Figure 7.4 Groundwater and Surface-Water pH in the TSCAS.

7.6.3. Alkalinity

Alkalinity is a measure of the capacity of water to neutralize acid by reaction with carbonate, bicarbonate, and other ions (Hem, 1985). Carbonic acid and its ions constitute one of the major contributors to alkalinity (pH buffering) in many natural environments. Concentrations of carbonate species in aqueous solutions vary with pH (Hem, 1985). Alkalinity is important to the understanding of the chemistry of natural waters as influenced by water-rock interactions, and for the health and maintenance of aquatic habitat. Alkalinity results mainly from the dissolution of carbon dioxide, either from the atmosphere or from soil. Soil-zone carbon dioxide arises from plant respiration and the oxidation of organic matter (Hem, 1985). Figure 7.5 shows spatial variability of groundwater and surface-water alkalinity in the TSCAS. Groundwater and surface-water alkalinity values range from 100 to 294 mg/L; wells with the highest values are located in the Mexican portion of the study area.

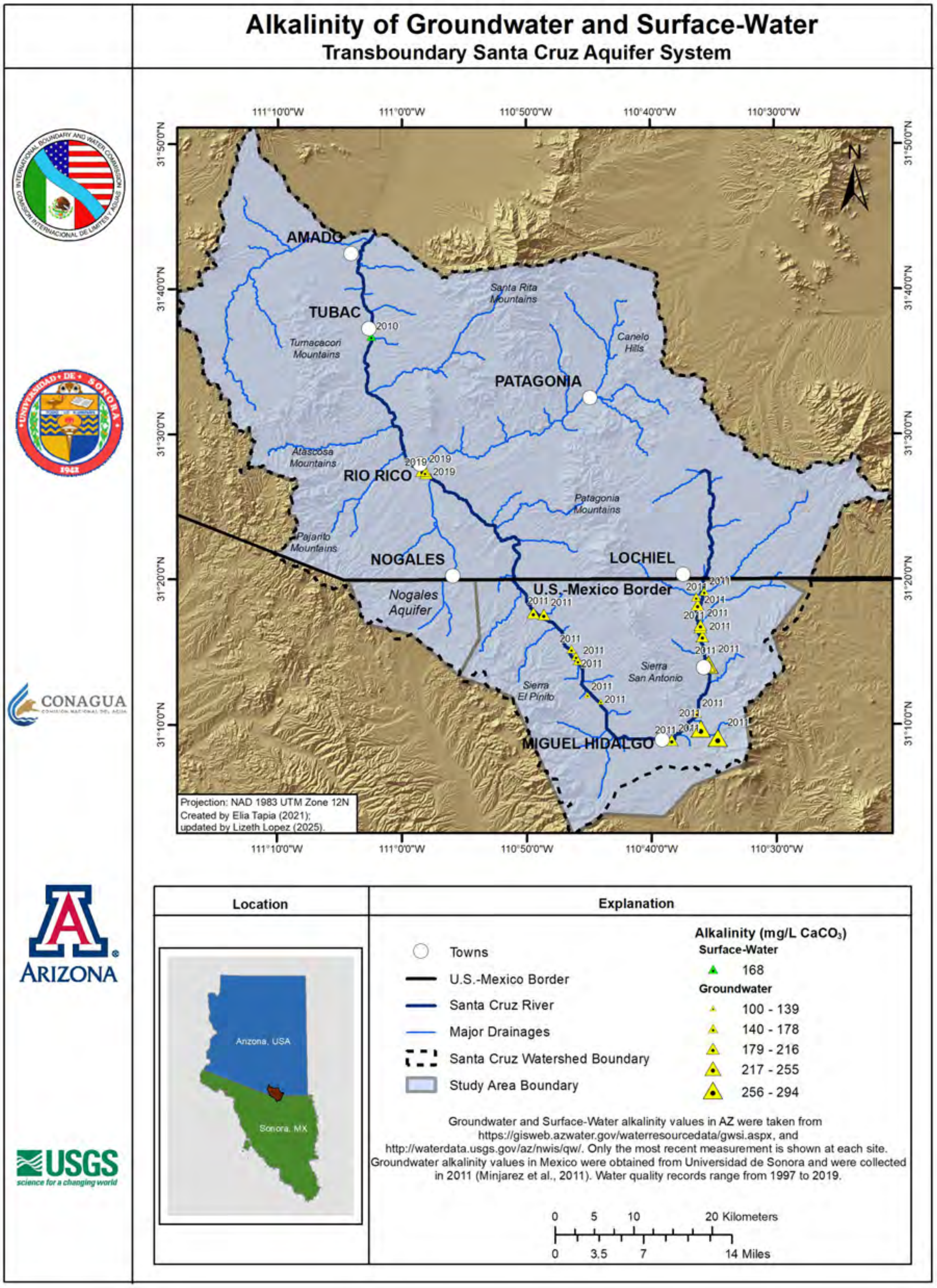

Figure 7.5 Groundwater and Surface-Water Alkalinity in the TSCAS.

7.6.4. Electrical Conductivity

Electrical conductivity (EC), also referred to as specific conductance (SC), is a measure of water's capacity to conduct electricity. It is an indicator of the total concentration of ions and serves as a useful proxy for concentration of total dissolved solids (TDS) (Hem, 1985). Concentrations of TDS are best determined through chemical analyses in laboratories; however, field conductivity meters allow an estimate of TDS. SC units in water are commonly reported in microSiemens per centimeter (µS/cm), whereas TDS concentrations are typically expressed in milligrams per liter (mg/L). The two methods report similar information. In this report, SC is used to facilitate the comparison of datasets from each country. Previous measurements of TDS have been converted to SC using the following approximation: 1.0 mg/L of TDS ≃ 0.67 µS/cm of SC (Weiner, 2012).

TDS and SC are often used as first line indicators of water quality. TDS is the sum of all dissolved constituents in a sample (Drever, 1997), and as such is important for multiple reasons including taste (it is regulated as a secondary drinking water standard by the USEPA), potential for aquatic health effects, and soil salinization (Terrell and Perfetti, 1989; USEPA, 2024). It is assumed that a 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).

In the Arizona portion of the San Rafael Valley, the values for SC in groundwater ranged from 293 to 1,637 µS/cm, averaging 540 µS/cm (ADEQ, 2003). In the study conducted by ADEQ (2003) in the San Rafael Valley, the groundwater TDS ranged from 185 to 1,070 mg/L. The SC of surface water in the Santa Cruz River was 314 µS/cm in Lochiel (ADEQ, 2003). In the Mexican part of the Santa Cruz River aquifer, SC ranged from 80 to 1,390 µS/cm (CONAGUA, 2009). Additional data indicated SC values ranged from 258 to 698 µS/cm in the Mexican part of the aquifer (Minjarez et al., 2011). Wells with the highest SC values were located in Cañada la Piedra and the town of Santa Cruz, Sonora (Figure 7.6The well with the lowest SC, 258 µS/cm, was located in Ejido Miguel Hidalgo on the west side of the Santa Cruz River aquifer (Figure 7.6). The hardness in the Santa Cruz River aquifer varied from 21 mg/L to 632 mg/L, with 83% of the wells having concentrations less than 200 mg/L. The remaining 17% had hardness greater than 200 mg/L (CONAGUA, 2024). SC gradually increased downstream of the international border with an abrupt increase downstream of the NIWTP at Rio Rico (Figure 7.6).

In the study conducted by Investigación y Desarrollo de Acuíferos y Ambiente (IDEAS) (2008) in the Santa Cruz aquifer, TDS ranged from 40 to 690 mg/L. In the groundwater study conducted by International Boundary and Water Commission (IBWC) (2001) in the Nogales aquifer along the Nogales Wash, SC ranged from 121 to 845 µS/cm. In the 1998 study conducted by the USGS and ADEQ in the upper Santa Cruz basin, SC ranged from 240 to 1,300 µS/cm, and TDS ranged from 120 to 890 mg/L. Figure 7.6 shows spatial variability of groundwater and surface water SC in the TSCAS. Groundwater SC values range from 250 to 3,420 µS/cm. The well with the highest value is D-22-16 30ACB1, which is located north of the Patagonia Mountains.

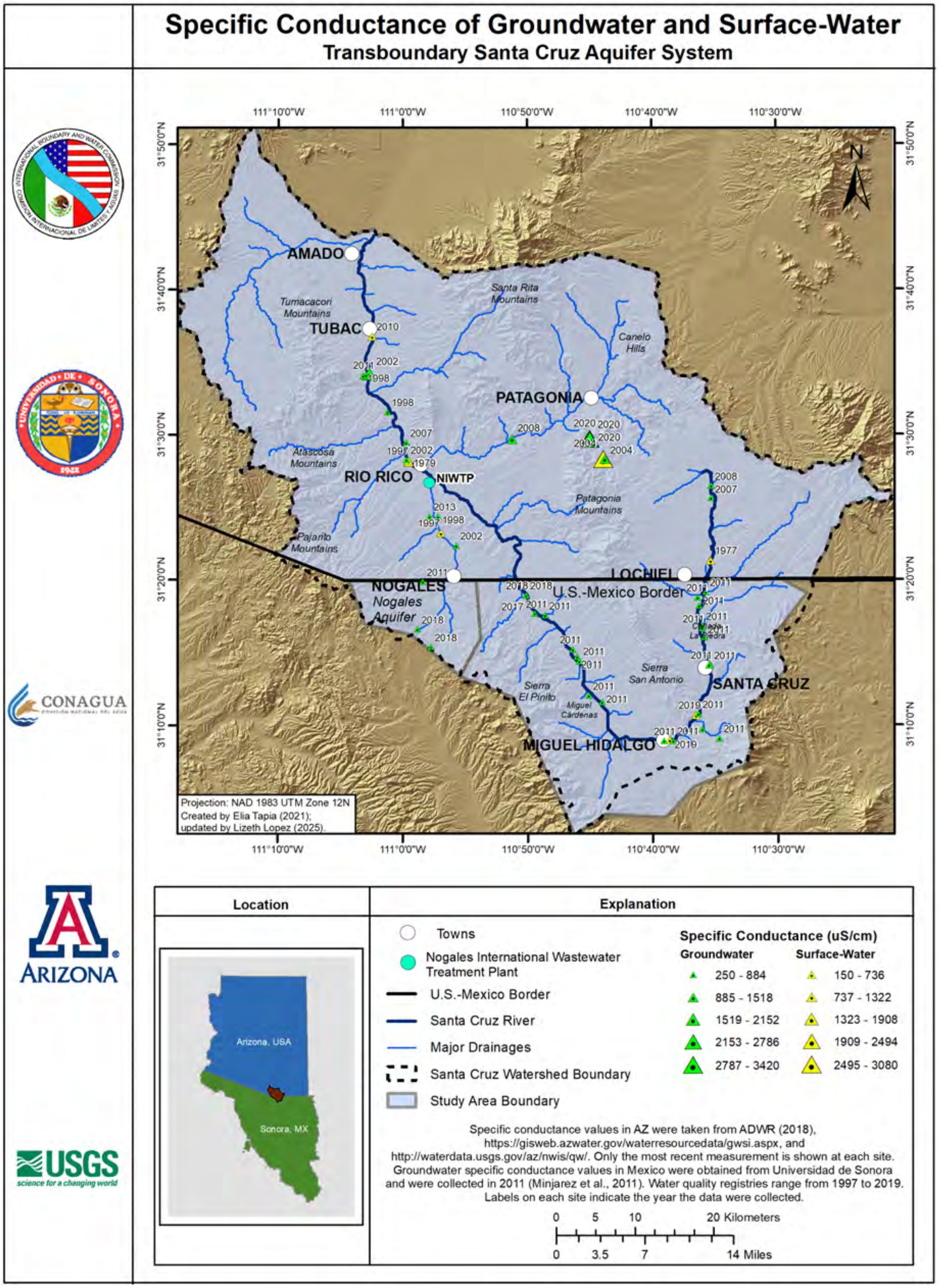

Figure 7.6 Specific Conductance in the TSCAS.

7.6.5. Major Ions

In this study, major ions include sodium, calcium, magnesium, potassium, bicarbonate, sulfate, and chloride. Table 7.4 shows the maximum and minimum concentrations found in the TSCAS, along with the MCL and a description of where maximum concentrations were found. Additionally, figures 7.7-7.13 show the geographic distribution of major ions within the TSCAS. Data for major ions for the U.S. portion were obtained from the Arizona Department of Environmental Quality (ADEQ) Ambient Groundwater Monitoring Program study conducted between 2000 and 2002 in the San Rafael groundwater basin (Towne, 2003) while the Mexican information were collected in 2011 (Minjarez et al., 2011).

Table 7.4 Major Ions and MCL in the TSCAS.

Major Ions	**Minimum conc. (mg/L)**	**Maximum conc. (mg/L)**	**MCL (mg/L)**	**Observations**
Sodium	0.01	169	200 mg/L (NOM-127-SSA1-1994)	Max. concentration located south of the town of Tubac, United States and the Tumacacori Mountains in well D-21-13 30DD1
Calcium	0.01	541	N.A.	Max. concentrations found in well D-22-16 32DCD in the Patagonia Mountains
Magnesium	0.01	275	N.A.	Max. concentrations located near the city of Patagonia, United States
Bicarbonate	122	359	50 and 350 mg/L (Custodio and Llamas, 1996)	Max. concentration found in the town of Santa Cruz, Mex.
Potassium	0.0.1	9.91	10 (Custodio and Llamas, 1996)	Max. concentration found in well Santa Cruz River NR Rio Rico Arizona, United States
Chloride	0.01	200	250 (USEPA)	Max. concentrations located south of Tubac, United States and near the Tumacacori Mountains
Sulfate	0	2580	250 (USEPA) 400 (NOM-127-SSA1-1994)	Max. concentrations located east of Miguel Higaldo Town in Mexico

Sodium

Sodium (Na) in groundwater is supplied from precipitation, from water-rock interactions involving igneous rocks, or from urban and industrial pollution (Custodio and Llamas, 1996). Sodium is part of the alkali metal group along with lithium, potassium, rubidium, and cesium; the most common source is the weathering of feldspars. Halite (NaCl), where present in evaporative areas in the basin fill, can cause increased concentrations of dissolved sodium. The maximum sodium concentration permitted by the Mexican Official Standard (NOM-127-SSA1-1994), is 200 mg/L. CONAGUA (2024) found sodium concentrations ranged between 5 and 81 mg/L. Figure 7.7 shows spatial variability of groundwater and surface water sodium concentrations in the TSCAS. Groundwater and surface water sodium concentration values range from 0.01 to 169 mg/L, the highest value was found in well D-21-13 30DCA1.

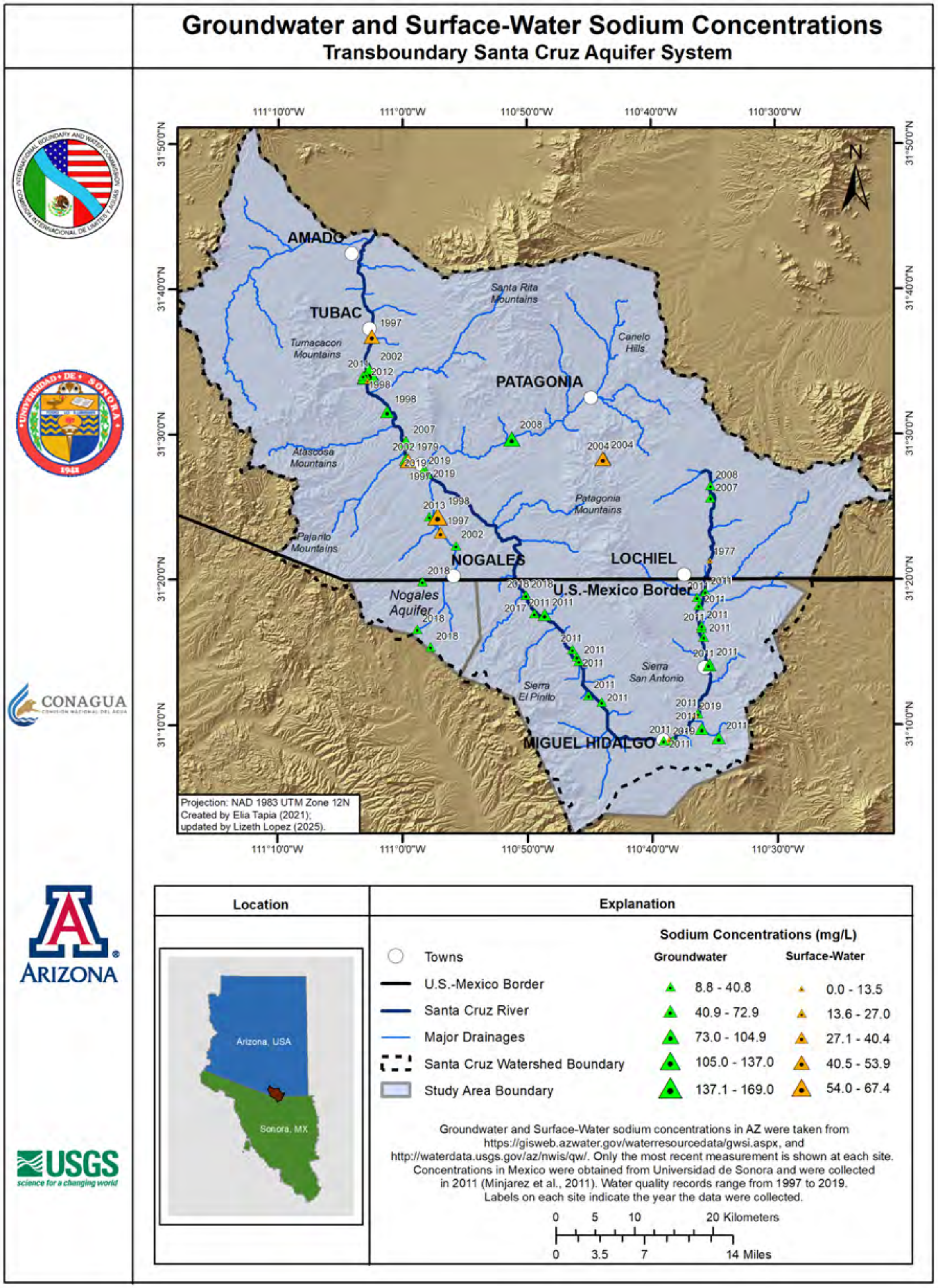

Figure 7.7 Spatial variability of groundwater and surface-water sodium concentrations from the TSCAS.

