

Concepts and considerations for riparian restoration on the Middle Santa Cruz River using effluent-based in-channel flows

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I love you all so much.

Cover photo:

Effluent outfall at Agua Nueva WRF. Tucson, Arizona. April 2025.

Photo by Rudy Malusa.

Cover illustration:

View from Monument No. XV, Looking West Towards Monument No. XIV.

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Abbreviations

AAC	Arizona Administrative Code
ADEQ	Arizona Department of Environmental Quality
ADWR	Arizona Department of Water Resources
AF	Acre-feet
AMA	Active Management Area
ARS	Arizona Revised Statutes
AWBA	Arizona Water Banking Authority
AWP	Advanced water purification
BEA	Bureau of Economic Analysis
CAIDD	Central Arizona Irrigation and Drainage District
CAP	Central Arizona Project
CAWCD	Central Arizona Water Conservation District
CDP	Census-designated place
CWS	Community water system
DRAM	Drought response and adaptive management
EPA	Environmental Protection Agency
ET	Evapotranspiration
FICO	Farmers Investment Company
GDP	Gross domestic product
GMA	Groundwater Management Act
GPCD	Gallons per capita per day
GSF	Groundwater savings facility
GVWRF	Green Valley Wastewater Recovery Facility
HUC	Hydrologic Unit Code
L3	Linked, local, leveraged
LCRB	Lower Colorado River Basin
LSCRMFSF	Lower Santa Cruz River Managed Storage Facility
MGD	Millions of gallons per day
MSCR	Middle Santa Cruz River
MUSF	Managed Underground Storage Facility
NASS	National Agriculture Statistics Service
NCEI	National Centers for Environmental Information
NIWTP	Nogales International Wastewater Treatment Plant
NLCD	National Land Cover Database
PAG	Pima Association of Governments
PDF	Portable document format
PCRFCDD	Pima County Regional Flood Control District
PCRWCDD	Pima County Regional Wastewater Reclamation Department
LSTSA	Long-term storage account
LTSC	Long-term storage credit
SCWC	Santa Cruz Watershed Collaborative
USBR	US Bureau of Reclamation
USF	Underground storage facility
USGS	United States Geological Survey
WBD	Watershed boundary dataset
WRF	Wastewater reclamation facility

Abstract

Abstract

This report describes new opportunities for creating hydriparian habitat on the Middle Santa Cruz River Valley, in Pima County, Arizona, including lands within Sahuarita, Green Valley, and Canoa Ranch. It presents four concepts for in-channel flows using high-quality reclaimed wastewater ("effluent"). These concepts consider local growth projections, estimated wastewater flows, and various effluent-availability scenarios. A new conceptual framework based on past successes, "Linked, Local, and Leveraged" (L3) characterizes high-value riparian restoration projects. The preferred concept best comports with the L3 framework, and it includes distributed outfall points that maximize habitat connectivity between outlying conservation lands. Proposed management tools mimic natural flow variability and allocate a water reserve for drought response and adaptive management needs. These tools rely on physical features of the project design as well as existing water policy in Arizona. The report also considers the origin of effluent-based in-channels in the Tucson area, historic flow regimes in the study area, and long-term factors affecting the viability of effluent-based riparian restoration projects, as revealed through recent price signals and management decisions.

Introduction

Problem statement and proposed solution

In the Santa Cruz River watershed (**Fig. 1**), demand for groundwater has resulted in widespread water table decline since the introduction of mechanized pumping in the late 19th and early 20th Centuries. These declines have resulted in the dewatering of riparian areas that once conveyed seasonal or perennial surface flows (Logan, 2002; Webb et al., 2014b). Cessation of flow has led to extinction or local extirpation of riparian species in the Tucson area (Logan, 2002; Webb et al., 2014b). Effluent-based environmental flows are a proven tool for riparian restoration on ephemeral watercourses in arid lands (M. T. Bogan et al., 2020; Eppehimer et al., 2020; Hamdhani et al., 2020, 2023; Luthy et al., 2015).

In the years and decades since the initial dewatering of the Santa Cruz River, in-channel discharge of reclaimed wastewater (“effluent”) has created healthy riparian communities within and downstream of Tucson’s urban core (M. Bogan et al., 2024; M. T. Bogan et al., 2020; Hamdhani et al., 2023; Sonoran Institute et al., 2024a, 2024b; J. M. White & Stromberg, 2011). Farther south, robust effluent-supported flows originate from Nogales International Wastewater Treatment Plant (NIWTP) (Sonoran Institute, 2024b, 2024a).

An ephemeral stretch of the Santa Cruz River separates these perennially flowing reaches. Hydroriparian habitat is absent here. This ephemeral section includes the Middle Santa Cruz River (MSCR), defined here as reaches of the Santa Cruz River between the Pima-Santa Cruz County line and the San Xavier District of Tohono O’odham Nation (**Fig. 2**, next page). Environmental planning documents reflect a longstanding local interest and recent prioritization of effluent-based environmental flows on the MSCR (Greeley and Hansen, 2007; SCWC, 2022).

Santa Cruz watershed and project context area

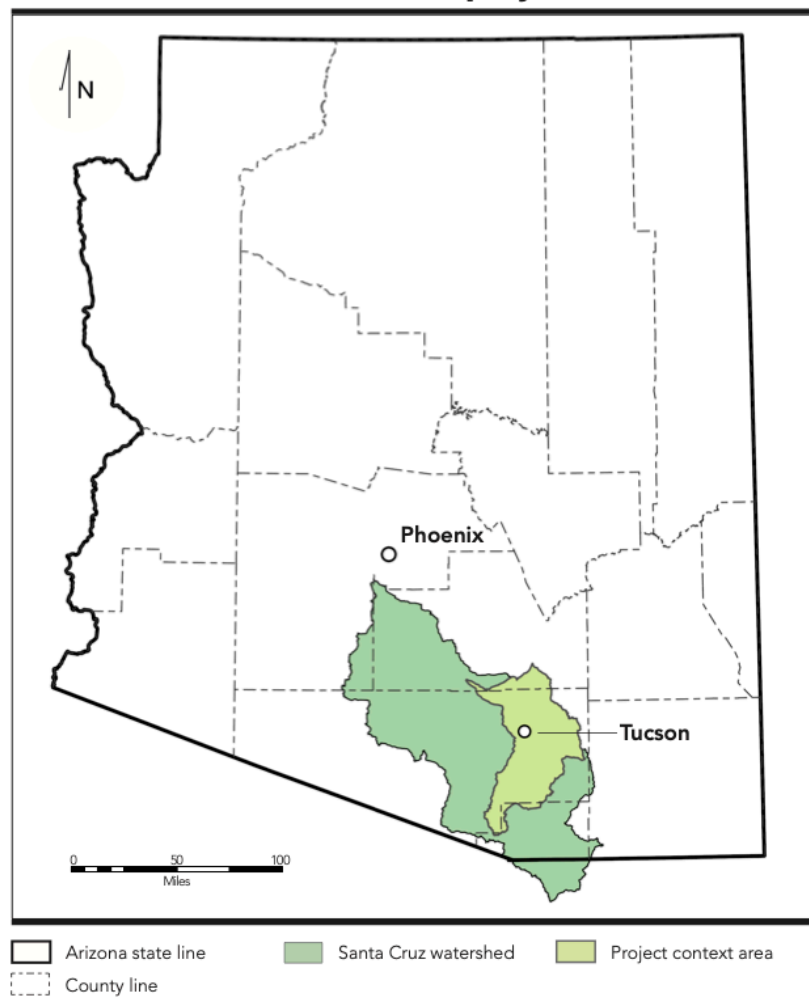


Figure 1. The Santa Cruz Watershed is shown in relation to the state of Arizona. The “project context area,” a region surrounding the study area and used for spatial analyses (defined in the Methods section) is also shown.

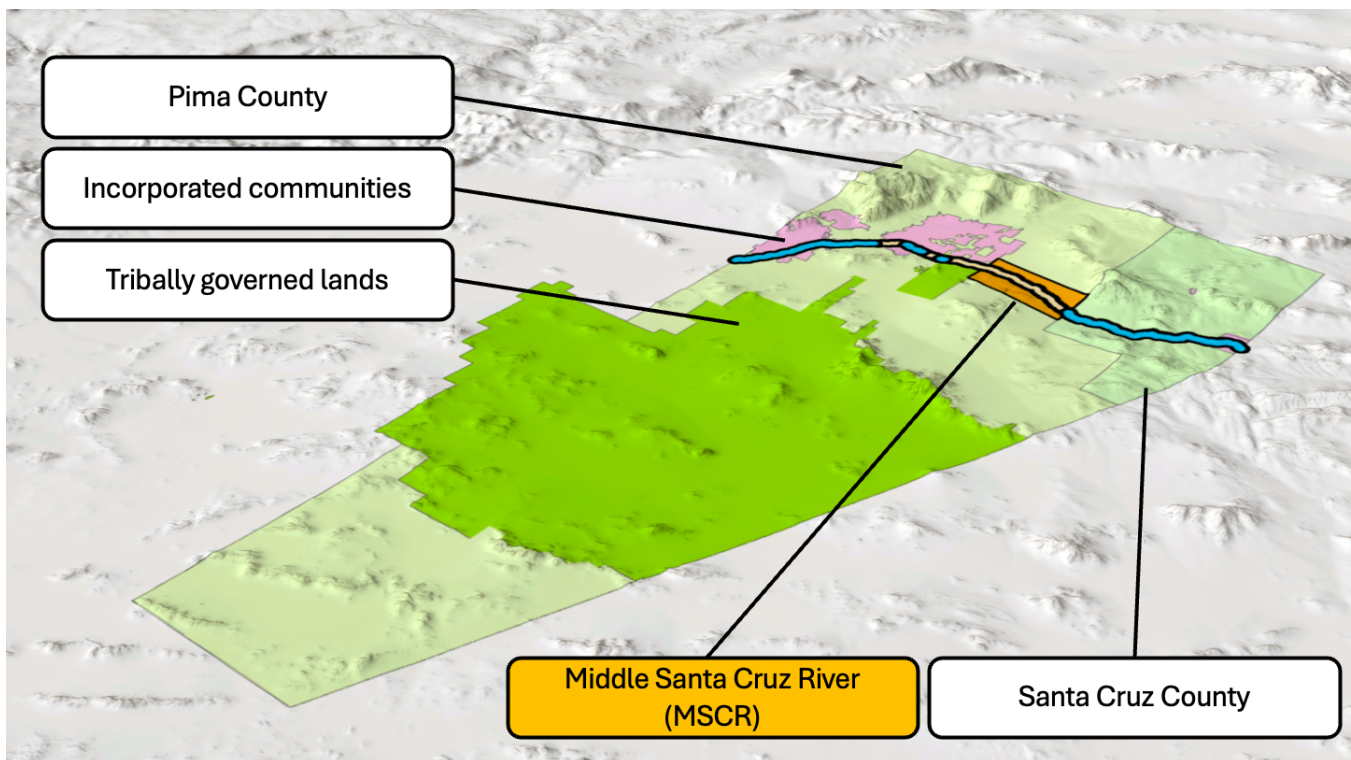


Figure 2. The Middle Santa Cruz River is shown in relation to Pima County, Santa Cruz County, and nearby tribally governed lands.

This report presents concepts for effluent-based riparian restoration projects in the MSCR. These concepts consider current and future effluent production volumes, outfall locations, and management tools. New effluent-based flow on the MSCR would create hydriparian habitat that augments existing flows to the north (Sonoran Institute et al., 2024a, 2024b) and south (Sonoran Institute, 2024b, 2024a), linking together a network of local-scale restoration projects across the watershed. This work was initiated under the supervision of Luke Cole, Santa Cruz River program manager at the Sonoran Institute, and partially funded by a US Bureau of Reclamation (USBR) Phase 1 WaterSMART grant.

Two major constraints governed concept development:

- 1.) Effluent-based flows should not encroach onto Tohono O’odham tribal lands.
- 2.) Restoration concepts require the physical and legal availability of effluent.

The first constraint honors the current preferences of the Tohono O’odham tribal government. The second constraint is practical necessity for successful implementation.

This report presents four concepts for effluent-based riparian restoration projects on the MSCR, proposed management tools, and an implementation roadmap for the preferred concept. These management tools take advantage of physical project design (specifically, a multi-outfall distributed setup) and existing Arizona water policy. They allow water managers to mimic the variability of natural flow regimes and allocate a water reserve for drought response and adaptive management.

This report also documents the early history of effluent-based flows and effluent reuse in Tucson, presents an overview of existing conditions in the study area, and assembles evidence for the historical presence of hydriparian habitat on the MSCR. Additionally, it considers factors that might affect the viability of new effluent-based flows in Arizona. These factors include policy issues and increasing demand for new and existing water sources, as revealed through price signals.

Area of study

Land-use analyses in this report refer to a *study focus area* and a *project context area* (**Fig. 3**). These areas comport with wording in the grant application that funded initial work on this project.

While the grant was specifically concerned with riparian restoration opportunities on the MSCR and its tributaries, it also considered the relationship of that area to water resources managed at a broader scale — specifically, the planning area within which the Santa Cruz Watershed Collaborative (SCWC) focuses its efforts.

The “study focus area” refers to the MSCR area specifically, while the “project context area” refers to a larger area encompassing the SCWC planning area. The “project context area” includes the study focus area and the urbanized core within eastern Pima County. It also includes surrounding portions of the watershed that drain to and provide environmental services to MSCR/Tucson Basin lowlands. The Methods section gives working definitions of these areas.