Calcium

Calcium (Ca) in groundwater is typically derived from a major constituent of commonly occurring aluminosilicate minerals that form part of the geological environment (Hem, 1985). Gypsum and anhydrite, although restricted to playas or evaporites in the broader areas of the upper Sonoita basin, are important sources of calcium. Weathering of plagioclase and dissolution of calcite and dolomitic limestones are common sources of calcium, specifically near the Canelo Hills. Ferromagnesian minerals, pyroxenes and amphibole, are also minor sources found throughout the basin. The Official Mexican Standard does not set a maximum limit for calcium, but typical concentrations in drinking water can reach 250 mg/L (Custodio and Llamas, 1996). CONAGUA (2024) found that calcium ranged from 5 to 188 mg/L, which would be considered tolerable for human use and consumption. Figure 7.8 shows spatial variability of groundwater and surface-water calcium concentrations in the TSCAS. Groundwater and surface-water calcium concentrations range from 0.01 to 541 mg/L. The highest values were found at two sites, D-22-13 34ADD UNSURV and Alum Gulch at January Adit, north of Patagonia Mountains.

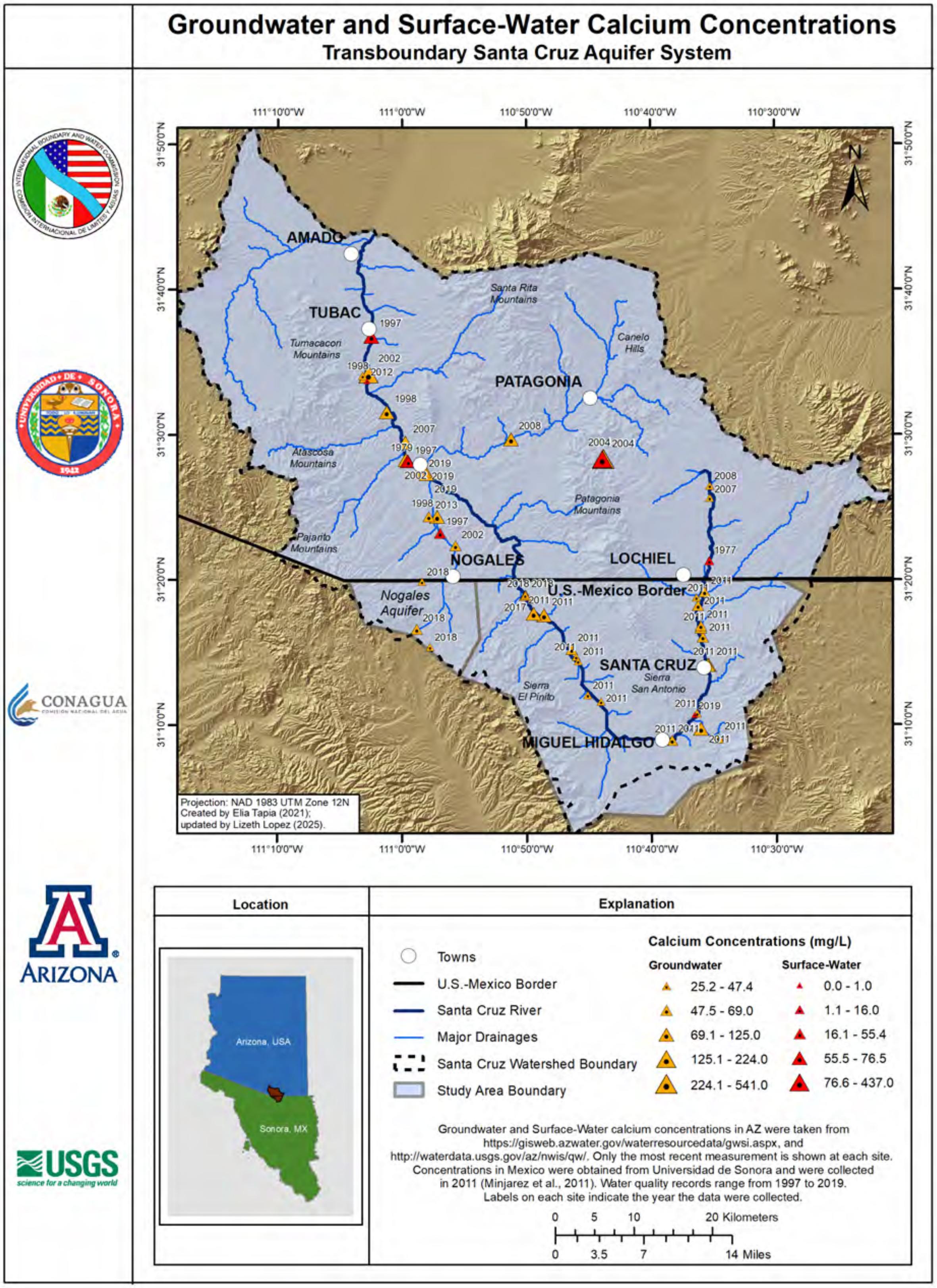

Figure 7.8 Spatial variability of groundwater and surface-water calcium concentrations from the TSCAS.

Magnesium

Magnesium (Mg) is one of the most abundant elements in the earth's crust (Lide, 2005). It is part of both sedimentary and igneous rocks, and its chemical role in the environment has some features in common with calcium. However, in primary igneous rocks, magnesium behaves more like iron or manganese than calcium (Rankama and Sahama, 1950). The main source of magnesium in groundwater is typically dissolution of dolomite and dolomitic limestone (Custodio and Llamas, 1996), though whether that is the case in the TSCAS is not known. Minor sources include the ferromagnesian minerals of the pyroxene and amphibole groups.

The Mexican NOM and EPA 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 high concentrations can form precipitates in pipelines and boilers. CONAGUA (2024) found magnesium concentrations ranged from 1 to 31 mg/L. Figure 7.9 shows spatial variability of groundwater and surface water magnesium concentrations in the TSCAS. Groundwater and surface-water magnesium concentrations range from 0.01 to 275 mg/L. Highest values were found in wells D-22-16 32DCD and Alum Gulch at January Adit, north of Patagonia Mountains.

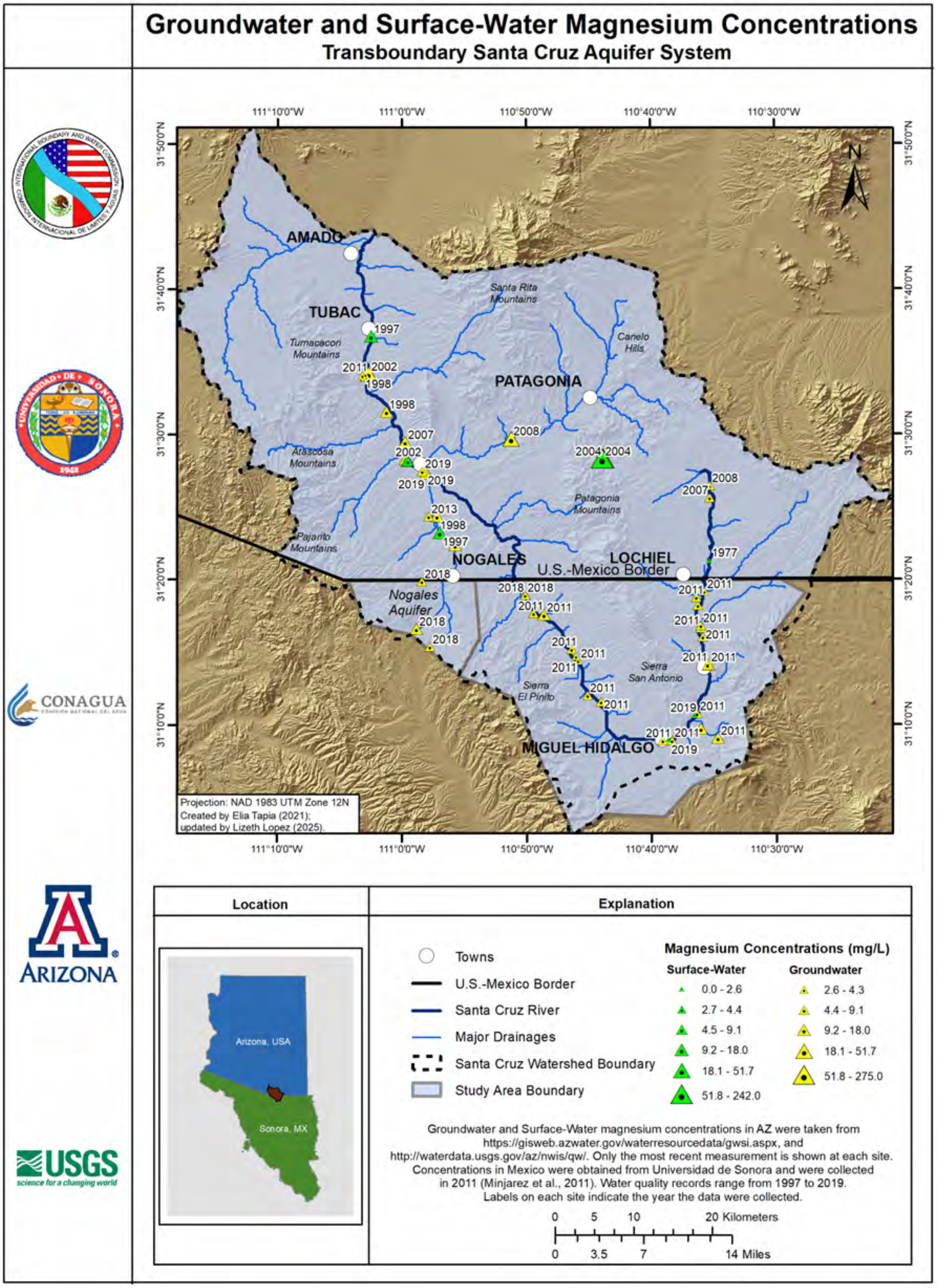

Figure 7.9 Spatial variability of groundwater and surface-water magnesium concentrations from the TSCAS.

Bicarbonate

Primary natural sources of bicarbonate in water are biological activity in soils (producing carbon dioxide that can dissolve in water) and dissolution of calcium carbonate (in rock or soils) (Hem, 1985). It is the dominant ionized form of carbonic acid between pH 6 and 8.

There is no Mexican Official Standard or EPA drinking water standard with respect to bicarbonate. However, high concentrations of bicarbonate, along with calcium and magnesium 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 mg/L. Figure 7.10 shows spatial variability of groundwater and surface-water bicarbonate concentrations in the TSCAS. Groundwater and surface-water bicarbonate concentration values range from 122 to 359 mg/L. The highest value was found in well STC-10 in the Sonoran portion of the study area of the TSCAS.

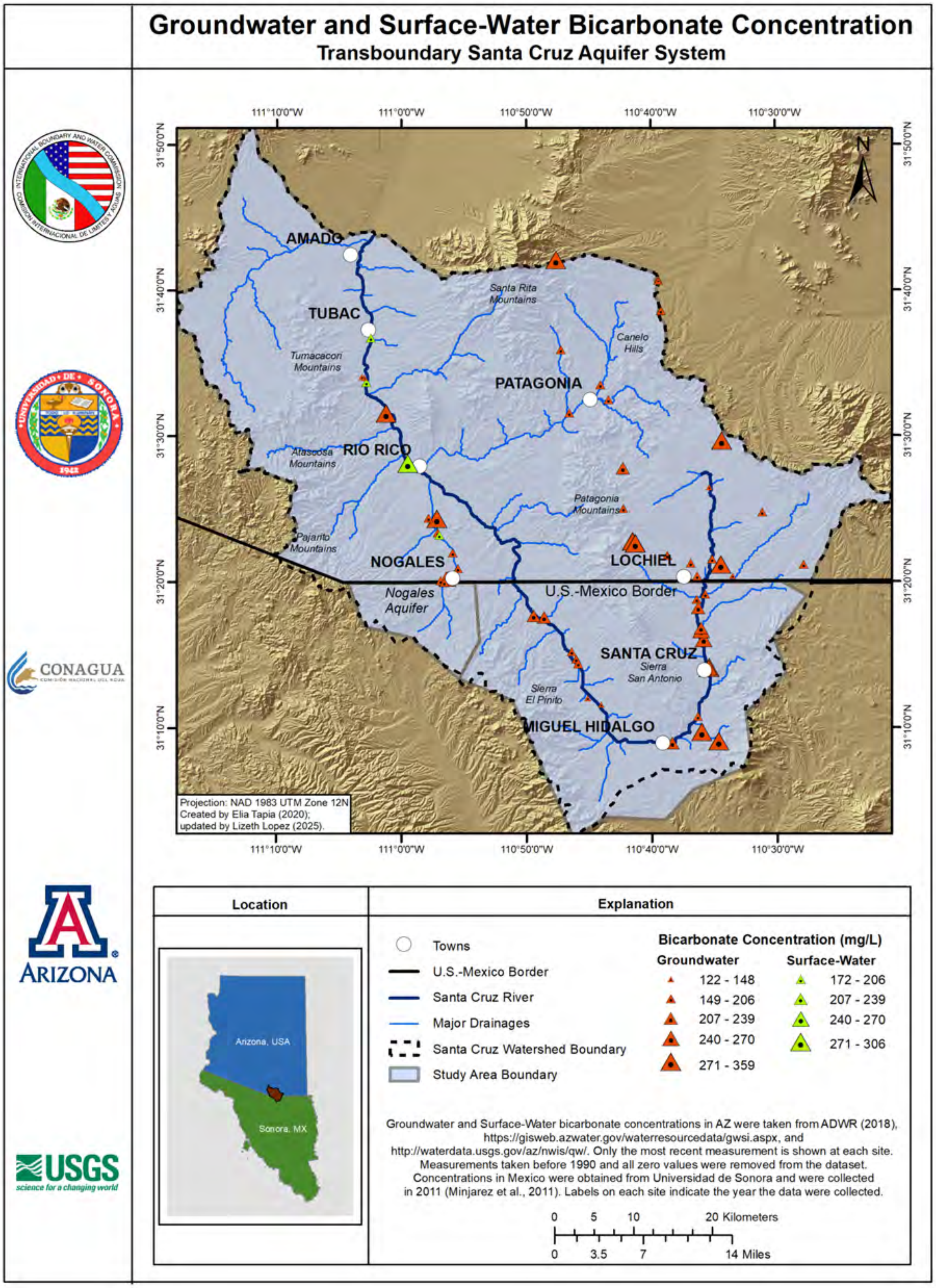

Figure 7.10 Spatial variability of groundwater and surface-water bicarbonate concentrations from the TSCAS.

Potassium

Potassium (K) is usually found at low levels in groundwater, and may be derived from leaching of soils, aluminosilicate minerals like potassium feldspar and micas, some evaporites, organic matter decomposition, salt-water intrusion, and anthropogenic pollution (Blakeet et al., 2008; Department of Energy [DOE], 1994). The Official Mexican Standard does not set a maximum limit for potassium, but Custodio and Llamas (1996) stated that concentrations of potassium should not be higher than 10 mg/L. CONAGUA (2024) found potassium concentrations between 1 and 5 mg/L. Figure 7.11 shows spatial variability of groundwater and surface-water potassium concentrations in the TSCAS. Groundwater and surface-water potassium concentrations range from 0.01 to 9.9 mg/L. The highest values were found in the wells SCT-07 and Santa Cruz River near Rio Rico, Arizona.

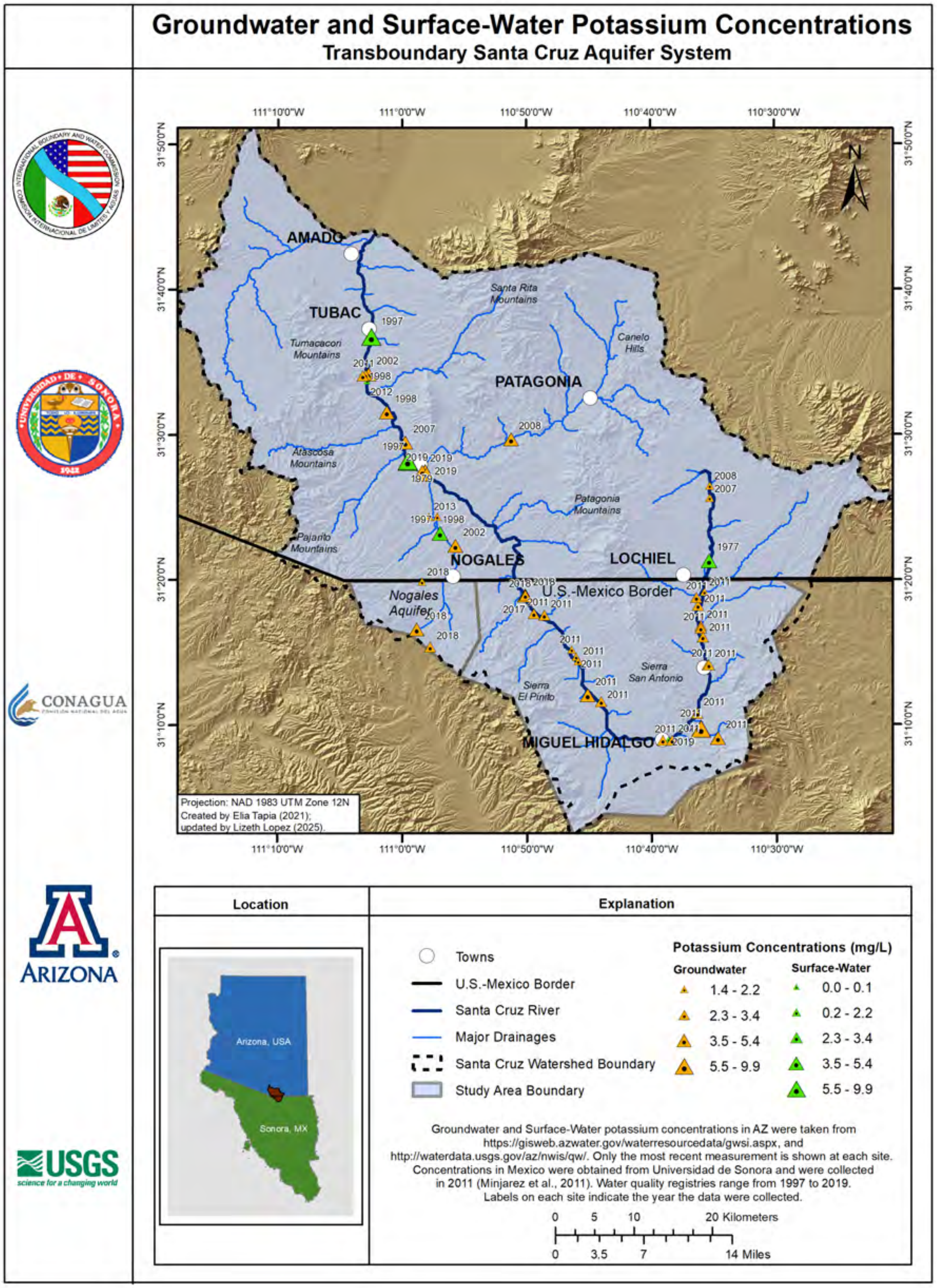

Figure 7.11 Spatial variability of groundwater and surface-water potassium concentrations from the TSCAS.

Chloride

Chloride (Cl^-) is the most abundant form of chlorine in water exposed to the atmosphere. The main natural sources likely in the study area are sedimentary rocks including evaporites and shales (Hem, 1985). However, ore deposits or hydrothermal deposits are other significant potential sources of chloride in most basins containing these deposits (Robertson, 1991). Chloride, therefore, is present in several common rock-forming minerals, (e.g., micas, amphiboles, and apatite), that may contribute chloride ions during weathering (Mullaney et al., 2009). Chloride compounds are highly soluble, particularly halite, and these compounds are known to be concentrated in evaporites or playa deposits which may form in restricted areas of the basin. Anthropogenic sources are likely industrial waste, treated and untreated effluent, and chlorine used for disinfection. It is largely transported conservatively (no sorption or precipitation) in non-saline water (Hem, 1985).

The EPA (secondary standard) has established a maximum allowable limit of 250 mg/L for use and human consumption of chloride. In the Sonoran portion of the aquifer, the chloride concentrations were below the maximum allowable limit, varying between 4 and 43 mg/L. Figure 7.12 shows spatial variability of groundwater and surface-water chloride concentrations in the TSCAS. Groundwater and surface-water chloride concentrations range from 0.01 to 200 mg/L, the highest value was found in well D-21-13 30DD1 in the Arizona portion of the study area.

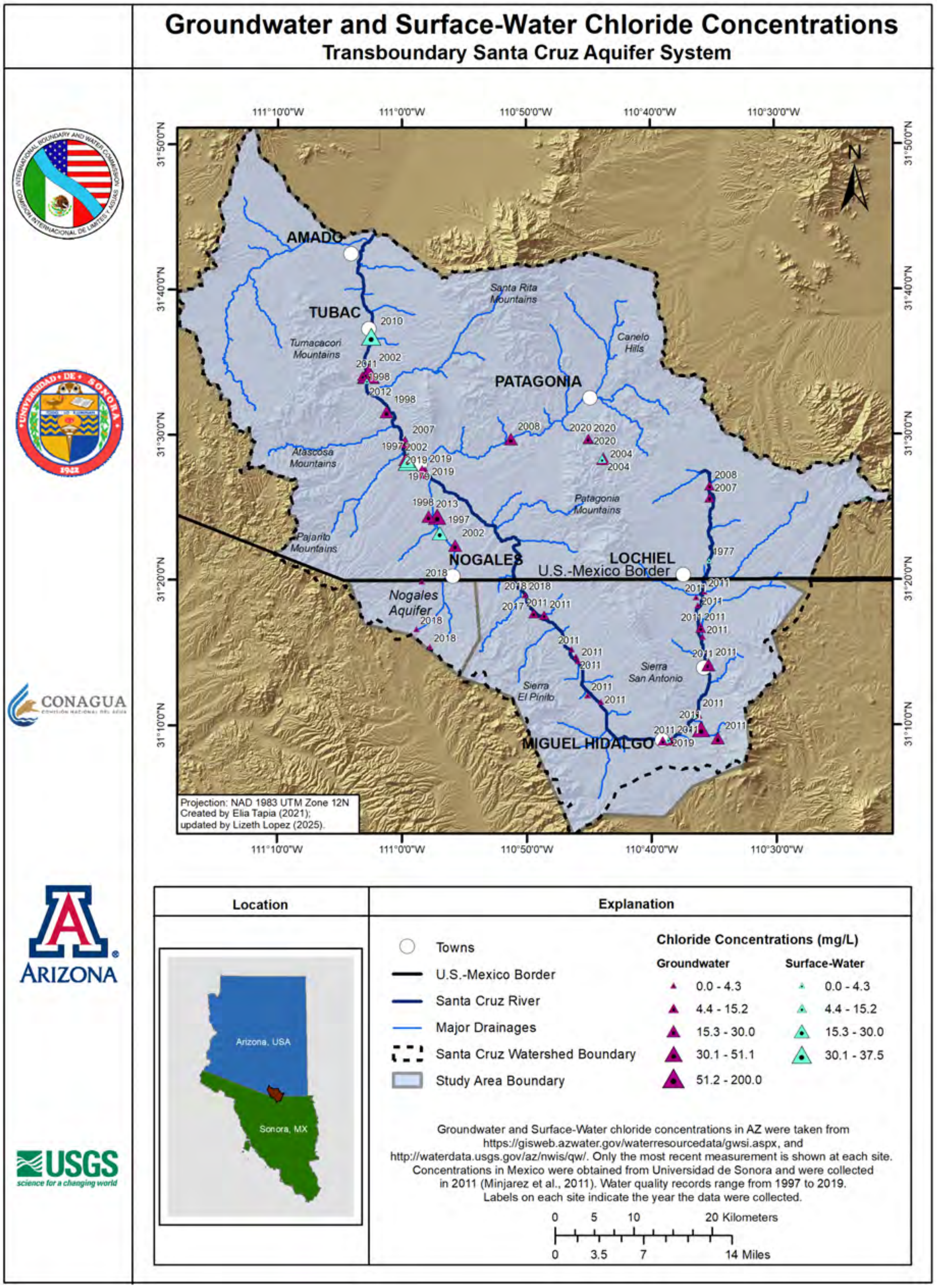

Figure 7.12 Spatial variability of groundwater and surface-water chloride concentrations from the TSCAS.

Sulfate

Sulfate (SO_4^{2-}) is found in groundwater, from both natural and anthropogenic sources. The primary natural sources of sulfate include atmospheric deposition, sulfate mineral dissolution, and sulfide mineral oxidation. In high-temperature volcanic and hydrothermal environments, sulfur occurs as sulfides; when exposed to the atmosphere or oxygenated water during weathering, sulfides are oxidized to sulfates. The moderate solubility of sulfates allows concentrations to occur in evaporites and playa deposits as anhydrite and gypsum (Robertson, 1991). These deposits can be the source of large sulfate concentrations found in the upper headwaters portion of the Santa Cruz basin; however, ore deposits are the most likely sources of sulfate in most basins. Anthropogenic sources include coal mines, power plants, phosphate refineries, and metallurgical refineries (Miao et al., 2012).

Figure 7.13 shows spatial variability of groundwater and surface-water sulfate concentrations in the TSCAS. In the Arizona portion, groundwater and surface-water sulfate concentrations range from 0 to 260 mg/L. The concentrations of sulfate on the Sonoran side of the Santa Cruz aquifer ranged from 8 to 103 mg/L. The highest sulfate values (between 1,480 and 2,580 mg/L) were found in wells D-22-16 30ACB2 (Alum Gulch above Reef Mine), D-22-16 30BDA1 (Alum Gulch below Reef Mine), D-22-16 30ACB1 (Reef Mine Seep), D-22-16 32DCD, and Alum Gulch at January Adit. These sulfate concentrations surpass the EPA secondary standard of 250 mg/L and the Mexican Official Standard Limit of 400 mg/L.

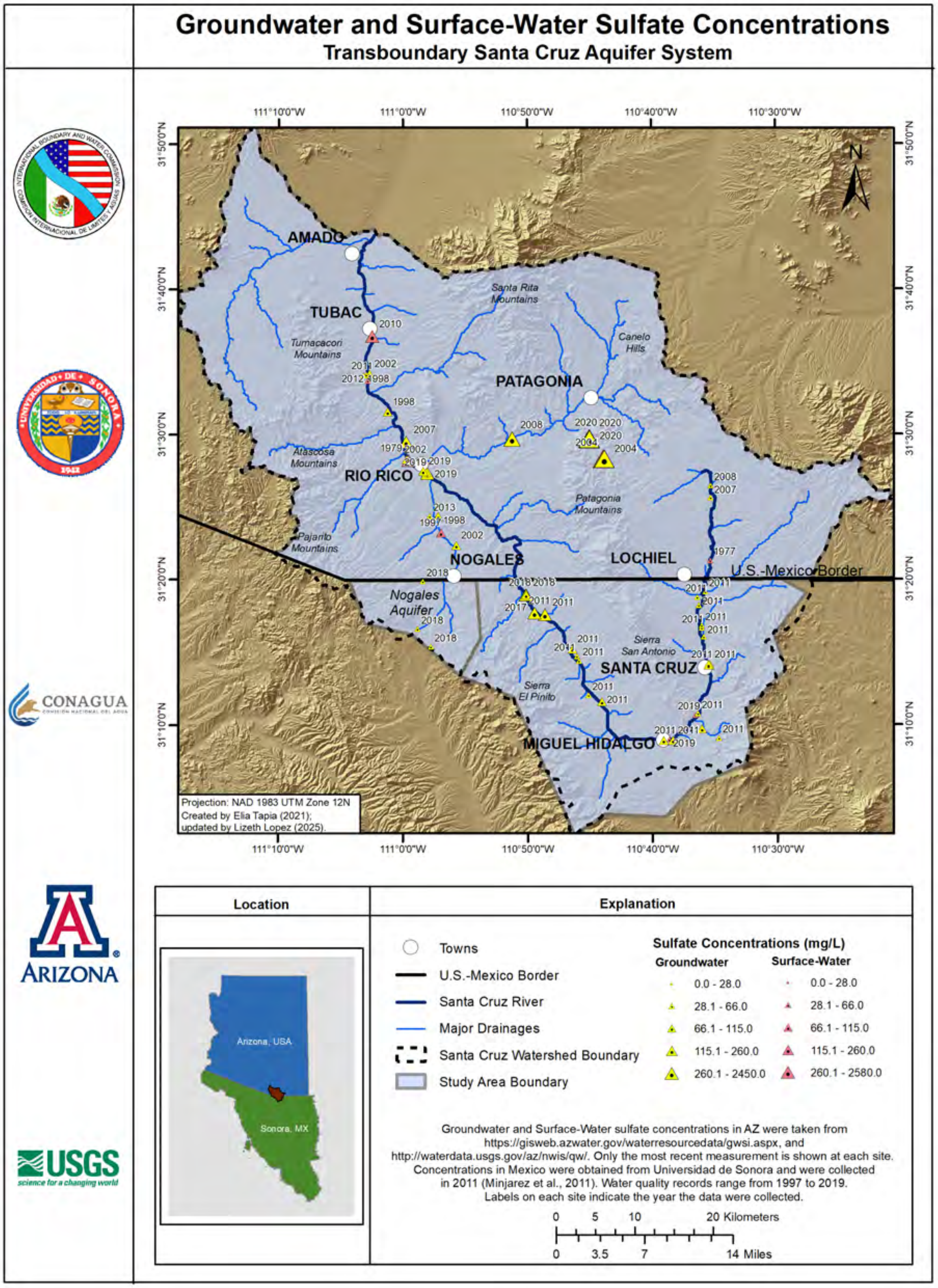

Figure 7.13 Spatial variability of groundwater and surface-water sulfate concentrations from the TSCAS.

Stiff Diagrams

The Stiff diagram is useful for rapid visualization and comparison of water from different sources. The pattern is created from three or four horizontal axes that are parallel to each other and extend on either side of a vertical zero axis (Fetter, 2001). These diagrams delineate the concentrations of ions found in selected samples along its axes. The first axis represents the proportion of Mg and SO_4; the second axis plots Ca and HCO_3+CO_3; and the third axis combines Na and K on one side of the zero axis and Cl on the other. The left side of the resulting polygons represents the major cations: sodium (Na^+) plus potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}), while the right side represents the main anions: chloride (Cl^-), bicarbonate (HCO_3^-) plus carbonate (CO_3^{2-}), and sulfate (SO_4^{2-}).

Stiff diagrams were created from the laboratory results from studies including ADEQ (2003) and Minjarez et al. (2011). These diagrams delineate the concentrations in milliequivalents per kilogram (meq/kg) of ions found in selected samples along its axes.

The diagrams show that the highest HCO_3+CO_3 concentrations of groundwater were observed in the Sonoran region, particularly in well STC-10, near the town of Santa Cruz, Mexico. It is important to note that these elevated values were from wells predominantly clustered around streams and the river, suggesting localized influences. Lower concentrations were found near the Tumacácori mountains. Additionally, chloride concentrations depicted in the Stiff diagrams remained within the maximum limits established by both the NOM and EPA. Below are the generated Stiff diagrams, each labeled with the name of its corresponding site (Figure 7.14-Figure 7.17). Figure 7.18 shows the locations of each of the Stiff diagrams within the study area.

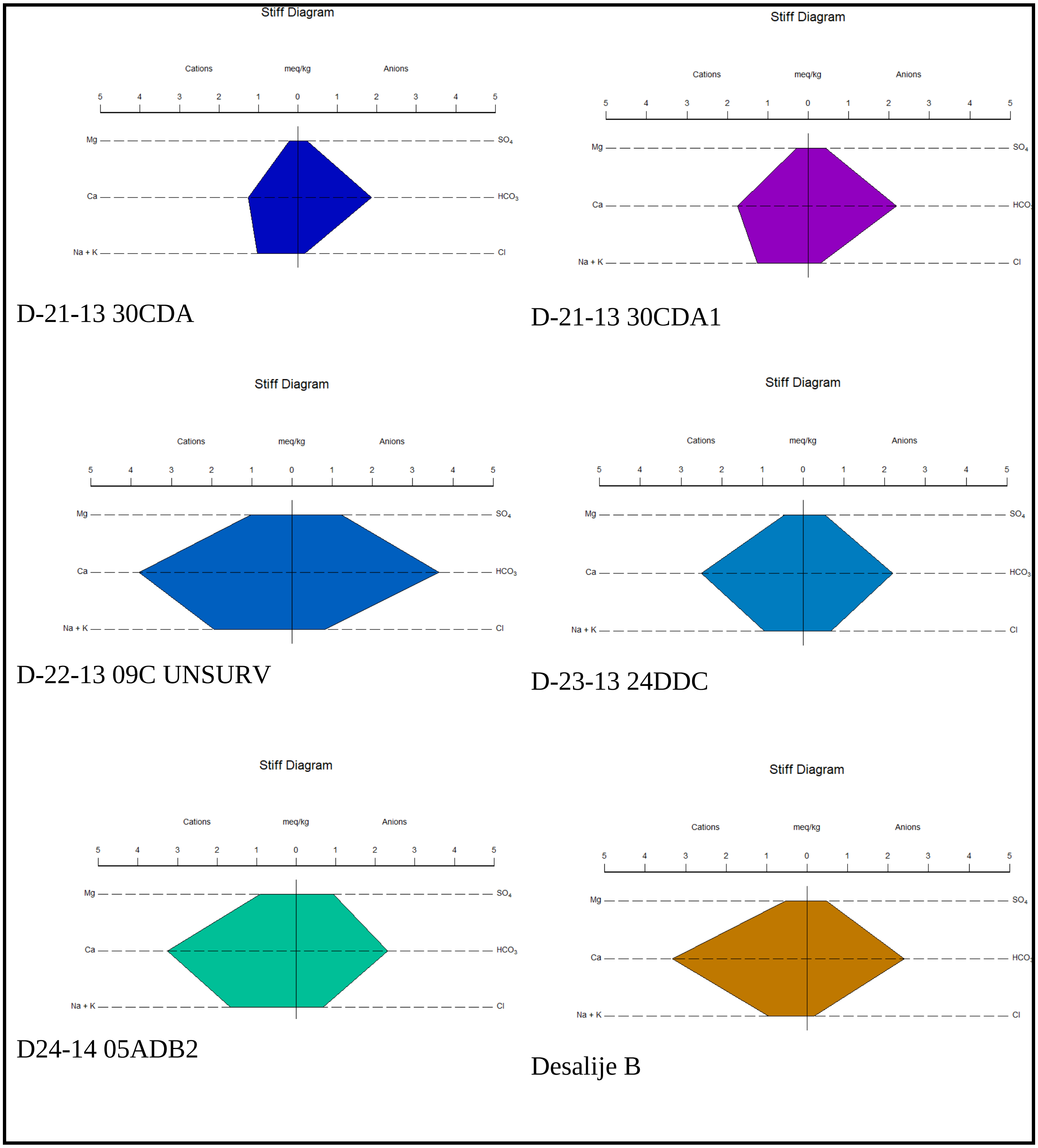

Figure 7.14 Stiff diagrams showing the ionic composition of the analyzed water samples, expressed in milliequivalents per kilogram (meq/kg).