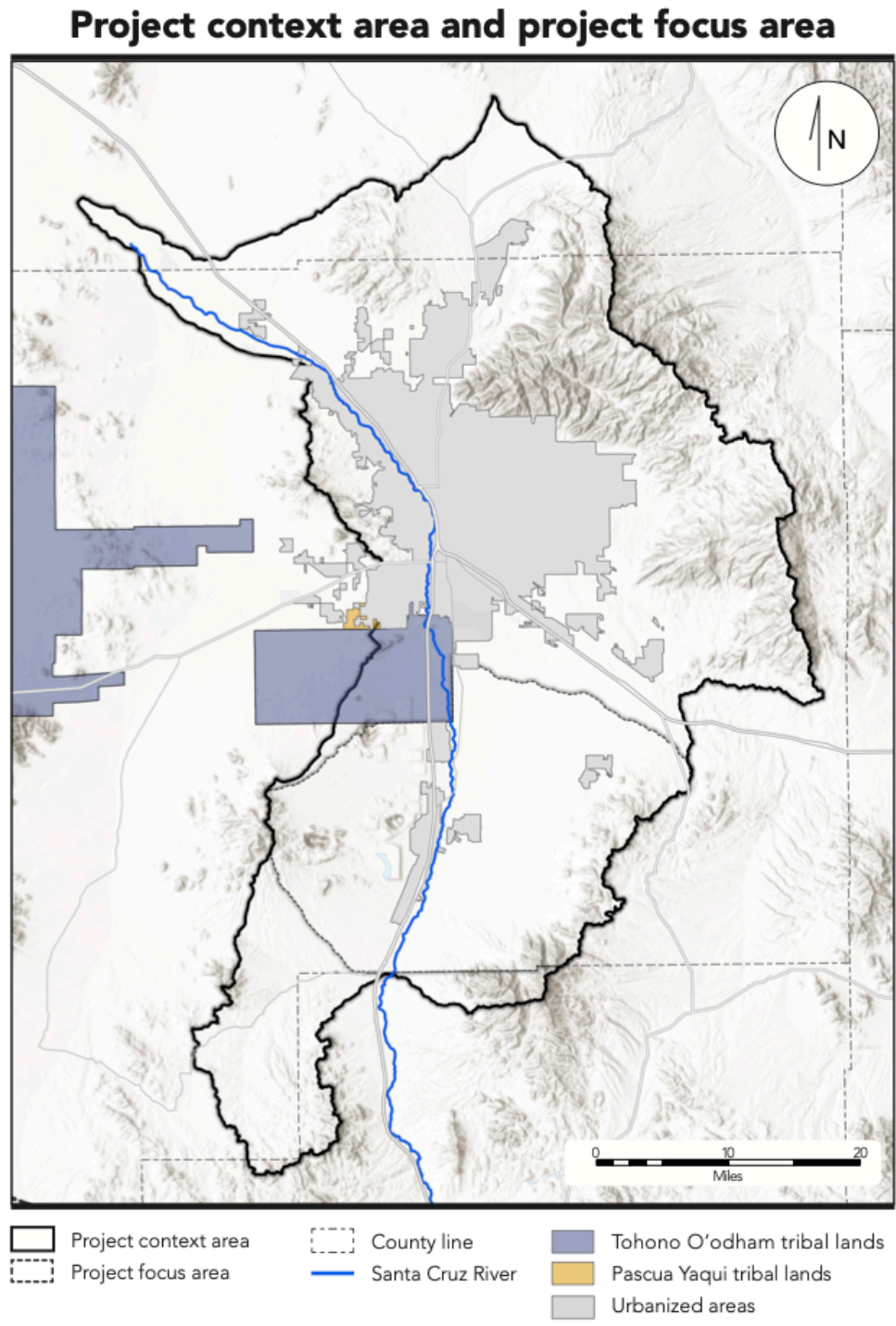


Figure 3. The project context area (bold line) and project focus area (dashed line).

Background: Groundwater decline and the de-watering of the Santa Cruz River system

The Santa Cruz River flows south from its Southern Arizona headwaters into Mexico before changing course and flowing north. A short distance east of Nogales, the river re-enters the United States in rural Santa Cruz County. Downstream of Nogales, the Santa Cruz River conveys effluent-based flows from NIWTP north through Santa Cruz to (roughly) the Pima County line. The river continues north as an ephemerally flowing stream.

North of the San Xavier District of the Tohono O'odham Nation, the river again carries anthropogenic and engineered flows. Beyond Pima County, the river flows into Pinal County. Here, the channel dries. Its course becomes indistinct in an area known locally as the Santa Cruz Flats.

Macro- and local-scale pressures dewatered the Santa Cruz River and caused loss of riparian habitat (**Fig. 4.**)

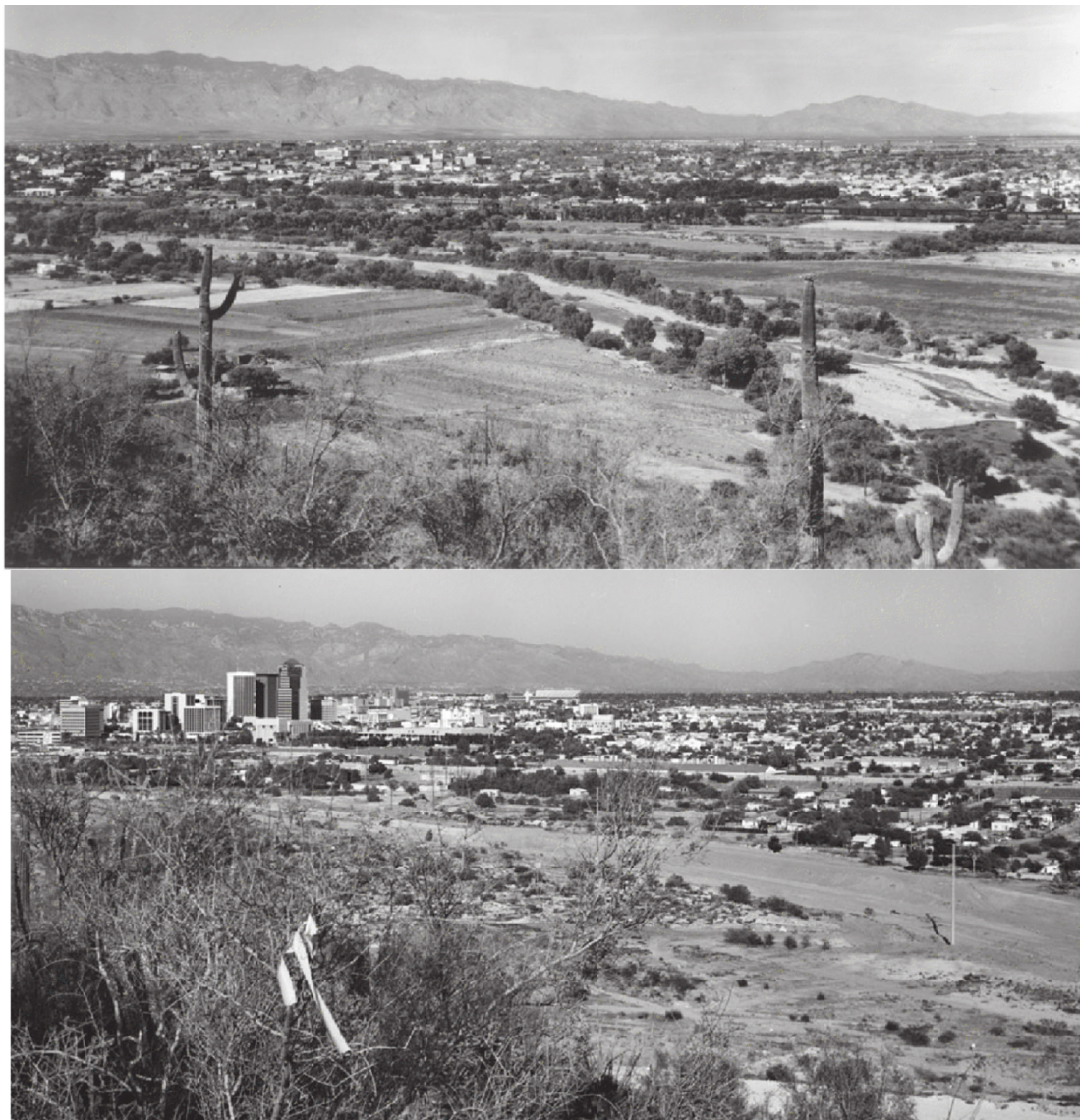


Figure 4. A dewatered reach of the Santa Cruz River as it appeared from Sentinel Peak (A Mountain) in 1927 (above) and 1987 (below). Photos are respectively from the Norman Wallace collection and by RM Turner, via *Requiem for the Santa Cruz* (Webb et al., 2014b).

When European settlers first arrived in the Santa Cruz River Valley, the river system had numerous flowing reaches. Since the late 1800s, demand for pumped groundwater has dewatered formerly flowing reaches of the Santa Cruz River (Logan, 2002; Webb et al., 2014b). Industrial, agricultural, and municipal demand are all responsible for groundwater consumption.

The arrival of imported Colorado River water in the 1990s, delivered via Central Arizona Project (CAP) canals, reversed a decades-long trend of regional groundwater overdraft. Imported water, augmented with reclaimed water for non-potable uses, allowed widespread aquifer recovery, although localized declines persist (Tucson Water, 2018).

However, supply-demand imbalance also derives from reduced inflows. Broadly, anthropogenic climate change will likely reduce groundwater inputs (**Fig. 5**, Meixner et al., 2016) through increased evapotranspiration demands, aridification, reduced precipitation volumes, and modified precipitation regimes (Amanambu et al., 2020; Berghuijs et al., 2024; Davamani et al., 2024; Lall et al., 2020; Meixner et al., 2016; Smerdon, 2017).

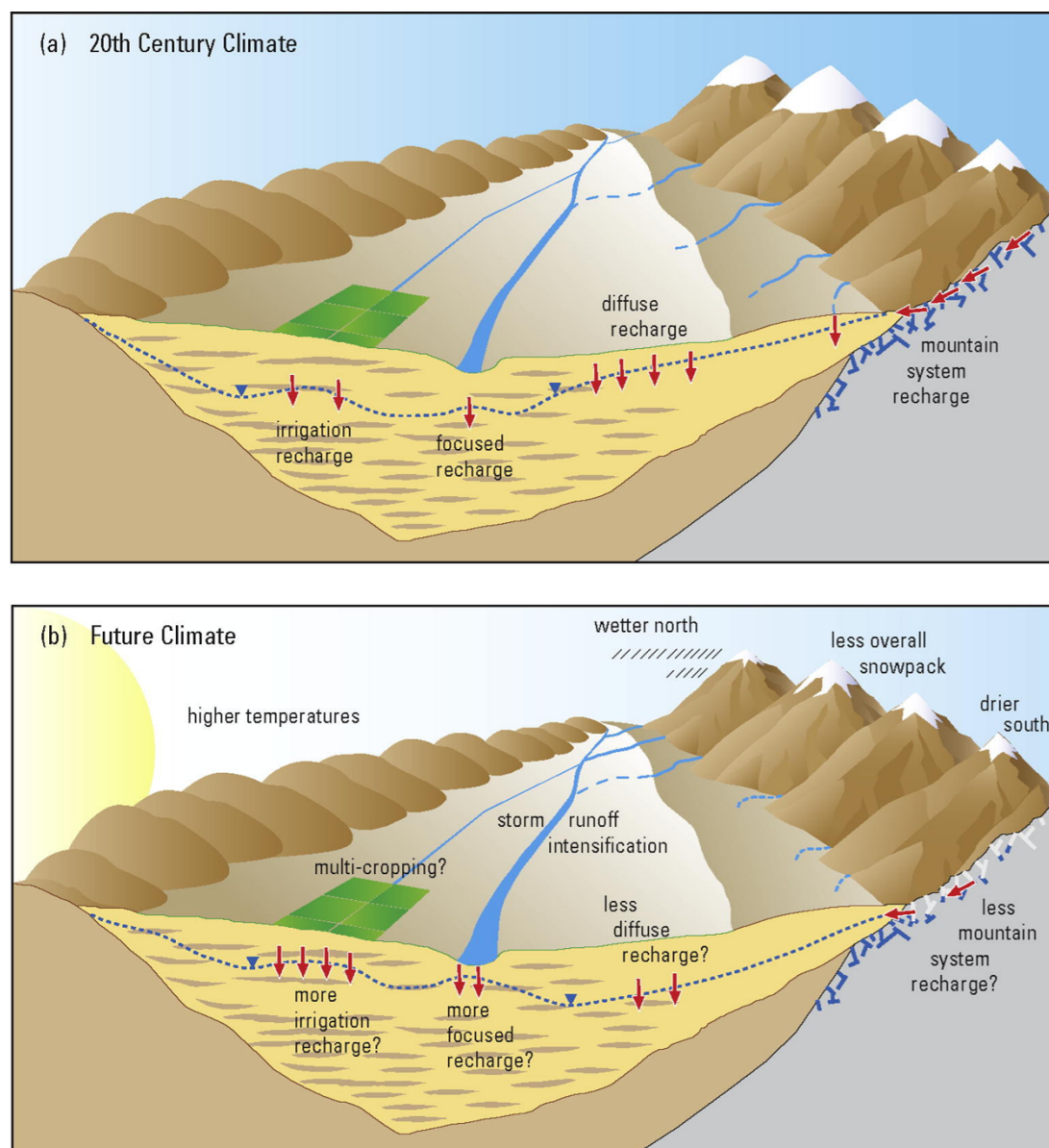


Figure 5. Modified groundwater inputs under climate change. Figure reproduced from Meixner et al. (2016).

Climate predictions at the local and regional scale involve greater uncertainty than those at the global scale. Examining the Upper Santa Cruz River basin, Shamir et al. (2021) find divergent and uncertain changes in precipitation inputs from monsoon systems, tropical storm remnants, winter precipitation patterns, and atmospheric rivers, complicating long-term forecasting. However, the authors also report a pronounced decrease in streamflow within the historical record. Comparing seasonal study-area streamflow between 2001 and 2020 with that from 1955 and 2000, the authors observe an 87.6% decline in summer streamflow and a 63% decline in winter streamflow.

The implications of reduced precipitation inputs comport with large-scale gravimetric observations of Arizona groundwater levels (**Fig. 6**, Scanlon et al., 2025). Examining groundwater levels across the Lower Colorado River Basin (LCRB), Scanlon et al. (2025) find that the only exception to long-term trends (2000-2023) are those areas where imported Colorado River water augments natural recharge. Even in regions of “moderate” use, where groundwater recharge exceeds extraction, the authors observe an average groundwater decline of 3 meters over the study period.

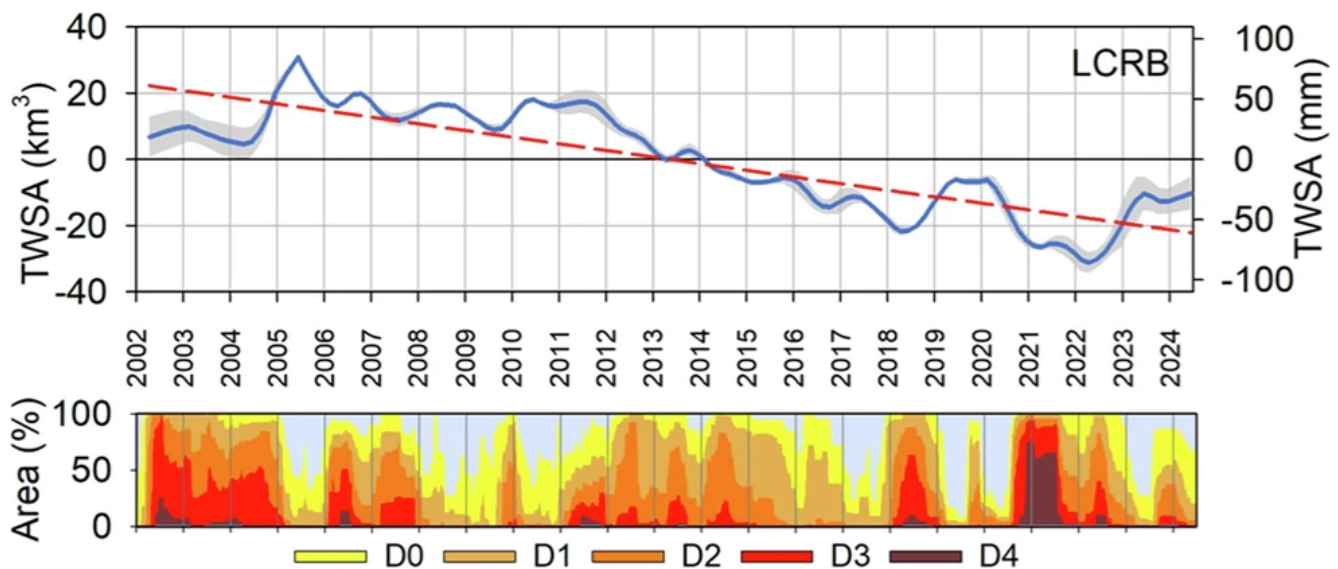


Figure 6. Large-scale groundwater loss over the LCRB since 2002. Interannual variability tracks the intensity and extent of ongoing drought. The total water storage anomaly (TWSA) on LCRB is an overall groundwater loss of 45 km³ of (36 million acre-feet). Figure reproduced from Scanlon et al. (2025).