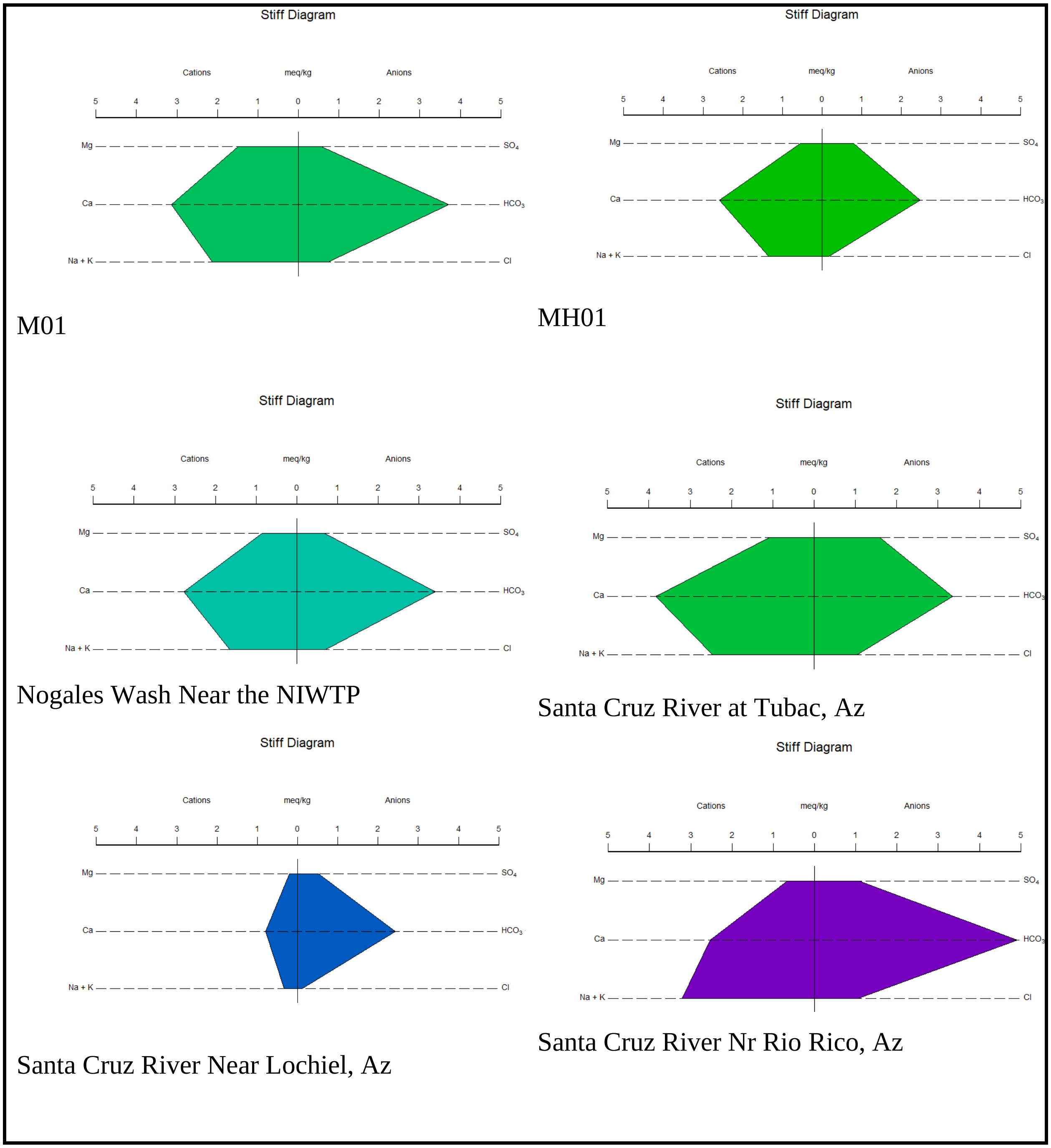

Figure 7.15 Stiff diagrams showing the ionic composition of the analyzed water samples, expressed in milliequivalents per kilogram (meq/kg).

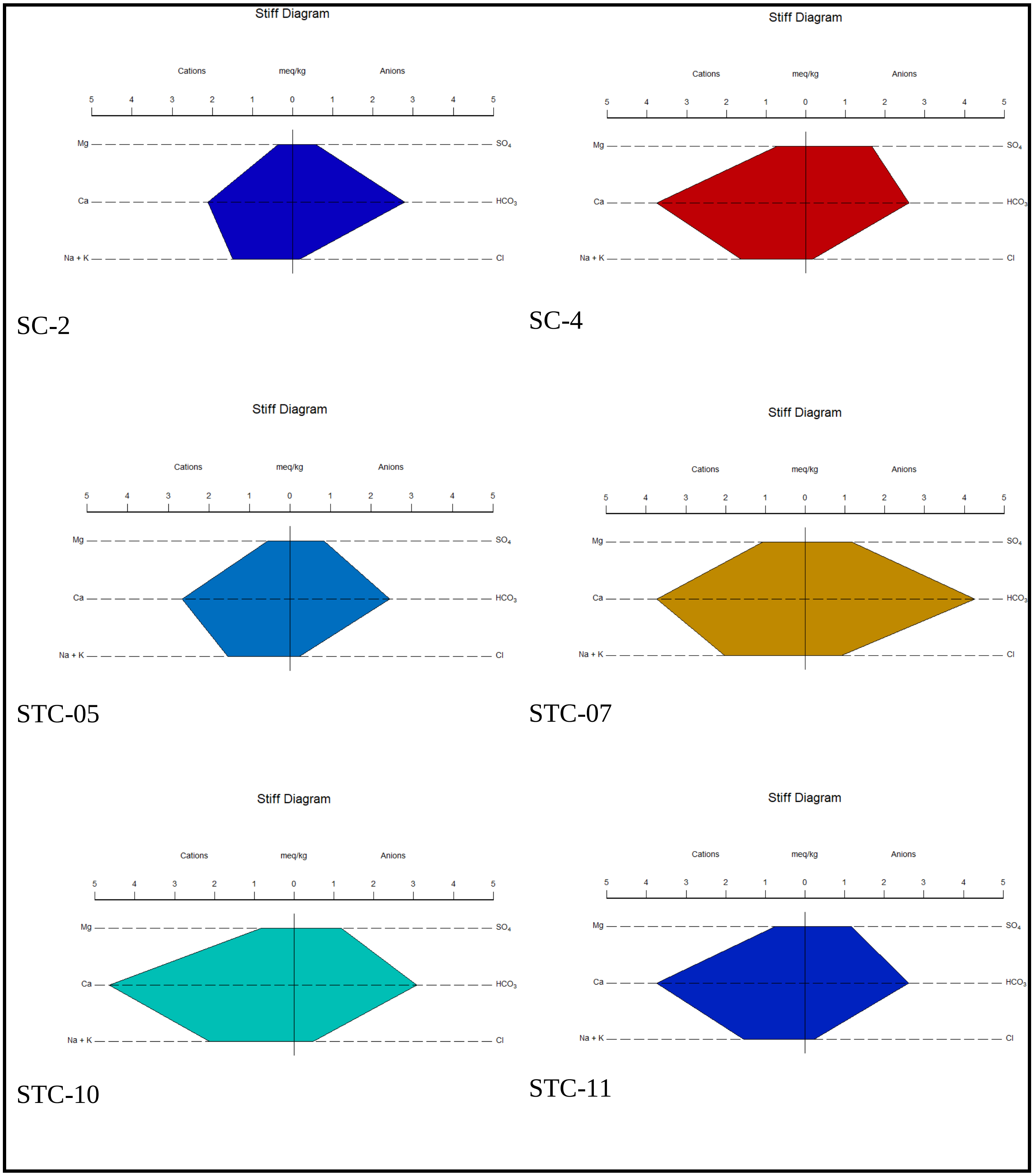

Figure 7.16 Stiff diagrams showing the ionic composition of the analyzed water samples, expressed in milliequivalents per kilogram (meq/kg).

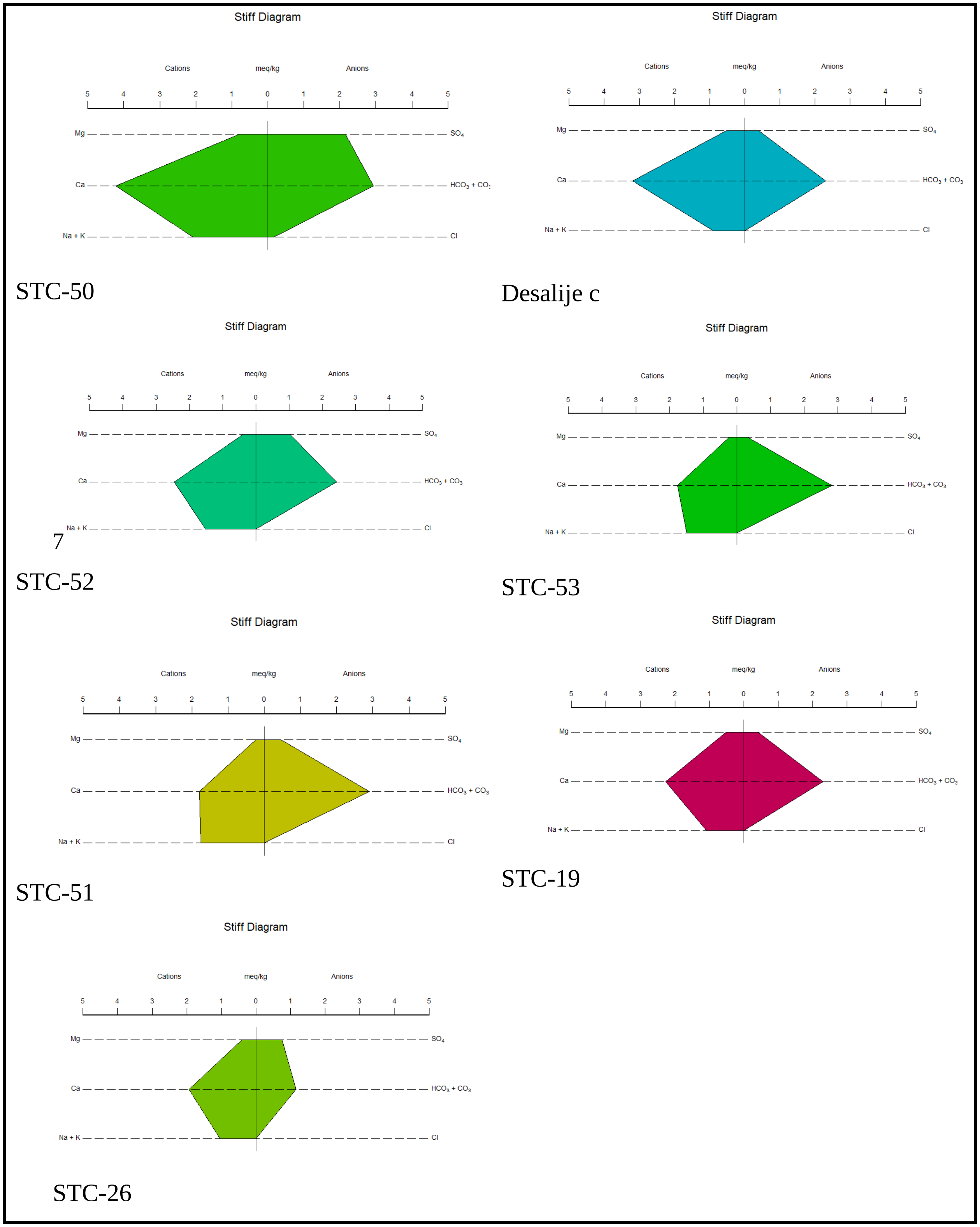

Figure 7.17 Stiff diagrams showing the ionic composition of the analyzed water samples, expressed in milliequivalents per kilogram (meq/kg).

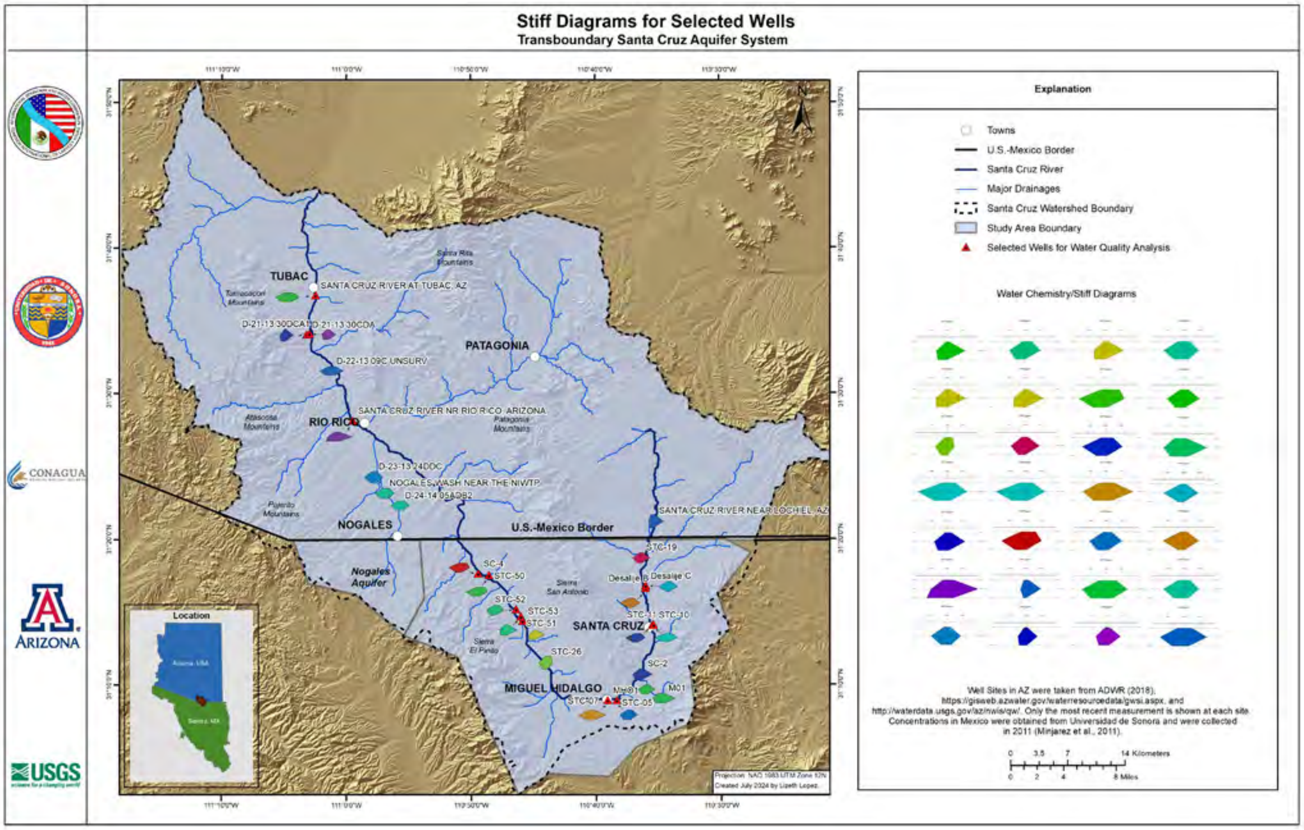

Figure 7.18 Stiff diagrams for selected wells, showing map locations for sample sites.

The Stiff diagrams indicate that the predominant water type at the analyzed sites is calcium-bicarbonate (Ca-HCO_3), with local variations toward mixed bicarbonate facies and, to a lesser extent, compositions showing greater influence of sodium and chloride. This pattern is observed in both groundwater wells and surface-water sites associated with the Santa Cruz River and its tributaries. The similarity in major-ion composition between water in some wells and surface-water sites suggests localized surface-water and groundwater interactions and local recharge, particularly in areas near Nogales Wash and the NIWTP, as well as in zones influenced by drainage from historical mining areas, which may locally contribute to varied water composition and quality.

In terms of major ion concentrations, the diagrams show that the highest values are primarily associated with bicarbonate (HCO_3^-) and calcium (Ca^{2+}), with localized increases in sodium (Na^+), chloride (Cl^-), and sulfate (SO_4^{2-}). These variations are likely related to site-specific hydrogeologic and anthropogenic conditions, including water-rock interaction, treated effluent inputs, and weathering of mineralized rocks.

7.6.6. IBWC Nogales International Wastewater Treatment Plant

Water quality in the Santa Cruz River near the international boundary is influenced by urban runoff and other flows from two cities: Nogales, Arizona and Nogales, Sonora. These cities are divided only by the international border and are collectively referred to as "Ambos Nogales" (*ambos* means 'both' in Spanish). In the 1940's as the population in the area began to increase, improved wastewater collection and treatment was needed. Based on the authority outlined in the 1944 treaty between the United States and Mexico (Utilization of waters... 1944), the International Boundary and Water Commission acting on behalf of both governments, and in partnership with Ambos Nogales, reached an agreement to construct a joint, binational international treatment plant in 1945. The plant, designed to treat wastewater from both communities, was completed in 1951 on the U.S. side of the border. In 1972, a new plant, the NIWTP, was constructed to meet growing population needs and was moved away from the border to its current location approximately 9 miles north in Rio Rico, Arizona. The NIWTP treats approximately 15 million gallons per day (mgd) (IBWC,2009) with the makeup of flows being approximately 80% from Mexico and 20% from the United States. The U.S. Section of the IBWC took over operation of the plant for the City of Nogales, Arizona in 1998.

The NIWTP is an important source of water for the Santa Cruz River. The effluent from the facility is one of the primary sources of return surface flow into this reach of the river. The facility and treatment plant processes were upgraded in 1992 and 2009 to improve water quality by improving the biological nutrient removal and disinfection process. This was done because the effluent concentrations for some parameters were impacting the water quality in the river. The effluent was not meeting the required water quality limits for cadmium, *Escherichia coli* (*E. coli*.), total chlorine, and ammonia-nitrogen. These parameters exceeded levels that led to a classification for this reach as "impaired" for water quality. As of 2018, due to improvements made at the NIWTP to the treatment process, the ADEQ has proposed to remove cadmium, total chlorine, and ammonia from the list of concerns for impairment leaving the indicator bacteria, *E. coli*, as the only impairment within this reach. In the past five years, *E. coli*. levels have been reduced with only minimal events that exceed the 126 cfu/100 ml standard (ADEQ, 2019).

Both sections of the IBWC also monitor other flows into the Santa Cruz River, such as Nogales Wash, on a routine basis. These monitoring efforts include working collaboratively on surface flows such as sanitary sewage overflows, taking necessary steps for prompt notification and action such as disinfection using chlorine, and making progress to mitigate the issue. Information from these events and the monitoring programs are shared with Ambos Nogales stakeholders that meet every quarter in a binational technical meeting to share information and discuss ongoing issues and solutions.

The U.S. Section of IBWC also operates under an Aquifer Protection Permit (APP) to monitor the groundwater level and water quality near the NIWTP and Santa Cruz River. Under the APP, alert levels are established to ensure any migration from surface flows or infiltration do not cause water quality concerns within the Santa Cruz River aquifer. Data are collected on a routine basis for bacteria and general water quality such as temperature, pH, inorganic and organic compounds, heavy metals, and pesticides. Data from 2012 through 2020 demonstrate that the parameters are below alert levels, with results below the detection limits for many parameters (IBWC data are reported to ADEQ and may be obtained from EPA Water Quality Portal). The 2009 upgrade at the NIWTP is helping to sustain surface and groundwater supplies in the transboundary area of Ambos Nogales.

7.6.7. Organic Compounds

Under the auspices of an IBWC accord between the U.S. and Mexico signed in 1996, a multi-agency study of groundwater and soil quality was carried out in 1997-1998 along Nogales Wash (CONAGUA, 2015). The study identified the presence of perchloroethylene, nitrate, and fecal coliform bacteria in Nogales, Sonora with volatile organics detected at levels above Mexican regulatory limits. Perchloroethylene, nitrate, and arsenic were detected in Nogales, Arizona. A 1999 U.S. Fish and Wildlife Service (USFWS) study (King et al., 1999) looked at water, sediment, macroinvertebrates, fish, and birds along the upper Santa Cruz River. Most samples were analyzed for trace metals and organochlorines (pesticides) and polychlorinated biphenyls (PCBs). Results indicated that trace metal concentrations were low and did not pose a significant risk to organisms. The same study (King et al., 1999) also found that organochlorine compounds did not present a threat to fish survival and reproduction. They did, however, identify that un-ionized ammonia was the primary toxicant for fish mortality.