Linked, local, and leveraged: Realizing large scale success through local-scale projects

Water management challenges in the Colorado River Basin are caused by supply-demand imbalances, uncertainty, ambiguity, and complexity (Castle & Fleck, 2019; Fleck & Castle, 2022; USBR, 2012). Each of these factors is compounded by anthropogenic climate change and prolonged drought, which will likely lead to permanent and severe reductions in Colorado River flows (Udall & Overpeck, 2017). These issues manifest in basin-wide groundwater declines and reservoir depletion (Scanlon et al., 2025).

These macro-level challenges affect water management at regional and community scales. Because the greater Tucson area is dependent on Colorado River water imported via Central Arizona Project (CAP), its water security is affected by the basin-wide water scarcity (Scanlon et al., 2025).

Emerging water problems require multi- and interdisciplinary solutions at basin scale (Cosens et al., 2011; Jury & Vaux, 2005; USBR, 2012). In the Colorado River Basin, large-scale riparian restoration often relies on “multiple, linked local site restoration efforts” (Ralston & Starr, 2017). Successful restoration projects can confer sociocultural, recreational, and economic co-benefits (Samonte et al., 2017).

In other words, successful restoration projects are *linked, local, and leveraged*. These attributes respectively describe (1) the spatial arrangement and ecological connections between project sites, (2) the implementation scale, and (3) the ability of such projects to use existing resources or assets to confer co-benefits.

This work proposes “linked, local, and leveraged” (L3) as an accessible and easily understood conceptual framework that adapting best practices from restoration ecology for planners, resource managers, and other decision makers. Examples of L3 networks can be found on the mainstem Colorado River and within various tributary watersheds (CCRN, 2024; Oppenheimer et al., 2017; B. Orr et al., 2017; Ralston & Starr, 2017; Rasmussen et al., 2017). Near the Santa Cruz River, on the lower San Pedro River, conservation easement sites form a linked network (**Fig. 7**) (National Conservation Easement Database, 2025). This study relies on the linked,

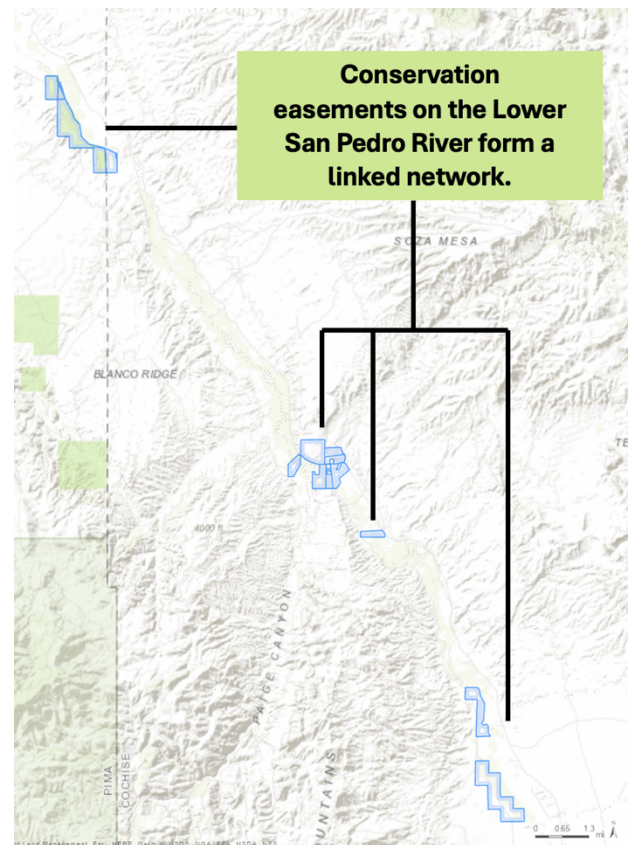


Figure 7. Conservation easements on the lower San Pedro River near the boundary between Pima and Cochise Counties. The spatial arrangement of these easements forms a linked network of sites. Via the Nation Conservation Easement Database (2025).

local, and leveraged framework to guide concept design and selection of a preferred alternative.

Effluent is typically produced by municipal or municipal-scale entities, often situated along major watercourses. The inherent attributes of its production make it an ideal tool for creating networks of linked, local, and leveraged restoration sites, especially in arid lands (**Table 1**).

Tendency of effluent-based restoration projects to fulfill L3 framework criteria	
Linked	Population centers are often distributed along significant regional watercourses. WRFs are sited downgradient from service areas, so outflows tend to be located along those watercourses.
Local	With rare exceptions, effluent production and management is handled at the local scale. When not directly produced by a county or municipal agency, it is often produced by an entity of similar scale.
Leveraged	Because effluent is created by a service area population, the benefits of effluent-dependent restoration confer to those populations. These benefits are economic, environmental, social, cultural, and recreational.

Table 1. The inherent production characteristics of effluent make it a logical choice for meeting L3 criteria for riparian restoration projects in arid lands.

Environmental benefits of effluent-based flows and their use elsewhere on the Santa Cruz River

The National Academy of Sciences highlight in-stream flows and aquifer recharge as important environmental benefits of wastewater reuse (National Research Council, 2012, pg. 154). EPA proposes to compile case studies of successful wastewater re-use (EPA, 2019, proposed action 2.1.2) and to incorporate the practice into local planning (EPA, 2019, proposed action 2.1.3). Effluent-based flows produce significant environmental benefits, especially in arid and semi-arid regions with dewatered streams (Eppehimer et al., 2020; Hamdhani et al., 2020, 2023; Luthy et al., 2015).

In recent decades, the use of reclaimed wastewater (“effluent”) has become a locally preferred tool for riparian restoration (Sonoran Institute, 2024a, 2024b; Sonoran Institute et al., 2024a, 2024b). Effluent-based flows are widespread throughout Arizona (Uhlman et al., 2012), with the Arizona Department of Environmental Quality (ADEQ) reporting 11 effluent-dependent lakes and 53 effluent-dependent streams (ADEQ, 2025b).¹

Flowing section	MUSF	Source description	Originating source(s)	Outfall location or beginning of flow	Length (miles)
Nogales International WWTP - Pima County line	No	Effluent	Nogales International WWTP	Santa Cruz River at Potrero Creek	23.4
Martinez Hill reach	No	Agricultural	Irrigated agriculture	Base of Martinez Hill	0.9
Downstream of Irvington Road	No	Treated groundwater	Tucson Airport Remediation Project	Irvington Road on Santa Cruz River	1.3
Santa Cruz River Heritage Project (SCRHP)	Yes	Effluent	Tucson Water dedicated distribution system for reclaimed water, delivering water from PCRWRD	Between Silverlake and Starr Pass Roads, near 26th St alignment	1.4
Santa Cruz River Managed Underground Storage Facility (SCRMUSF)	Yes	Effluent	Agua Nueva WRF	Agua Nueva outfall, between Sweetwater Dr alignment and W El Camino del Cerro	5.2
Lower Santa Cruz River Managed Recharge Project (LSCRMRP)	Yes	Effluent	Tres Rios WRF	Tres Rios outfall near Ina Road	21.5
Pinal County reach	No	Effluent-based flow from Tres Rios WRF extending downstream beyond LSCRMRP boundary			3
Total					56.7

Table 2. Surface flows on the Santa Cruz River between the US-Mexico border and southern Pinal County.

¹ Additional work is necessary to better characterize engineered flows on these “effluent-dependent streams.” In some, if not many instances, these stream reaches may function as a fail-safe or backup option to be used when infiltration basins are unavailable. In these cases, WRFs may discharge effluent to these streams and lakes only rarely, if ever. However, the availability of shapefile containing these allegedly effluent-dependent reaches can facilitate future study. For instance, effluent-dependent reaches could be compared with control reaches on nearby streams of similar size and character by measuring indices of ground cover.

The Santa Cruz stands out among these rivers as an exemplar collection of successful deployments (**Fig. 8**, end of section). The Santa Cruz River is likely home to more miles of continuous effluent-dependent streamflow than all other Arizona streams combined. **Table 2** (above) summarizes the extent of these and other surface flows attributable to engineered water systems.

Most of the effluent-based flows in **Table 2** originate from an outfall point located on or near a WRF, but this is not strictly necessary. On the Santa Cruz River Heritage Project (SCRHP), the City of Tucson conveys effluent upstream from Agua Nueva WRF to a historically flowing reach of the Santa Cruz River (ADEQ, 2018).

In addition to the flowing reaches given in **Table 2**, another effluent-dependent reach can be found on the North Branch Santa Cruz Wash, downgradient from Casa Grande, at the Casa Grande Managed Recharge Facility (ADWR Permit No. 71-221492).

Riparian restoration via effluent-based flows on the MSCR would fulfill each element of the “linked, local, and leveraged” framework. It is well-linked: the MSCR is situated between effluent-based flows on upstream reaches in Santa Cruz County and downstream reaches in Pima County (ADEQ, 2025b; Turner & List, 2021; Uhlman et al., 2012). Implementation of concepts described here would link and support not only these reaches but other local-scale restoration efforts (Fabre & Cayla, 2009; Pima County, 2025; SCWC, 2023).² The project is locally scaled: each concept would be executed primarily at the local level, by Pima County Regional Wastewater Reclamation Department (PCRWRD). Additionally, the concepts all leverage nearby existing recreational and conservation lands, adding value to current investments. For some concepts, additional value may be realized by future land-use conversions along flowing reaches. The preferred concept leverages an existing bridge over Demetrie Wash on I-19 to facilitate habitat connectivity.

Effluent-based flows on otherwise ephemeral streams in arid lands can result in significant environmental benefits. The resulting riparian habitat resembles naturally flowing reaches in some ways and differs in others.

Riparian woodlands on effluent-dominated reaches of the Santa Cruz River have a mix of woody species resembling those seen on the naturally flowing San Pedro River elsewhere in southern Arizona (M. S. White, 2011). Where effluent-based flows have re-watered urbanized reaches of the Salt River in Phoenix, researchers have found that vegetation and soil seed banks closely resemble those on naturally flowing rural reaches of the river (J. M. White & Stromberg, 2011). After the introduction of effluent-based flows, rapid species recruitment and establishment of odonates has been observed even on urbanized reaches near downtown Tucson (M. T. Bogan et al., 2020).

² The most complete inventories of riparian restoration projects on the Santa Cruz River system (Fabre & Cayla, 2009; Zugmeyer et al., 2015) are now ten to fifteen years old and omit many significant projects. Although it would represent a significant undertaking, a more up-to-date and exhaustive inventory would be a valuable resource for local conservation efforts.

South of the study focus area, Sonoran Institute has previously catalogued diverse and complex riparian woodlands on the Santa Cruz River (Sonoran Institute & University of Arizona Remote Sensing Center, 2008). Effluent-based perennial flows originating from the NIWTP coexist with seasonal high-flow events that periodically distribute seeds and scour the channel, improving water infiltration (Sonoran Institute & University of Arizona Remote Sensing Center, 2008). Poor infiltration due to low water quality from NIWTP was an ongoing problem before facility upgrades in the late 2000s, with channel clogging downstream of NIWTP even lead to cottonwood die-off at upstream reaches near the discharge point in the mid-2000s (Sonoran Institute, 2019a; Treese et al., 2009). Clogging nearest the discharge point reflects a fairly well-characterized tendency for effluent-dependent streams to exhibit increased water quality farther downstream of the effluent outfall (Hamdhani et al., 2023). Facility upgrades completed in 2009 appear to have resolved the issue with clogging, although improved infiltration reduced the extent of surface flow and had consequent effects on dewatered downstream reaches (Sonoran Institute, 2019a, 2019b).

Effluent-based flows underlie similarly dynamic conditions on Lower Santa Cruz River reaches north of the study focus area. Effluent-based flows typically constitute most of the observed annual flow volume downstream of discharge points, with occasional high-volume years caused by wet-season runoff (Pima County Regional Flood Control District et al., 2013). A similar issue with channel clogging played out on these reaches, albeit without the initial clogging-related mortality. After facility upgrades were completed in 2014, observers saw reduced flow extent on Lower Santa Cruz reaches downstream of Tucson, with loss of willow and “increased variability in streamside plants” (Sonoran Institute, 2020).

On these lower (more northerly) reaches, PCRFC has observed that “maintaining or restoring flood-dependent cottonwood-willow forests will be easier in reaches with floodplains lacking bank protection and having effluent flows” (Pima County Regional Flood Control District et al., 2013). The absence of nearly continuous bank protection seen in the heavily urbanized reaches elsewhere in Pima County make the MSCR an excellent restoration candidate.

Widespread community support for in-channel flows is evident on social media and at in-person events, with over 300 in-person attendees present for the first in-channel release on the Santa Cruz River Heritage Project reach (Kmiec, 2019).

In-channel discharge of effluent efficiently replenishes groundwater while still achieving restoration goals. The USGS reports that 92-98% infiltration rates for water discharged into the Santa Fe River near La Bajada, New Mexico, with evaporative losses of 2-8% (Thomas et al., 2000). The authors do not attempt to determine the fraction of infiltrated water taken up by riparian vegetation, but the unaccounted fraction (2% to 6%) is comparable to the 5% evaporative losses that authors may assume for groundwater recharge via engineered basins (Dillon & Arshad, 2016).

Tucson Water reports evapotranspiration losses on its in-channel effluent-based flows as low as 3.5% (Kmiec, 2021). Examining effluent-dependent flows originating from NIWTP in the Santa Cruz AMA, Scott et al. (1997) found that riparian ET consumed 11% (3,162 AF/yr) of the total study area water budget (28,170 AF/yr). The relatively high ET reported by Scott may be due to low infiltration rates caused by clogging layers attributable to water quality issues before facility upgrades completed in 2014.

Flowing and ephemeral reaches on the Santa Cruz River north of the US-Mexico border

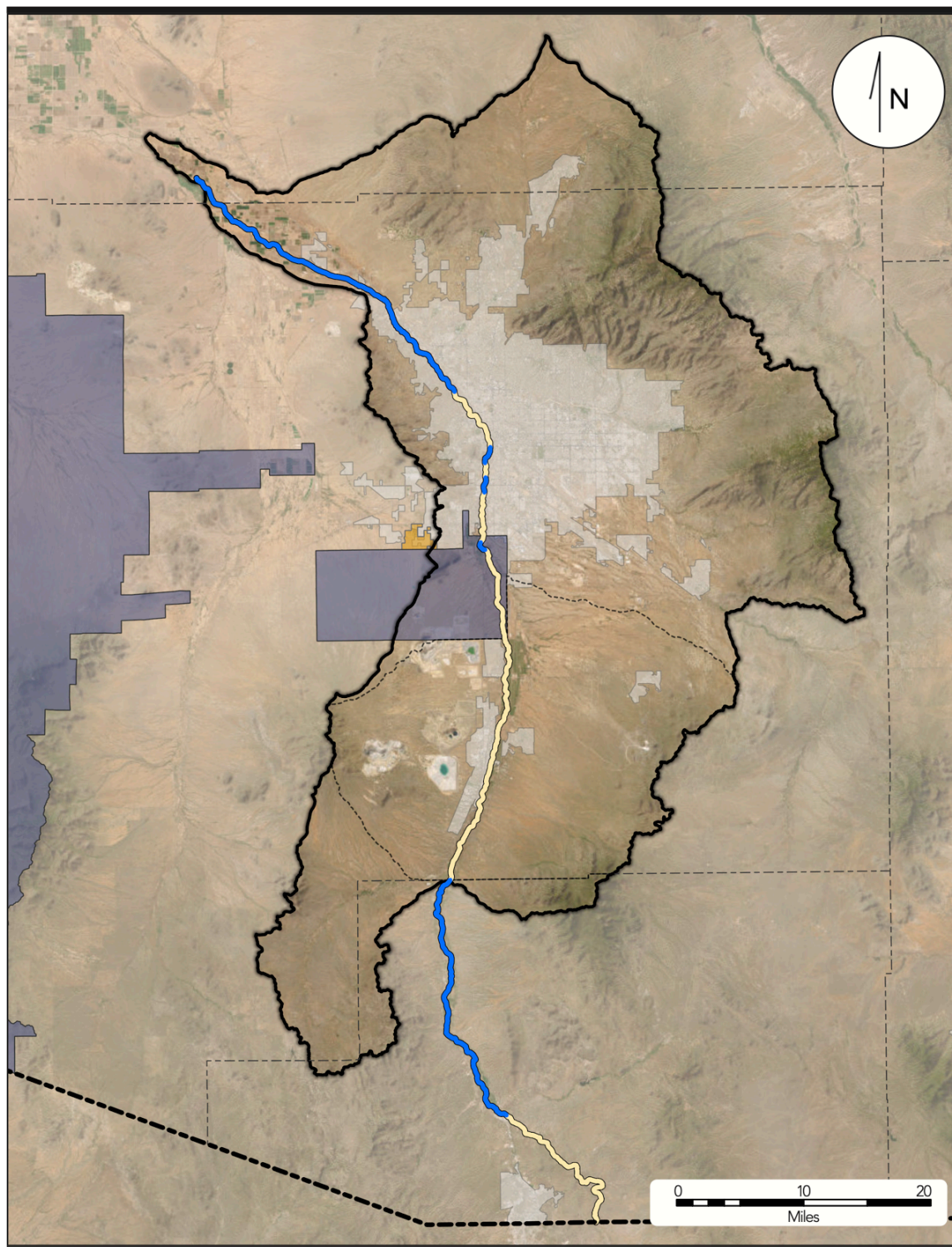
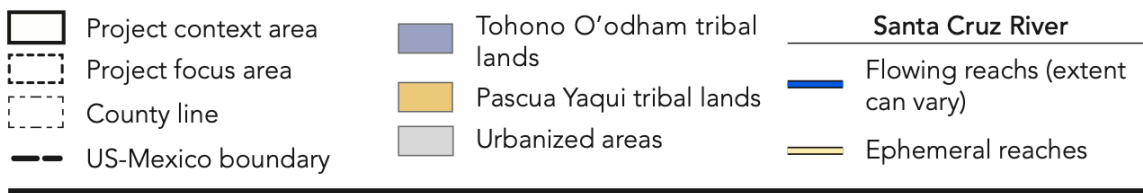


Figure 8. Approximate current extent of flow on the Santa Cruz River between the US-Mexico border and southern Pinal County, where the channel becomes indistinct. The longest ephemeral reach shown bisects the project focus area.



Economic and practical benefits of wastewater reuse and effluent-based flows

Effluent-based flows can confer economic benefits and support local water security. Ecological restoration is one of several principles that motivates the EPA’s Draft National Water Reuse Action Plan (EPA, 2019, pg. 7). The agency specifically identifies the need for wastewater reuse within a watershed-scale context (EPA, 2019, pg. 15) — a recommendation that aligns with the “linked, local, and leveraged” framework used here. Effluent-based restoration is an especially important strategy in arid lands with limited surface water (National Research Council, 2012, pg. 37). Wastewater re-use also confers reputational benefits to communities, while diversifying and strengthening their water portfolios (National Research Council, 2012, pg. 154).

Various works have been published on the economic value of in-stream flows in undeveloped and rural areas (Lowe et al., 2020), but relatively few studies have examined the economic value of in-stream flows through developed areas. In a contingent valuation method study, Loomis (2012) reports a total economic value of \$172 acre feet for in-stream flows through the Poudre River in Fort Collins, Colorado, or roughly \$242 in inflation-adjusted dollars. This public good is an additional economic value realized beyond the dollar value of long-term storage credits realized through in-channel aquifer recharge.

Properties adjacent to in-stream flows may be able to realize higher property values (Bark, 2011). Studies in the Tucson area has shown a positive association between home value and nearby hydriparian vegetation in particular (Bark et al., 2009). Other studies have found homes within 1.1 miles of riparian areas realizing an average 3.1% increase in value (Bark, 2011; Bourne, 2007).

Arizona tourism relies on nature-based activities. In-stream flows will improve recreation conditions on the MSCR, likely increasing the frequency and economic value of outdoor recreation to surrounding communities. In Pima County, 60% of Tucson-area visitors report engaging in “outdoor desert activities,” and their top reason for recommending the area to other travelers was the “surrounding natural environment (Coalition for Sonoran Desert Protection, n.d., citing information derived from Strongpoint Research, 2012).

A 2019 study commissioned by the Audubon Society estimates that Arizona’s surface waters result in outdoor recreation that supports 114,000 jobs with \$4.5 billion in household income. In total, these surface waters directly contribute \$7.1 billion to Arizona’s GDP and drive a total economic output of \$13.5 billion (Audubon Society, 2019a). Of these jobs, the study attributes 12,000 to Pima County waterways, which see recreational use by 222,000 in-state residents per year (Audubon Society, 2019b). Collectively, Arizona watercourses and their nearby lands host 48.0 million user-days per year from the state’s residents (Southwick Associates, 2019).

Figures from the 2019 study align well with those reported by the federal government for outdoor recreation in the state. The Bureau of Economic Analysis reports a 2023 statewide total economic impact of \$14.1 billion (2.7% of statewide GDP) and 110,794 jobs (3.4% of statewide employment) with \$6.7 billion in compensation (BEA, 2024b).

Nationwide, outdoor recreation accounted for 2.3% of GDP in 2023, adding \$639.5 billion of value to the US economy (BEA, 2024a). Outdoor recreation also contributes over \$65 billion in federal tax revenue per year, and more than \$59 billion annually in state and local tax revenue (Outdoor Industry Association, 2017).

The Bureau of Economic Analysis also reports that, in 2023, outdoor recreation's contribution to growth in real GDP, real gross output, compensation, and employment, all outpaced the US economy as a whole (BEA, 2024a).

Orr and Colby (2002) report that birding on the San Pedro River in Cochise County results in a total economic impact of \$17.0 and \$28.3 million (\$30.7 to \$51.1 million in 2025 dollars). The San Pedro River here has a baseflow of roughly 5,000 acre-feet per year (Kennedy & Gungle, 2010). Assuming that birding on this flyway is wholly dependent on surface flow, each acre-foot of instream flow supports an economic impact of roughly \$6,000 to \$10,000 per acre-foot (2025 dollars).

History of effluent reuse and watercourse discharge in the Tucson area

Local governments in the study area have recognized the potential of effluent-based groundwater recharge since at least the early 1960s (“Water Reuse Study Under Consideration,” 1964). Some experts at the time even considered direct potable reuse a long-term, inevitable outcome (Starrett, 1962b). As early as 1963 the Tucson had even agreed to a pilot facility to research direct potable reuse (Starrett, 1963). However, it was only in the mid-1970s, after decades of effluent-based flows in the Santa Cruz River, that historic record begins to reflect any appreciation for these flows.

The City of Tucson’s first municipal wastewater system was completed in 1917: a sewer system conveyed wastewater to open fields where it was spread and left to dry (Starrett, 1962a). In 1928, the city built its first actual treatment plant (Starrett, 1962a), although sewage was being discharged to the Santa Cruz River as late as the 1940s in some areas (“Indian School to Have Sewer System,” 1940).

The city replaced its original plant with a new facility in 1951 and upgraded it in 1960, giving it a total treatment capacity of 24 million gallons per day (Starrett, 1962a). By 1962, it was operating at 75% capacity and the city was considering plans to construct an additional plant capable of treating an additional 10 million gallons per day (Starrett, 1962a).

The new plant discharged treated effluent into the Santa Cruz River after it opened in 1951 (“Cortaro Asks Sewage Water,” 1951; Harrington, 1952, **Fig. 9**). Consultants at the time were uncertain whether effluent-based flows over private land would constitute a trespass (Harrington, 1950). Arizona courts have since ruled that this is a permissible use of a watercourse (see e.g., *West Maricopa Combine, Inc v. ADWR*).

Initially, 3,200 AF of effluent per year were sold to “the contractor for the city’s farm” and 1,200 AF of effluent per year were sold to the local utility for optional use as a coolant (“City to Call for Bidding on Unused Sewage Outflow,” 1954). Collectively, this represented about half the effluent production of the plant; the other half

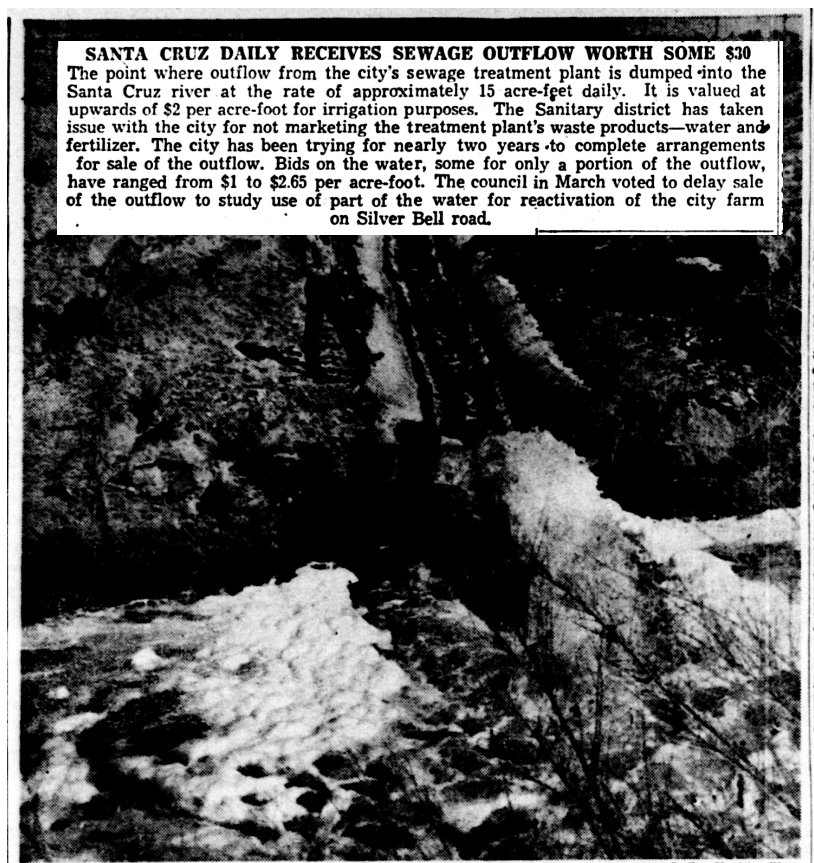


Figure 9. Effluent is discharged into the Santa Cruz River, 1952. The *Tucson Daily Citizen* reported that the effluent might be worth “upwards of \$2 per acre-foot” to farmers. It was ultimately sold for \$1 per acre-foot (Harrington, 1952, with photo credit to “Sedley-Hopkins”).

was discharged into the river (“City to Call for Bidding on Unused Sewage Outflow,” 1954). However, the utility company did not rely on its optional fraction, and it too was discharged into the river (“City to Call for Bidding on Unused Sewage Outflow,” 1954), suggesting a total annual discharge of some 5,600 AF per year in 1954. An unsourced news report claimed farmers were appropriating the water without paying for it (“Council Votes Down Appeal To Promote Clean-Up Drive,” 1954).

The city solicited bids on the unused effluent, expecting revenues of about \$2 per AF (Cooper, 1954a). In 1955, Cortaro Cotton & Cattle Company partner-manager Albert Oshrin signed a twenty-year agreement to purchase effluent from the City of Tucson at \$1 per acre-foot (“City to Call for Bidding on Unused Sewage Outflow,” 1954; Starrett, 1962b). Oshrin agreed to pay the cost of conveyance infrastructure (Harrington, 1955, **Fig. 10** and **11**) Before the contract was signed, Oshrin had quoted the cost of pumped groundwater at \$7 per acre-foot (“City to Call for Bidding on Unused Sewage Outflow,” 1954). When the city council rejected farmer James Shumaker’s bid of \$1.25 per AF, his lawyer claimed at least one of the votes resulted from the council member’s “deliberate cultivation by Al Oshrin for his friendship” (Cooper, 1954b). Shumaker later filed a claim to appropriate surface flows, including effluent (“Man Refused Effluent Files Water Claim,” 1955). The outcome of Shumaker’s attempt is not immediately clear, but Arizona courts later rejected such claims (Chapman, 2005).

City officials soon came to believe that the city had sold the effluent for too low a price, and regretted the contract’s far-off 1975 sunset date (Starrett, 1962b). Meanwhile, when complaints about sewage odors were traced to effluent storage ponds along Oshrin’s conveyance route, the city and Oshrin disagreed over maintenance responsibilities (Starrett, 1962b).

In 1969 Oshrin proposed extending the agreement another twenty years — through 1995 — and transferring his interest in effluent delivery to a Salinas-based grower with local operations (“Antle Asks Effluent Pact To ’95,” 1969). By this time, the city was interested in finding a way to reclaim the effluent if a superior use could be found.

Sometime between 1968 and 1971, Oshrin had sold his interest in effluent deliveries to Dow Chemical (“Oshrin No Longer Defendant,” 1971; “Sheik Appointed City Magistrate,” 1968). By 1971, Dow had stopped paying for effluent and refused delivery,

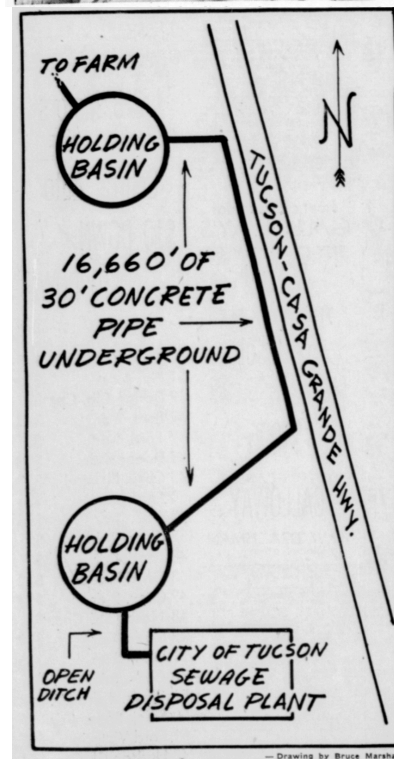


Figure 10 (top). Oshrin’s effluent conveyance line under construction. (Harrington, 1955, uncredited photo)

Figure 11 (bottom). Map of conveyance infrastructure (via Harrington, 1955, map credited to Bruce Marshall).

demanding indemnification against liability for pollution caused by its use (“Oshrin No Longer Defendant,” 1971). The city sued Dow, and their unwanted effluent was again discharged into the Santa Cruz River (“Oshrin No Longer Defendant,” 1971). Dow’s complaints preceded their successful attempt to rezone agricultural holdings on the Santa Cruz River for large-scale residential development (Lee, 1975). This likely reduced the company’s long-term need to source water for irrigation source, regardless of effluent quality. Indeed, the city water director accused Dow of wanting to develop the land and “throwing up a smoke screen” (Cline & Donahue, 1971).