As mentioned above, the NIWTP was upgraded in 2009 (IBWC, 2020) and ammonia concentrations were reduced. Paretti et al. (2010), in part for comparison with the King et al. (1999) study, sampled the Santa Cruz River and associated aquifer for a variety of organic compounds and metals. The goal was to determine what additional chemical stressors might be affecting the recovery of the aquatic ecosystem after the reduction in nitrate. Their approach was to use seasonal grab and passive sampling to identify and quantify organic and inorganic contaminants in water, sediment, plants, aquatic macroinvertebrates, and fish at the five locations within the watershed. Seasonal sampling was also conducted to understand the temporal variability of contaminants in the aquatic ecosystem. Two types of passive samplers were deployed for a month at a time to obtain time-integrated organic compounds. Classes of compounds that were analyzed include halogenated organic compounds (pesticides, PCBs, and flame retardants), pharmaceutical products, wastewater compounds (plasticizers, detergent metabolites, fragrances, polycyclic aromatic hydrocarbons, sterols), and hormones. Findings showed compounds from many classes in surface water downstream of the NIWTP and at Tumacácori National Historical Park with bioaccumulation of pesticides, fire retardants, and triclosan in fish and macroinvertebrates (Paretti et al., 2010).

7.6.8. Microbes

Several studies have conducted work on microbes. These include studies by McOmber (2014), Paretti et al. (2019), Norman et al. (2012), and the study mentioned above in section 7.6.7 published by IBWC in 2001. Norman et al. (2012) conducted a study of household water supplies in two colonias (neighborhoods) in Nogales, Sonora. This water originates as groundwater but is transported either by truck or by the municipal water system. They found *E. coli* above the USEPA drinking water standard in Colonia Colosio, and total coliform bacteria were detected in more than 50% of households in both colonias (Norman et al., 2012). Levels of each were significantly higher in summer than in winter. Paretti et al. (2019) conducted a study of *E. coli* and microbial source markers to understand sources and timing in the Santa Cruz River and tributaries between the U.S.-Mexico border and Tubac, Arizona. The *E. coli* levels were highly variable in space and time with significant variability during floods and even on a scale of 24 hours with some concentrations exceeding water quality standards. Travel times of floods averaged about 8 hours between the Nogales Wash gage and the Santa Cruz River at Tubac gage. The highest concentrations of *E. coli* in this study (Paretti, 2019) were found in Nogales Wash. McOmber (2014) tested for *E. coli* along a reach of the Santa Cruz River north from Nogales and also found the highest concentrations of *E. coli* at the Nogales Wash gage, and the lowest concentration at the NIWTP outfall. These results highlight the importance of continued monitoring in areas hydraulically connected to the river system.

7.7. Geochemical and Hydrologic Conceptual Model using Isotopes

Measurements of stable oxygen (O) and hydrogen (H) isotopes in water provide information on the origin and evolution of groundwater. In the arid to semiarid southwestern U.S., the stable isotope data are useful for constraining the altitude at which precipitation fell, and the amount of evaporation prior to infiltration (Eastoe and Wright, 2019; Eastoe and Towne, 2018). Sulfur (S) isotopes of sulfate (SO^{2-}) used in conjunction with sulfate concentration provide a tracer for groundwater contributions to base flow (Gu et al., 2008). They are particularly useful in areas where rock sources of contrasting S isotope character are compared. Stable isotope data are measured as ratios, in these cases $^{2}H/^{1}H$ (or D/H), $^{18}O/^{16}O$, and $^{34}S/^{32}S$ (Clark and Fritz, 1997). The results are expressed using δ-notation: $\delta^{2}H = ((R_{sample}/R_{standard})-1) \times 1000$ ‰ where $R = {}^{2}H/{}^{1}H$ and the standard is Vienna Standard Mean Ocean Water (VSMOW). The definition of $\delta^{18}O$ is analogous, with $R = {}^{18}O/{}^{16}O$, and the standard is VSMOW. For $\delta^{34}S$, $R = {}^{34}S/{}^{32}S$ and the standard is Vienna Canyon Diablo Troilite (VCDT) (Krouse and Coplen, 1997).

Tritium, with a half-life of 12.32 years (Lucas and Unterweger, 2000), is continuously generated in the upper atmosphere as a result of nuclear reactions caused by cosmic rays. In Tucson, Arizona, the average level of cosmogenic tritium in rainwater is 5.4 TU (tritium units; 1 TU = 1 atom of tritium per 10^{18} atoms of hydrogen) (Eastoe et al., 2011). A pulse of tritium was added to the atmosphere between 1953 and 1975 as a result of atmospheric testing of nuclear weapons. Tritium released to the atmosphere during testing of nuclear weapons between 1953 and 1975 can be detected in groundwater that has been recharged by precipitation since about 1955. If tritium levels in water are below the detection limit of 0.6 - 0.7 TU, then the water is considered to be older than 1953 recharge containing tritium above the detection limit.

Carbon-14 (^{14}C), with a half-life of 5,730 years, can give useful comparative information on groundwater residence times for recharge that occurred hundreds to thousands of years ago. It can be measured in dissolved inorganic carbon species (usually bicarbonate) in groundwater. Precise determination of residence times is difficult because of the complex evolution of dissolved inorganic carbon species in groundwater. Like tritium, ^{14}C is generated in the upper atmosphere and in nuclear explosions in the atmosphere. Isotope data from multiple sources have been combined and are shown in Figure 7.19, Figure 7.20 and Figure 7.21. The following discussion focuses on interpreting the combined dataset, rather than on the conclusions of the individual studies.

7.7.1. Stable Isotopes of Water

Precipitation

Few stable isotope measurements from water are available in the immediate study area. Seasonal amount-weighted means of $\delta^{18}O$ and $\delta^{2}H$ have been estimated from long-term datasets for Tucson basin (Eastoe and Dettman, 2016; Eastoe and Wright, 2019), adjusted to an altitude of 1,600 m above mean sea level (asl) using lapse rates from Eastoe and Wright (2019). Winter is considered here to encompass the months November to May, and summer is considered to encompass the months June to October. The data are presented in two forms: (1) means based on the data for all precipitation events, and (2) means based on data for the wettest 30% of months. The latter form arises from the observation that $\delta^{18}O$ and $\delta^{2}H$ data commonly plot close to a modified local meteoric water line (LMWL) defined by the means for the wettest 30% of months, but not on the LMWL defined by the means for all data. Measurements of $\delta^{18}O$ and $\delta^{2}H$ in groundwater from alluvial basins in southern Arizona, one alluvial basin in northern Sonora, and lower-elevation parts of mountain blocks in the same region plot on the modified LMWL (Eastoe and Towne, 2018; Eastoe and Wright, 2019). This observation implies that recharge occurs mainly during wetter months.

Surface Water

A large set of $\delta^{18}O$ and $\delta^{2}H$ measurements exists for the Santa Cruz River near Tubac, Arizona (Treese et al., 2009; Callegary et al., 2018). Water in the Santa Cruz River consists of a mixture of several sources: discharge from the NIWTP (including groundwater pumped from the Santa Cruz aquifer and Los Alisos wellfields for municipal supply in Nogales, Sonora, and water pumped from the "microbasin" aquifers and the Potrero wellfield for municipal supply in Nogales, Arizona), natural runoff, and bank storage. For plotting in Figure 7.19, Santa Cruz surface water isotope data have been separated into monsoon (July to September) and base flow (October-June, denoted by BF) seasons. Data from both seasons plot on trends with slope near 4, considered to be the slope of evaporation trends in southern Arizona (Gungle et al., 2016; Eastoe and Towne, 2018).

The linear trends pass through the long-term amount-weighted mean for all winter precipitation and could be interpreted as evaporation of winter bank storage; however, mean summer precipitation plots close to the trend, allowing the possibility of summer contributions in addition to winter contributions to flow. The linear trends also pass through the main cluster of data for groundwater in the Patagonia Mountains. The scatter of data, which is greater during monsoon flood events than in base flow, suggests transient influence of individual precipitation events. These are thought to vary greatly in $\delta^{18}O$ and $\delta^{2}H$ in the study area, as observed in Tucson (Eastoe and Dettman, 2018).

A smaller dataset for Nogales Wash south of Tubac in Arizona (Treese et al., 2009; Callegary et al., 2018) plots close to the evaporation trends defined by surface water from the Santa Cruz River. A single datapoint from Sonoita Creek downstream of Patagonia Lake also plots close to the trends and is more evaporated than any other surface water in the dataset. Upstream of Patagonia Lake, base flow and monsoon flood-stage data for Sonoita Creek (Montgomery et al., 2009; Gu et al., 2008) plot along a single trend of slope 6, too steep to be an evaporation trend, and more likely explained by mixing. The end members are discussed below. The lack of higher values of $\delta^{18}O$ and $\delta^{2}H$ in monsoon surface water probably resulted from limited sampling, which took place on four days only. A small amount of data for surface water in the Patagonia Mountains (Wanty et al., 2001; Gu et al., 2008) have been omitted from Figure 7.19 to improve the clarity of the figure.

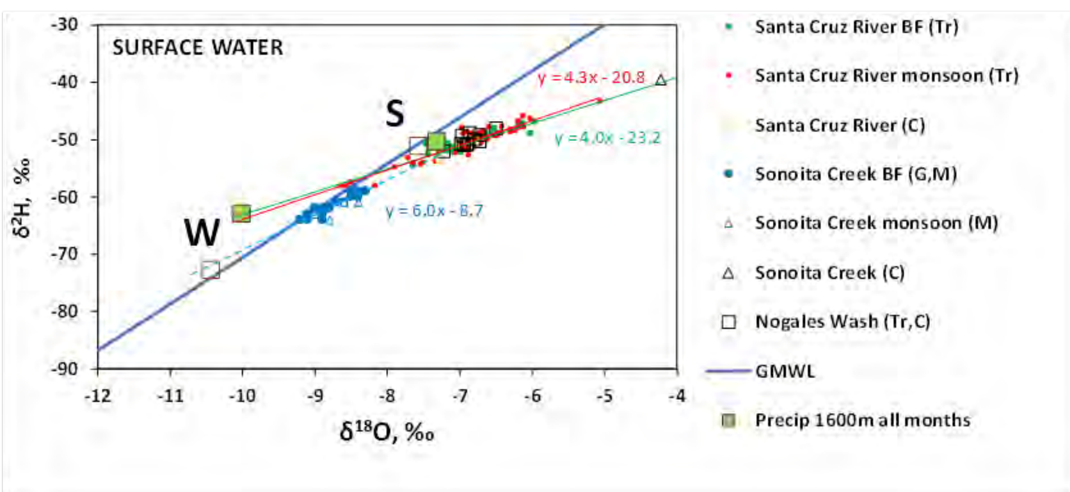

Figure 7.19 Plot of $\delta^{2}H$ vs. $\delta^{18}O$ for surface water in the Upper Santa Cruz basin.

Also shown are amount-weighted means for seasonal precipitation (S=summer; W=winter), calculated for all data and for the wettest 30% of months (Eastoe and Towne, 2018), and the GMWL (Craig, 1961). Data sources are shown in the legend, in parentheses: (C) Callegary et al., 2018; (G) Gu et al., 2008; (M) Montgomery et al., 2009; (Tr)Treese et al., 2009.

Mountain groundwater

Data from high elevations, about 1,600 masl, in the Patagonia Mountains, may be taken as representative of mountain groundwater throughout the study area. Three groundwater stable isotope datasets exist (Wanty et al., 2001; Gu, 2005; Schrag-Toso, 2020), plus a single measurement for Alum Gulch well from Montgomery et al. (2009). Mountain groundwater is shown as yellow diamonds in Figure 7.20. Most of these data plot as a group near (δ^{18}O, δ^{2}H) = (-8.6 +/- 0.5, -56 +/- 4‰), with evaporated equivalents plotting to the right of the group. A small set of outliers (four points) plot below the main group (Figure 7.20).

Least-evaporated samples of the main cluster include groundwater recharged from all precipitation in some cases (plotting near the LMWL for all data) and recharged from precipitation during the wettest months only in other cases (plotting near modified LMWL for the wettest 30% of months). Summer and winter precipitation contribute about equally to recharge. Most main-cluster samples contain finite tritium (Gu, 2005; Schrag-Toso, 2020), indicating that this is a young groundwater system, much of the water having infiltrated since 1953. Some older water is present, as indicated by ^{14}C contents of 34.0 and 56.8 pMC in two samples with undetectable tritium (Schrag-Toso, 2020).

The outliers include a sample (Alum Gulch Well) with the same isotope composition (-10.5, -73‰) as the mean for the wettest 30% of winter months. Schrag-Toso (2020) obtained a ^{14}C content of 9.5 pMC for a sample from this well, with (δ^{18}O, δ^{2}H) = (-10.2, -73‰). Other outliers include samples near (-9.2, -72‰), present in all three datasets, and a highly evaporated sample (-4.5, -58‰) of water seeping from tailings at the European Mine. The outlier sample in the dataset of Gu (2005) contains no detectable tritium. The outliers cluster with isotopic data for ancient groundwater in southeastern Arizona (Figure 7.21). The ancient groundwater was identified as having pMC < 10 (Eastoe, 2023; using data from Smalley, 1983; Eastoe et al., 2004; Earman, 2004; Eastoe, 2007; Hopkins et al., 2013; Eastoe and Towne, 2018; Tucci, 2018) from a time when values of δ^{18}O were 2-3‰ lower than those in present-day average precipitation. The increase in δ^{18}O values in precipitation has been dated to have occurred 13,000 to 15,000 years ago based on age dating of a speleothem collected from the Santa Rita Mountains immediately north of the study area (Wagner et al., 2010). Thus, the outlier samples in the Patagonia Mountains represent recharge from a time prior to 13,000 years ago.

The Patagonia Mountains therefore contain two distinct groundwater systems: one containing mainly groundwater resident for several decades, and the other of groundwater more than 13,000 years old. Similar groundwaters of contrasting age occur at similar altitude in the northern Santa Rita Mountains (Eastoe and Wright, 2019, using data from Montgomery et al., 2009), where the stable isotopes show evidence of mixing between both types of water.

Basin groundwater

Groundwater from the alluvial basins surrounding the Patagonia Mountains (San Rafael Valley, the Santa Cruz aquifer in Sonora, and along Sonoita Creek at the town of Patagonia) plots in a quadrilateral field bounded above by the identical evaporation trends of Patagonia Mountains and Santa Cruz River water, and to the left by the modified LMWL for the wettest 30% of months. The lower boundary may include ancient groundwater in addition to present-day winter recharge. Basin groundwater therefore includes a variety of mixtures between evaporated surface water, and non-evaporated combinations of summer and winter precipitation. The combinations of summer and winter precipitation are likely to be mountain groundwater, as in the case of San Rafael Valley where the array of data extends from Patagonia Mountain groundwater toward the surface-water evaporation trends. In San Rafael Valley, groundwater with the highest values of $\delta^{18}O$ and $\delta^{2}H$, i.e. that most resemble evaporated surface water, occurs in the center of the basin (Towne, 2003). The same regime of mixing explains the linear trend of base flow in Sonoita Creek upstream of Patagonia Lake (Figure 7.20).

Groundwater from the aquifer adjacent to the Santa Cruz River at Tubac has values of $\delta^{18}O$ and $\delta^{2}H$ forming a linear trend essentially identical to that of base flow in the river (Figure 7.20).

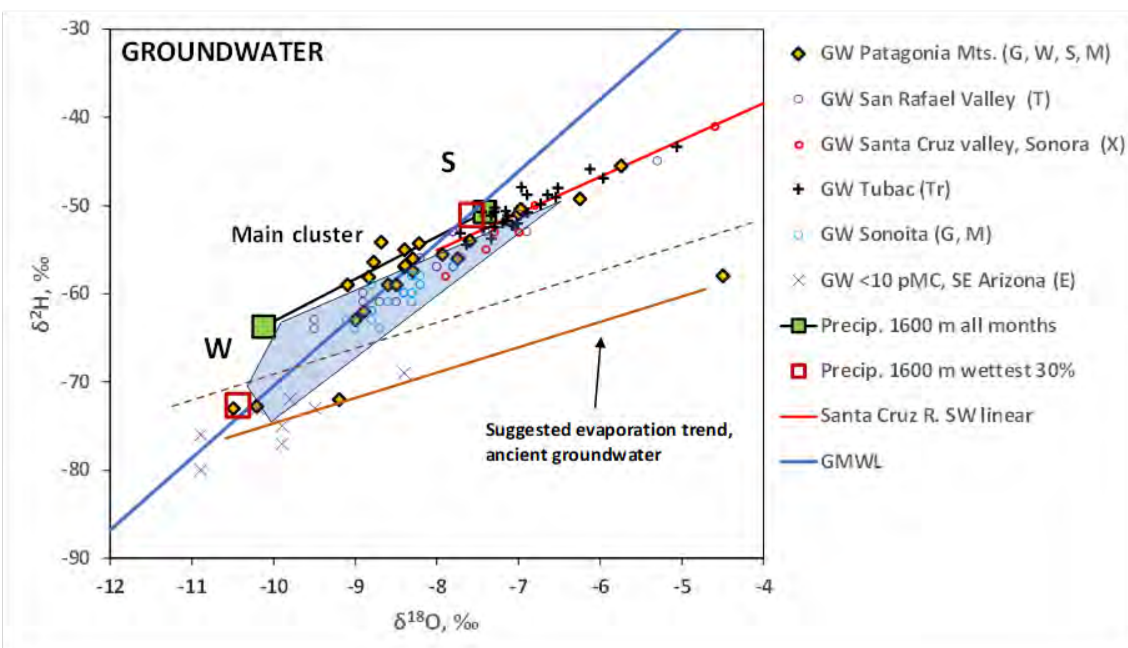

Figure 7.20 Plot of $\delta^{2}H$ vs. $\delta^{18}O$ for groundwater (GW) from the Patagonia Mountains and surrounding alluvial basins (San Rafael, Sonoita, Santa Cruz Valley, Sonora).

Also shown are amount-weighted means for seasonal precipitation (S=summer; W=winter), calculated for all data and for the wettest 30% of months (Eastoe and Towne, 2018), the trend line for evaporated surface water (SW) in the Santa Cruz River, the GMWL, and data for ancient groundwater with ^{14}C content < 10 pMC in southeastern Arizona. Data sources are shown in the legend, in parentheses: (E) Eastoe (2023) and references therein; (G) Gu et al., 2008; (M) Montgomery et al., 2009; (S) Schrag-Toso, 2020; (T) Towne, 2003; (Tr) Treese et al., 2009; (W) Wanty et al., 2001; (X) IDEAS, 2008. The blue polygon is the mixing field for alluvial basin waters in the San Rafael, Santa Cruz (Sonora) and Sonoita Creek valleys.