Delivery cessations likely increased the extent of flow on the Santa Cruz River (**Fig. 12**). Aerial imagery from mid-May 1972 shows contiguous surface flow beginning near Roger Road outfall and extending very nearly to Marana Road (USGS, 1972a, 1972b). This is roughly 8 miles farther downstream than the extent of flow shown in aerial images from early-April 1969, when flow terminated in the vicinity of Avra Valley Road (USGS, 1969).

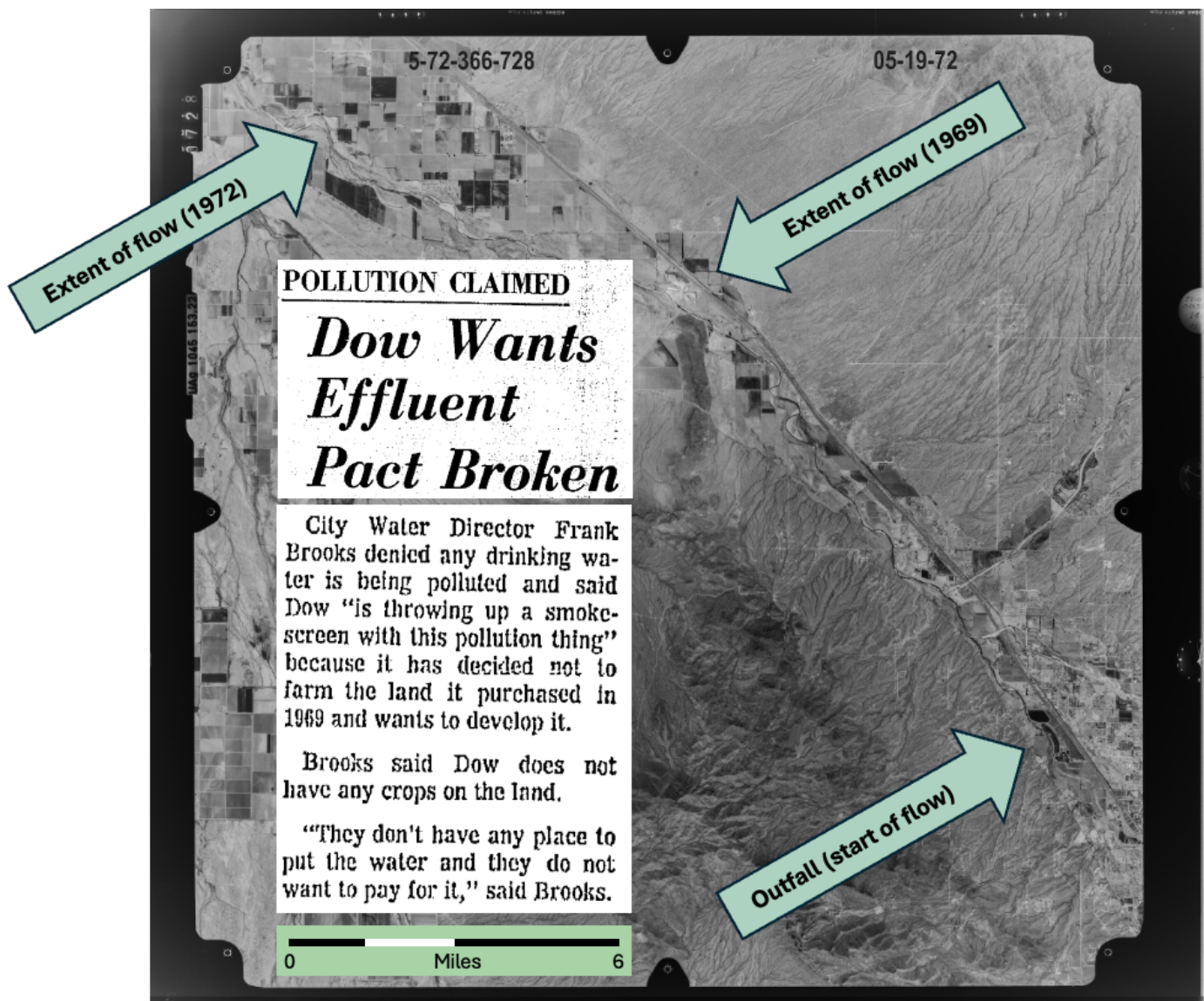


Figure 12. Extent of flow in May 1972 versus April 1969, as derived from USGS (1969, 1972a, 1972b). News clipping from *Tucson Daily Citizen* (Cline & Donahue, 1971).

The cessation of contracted deliveries coincides with a pronounced shift in how communities in the Tucson area perceived and used effluent. The 1960s showed hints of this emerging attitude, including discussion of nonpotable reuse, direct potable reuse, and trading effluent for imported Colorado River water (Starrett, 1963; Turbyville, 1965; “Water Reuse Study Under Consideration,” 1964). Even non-specialists were interested in the possibility of direct potable reuse (Hayden Excavation Service, 1969, **Fig. 13**). However, the next decade saw new ideas for and new deliveries of effluent for non-agricultural uses.

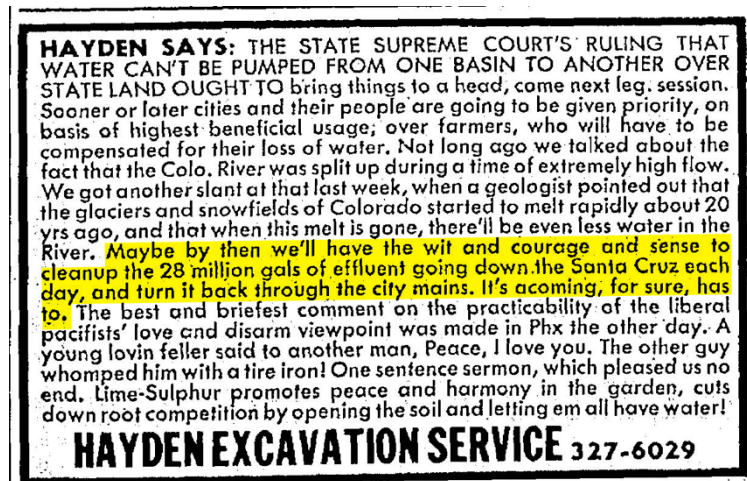


Figure 13. An editorialized advertisement advocates for the direct potable reuse of wastewater, among other things (Hayden Excavation Service, 1969).

During the 1970s, various plans for effluent reuse became a reality. The City of Tucson began using effluent to irrigate Randolph Park, and in Marana, a private hunting club lured ducks to the area using effluent-supported wetlands (Goodkind, 1971; Quimby, 1975; “Randolph’s New ‘Lake,’” 1975). Consultants studied the feasibility of using effluent at mining operations south of Tucson (Collins, 1975), and the city envisioned effluent-based flows as the centerpiece of the Santa Cruz River Park downtown (Kimble, 1976, **Fig. 14**). Although the original River Park concept was not implemented in full — the official plan even included a hang glider landing area (City of Tucson, 1982, p. 49) — the core concept finally became a reality when flows began at the Santa Cruz River Heritage Project more than forty years later.

When Arizona passed its Groundwater Management Act (GMA) in 1980, effluent became an even more valuable commodity.



Figure 14. This concept art for effluent-based flow in downtown Tucson (via Kimble, 1976) predates the Santa Cruz River Heritage project by some 40 years.

Water governance and effluent regulation

Water management in Arizona embodies Ostrom's (1990) concepts of polycentric governance of a common pool resource, with institutional arrangements in place at the international, interstate, intrastate, and local scales. At the international and interstate level, appropriation of surface water is governed by the Colorado River Compact, with the IBWC overseeing water sharing between the US and Mexico. Within Arizona, water rights are overseen statewide by ADWR.

Groundwater in Arizona is governed by the GMA, a first-of-its-kind legislation passed in 1980 that established several "active management areas" (AMAs) and "irrigation non-expansion areas" (INAs) across the state. Both are intended to reduce or halt the unsustainable drawdown of groundwater reserves; AMAs are typically managed with the goal of "sustainable yield."

The GMA is augmented by the Underground Water Storage and Recovery Act (1986), Underground Water Storage, Savings, and Replenishment Act (1994), and Arizona Water Banking Authority Act (1996). Collectively, these laws establish a groundwater banking regime that allows for the storage and later recovery of effluent and other water sources using "managed aquifer recharge."

In other words, groundwater banking allows a party to save one source of water, such as effluent or imported Colorado River water, as a different source of water, i.e., groundwater. Conversion of the source water to groundwater occurs when it infiltrates soil and joins the aquifer below.

Broadly, there are two ways of converting effluent into groundwater. The first is to infiltrate the soil within a constructed basin. Within AMAs, these are regulated by ADWR as underground storage facilities (USFs).

The second is to discharge the source water into a natural watercourse, where it infiltrates the soils there (typically channel sands with good hydraulic conductivity). Within AMAs, ADWR regulates these as managed underground storage facilities (MUSFs). Except for outflows from the NIWTP in the Santa Cruz AMA, all major effluent-based flows in Arizona's AMAs take place within an MUSF.

Various aspects of effluent releases into USFs and MUSFs are regulated by ADEQ, ADWR, and the Arizona Water Banking Authority (AWBA). ADEQ aquifer protection permits allow the discharge of effluent into a watercourse, while ADWR oversees matters related to groundwater storage and recovery in AMAs. Water banking credits are tracked by the AWBA.³

AWBA tracks the award and transfer of water banking credits stored in USFs and MUSFs. These credits are known as long-term storage credits (LTSCs). Crediting rates vary across project types

³ For a concise overview of permitting requirements, see Table in the final report prepared for the state's Long-Term Water Augmentation Committee (Carollo Engineers, 2019). This two-page table summarizes many statutory requirements and the respective agencies responsible for administering them. The rights of Arizona municipalities to effluent discharge and conveyance through natural watercourses are affirmed by case law including *Arizona Public Service Corporation v. Long* and *West Maricopa Combine, Inc. v Arizona Department of Water Resources*.

and implementation dates as shown in **Table 3**. The “cut to the aquifer” reflects a forfeit fraction of withdrawal rights that depends on recovery timeframe (same-year or long-term) and project type.

Water source	Type of recharge project	Cut to the aquifer	
		Annual storage and recovery	LTSC
CAP water	Any	0%	5%
Surface water	Any	0%	N/A
Effluent	Constructed USF basin	0%	5%
Effluent	Groundwater savings facility (GSF)	0%	5%
Effluent	In-channel MUSF approved on or before January 31, 2019	5%	5%
Effluent	In-channel MUSF approved after January 31, 2019	50%	50%

Table 3. LTSC crediting for different effluent-based recharge projects, adapted from ADWR (2019).

Note the difference in crediting rates for the last four rows of **Table 3**. A party that stores effluent in a newly created MUSF (natural watercourse) is rewarded with roughly half of the water recovery rights as a party storing that effluent in a USF (constructed basin).

Because there is a robust market for LTSCs (Bernat et al., 2020), the crediting disparity creates a profound disincentive for discharging water into an MUSF. This, in turn, disincentivizes jurisdictions from realizing the social, cultural, economic, and environmental benefits of effluent-based flows.

While the creation of an ADWR-sanctioned USF or MUSF confers benefits, it is not mandatory. Within the Santa Cruz AMA, effluent from the Nogales International Wastewater Treatment Plant (NIWTP) is discharged into a portion of the Santa Cruz River not designated as an MUSF (ADWR, 2020a). In-stream flows from NIWTP do not result in the award of groundwater withdrawal rights, unlike Pima County flows within MUSFs.⁴

In many respects, the GMA and associated water banking legislation have been a success. They are responsible for a management regime that, along with the delivery of CAP water, has led to a 3 meter average recovery in groundwater levels across the state’s AMAs — indeed, these are the *only* areas in the lower Colorado River Basin not to experience widespread decline in groundwater reserves (Scanlon et al., 2025). However, AMAs are large, and widespread recovery coexists with localized drawdowns (Davis, 2019b; Ferris & Porter, 2021; House, 2022; Post-2025 AMAs Committee, 2020).

These changes, coupled with local water conservation efforts, have reduced the formerly close association between urban growth and new groundwater demand. This is broadly true within the Tucson AMA, but especially true within the Tucson Water service area (Tucson Water, 2023, p. 44).

⁴ A cursory review of ADWR’s relevant GIS product (ADWR, 2023) finds no managed or constructed USFs anywhere in the Santa Cruz AMA, suggesting fundamental differences in the water markets or hydrologic systems than those seen in the neighboring Tucson AMA. The Santa Cruz AMA was originally part of the Tucson AMA, but became a separate jurisdiction in 1994 (ADWR, 2020b, ARS §45-411.03).

However, a generalized solution for localized groundwater decline is elusive if not impossible. Localized decline can occur because banked groundwater can be extracted from anywhere within the AMA where it was stored. Indeed, the recovery well does not even need to exist within the same subbasin of any given AMA. Because of this “hydrologic disconnect,” extraction-site groundwater levels can fall even as water is added to the aquifer elsewhere (Ferris & Porter, 2021; Post-2025 AMAs Committee, 2020). Writing for the *Arizona Daily Star*, Tony Davis (2019a, 2019b, 2019c) has documented various examples of local water table decline and factors that prevent easy solutions.

Other allowed uses of effluent in Arizona

In addition to groundwater banking, state code allows high-grade effluent to be used for various agricultural purposes. ADEQ grades effluent quality on a scale of A+ (highest quality) to C (lowest acceptable quality), as defined in 18 AAC 11. The largest WRFs in the study focus area, the Sahuarita and Green Valley WRFs, both produce grade A+ effluent (PAG, 2020b; PCRWRD, 2023).

Grade A effluent can be used for surface and spray irrigation (i.e., direct application) on food crops (18 AAC 11, 2023; WRRC, 2023). Arizona growers use roughly 119,000 AF of effluent a year, a volume equal to 20% of the state’s effluent production (WRRC, 2023). However, this amounts to only 2.3% of all water (including groundwater and other sources) used for irrigated agriculture in the state (WRRC, 2023).

The fraction of effluent used statewide for aquifer recharge is even less: only 17% (WRRC, 2023). However, in Pima County, the region’s largest producer of effluent (PCRWRD) uses nearly 70% of all effluent for groundwater recharge (PCRWRD, 2023). This is done mostly through in-channel releases, north of the project focus area, with a small amount done mainly through recharge basins. Indeed, the Middle Santa Cruz River is the only portion of the Santa Cruz River in Pima County where PCRWRD facilities do not perform in-channel discharges.

Arizona state law also allows the direct potable reuse of high-quality effluent, also known as “enhanced water purification and reuse” or “advanced water purification.”⁵ The state recently updated its rules governing direct reuse (ADEQ, 2025a).

⁵ The phrase “toilet to tap” has fallen out of favor.

Project origin and summary of work

This project was initiated in partial fulfillment of a US Bureau of Reclamation (USBR) Phase 1 WaterSMART grant to Sonoran Institute. Sonoran Institute wished to identify opportunities for riparian restoration on the MSCR (Cole, 2021). This project was informed by the SCWC Watershed Restoration Plan (WRP) (SCWC, 2022), and included various collaborative elements not described here. SCWC is a watershed collaborative group whose stated vision is “people working together to ensure a healthy urban watershed with flowing rivers and streams” (SCWC, 2022).

Sonoran Institute performed an initial conservation opportunity assessment that identified effluent-based in-channel flows as the most feasible and practical option for riparian restoration in the Middle Santa Cruz area. Such flows required the development of water budgets and design concepts, which the author of this paper developed. Work was performed under the supervision of Luke Cole, Santa Cruz River Program Manager at Sonoran Institute. Cole provided project constraints described above, including the need for effluent-based flows not to encroach upon tribally governed lands.

This report builds on that work, expanding it to include an additional design concept (Concept 4) as well as consideration of long-term factors affecting ongoing viability of effluent-based flows in Arizona. Phil Stoker, faculty at the School of Natural Resources and Environment at the University of Arizona, advised work on this report.

This report describes multiple concepts for effluent-supported in-channel flows on the MSCR. These concepts cover water budgets that might exist under scenarios. The project included an analysis of existing conditions, projecting future wastewater inflows and effluent production, identifying viable effluent outfall points, approximating the extent of surface flow under various outflow volumes, and, for the final concept, developing an implementation road map.

The preferred concept presented here, Concept 4, is influenced by research findings from existing effluent-based flows, work by restoration ecologists elsewhere in the Colorado River System, Arizona groundwater law, water banking regulations, current effluent delivery obligations, anticipated development and related planning documents, and regional conservation needs. This report introduces the concept of “linked, local, and leveraged” restoration networks, a framework for planning professionals that adapts best practices from restoration ecology. It uses language and concepts relevant to non-specialist project leaders and program managers.

Finally, this work considers how external factors might influence the success of effluent-dependent environmental restoration. Newly approved infrastructure projects provide recent price signals suggesting that heightened supply-demand imbalance has the potential to harm environmental outcomes on the Santa Cruz River system. The report identifies opportunities for new research and modified resource governance that may improve ecological outcomes.

Methods

Areas of study

As described in the introduction, land-use analyses consider both the “study focus area” and “project context area.” The former encompasses the Middle Santa Cruz River area, while the latter includes the SCWC planning area.⁶ The “study focus area” is defined so that it relates to an “opportunity search area” relevant to the original planning grant. Additionally, a “Middle Santa Cruz River Corridor” is used to examine land-use on either side of the river itself.

Working definitions for each spatial area are given in **Table 4**.

Study area	Description	Inclusion criteria	Exclusion criteria
Opportunity search area	Riparian habitat in and near the Middle Santa Cruz River	Watercourses in watersheds HUC 10-1505030106 and HUC 10-1505030107 and in subwatershed HUC 12-150503010405. Riparian areas corresponding to the above watercourses.	Lands and waters of the Tohono O'odham Nation. Land and water outside Pima County. Portions of HUC 12-150503010405 that lie west of Arivaca Junction.
Study focus area	Opportunity search area watersheds and their associated engineered and natural water systems	Opportunity search area watersheds and subwatersheds. Engineered and natural water systems within the above areas.	Lands and waters of the Tohono O'odham Nation. Portions of the HUC 10-1505030104 watershed lying west of the Arivaca Junction census designated place (CDP) or south of Pima County.
Project context area	Santa Cruz Watershed Collaborative planning area	HUC-10 watersheds that contain or convey surface flow into Pima County reaches of the Santa Cruz River. ^a	Outlying watershed HUC 10-1505030201.
Middle Santa Cruz River corridor	Roughly 1-mile-wide corridor centered on river channel	Lands located within the study focus area and lying within one-half mile of the Middle Santa Cruz River channel	None. (Note that tribally governed lands fall outside the defined inclusion criteria.)

Table 4. Spatial definitions. *a.* These include HUC 10-1505030104, HUC 10-1505030106, HUC 10-1505030107, HUC 10-1505030108, HUC 10-1505030109, HUC 10-1505030202, HUC 10-1505030203, HUC 10-1505030301.

⁶ Because the SCWC planning area is illustrated but not explicitly defined in the text of the organization’s watershed restoration plan (SCWC, 2022), I approximated the boundaries using HUC-10 watersheds (see **Section x**, Methods, for details). However, the SCWC planning area could also be given by the Upper Santa Cruz groundwater subbasin boundaries, which are essentially similar.

Scenario development

Water budgets for effluent-based flows depend upon the type or types of wastewater treatment (regional or subregional WRF) and service area population. Scenarios were developed to encompass a reasonable variety of options that reflect both current conditions (subregional facilities and current service-area populations), partial or full effluent availability, and the likelihood of a future regional facility as described by PCRWRD (2016).

These scenarios include current effluent availability from Green Valley WRF (GVWRF, present-day production, less existing delivery obligations, reviewed in the Discussion section), an intermediate scenario (full production output from GVWRF, or partial availability from a future consolidated regional facility), and full effluent availability from a consolidated regional facility. Long-term projections use a future date of 2045 for consistency with PAG 208 plan estimates.

Projections for the long-term, full-availability scenario informed two unique design concepts. All other scenarios informed only one design concept, yielding a total of four final concepts.

Outfall selection

Outfall location in individual concepts is based on WRF placement, effluent generation, and future build-out scenarios. Concept 1, 2, and 3 all rely solely on the existing outfall point at GVWRF. Concept 4 relies on the existing GVWRF as one outfall in a multi-outfall system.

Outfall selection is informed by a design constraint: the need to prevent effluent-based flows from encroaching tribally governed lands of the Tohono O’odham Nation. The current outfall point at GVWRF is located well upstream of tribal lands, is located along the mainstem MSCR, and serves a mid-sized WRF under existing conditions. The GVWRF is an ideal discharge point for the “current availability scenario, and also for the scenario that assumes full output from GVWRF.

Future growth introduces a strong rationale for consolidating subregional facilities into a single regional facility. Such a facility is a long-term planning goal for PCRWRD (2016).⁷

Under a build-out scenario with subregional WRF consolidation, a new regional facility would be located downgradient from the service area population. The lowest-elevation subregional WRF currently operating in the study focus area is the Sahuarita WRF (~2,580 ft elevation). This site is located along Pima Mine Road, which runs parallel the border between Sahuarita and Tohono O’odham nation. The study presumes that Pima Mine Road represents an approximate north-south alignment for a future regional WRF. This general location is also given in public-facing PCRWRD documents (PCRWRD, 2016).

The study assumes that PCRWRD would be responsible for a consolidated regional WRF: it operates subregional facilities in the project focus area, operates regional-scale facilities elsewhere in the project context area, and benefits from economies of scale.

The study further assume that consolidation would afford the ability to convey effluent upstream to the existing Green Valley WRF site. Upgradient conveyance for in-channel flows have already been deployed locally at the Santa Cruz River Heritage Project. Moreover, new wastewater mains would be necessary to transport Green Valley WRF inflows to a new regional facility. Depending on project constraints, pipeline for upstream effluent conveyance could conceivably be installed alongside this project. Finally, the Project Renews pipeline provides, if nothing else, a local proof-of-concept for upgradient conveyance in the study focus area.

This line carries CAP water upgradient from Pima Mine Road to FICO orchards, and when extended to Project RENEWS basins will cover almost the entire distance between a future regional WRF and the existing Green Valley WRF (**Fig. 22**). The siting of this line informs outfall selection for the Concepts 3 and 4, as well as the “partial availability / regional WRF” component of Concept 2.

⁷ Compared to subregional facilities, Pima County RWRD reports a greater fraction of wastewater flows converted into effluent. This efficiency introduces water savings that can help offset water use by riparian evapotranspiration, although Tucson Water reports evapotranspiration to be as low as 3.5% of total effluent released in-channel (Kmiec, 2021).

Concept 4 relies on multiple outfall points including the GVWRF outfall. Additional outfall points are located to align with specific conservation needs, such as barrier crossing points, historically watered reaches, and interruption of long, otherwise ephemerally flowing gaps on the watercourse.

Water budgeting and extent-of-flow calculations

Concepts for effluent-based flows required water budgets for various scenarios. For effluent availability under current conditions, the author used existing flow volumes. For future conditions, the author derived water budgets arithmetically by first calculating gallons per capita per day (GPCD) of current wastewater inflows to regional facilities to obtain a representational volume and then multiplying that figure by the relevant populations of WRF service or planning areas. Individual sources for individual figures are given in **Supplemental Material S1**. These sources include 208 Plan documentation by Pima Association of Governments (PAG, 2020a, 2020b, 2020c) as well as volumetric reporting by PCRWRD (2023, 2024). Surface flows extents result from a ratio of one mile flow per million gallons of effluent discharged per day. This ratio is based on regional experience with surface flows and expert consultation.

Spatial analyses

Existing condition analysis and other spatial characterizations result from standard GIS methods. A list of data sources is given in **Supplemental Material S2**.

Existing conditions: Population and environment

Population, economy, and location

The Middle Santa Cruz River flows across eastern Pima County. Here the river overlies the Tucson/Avra Valley Aquifer. Groundwater recharge occurs via infiltration of local and imported water sources. Local sources include mountainfront recharge via natural systems. Imported sources include Colorado River water delivered via the Central Arizona Project.

The study focus area includes the Town of Sahuarita, incorporated in 1994, and the community of Green Valley, an unincorporated census-designated place. The area did not experience marked residential growth until the 1960s in Green Valley. However, the study focus area remains characterized by ongoing agricultural land uses along the MSCR, especially the extensive pecan orchards owned and operated by Farmers Investment Company (FICO). Other major land uses in the study focus area include Freeport McMoRan and ASARCO mining operations.

The recent history of Pima County is characterized by population and economic growth. During this era, local water portfolios diversified, and the arrival of Colorado River Water via the Central Arizona Project has led to groundwater levels beginning to recover in some areas. Water resources in Pima County, Arizona afford the same benefits as those seen elsewhere on the Colorado River system — agricultural, industrial, municipal, tribal, recreational, and environmental. An overview of the regional population and economy is given in **Table 5**, and populations of incorporated communities in the broader project context area are given in **Table 6**. Community populations in the study focus are shown in given in **Table 7**, with their spatial distribution shown in **Fig. 15**.

Region	Population	GDP
Arizona ^{a, b}	7,582,384	\$522,767,200,000
Pima county population ^{c, d}	1,080,149	\$62,169,929,000

Table 5. Regional populations and GDP (2023). Sources: *a.* (US Census Bureau, 2024b). *b.* (Federal Reserve Bank of St. Louis, 2024a) citing (Woodruff et al., 2024) *c.* (US Census Bureau, 2024a) *d.* (Federal Reserve Bank of St. Louis, 2024b) citing (Hinson et al., 2024).

Incorporated communities	Population
Tucson	543,348
Marana	54,487
Oro Valley	47,595
South Tucson	4,601

Table 6. Incorporated community populations in the project context area (2023). Source: (US Census Bureau, 2024c).

Study focus area population centers

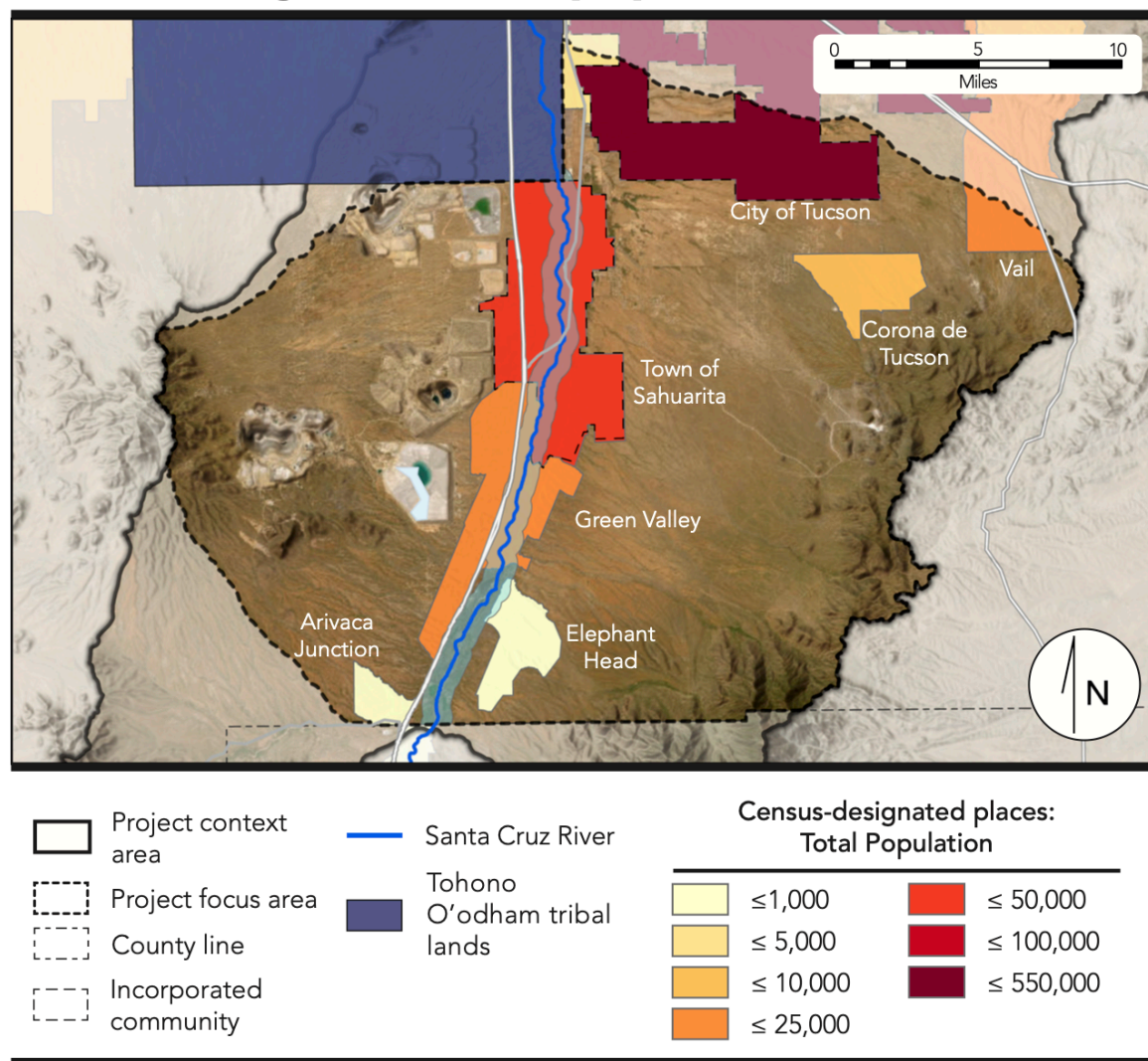


Figure 15. Population centers and their distribution across the study focus area. The incorporated limits of Tucson, a major population center in Southern Arizona, extend into boundaries of the study focus area. However, City of Tucson land within the study focus area is, compared to the rest of the city, either undeveloped or sparsely populated.