Relationships between surface water and groundwater.

The stable O and H isotope data are consistent with a common source, namely mountain groundwater, for most surface water and groundwater. The isotope differences between more- and less-evaporated groundwater in the upper catchments reflect different paths of evolution. More-evaporated water, resembling surface water in isotope composition, has evaporated in streambeds prior to infiltration. Less-evaporated water, closer to mountain groundwater in isotope composition, probably entered alluvial aquifers as mountain-front or mountain-block recharge. Mixtures of the two kinds of water account for the linear arrays of isotope data in San Rafael Valley and the Santa Cruz aquifer in Sonora.

7.7.2. Sulfate Isotopes

Datasets of Gu (2005), Gu et al. (2008), and Schrag-Toso (2020) include paired values of $\delta^{34}S$ and $\delta^{18}O_{SO4}$ for sulfate in groundwater and surface water of the Patagonia Mountains, where acid rock drainage from sulfide-bearing rock is present. Gu et al. (2008) also presented paired values of $\delta^{34}S$ and $\delta^{18}O_{SO4}$ for groundwater, including domestic supply, in alluvium around the northern and western flanks of the Patagonia Mountains, and base flow in Sonoita and Harshaw Creeks. Both datasets include sulfate concentrations. The data are plotted in Figure 7.21.

Acid rock drainage in the Patagonia Mountains, present as both groundwater and surface water, has broad ranges of $\delta^{34}S$ (-11 to +3‰), reflecting a wide range of $\delta^{34}S$ in rock sulfide in the mountain block. The range of $\delta^{18}O_{SO4}$ (-2 to +6‰) reflects the incorporation of oxygen from local meteoric water and from the atmosphere in different proportions; in the western United States, the effect of meteoric water is dominant (Taylor et al., 1984), leading to values of $\delta^{18}O$ less than 0‰ in southern Arizona (Gu and Eastoe, 2021). Averaged acid rock drainage with ($\delta^{34}S$, $\delta^{18}O_{SO4}$) that may be near (-4, +1‰) is the lower endmember of a mixing trend affecting sulfate in surface water in and around Sonoita Creek (Figure 7.21). The upper endmember is Permian or Early Cretaceous marine sulfate or reworked equivalents and is present in groundwater and evaporites elsewhere in southern Arizona (Gu and Eastoe, 2021). In the Sonoita Creek drainage, the source appears to be the deep alluvial basin northeast of the town of Patagonia; groundwater with this isotope signature is discharged into Sonoita Creek near the town (Gu et al., 2008).

Sulfate in samples from the Patagonia town well changed greatly in isotope composition between 1999 and 2003 (Figure 7.21). This was a period in which there was a severe drought, and the changing isotopic composition of the water reflected the changing input of sulfate from acid rock drainage relative to sulfate in groundwater from a Permian marine source. Over the same period, input of acid rock drainage changed to a lesser degree in several supply wells in the Sonoita Creek catchment on the Arizona side of the binational basin. This was demonstrated using plots of $\delta^{34}S$ vs. inverse sulfate concentration (Gu et al., 2008).

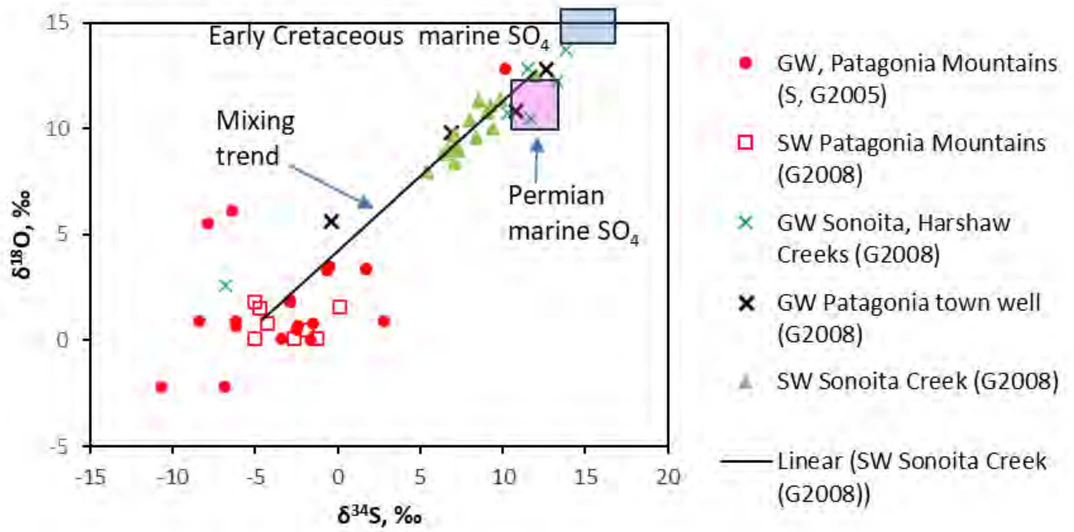

Figure 7.21 Plot of $\delta^{18}O_{SO4}$ vs. $\delta^{34}S$ for dissolved sulfate in groundwater (GW) and surface water (SW) from the Patagonia Mountains and adjacent alluvial aquifers.

Data sources are shown in the legend, in parentheses: (G2005) Gu, 2005; (G2008), Gu et al., 2008;(S) Schrag-Toso, 2020. Permian and Early Cretaceous marine sulfate ranges are from Claypool et al. (1980).

7.8. Summary and Future Work

An assessment of the water quality and both hydrochemical and geochemical characteristics of the Santa Cruz transboundary system between the U.S. and Mexico from studies conducted by various entities were presented in this report. Below are some notable conclusions from the chapter as well as some recommendations for future work.

Conclusions:

Relevant lessons from the Patagonia Mountains and surrounding areas include: 1) hydrothermal fluids associated with the emplacement of granitoid magmas have deposited concentrations of base-metal sulfides (veins, replacements and disseminations) within a broad envelope of hydrothermally altered wallrock that also bears disseminated base-metals (e.g., iron, nickel, lead, zinc, copper) sulfide minerals; 2) the altered wallrock may strongly influence groundwater flow because alteration modifies the physical properties of the rock; and 3) the wallrock influences water chemistry and quality by acting as a large-volume source of potential contaminants.

On the south side of the Patagonia Creek basin system, the Patagonia Fault forms the steep boundary between basin sediments and igneous rocks of the main mountain system (Menges, 1981). At this contact, basin sediments are exposed as high as 210 m above the valley floor. To the north on the Santa Rita side of the graben, bedrock appears abruptly along concealed fault structures along the banks of Sonoita Creek at the valley's lowest elevations. This geologic basin margin configuration has implications for the controls of the geochemistry of waters in the groundwater system.

A Stiff diagram analysis of lowland alluvial groundwater shows that the highest concentrations of HCO3+CO3 in groundwater were observed in the Sonoran region, particularly in well STC-10, near the town of Santa Cruz. It is important to note that these elevated values were predominantly clustered around streams and the river, suggesting localized influences. On the other hand, lower concentrations were typically found near the Tumacácori Mountains. Chloride concentrations depicted in the Stiff diagrams remained within the maximum limits established by both the Mexican NOM and USEPA; however, some sulfate concentrations exceeded the applicable secondary standards in both portions of the aquifer.

Based on stable isotopes δ^2H and $\delta^{18}O$ data, groundwater appears to originate from mountain rainfall through mountain block and mountain front recharge.

In the Sonoita Creek drainage, based on $\delta^{18}O_{SO4}$ vs. $\delta^{34}S$ stable isotope data, water appears largely to originate in the deep alluvial basin northeast of the town of Patagonia; groundwater with this isotope signature is discharged into Sonoita Creek near the town.

Potential future work includes the following:

Exploration and evaluation of other potentially useful projects and data sources that were not within the scope of the present report. One of these comprises daily water-quality data collected at the NIWTP, beginning in the 1970s.

Even considering the rich data sources available for this report, there is still a gap in binational information concerning Cu, Pb, Zn and other elements, particularly those produced through mining activities in the region. Comprehensive monitoring of metals from current mining operations in the Patagonia Mountains and in the future when operations commence at El Pilar in Sonora would be useful additions since metals can have a significant impact on human and aquatic health. This is also an issue that could be part of future binational studies.

An updated sampling and analysis (including numerical modeling) of geochemical characteristics of the study area could provide information for land and water managers in both the U.S. and Mexico that could serve for the implementation of methods for improving water quality in the TSCAS.

Coordinated binational geochemical surveys could be conducted simultaneously in both the U.S. and Mexico, ensuring that the same sampling parameters and criteria are followed on both sides of the border. Harmonizing these methods would improve data consistency and comparability between the two countries.

Incorporating isotopic analysis as part of future geochemical studies to provide deeper insights into the sources and pathways of contaminants in the region. Isotopic data can complement traditional geochemical methods by helping to track contamination sources and movement through the watershed.

Annual monitoring of the aquifer could be implemented to assess ongoing changes in water quality and the potential impacts of mining and other activities on both sides of the border.

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8. CONCEPTUAL AND NUMERICAL MODELS OF HYDRODYNAMIC BEHAVIOR

This chapter presents available conceptual and numerical models describing groundwater flow within the TSCAS (Figure 8.1), identifies gaps in knowledge, and outlines research directions to address them. The hydrodynamic behavior of the TSCAS is determined by factors such as geology, climate, and time coupled with human-determined factors such as groundwater pumping. Together, they control precipitation, vegetation, infiltration, runoff, and groundwater flow and storage.

8.1. Aquifer Recharge and Discharge

Recharge to the TSCAS varies temporally and spatially and depends on factors such as geology, climate, and topography (Eastoe and Wright, 2019; Markovich et al., 2019). The main source of recharge to the TSCAS is precipitation (Comisión Nacional del Agua [CONAGUA], 2024a), although some water transfers are derived from the adjacent Rio Alisos aquifer in Sonora, Mexico (Figure 8.1) (Tapia-Villaseñor et al., 2020). Most precipitation in the TSCAS falls at higher elevations where the majority of recharge also occurs via infiltration and deep percolation in bedrock, in part through faults and fractures (Eastoe and Wright, 2019, Earman et al., 2006; Scanlon et al., 2006). Higher fluxes tend to occur via permeable rocks such as sandstone and limestone (Flint and Flint, 2007). Recharge also occurs at the mountain front and at lower elevations in places where water concentrates and permeable sediments facilitate infiltration, such as in perennial streams and rivers and in ephemeral channels. Information from Eastoe and Wright (2019) as well as from the isotopic analysis in Chapter 7, indicate that mountain recharge in the study area is generally equally derived from summer and winter precipitation.

In general, groundwater moving towards lower elevations discharges along the major rivers either to the river aquifer or, depending on the water-table elevation, as surface-water flow (Nelson, 2007). Within the TSCAS, the lower elevations in reaches of the Santa Cruz River and its tributaries act as discharge locations (Figure 8.1). Other types of discharge that occur in the TSCAS are pumping of wells, transpiration by riparian vegetation, and springs in canyons that intersect layers of sandstone or limestone overlying low permeability layers.

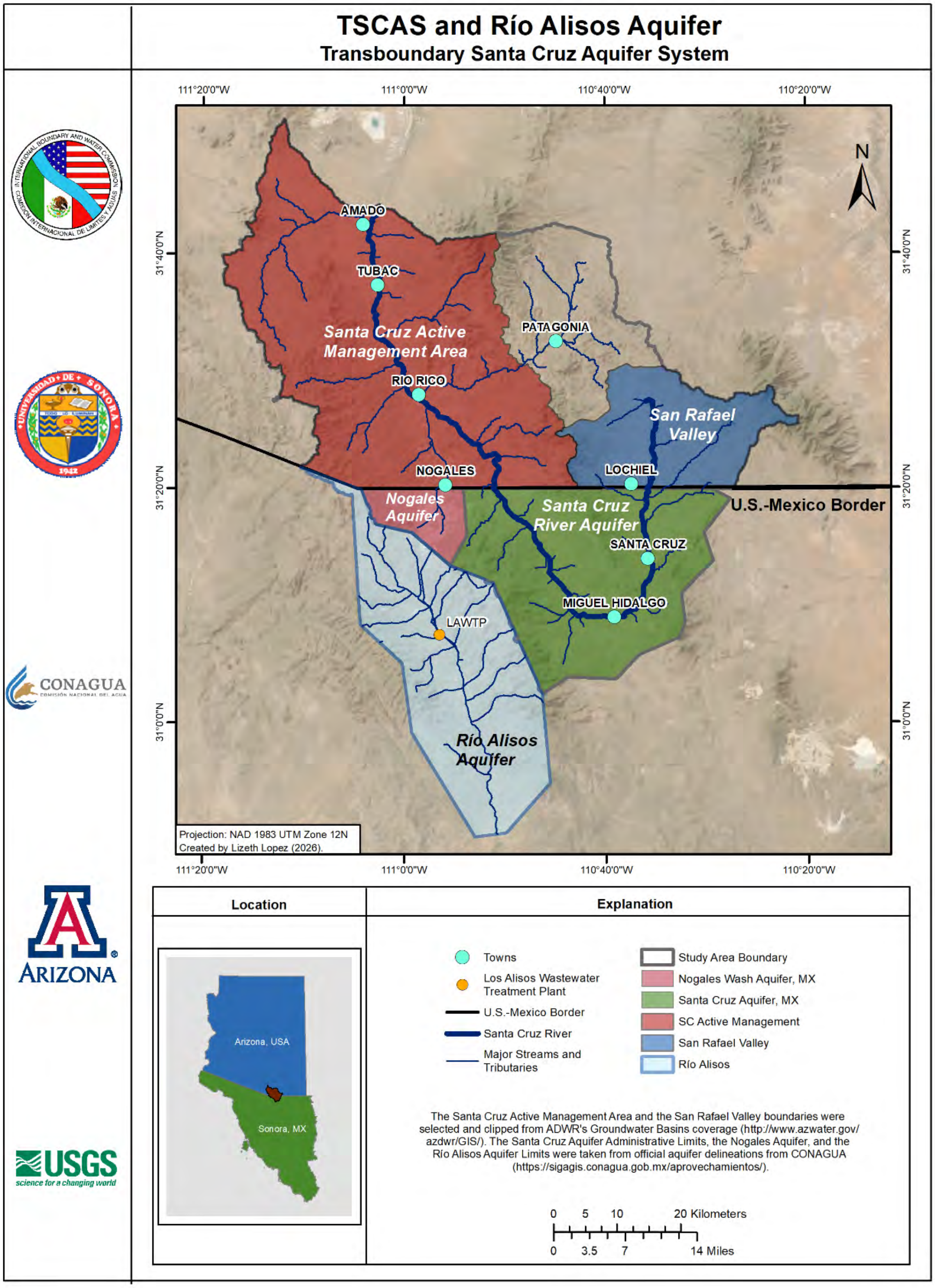

Figure 8.1 Spatial configuration of the Transboundary Santa Cruz Aquifer System (TSCAS) and the adjacent Río Alisos Aquifer.

8.2. Previous Work

Although there are published studies for both the Sonoran and Arizona portions of the TSCAS (Figure 8.1), no fully binational numerical modeling studies have been carried out to date. In this section, we provide a brief listing of the models that have been developed. In subsequent sections, we give more detailed descriptions of selected models including information on model geometry, coverage, and results.

8.2.1. Groundwater Flow Models in Arizona (ADWR)

Three regional groundwater-flow models have been developed by the Arizona Department of Water Resources (ADWR) to inform the management of regional water resources in the Santa Cruz Aquifer Management Area (SCAMA). ADWR Modeling Report No. 15 addressed the area between the U.S.-Mexico border and the NIWTP and underscored the importance of seasonal recharge and discharge on groundwater in what were termed "microbasins" (Figure 8.2) (Erwin, 2007). The microbasins were described as high permeability river-associated aquifers of limited extent which typically undergo large seasonal changes in groundwater levels and storage. ADWR Modeling Report No. 14 covered the effluent-dominated portion of the Santa Cruz River between the NIWTP and a northern boundary near Amado, Arizona (Figure 8.2) (Nelson, 2007). Both models simulated hydraulic heads, flows, and water budgets for transient conditions based on a calibration period of 1997 to 2002. Subsequently, Hart (2019) documented updates to the groundwater flow model of the North Santa Cruz AMA. In addition to the previous two models, ADWR completed a groundwater-flow model for the entire SCAMA (ADWR, 2020). The model expanded on the previous two (Erwin, 2007; Nelson, 2007) by incorporating the Nogales sub-basin, as well as updating the models with additional data. Figure 8.2 shows the different modeling regions that are described in this chapter.

8.2.2. Groundwater Flow Models in Sonora (Mexico)

Studies in the Mexican portion of the TSCAS have focused primarily on the Santa Cruz River Aquifer in Sonora (SCRAS) and the Nogales Aquifer System in Sonora (NASS) (Figure 8.2). These efforts include academic research, technical studies, and official groundwater availability assessments conducted by Mexico's National Water Commission (CONAGUA).

One of the earliest numerical modeling efforts is the steady-state groundwater flow model developed by Tapia Padilla (2005) as a master's thesis at the Universidad de Sonora. This study focused on the western portion of the SCRAS and provided a foundational conceptualization of regional groundwater flow and cross-border fluxes under steady-state conditions. A subsequent study by Minjarez et al. (2011), carried out by CILA, CONAGUA, and Universidad de Sonora, expanded the hydrogeologic understanding of the Mexican side of the aquifer system through the compilation and analysis of hydrologic, hydrogeologic, and water-use data.

In parallel, CONAGUA has published groundwater availability studies for the SCRAS and NASS (CONAGUA, 2009, 2015, 2018, and 2024) as required under the National Water Law and its regulations. These assessments follow the Official Mexican Standard NOM-011-CONAGUA-2015, which defines groundwater availability using a water balance approach:

$$DMA = R - DNC - VEAS$$

where total recharge (R), natural committed discharge (DNC), and groundwater extraction volumes (VEAS) are estimated annually. Although these studies are not numerical flow models, they provide a framework for quantifying recharge, discharge, and pumping and offer valuable insight into groundwater sustainability trends in a binational context.

Collectively, the studies by Tapia Padilla (2005), Minjarez et al. (2011), and CONAGUA form the principal basis for understanding groundwater flow conditions in the Sonoran portion of the TSCAS and provide the conceptual foundation for the post-development water balance analyses described in the following sections.

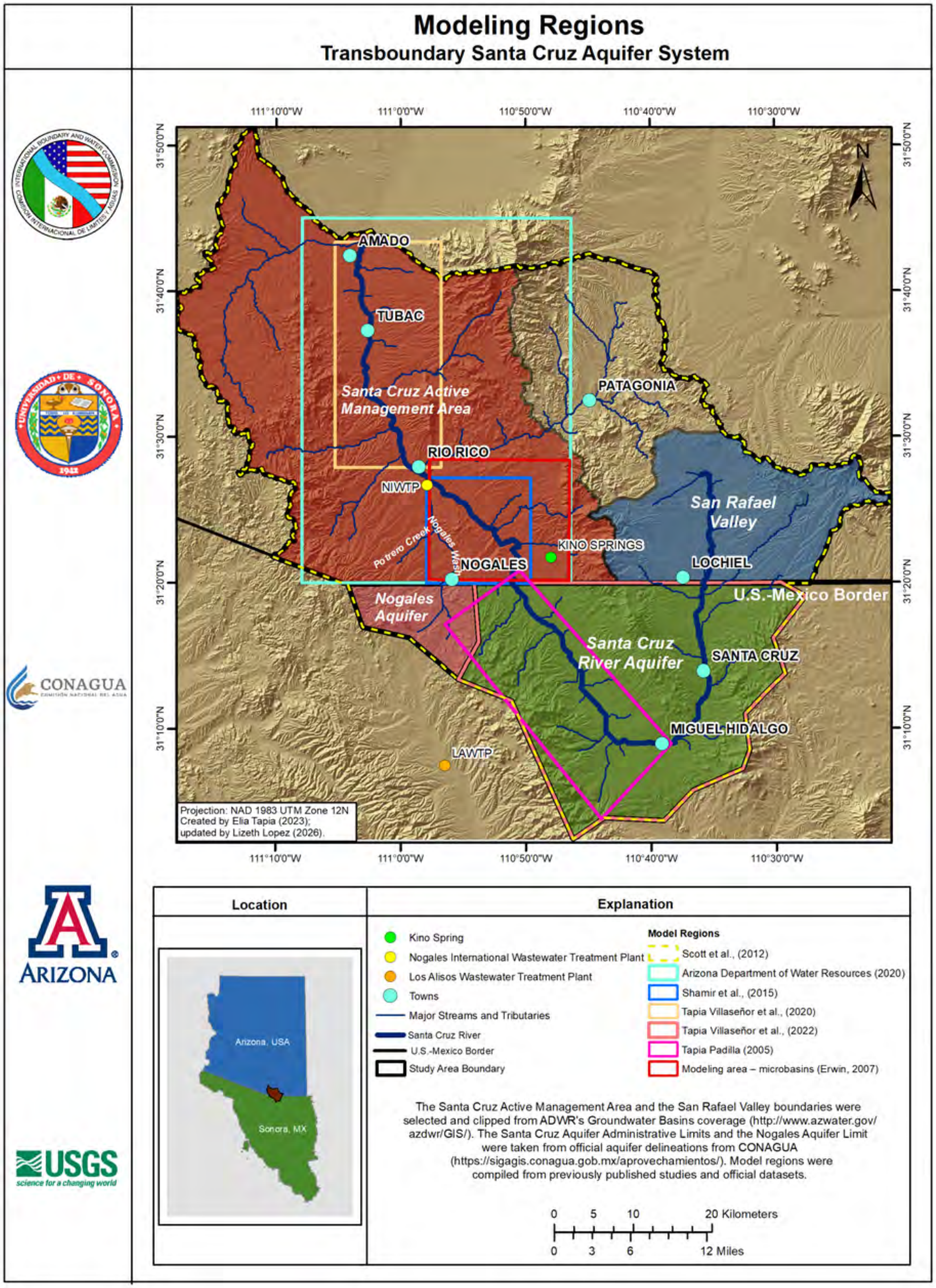

Figure 8.2 Modeling regions within the Transboundary Santa Cruz Aquifer System (TSCAS).

8.3. Pre- and Post-Development Hydrodynamic Behavior

The following sections describe modeling results with respect to the pre- and post-development behavior of the Arizona portion of the TSCAS. Additionally, we present similar findings from groundwater modeling efforts for the Mexican portion of the TSCAS.

8.3.1. Pre-Development

A pre-development conceptual or numerical model typically consists of an estimate of the groundwater inflows and outflows when the groundwater system was in a quasi-steady state, prior to the effects of climate change as well as agricultural, municipal, and industrial development. In the TSCAS, however, due to a lack of adequate historical data, it is difficult to know with any certainty the pre-development hydrodynamic behavior.

Conceptual and numerical models of the pre-development water balance were developed for the effluent-dominated portion of the SCAMA (between the NIWTP and Amado, AZ) to estimate steady-state conditions circa 1880 (Figure 8.3) (Nelson, 2007). The simulated pre-development flow components included: groundwater inflow near the NIWTP, estimated at 8 Mm^3/yr; mountain front recharge of 4 Mm^3/yr; tributary recharge of 9 Mm^3/yr; and a net recharge along the river between Tubac and Amado of 14 Mm^3/yr (Table 8.1). Groundwater discharge near Amado towards the Tucson AMA was estimated at 28 Mm^3/yr, and the net discharge along the river between the NIWTP and Tubac at approximately 8 Mm^3/yr. No pumping was included in the simulation, which is consistent with the definition of the pre-development period. Differences between the conceptual model and the simulated estimates of flow were less than 15%, with the exception of the groundwater inflow from the microbasins area and the tributary and mountain front recharge components. Uncertainties were generally large due to lack of data, with the largest calculated uncertainties associated with the recharge and subsurface inflow estimates. For a full description of the modeling equations, assumptions, and key characteristics, consult Nelson (2007).

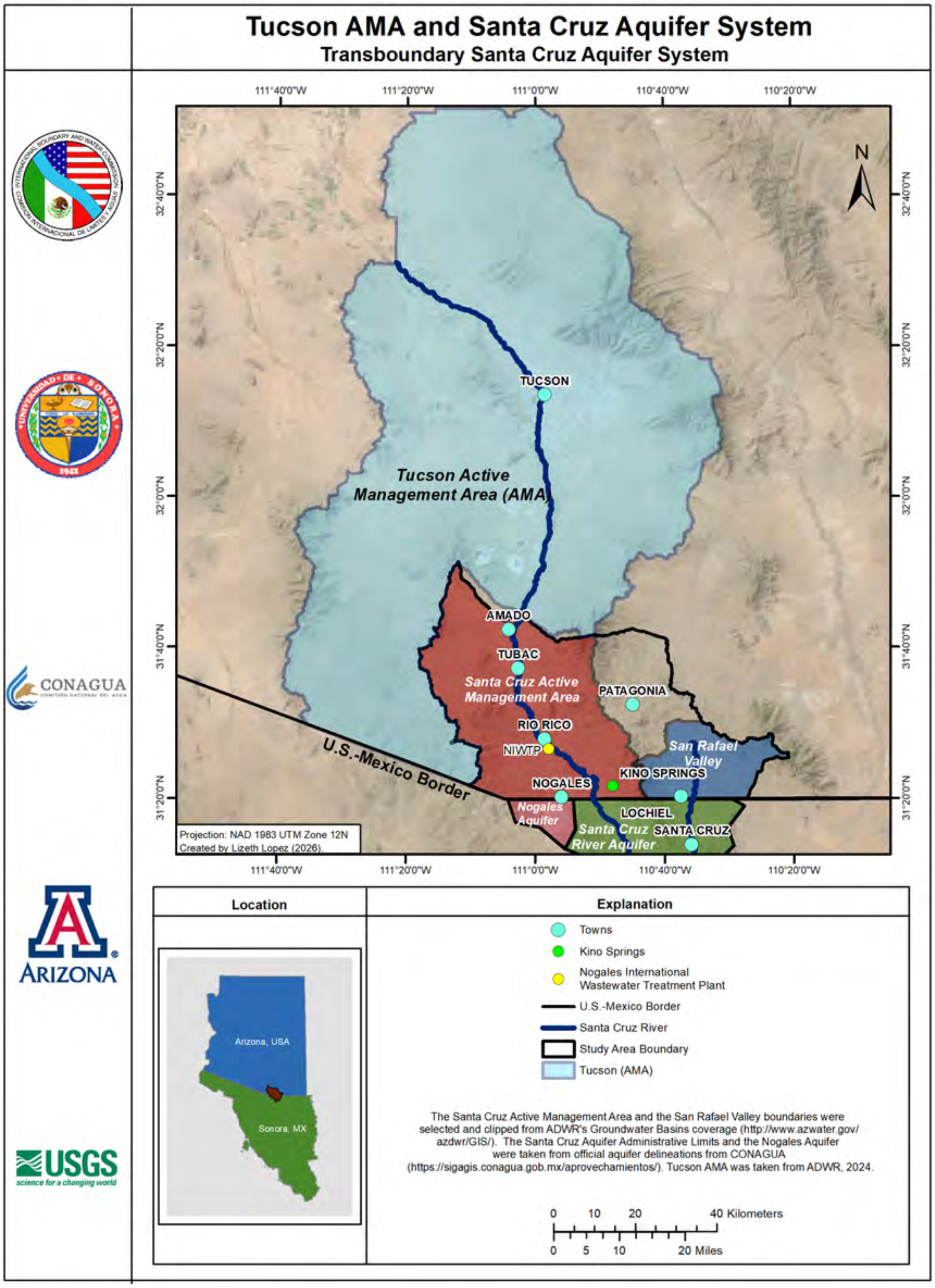

Figure 8.3 Map showing the location of the Tucson Active Management Area (AMA) in relation to the Santa Cruz Aquifer System.

Table 8.1. Comparison of annual water balances derived from steady-state conceptual and simulated models, for the area between the Nogales International Wastewater Treatment Plant (NIWTP) and Amado, Arizona, for pre-development and for the 1997-2002 period (modified from Nelson, 2007).

INFLOW	CONCEPTUAL (1997-2002) (Mm^3/yr)	SIMULATED (1997-2002) (Mm^3/yr)	CONCEPTUAL Pre-development (Mm^3/yr)	SIMULATED Pre-development (Mm^3/yr)
Groundwater Inflow	12.3	11.5	6	8
Mountain Front Recharge	6.17	2.34	6	4
Tributary Recharge	8.14	10.3	8	9
Irrigation Return Flows	2.10	1.89	0	0
Net Recharge along Santa Cruz River from Tubac to Amado	17.0	17.6	14	14
Total	45.8	43.6	35	36
OUTFLOW	CONCEPTUAL (1997-2002)	SIMULATED (1997-2002)	CONCEPTUAL Pre-development	SIMULATED Pre-development
Groundwater Outflow	27.1	26.2	28	28
Well Pumping	13.3	13.3	0	0
Net Discharge along Santa Cruz River from NIWTP to Tubac	5.30	4.07	7	8
Total Outflows	45.8	43.6	35	36

8.3.2. Post-Development

The post-development water balance includes anthropogenic impacts such as artificial recharge, changes in evapotranspiration (from the saturated zone only), and pumping. The artificial recharge comes from different sources such as surplus irrigation water and wastewater from the towns and septic systems.

The post-development conceptual models of hydrodynamic behavior in the NASS and the SCRAS (Figure 8.2) were updated by CONAGUA (2024a; 2024b), but there are no published NASS- or SCRAS-focused models with transient simulations to estimate the seasonal variation of flows that affect the aquifer. The CONAGUA (2024a) groundwater availability report on NASS estimated evapotranspiration to be 0.6 Mm^3/yr along with a total pumping rate of 0.8 Mm^3/yr (Table 8.2). Darcy's Law was used to calculate groundwater outflow to the U.S. estimated to be about 3.4 Mm^3/yr. The annual average change in storage between 1994 and 2005 was calculated as 0.4 Mm^3/yr. Using these values for the water balance components, a recharge rate of 5.2 Mm^3/yr was calculated.

The CONAGUA (2024b) groundwater availability report on SCRAS estimated evapotranspiration to be 8.8 Mm^3/yr and the total pumping rate was 26.4 Mm^3/yr (Table 8.2). Darcy's Law was used to calculate groundwater fluxes with outflows to the U.S. estimated to be approximately 2.0 Mm^3/yr and inflows of 10.2 Mm^3/yr via mountain front and mountain block recharge. Recharge induced by agricultural return flows was estimated to be 4.1 Mm^3/yr. The annual average change in storage between 1994 and 2005 was calculated to be 0.9 Mm^3/yr. With these values for the water balance components, a vertical recharge rate of 23.8 Mm^3/yr was calculated (Table 8.2). Vertical recharge includes recharge from all sources except agricultural return flows, mountain front, and mountain block recharge. For more detailed information on the assessment of water availability in Mexico, please refer to Mexico's Official Standard NOM-011-CONAGUA-2015, *Conservation of Water Resources*, which establishes the specifications and the method for determining the average annual availability of national waters.

Table 8.2 CONAGUA's Nogales Aquifer System in Sonora (NAS) and Santa Cruz River Aquifer in Sonora (SCRAS) water budget model components for the year 2024 (CONAGUA, 2024a and CONAGUA, 2024b).

Inflow and outflow components		**NASS (** Mm^3/year)	**SCRAS (** Mm^3/year)
Inflows	Groundwater inflows		10.2
	Agricultural return		4.1
	Vertical recharge	5.2	23.8
Outflows	Groundwater pumping	0.8	26.4
	Groundwater out	3.4	2.0
	Evapotranspiration	0.6	8.8
	Change in storage	0.4	0.9

Tapia Padilla (2005) developed a steady-state model of the western portion of the SCRAS (Figure 8.2). The rectangular model grid was rotated about 24° west of north to accommodate the orientation of the river. Only one layer was used in this model representing a unit composed of alluvium and conglomerate, the main aquifer materials in the study area. Boundary conditions included estimated flow in the Santa Cruz River, vertical recharge, and evapotranspiration, as well as constant head boundaries at the upstream (Miguel Hidalgo) and downstream (U.S.-Mexico border) ends of the model. The initial conditions (piezometric values) for the steady-state simulation were those measured in the year 1989 and were taken from Técnicas Geológicas y Mineras, S.A. (1989). The simulation generated an outflow to the U.S. of 1.54 Mm^3/yr (compared to Erwin's (2007) estimate of 1.66 Mm^3/yr). Additional information such as that from aquifer tests could be used to improve the model.

Erwin (2007) developed a groundwater-flow model for the portion of the aquifer along the Santa Cruz River between the U.S.-Mexico border and the NIWTP (Figure 8.2). They used seasonal water balances for the years 1998 to 2002 to carry out model calibration (Table 8.3). Stress periods ranged from 1 to 273 days. There were a few substantial differences between the simulated and conceptual model fluxes. The conceptual evapotranspiration was 40% higher than simulated, possibly owing to the difference in timesteps (daily for conceptual, monthly for the numerical model), or to the model assumption that all water for transpiration is derived from the saturated zone. It is well established that some tree species present in this area utilize near-surface soil water following precipitation events. Annual water budget estimates were developed for water years 1998 to 2002 (e.g., water year 1998 would be October 1, 1997 through September 30, 1998) (Table 8.3). Values are reported as medians from the conceptual model or the median or mean of simulations. Differences between the median and mean can indicate some skewing of mean values toward outliers. Groundwater inflow (main channel) estimates from Sonora into the microbasins area (Figure 8.2) ranged from 0.4 to 0.7 Mm^3/yr (Table 8.3). Recharge in the Santa Cruz River channel varied between 4.6 and 10.6 Mm^3/yr, and mountain front recharge between 1.5 and 1.7 Mm^3/yr. The discharge in the riparian area (evapotranspiration) varied between 2.3 and 4.5 Mm^3/yr and pumping between 3.5 and 3.8 Mm^3/yr. The groundwater outflows towards the Tucson AMA ranged from 0.7 to 1.2 Mm^3/yr. Conceptual values for surface water into the model were used as model inputs, whereas surface water out of the system was not conceptualized but estimated from the model (Table 8.3).

Table 8.3 Comparison of the annual water balances of conceptual and numerical steady-state models for the microbasins area based on water years 1998-2002 (Erwin, 2007).

	Conceptual (median) (Mm^3/yr)	Simulated (median) (Mm^3/yr)	Simulated (mean) (Mm^3/yr)
GROUNDWATER IN			
Recharge			
Main Channel	7.1-10.6	5.6	4.6
Mountain Front	1.7	1.5	1.5
Groundwater Inflow			
Main Channel	0.5-0.7	0.4	0.5
Total Groundwater In	7.3-10.2	7.4	6.5
GROUNDWATER OUT			
Riparian Evapotranspiration	4.5	2.4	2.3
Groundwater Pumping			
Municipal	3.3		
Agricultural	0.37		
Other	0.15		
Total Groundwater Pumping	3.8	3.5	3.6
Groundwater Outflow			
Main Channel	0.7-1	1.2	1.1
Total Groundwater Out	9.1-9.6	7.2	7.6
Change-in-Storage		1.5	0.4

For the effluent-dominated portion of the SCAMA, in addition to the pre-development water budget discussed above, Nelson (2007) developed conceptual and calibrated numerical models to understand post-development steady and transient behavior. Alternative conceptual models were developed and ranked according to the estimated and observed parameters and according to the resulting hydraulic heads and flows. Although most of the alternative models were similar to the final model in terms of recharge, geology, and boundary conditions, several deviated in terms of spatial distribution of hydraulic conductivity. Because of the high uncertainty associated with the pre-development model, a quasi-steady-state water budget was developed for winter flows during the period 1997-2002 to utilize winter seasonal equilibrium and the availability of high-quality data. Simulations were also developed for steady-state and transient conditions for the period 1949-1959 (before the influence of the NIWTP wastewater discharge).

The final calibrated estimate (1997-2002) of groundwater inflow from the microbasins area (Figure 8.2) was 11.5 Mm^3/yr (Table 8.1). Recharge in the Santa Cruz River channel was 17.6 Mm^3/yr, and mountain front recharge was 2.34 Mm^3/yr. The discharge in the riparian area (evapotranspiration) was 16.0 Mm^3/yr, and pumping was 13.3 Mm^3/yr. The discharge towards the Tucson AMA was estimated to be 26.2 Mm^3/yr. During the period of 1949-1959, several flows (recorded as cumulative inflows and outflows) were substantially greater than those from the 1997-2002 period. This was especially the case for the recharge coming from agriculture return flow, which during the 1949-1959 period was approximately two times greater than return flow in the 1997-2002 modeling period. During 1949-1959, both groundwater flow from Sonora and pumping were greater than during the 1997-2002 period. The decrease in pumping over time is linked primarily to the decrease of agricultural lands in the area after 1980.