Study focus area communities ^a	Population
Sahuarita (incorporated town)	35,012
Green Valley (CDP)	21,581
Corona de Tucson (CDP)	9,039
Elephant Head (CDP)	572
Arivaca Junction (CDP)	650
CDP and town subtotal	66,854
Study focus area aggregate population^b	75,349

Table 7. Incorporated community, CDP, and aggregate populations for study focus area (2023). ^aPopulations are given only for towns or CDPs located entirely within the study focus area. Summit (CDP, population 4,410), Vail (CDP, population 15,722), and Tucson (incorporated city, population of 543,348), partially overlap the study focus area. ^bAggregate population is the sum of populations for all census tracts whose footprint overlaps that of the study focus area by at least fifty percent. Source: (US Census Bureau, 2024d)

Land use and land cover

Data derived from the Annual National Land Cover Database (NLCD) (USGS, 2024) show that the study focus area remains dominated by open lands, but with increasing development over the last several decades (**Fig. 16**, end of section). **Table 8** shows spatial extent of land cover in the study focus area in both absolute and fractional terms in 1985 and 2023. **Table 9** (next page) provides the same figures for a one-mile corridor centered on the MSCR.

Land cover	Land cover within study focus area				Change in land coverage, 1985-2023	
	1985		2023			
	Area (sq. mi)	Percent	Area (sq. mi)	Percent	Area (sq. mi)	Percent
Developed, open space	5.2	1.0%	13.0	2.6%	7.8	149.7%
Developed, low intensity	8.4	1.7%	15.9	3.1%	7.5	90.0%
Developed, medium intensity	2.0	0.4%	8.6	1.7%	6.6	322.3%
Developed, high intensity	0.1	0.0%	0.4	0.1%	0.2	185.1%
Any developed land	15.8	3.1%	37.9	0.1%	22.1	140.5%
Open water	0.4	0.1%	1.0	0.2%	0.6	142.4%
Barren land (rock/clay/sand)	13.2	2.6%	18.4	3.6%	5.2	39.0%
Evergreen forest	11.7	2.3%	10.0	2.0%	-1.7	-14.2%
Shrub/scrub	456.0	90.2%	430.5	85.2%	-25.5	-5.6%
Cultivated crops	7.4	1.5%	6.8	1.3%	-0.6	-8.7%
Undeveloped land	489.3	96.8%	467.2	92.4%	-22.1	-4.5%

Table 8: Land cover by year for 1985 and 2023. Categories with less than 0.1% coverage are omitted. Open water includes tailing ponds at mines and does not reflect riparian flows. Derived from NLCD annual data sets (USGS, 2024).

The study focus area contains approximately 4,900 acres of cropland, about 12% of all cropland in Pima County (USDA NASS, 2024). **Table 10** (next page) shows crop acreages for Pima County, the study focus area, and the MSCR corridor.

The Study context area spans two different level III ecoregions, Sonoran Basin and Range (lowlands) and Madrean Archipelago (highlands), subdivided into Level IV ecoregions as shown in **Fig. 17** (end of section). The spatial extent of Level III and Level IV ecoregions are given in **Tables 11** and **12**, respectively.

Land cover	Land cover within MSCR corridor				Change in land coverage, 1985-2023	
	1985		2023			
	Area (sq. mi)	Percent	Area (sq. mi)	Percent	Area (sq. mi)	Percent
Developed, open space	1.0	4.9%	1.9	9.1%	0.9	86.0%
Developed, low intensity	1.6	7.7%	2.3	11.2%	0.7	44.8%
Developed, medium intensity	0.6	2.7%	1.5	7.0%	0.9	161.7%
Developed, high intensity	0.0	0.0%	0.0	0.2%	0.0	331.8%
Any developed land	3.2	15.3%	5.8	27.5%	2.5	79.0%
Shrub/scrub	13.0	61.7%	10.7	51.0%	-2.3	-17.4%
Pasture/hay	0.3	1.4%	0.3	1.5%	0.0	3.6%
Cultivated crops	4.4	20.8%	4.1	19.6%	-0.3	-6.2%
Woody wetlands	0.1	0.5%	0.1	0.5%	0.0	-9.8%
Undeveloped land	17.8	84.5%	15.2	72.5%	-2.5	-14.2%

Table 9: Land cover by year for 1985 and 2023. Categories with less than 0.1% coverage are omitted. Open water includes tailing ponds at mines and does not reflect riparian flows. Derived from NLCD annual data sets (USGS, 2024).

Crop	Total acres planted (2023)		
	Pima County	Study focus area	1-mile corridor
Fallow/idle	16,554	17	5
Cotton	8,123	8	5
Alfalfa	6,161	126	103
Pecans	5,239	4,546	2,730
Corn	1,906	8	7
Barley	1,107	0	0
Durum wheat	1,101	1	0
Other hay/non-alfalfa	651	64	36
Oats	301	24	24
Oat/corn double crop	141	2	1
Triticale	131	0	0
Sorghum	129	115	74
Winter wheat	76	0	0
All other crops	59	2	1
Total	41,701	4,914	2,986

Table 10. Study area cropland for 2023, derived from data published by USDA National Agricultural Statistics Service (2024).

Level III Ecoregion	Project context area		Study focus area	
	Area (sq. mi)	Percent	Area (sq. mi)	Percent
Madrean Archipelago	917	46.1%	243	48.0%
Sonoran basin and range	1,072	53.9%	263	52.0%

Table 11. Level III ecoregion extent in project context area and study focus area.

Level IV Ecoregion	Project context area		Study focus area	
	Area (sq. mi)	Percent	Area (sq. mi)	Percent
Lower Madrean Woodlands	305	15.3%	49	9.8%
Madrean Basin Grasslands	123	6.2%	34	6.7%
Apachian Valleys and Low Hills	378	19.0%	158	31.2%
Madrean Pine-Oak and Mixed Conifer Forests	110	5.6%	2	0.3%
Arizona Upland/Eastern Sonoran Mountains	131	6.6%	—	—
Arizona Upland/Eastern Sonoran Basins	877	44.1%	263	52.0%
Gila/Salt Intermediate Basins	42	2.1%	—	—
Middle Gila/Salt River Floodplains	23	1.1%	—	—

Table 12. Level IV ecoregion extents in project context area and study focus area.

Land cover changes, 1985 to 2023

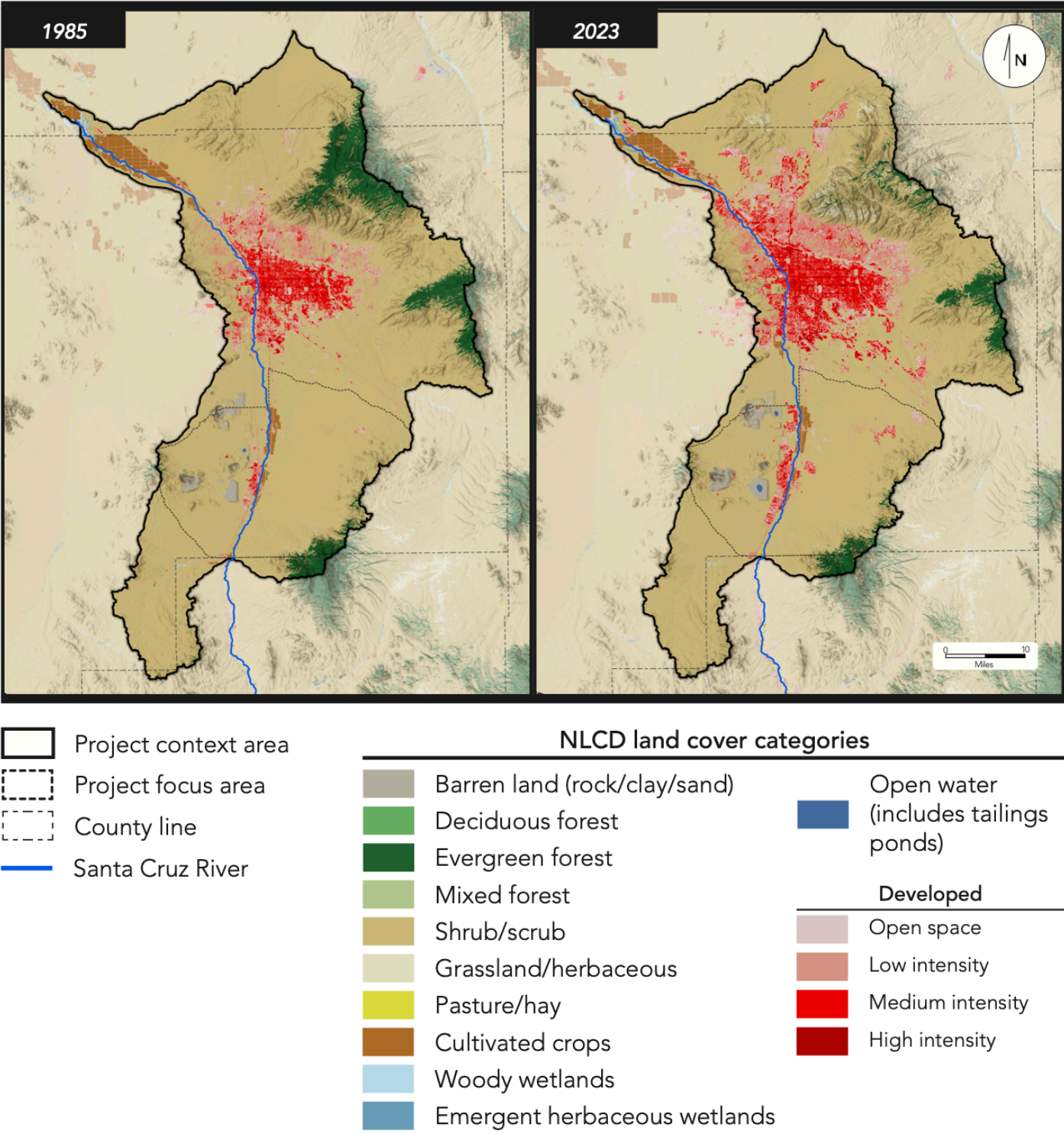
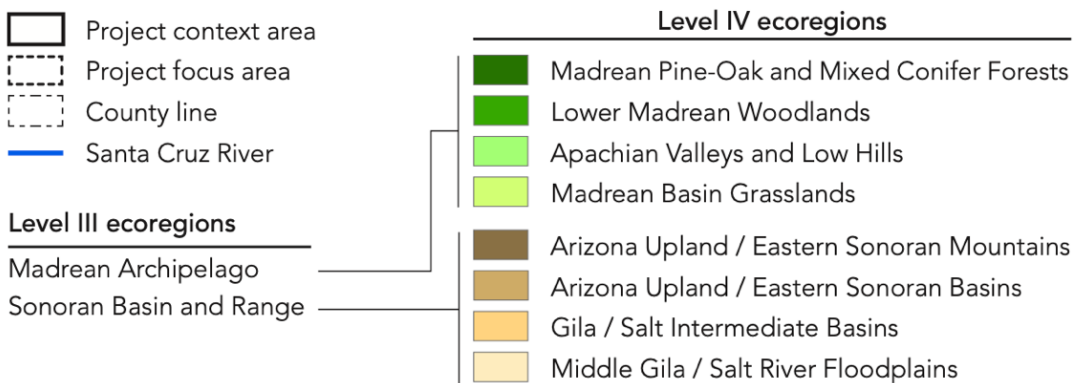
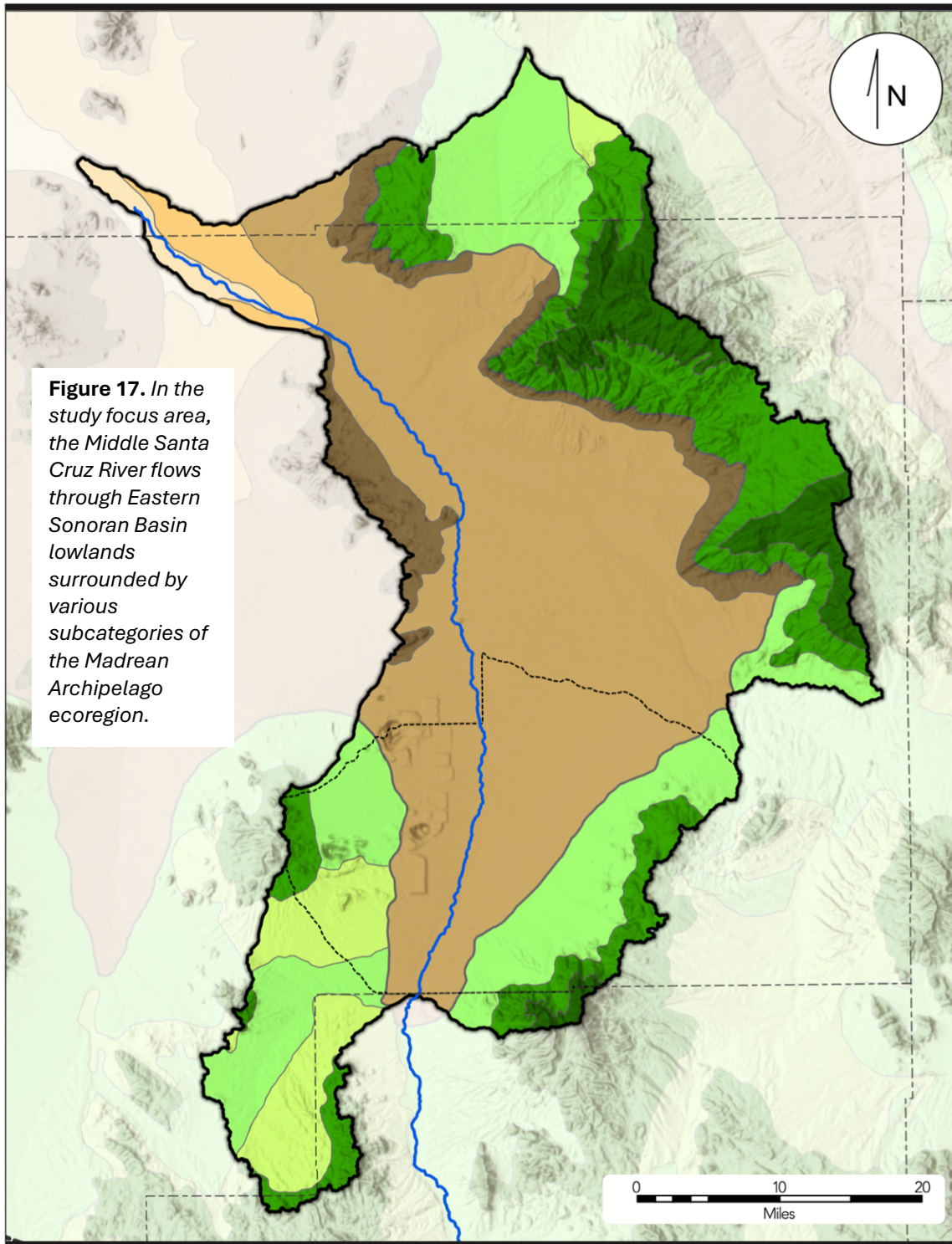


Figure 16. Changes in NLCD land cover classification extents for the project context area (1985-2023).