8.3.3. Updated Model of the Santa Cruz Active Management Area

In 2020, the ADWR (ADWR, 2020) published a regional groundwater-flow model of the SCAMA that used MODFLOW. Objectives included combining and updating ADWR's previously published models and expanding the model domain into the Nogales sub-basin. The transient model was calibrated to aquifer conditions in SCAMA between October 1, 1997, and December 31, 2018. In contrast to earlier models (Erwin, 2007; Nelson, 2007), which were calibrated over the 1997-2002 period, the ADWR (2020) model extended the calibration period to 16 years, allowing it to capture a broader range of climatic variability and groundwater management conditions. To simulate this behavior, initial heads were conditioned to represent the dynamic equilibrium which the system achieves over the course of a few years (Maddock and Vionnet, 1998). This is the same approach used in Nelson (2007). A large number of observed groundwater levels (6,115), streamflows (1,237), and prior information calibration targets (17) were used to calibrate the model. A transient model was successfully developed because water levels and fluxes varied substantially seasonally and annually. One result of having only a transient model is that parameter values are less sensitive and therefore less certain. In addition, uncertainty related to physical properties, inflow and outflow from the aquifer, and the recharge model led to the testing of numerous alternative conceptual models. The final model selected had the lowest uncertainty and observation error. In the model, seasonal changes in pumping, riparian evapotranspiration, and stream recharge were input on a monthly time step.

Overall, the model was able to reproduce stream-aquifer interactions along Nogales Wash as well as seasonal and interannual changes in discharge and recharge along the Santa Cruz River (Figure 8.2). It also reproduced the increased recharge downstream of the NIWTP caused by the upgrade to the treatment plant and the consequent reduction in bioclogging. The results suggest that runoff-induced recharge along the Santa Cruz River supports long-term sustainability of groundwater levels. In addition, groundwater flow is affected both by distribution of sediments and faulting that control hydraulic conductivity and flow direction; fault control of flow is substantial at both local and regional scales. Although the regional aquifer is unconfined, confining layers exist at Kino Springs and near the confluence of Potrero Creek and Nogales Wash (Figure 8.2). The confining layers locally affect groundwater levels, but do not affect the regional groundwater system.

8.3.4. Other Water Budget Models (WBM)

Some modeling has been carried out with respect to climate impacts on groundwater. Scott et al. (2012) analyzed the impact of climate change and population growth in the TSCAS. The study incorporated climate uncertainties and human demand drivers into a water-budget model (WBM). A Global Circulation Model (GCM) that was considered to best predict regional precipitation patterns was used along with several carbon emission scenarios to estimate that recharge was 15% of precipitation. Urban water demand was increased in proportion to population growth projections. Results suggested that demand would eventually be greater than supply and the supply would require supplementation from outside sources. The authors concluded that, if Mexico were to retain the portion of wastewater it currently sends to the NIWTP, streamflow, aquifer storage, and riparian habitat would likely be substantially affected.

Climate-change impacts were also addressed in the modeling framework for water resources planning in the "microbasins" reach of the Santa Cruz River developed by Shamir et al. (2005), Shamir et al. (2007), and Shamir et al. (2015) (Figure 8.2). The modeling framework consisted of stochastic hourly precipitation and streamflow generators, a simplified lumped rainfall-runoff model to produce hourly streamflow, and streamflow routing with channel transmission losses and groundwater recharge. One of the goals of Shamir et al. (2005) was to explore the frequency of pumping that would cause aquifer storage declines below certain thresholds. They found that individual microbasins vary in their sensitivity to pumping. In addition, they found that streamflow projections based on historical (67 years) precipitation records were underestimated when compared with streamflow projections using both historical records and paleoclimatic information.

This model was updated in Shamir et al. (2015). Climate-change projections were generated using eight dynamically downscaled GCMs. The groundwater module was modified to allow hourly runs, and depth to water was estimated as a linear function of groundwater storage. The model was used to test the effects of climate change and management scenarios (pumping rates) on groundwater levels in the TSCAS, a management consideration affecting riparian forest health. Results varied among the microbasins and indicated that water-supply, recharge, and aquifer recovery are highly dependent on the management scenario. Climate impacts were predicted to decrease water-supply reliability and streamflow recharge and increase long-term water shortages and periods of depth-to-water below thresholds representing riparian-vegetation mortality-risk levels.

TAAP efforts in the Arizona-Sonora border have included the development of WBMs for the TSCAS, particularly for the area located downstream of the NIWTP (Tapia-Villaseñor et al., 2020), the SCRAS (Tapia-Villaseñor et al., 2022), and a planned effort in the NAS. Tapia-Villaseñor et al. (2020) developed a conceptual WBM for the region to determine the effect of changes in groundwater demand within the SCAMA and downstream of the NIWTP, the role of binational effluent discharges from the cities of Nogales, Sonora, and Nogales, Arizona, that are treated at the NIWTP, and the impact of climate uncertainties within the region (Figure 8.2). Even though the study focused on the area located downstream of the NIWTP, it provided insight on the influence of possible changes in binational effluent discharges to the Santa Cruz River (Figure 8.2).

WBM inputs included mountain front recharge (6.17 Mm^3/yr), tributary recharge (9.22 Mm^3/yr), the natural Santa Cruz River flow (an average of 33.57 Mm^3/yr for the years 1945–2017), incidental agricultural return (3.65 Mm^3/yr), groundwater inflows (9.25 Mm^3/yr), and eight effluent discharge scenarios from the NIWTP (ranging from 5.42 to 24.6 Mm^3/yr). Effluent discharge scenarios were based on International Boundary and Water Commission registries from 1996 to 2018 and interviews with key stakeholders (Tapia-Villaseñor et al., 2020). Effluent discharge scenarios considered the average, maximum, and minimum effluent discharges before and after the development of Los Alisos Wastewater Treatment Plant in Mexico in 2012. System outflows included evapotranspiration (ranging from 16.05 to 20.97 Mm^3/yr for dry to wet seasons), groundwater pumping (ranging from 19.49 to 28.37 Mm^3/yr), subsurface outflow (27.14 Mm^3/yr), and surface outflows (10.98 Mm^3/yr). According to this study, the Santa Cruz River natural flows and the effluent discharge from the NIWTP represent 65% of the inputs to the system, whereas groundwater pumping represents about 24% of the outflow. These three components, related to either climate uncertainties and water and wastewater management decisions in the U.S. and Mexico, indicate that monitoring efforts, communication, and collaboration can support managers in the treatment and use of binational effluent from the TSCAS.

In Tapia-Villaseñor et al. (2022), the WBM focused on assessing the amount of annual groundwater withdrawal that would maintain the long-term sustainable conditions for the SCRAS. The authors considered the ADWR safe yield definition to describe the management goal of achieving a balance between groundwater withdrawal and groundwater recharge. This goal is often used to describe sustainable conditions. Also, sustainable groundwater withdrawals according to Alley et al. (1999) and Alley and Leake (2004) are defined as the “amount of water that can be extracted from the aquifer without causing undesirable consequences to the environment, economy, and society”.

Inflows and outflows for the model were based on water availability studies for the region (CONAGUA 2009, 2015, and 2018), and a hydrologic model was utilized to simulate the inflow and outflow as a function of precipitation. The hydrologic model that was used is the Sacramento Soil Moisture Accounting model (SAC-SMA)

(Burnash et al., 1973), configured for the region by the Colorado River Basin River Forecast Center. The WBM was solved to obtain the average inflow and outflow fluxes that maintain sustainable conditions, including an average groundwater pumping rate of 23.26 Mm^3/yr. This quantity was determined using climate-dependent recharge data from 1954–2020 and represents the amount of groundwater withdrawal that results in an annual average change in storage of zero. For more details on this method, see Tapia-Villaseñor et al. (2022).

8.4. Conclusions

The groundwater-flow system in the TSCAS has been studied by researchers in both the U.S. and Mexico, along with members of different governmental agencies. The complexity of the studies has varied across the decades, as has the area of focus. Currently (2026), the majority of the studies refer to a specific political administrative subset of the TSCAS and not the whole binational setting (refer to Chapter 1 for more information about political-administrative subsets).

This chapter presented a summary of available conceptual and numerical models for the region (Table 8.2 and Table 8.3). Even though there is an evident lack of binational groundwater-flow models, there is a strong body of knowledge regarding the study region that could form the basis for binational modelling efforts in the future. A binational groundwater model could improve estimates of cross-border flows and allow better understanding of climate impacts, which would aid in developing model scenarios to simulate the effects of changes in management practices, land use, and industrial uses. There are disparities between the methods used to process and analyze data on each side of the border that make it difficult to compare and reconcile inflow and outflow components from the available water balance models. Some potential research and monitoring efforts that could enhance development and refinement of a binational model include:

1. Monitoring of groundwater levels in all the TSCAS political-administrative subsets could be implemented at least once every five years, with special focus on understudied regions.
2. Additional groundwater pumping tests could improve information regarding different hydrogeologic parameters.
3. Installation of a streamgage in Mexico could support calibration of surface water information.
4. Installation of a streamgage in Potrero Creek could enhance understanding of down-gradient recharge effects.
5. Installation of meteorological stations in places lacking historic climate information could support refinement of precipitation and evapotranspiration.
6. Harmonization of inflows and outflow components of available groundwater-flow models could aid in more comprehensive modeling of the entire study area.

Water budget modeling efforts, both historical and current, within the TSCAS represent a step towards enhancing the understanding of aquifer recharge and storage in the SCRAS. This information, coupled with a planned WBM for the NASS, and previous modeling efforts for the microbasins area (the area located between the U.S.-Mexico border and the NIWTP to the north), provide data coverage across all the subregions that comprise the TSCAS. Furthermore, the components (inputs and outputs) of each of these WBMs may prove valuable for developing future groundwater models for the transboundary region.

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9. CONCLUSIONS AND RECOMMENDATIONS

9.1. Concluding Summary and Observations

The study area is situated within the Basin and Range Province, a tectonically active region characterized by alternating mountain ranges and alluvial basins. Within this structural framework, the Santa Cruz Basin functions as a critical hydrologic corridor, connecting upland recharge areas with the Santa Cruz River valley. The binational approach adopted for this study enabled the harmonization of methods and data sources, resulting in a more complete representation of the aquifer system than could be achieved by either country independently. This work has significantly expanded the knowledge base regarding the geology, hydrology, and groundwater flow dynamics of the TSCAS and has established the necessary foundation for the continued scientific analysis of transboundary aquifer systems.

9.2. Summary of Findings

9.2.1. Geological and Structural Framework

The TSCAS occupies a structurally complex basin within the Basin and Range Province, where alternating mountain ranges and fault-bounded valleys formed through Cenozoic extension. Precambrian basement rocks, overlain by Paleozoic and Mesozoic sedimentary and volcanic successions, provide the low-permeability foundation of the aquifer. Subsequent faulting produced asymmetric grabens that accumulated thick sequences of continental sediments and volcanic deposits, creating the alluvial basin within structural depressions that now store groundwater. Geophysical and stratigraphic data show that basin-fill thickness ranges from about 200 to 500 m in Arizona and up to roughly 450 m in Sonora, with the deepest zones aligned along the Santa Cruz River. These geological and structural features determine the spatial distribution of aquifer materials, permeability contrasts, and the pathways that direct subsurface flow across the international boundary.

9.2.2. Climate and Surface Water Hydrology

The regional hydrologic setting is semi-arid and strongly seasonal. Precipitation is dominated by the North American Monsoon from July through September, with lesser winter contributions from Pacific frontal systems. Annual rainfall increases with elevation, from approximately 350 mm in the valley floor to more than 600 mm in upland areas, whereas potential evapotranspiration greatly exceeds precipitation throughout most of the basin. Streamflow in the Santa Cruz River and its tributaries is largely ephemeral; only short reaches near Nogales, Arizona remain perennial, supported by shallow groundwater and treated effluent. Recharge occurs through mountain-front infiltration, stream-channel percolation from the main channel of the Santa Cruz River and ephemeral tributary channels, and localized infiltration from precipitation and return flows. Long-term hydrometeorological records from both countries reveal comparable variability and demonstrate that climatic fluctuations and extreme events control episodic recharge and runoff in the basin.

9.2.3. Hydrogeology

Hydrogeologic characterization indicates that the aquifer system is composed of three principal hydrostratigraphic units. Coarse, unconsolidated alluvial deposits form highly permeable unconfined zones near active channels; semi-consolidated basin-fill sediments with fine interbeds produce semi-confined conditions toward the basin center; and fractured volcanic and sedimentary rocks provide localized secondary permeability along mountain fronts. Groundwater generally moves from the upland margins toward the Santa Cruz River and then northward along the valley, following the regional topographic gradient. Variations in aquifer thickness, faulting, and lithologic composition create pronounced heterogeneity in hydraulic conductivity and storage capacity.

9.2.4. Groundwater Levels and Hydraulic Parameters

Groundwater-level measurements and hydraulic tests confirm this heterogeneous behavior. Water levels are shallow near the Santa Cruz River and deepen toward the basin edges, while hydrographs display seasonal and multi-year oscillations that correspond to climatic variability. Calculated hydraulic conductivities are highest in coarse alluvial deposits and lower in fine-grained basin fill; storage coefficients indicate predominantly unconfined to semi-confined conditions. A comparison of piezometric data from Arizona and Sonora underscores the value of binational datasets, revealing that depth to groundwater generally increases away from the Santa Cruz River channel, even in wells located along tributaries, and becomes deeper near the mountains. Depth to water data from 2011–2012 and 2025 range from 0 to 128 m, and several wells show minimal variation over time, indicating some areas with limited groundwater-level variation during the period of record.

9.2.5. Geochemistry

The chemical composition of groundwater reflects progressive evolution along flow paths. Waters near recharge zones are typically calcium-bicarbonate type, becoming sodium-sulfate or sodium-chloride dominated downgradient as total dissolved solids increase with residence time and water–rock interaction. Carbonate dissolution, silicate weathering, and minor evaporite contributions account for the observed ion patterns. Vertical variations in chemistry reveal stratification and mixing between shallow and deeper zones. Trace-element concentrations mostly remain within natural background ranges, and comparable geochemical trends observed in both countries confirm that similar hydrogeochemical processes act throughout the basin.

9.2.6. Conceptual and Numerical Modeling

Multiple modeling approaches have been applied to the TSCAS to support the scientific interpretation of groundwater conditions. Conceptual models integrate geologic, hydrologic, and hydrogeologic information to describe the structure and functioning of the aquifer system. Local-scale numerical groundwater-flow models quantify flow patterns, recharge–discharge relationships, and storage behavior under various hydrologic scenarios. Water-budget analyses provide estimates of the relative magnitudes of inflows and outflows, clarifying the balance among recharge, evapotranspiration, and baseflow.

A central feature of this study is the integration of binational data and collaboration between U.S. and Mexican institutions through the TAAP. Shared geologic, hydrologic, hydrogeologic, and geochemical datasets have enabled a unified description of the aquifer system and harmonization of analytical methods and data standards. The collective findings presented in this report represent a significant advancement in the binational scientific knowledge of the TSCAS and provide a robust foundation for future technical collaboration.

9.3. Scientific Gaps and Limitations

Although the TSCAS has been characterized through extensive binational collaboration, the work revealed several gaps and limitations that should guide future technical efforts. The availability and continuity of hydrogeologic data remain uneven between both sides of the border. Differences in monitoring frequency, instrumentation, and data resolution constrain temporal analyses and make it difficult to evaluate long-term aquifer responses. Many datasets pre-date coordinated binational protocols and therefore require harmonization to ensure full comparability.

Spatial coverage of wells suitable for water-level, hydraulic, and geochemical observation is still limited, particularly in the southern portion of the aquifer and in areas where access is restricted. This limits the ability to delineate hydraulic gradients with confidence and to detect vertical variations in groundwater chemistry or pressure conditions. Similarly, detailed lithologic information is available for a relatively small subset of wells, which restricts the ability to refine the three-dimensional representation of aquifer units and confining layers.

Modeling efforts, though scientifically valuable, have been conducted at local scales using varying boundary conditions and parameterizations. These models are best viewed as complementary components rather than a single, continuous representation of the system. Their integration into a consistent conceptual framework remains an important scientific challenge. Uncertainties also persist regarding recharge magnitudes and spatial distribution, owing to the episodic nature of precipitation and the complexity of mountain-front infiltration processes. Geochemical data, while robust in defining major-ion evolution, remain limited in isotopic and age-tracer coverage. Additional isotope sampling would strengthen interpretations of recharge sources, residence times, and groundwater flow connectivity. Lastly, data on groundwater–surface-water exchanges are sparse. Quantifying these interactions would improve understanding of baseflow contributions to the Santa Cruz River and the potential impacts of hydrologic variability on riparian ecosystems. Despite these limitations, the collective datasets compiled through TAAP represent an important scientific foundation for ongoing investigation.

9.4. Scientific Recommendations

Building upon the technical findings and identified gaps, several critical scientific directions are recommended to advance the understanding of the TSCAS. Sustained binational monitoring of groundwater levels, streamflow, and climatic variables is indispensable for detecting temporal trends and refining recharge and discharge estimates. Establishing unified observation protocols and shared digital repositories is crucial, as this would significantly enhance data comparability and accessibility for researchers on both sides of the border.

The expansion of well networks for hydraulic and geochemical sampling is necessary to mitigate spatial uncertainty within the hydrogeologic framework. Priority must be assigned to strategically located sites that accurately capture vertical gradients and transitions between hydrostratigraphic units. Enhanced lithologic logging and geophysical profiling at these locations are required to enable a more accurate delineation of aquifer boundaries and confining zones.

Further refinement of numerical models is recommended, beginning with the development of a regional-scale model to characterize large-scale flow patterns, define appropriate boundary conditions, and incorporate the heterogeneity identified in this study. Based on this regional framework, local-scale models can then be refined to represent hydraulic-property variability, incorporate new field data as they become available, and evaluate areas of specific interest. Calibration and sensitivity analyses should continue to emphasize recharge estimation and groundwater–surface-water interactions. Water-budget components would benefit from periodic re-evaluation using updated climatic and land-use information.

Expanded geochemical and isotopic investigations are recommended to characterize groundwater age, flow paths, mixing processes, and hydrogeochemical processes such as water-rock interaction and oxidation-reduction reactions. Coordinated sampling campaigns designed under shared analytical protocols would ensure comparability and allow tracing of transboundary flow components. Integrating geochemistry with hydraulic and geologic datasets in a unified interpretive framework will strengthen the overall conceptual model of the aquifer system.

Finally, it is recommended that TAAP partners continue to foster binational scientific collaboration through joint technical exchanges, data harmonization, and training initiatives. The cooperative approach that underpinned this study remains vital to sustaining a shared, science-based understanding of the TSCAS and to informing future binational hydrogeologic investigations.