Ecoregions



Climate

30-year mean temperature and annual precipitation (1991-2020) from the nearby Green Valley weather station⁸ are 68.4° F and 12.85 inches (NCEI, n.d.-b). The average summer high temperature and winter low temperatures reported by the same dataset are 98.6°F and 37.1°F respectively (NCEI, n.d.-b). Additional 30-year mean data is reported in **Table 13**.

The Köppen climate classification system categorizes lowlands in the study area as a mix of BWh (hot arid climate) and BSh (hot semi-arid climate). The study focus area lies in or near the boundary between these two zones.

Mean annual temperature for the project context area is shown alongside the rest of the state in **Fig. 18**. Seasonal variations in precipitation patterns are evident both locally and statewide in **Fig. 19** (next page).

Mean annual temperature, 1991-2020

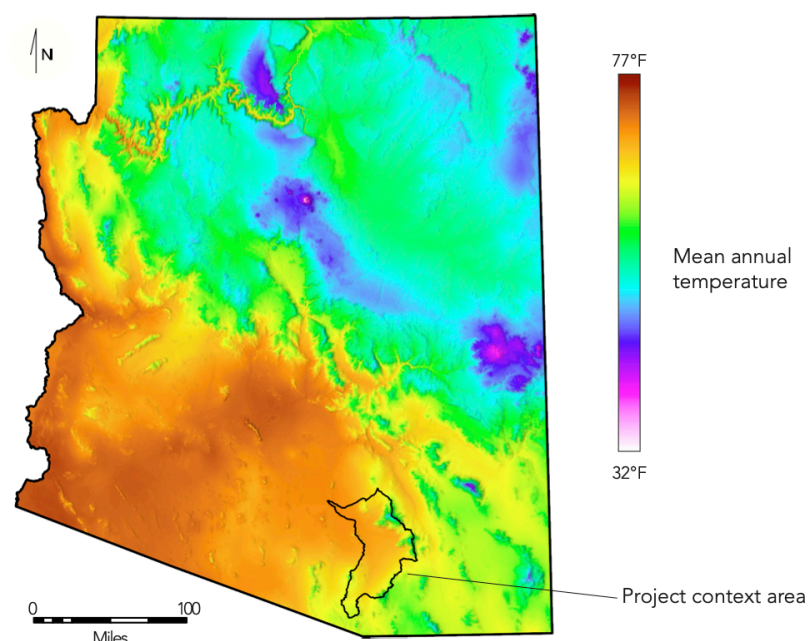


Figure 18 (above). The mean annual temperature for the project context area exceeds that of high-elevation regions elsewhere in the state, but generally remains cooler than the hyperarid southeast corner of the state.

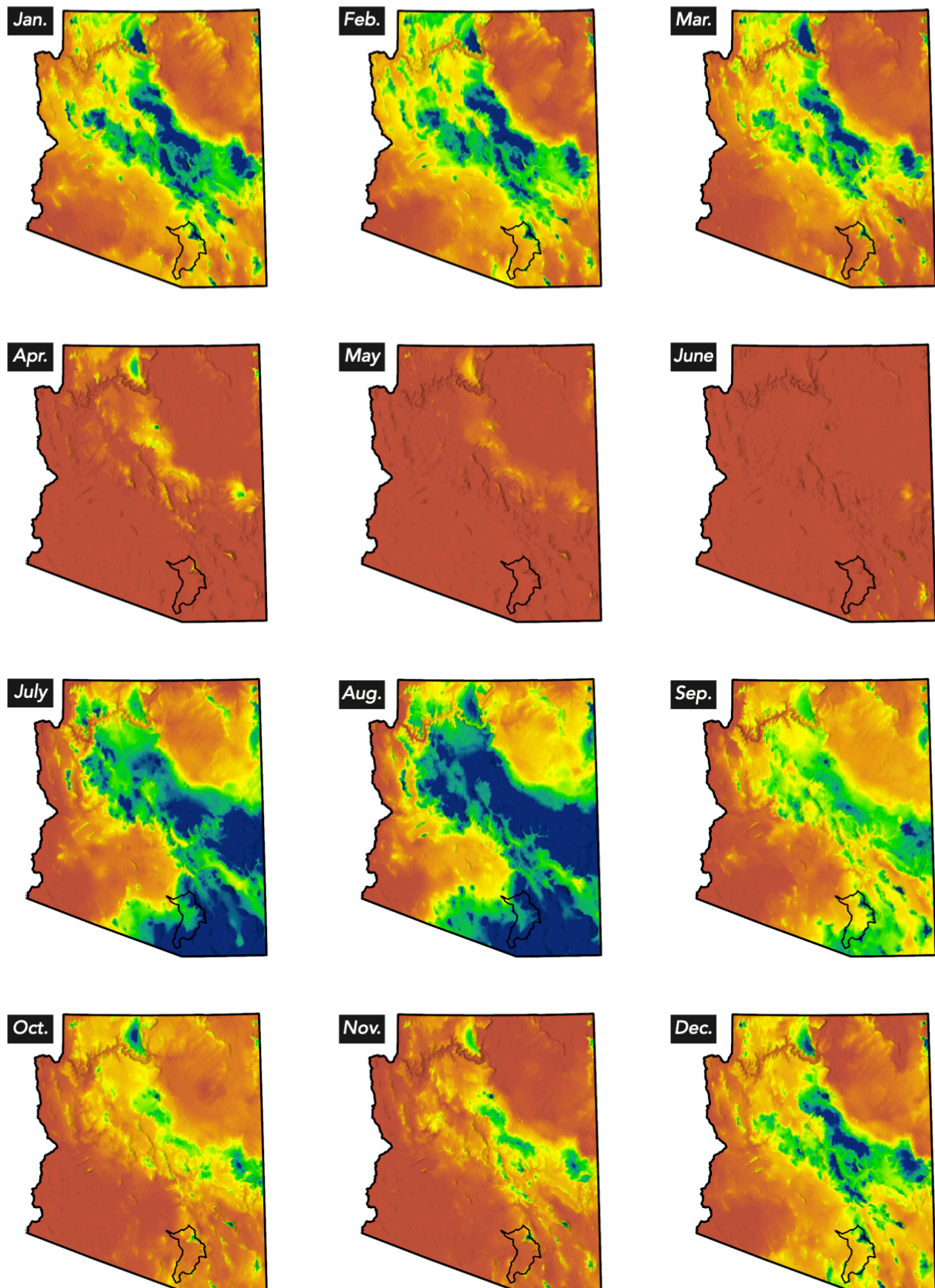
Figure 19 (next page). Seasonal precipitation patterns are apparent in month-to-month changes in mean precipitation. Monsoonal precipitation (which can vary considerably from year to year) is typically preceded by a late-spring and early-summer dry season.

Season	Maximum temperature (°F)	Minimum temperature (°F)	Average temperature (°F)	Precipitation (in.)	Snow (in.)
Winter	67.5	37.1	52.3	2.78	0.0
Spring	82.8	51.0	66.9	1.03	0.1
Summer	98.6	70.3	84.5	5.99	0.0
Autumn	88.5	54.7	70.1	3.05	0.0
Annual	83.6	53.3	68.4	12.85	0.1

Table 13. Annual mean weather data for study focus area (NCEI, n.d.-b).

⁸ Weather station USC00023668 (NCEI, n.d.-a)

Mean monthly precipitation, 1991-2020



0 200
Miles

Mean monthly precipitation
 ≤ 0.5 in. ≥ 3.0 in.



Project context area

The Colorado River Basin has experienced persistent drought since 2000 (USGS, 2023), complicating water management. Pima County has experienced the basin-wide drought at varying intensity over the years, including a handful of years where drought was locally absent (**Fig. 20**).

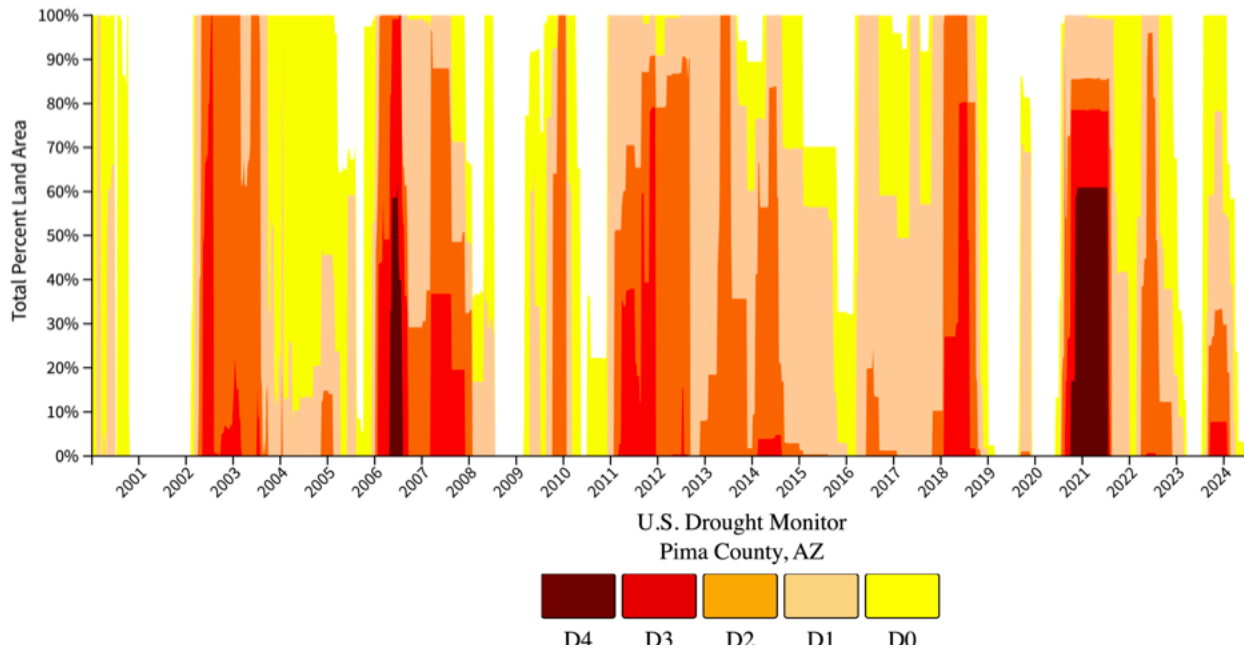


Figure 20. Persistence, extent, and severity of drought conditions in Pima County since 2000 (NIDIS, 2024). Drought severity varies between D0 (least intense drought) and D4 (most intense drought).

Existing conditions: Water infrastructure

Water infrastructure: Reclaimed sources

The study focus area is currently served by several subregional wastewater reclamation facilities (WRFs): Sahuarita WRF, Green Valley WRF, Corona de Tucson WRF, and Arivaca Junction WRF (**Fig. 21**). These WRFs collectively produce roughly 3,500 AF/yr of effluent, delivered or recharged as groundwater as shown in **Table 14**. We compare these to the regional WRFs elsewhere in the study context in **Table 15**. Sahuarita WRF is operated by the Town of Sahuarita; all others are operated by PCRWRD.

Wastewater reclamation facilities and service areas

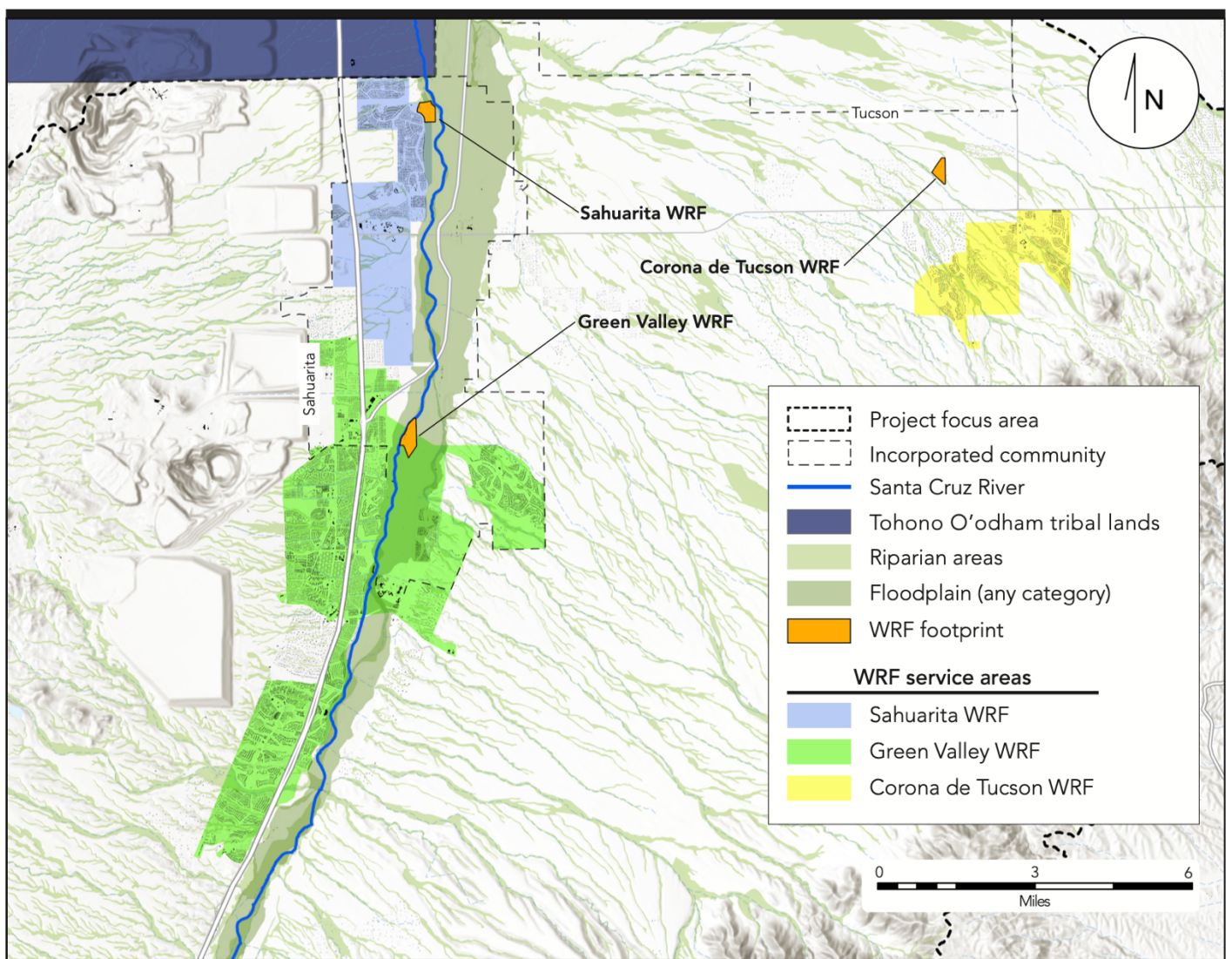


Figure 21. WRF service areas and facility footprints. Note that the service area footprints do not necessarily follow jurisdictional boundaries. While the Sahuarita WRF, a municipal facility, serves portions of the Town of Sahuarita, other parts of Sahuarita are served by Green Valley WRF, a Pima County RWRD facility.

Green Valley WRF			
Permitted capacity (MGD) and quality:	4.1 MGD (total) 2.8 to BNROD system (A+) 1.3 to lagoon/pond system (B)	2023 inflow (AF): 2023 effluent production (AF): Production ratio:	2,255.72 2,073.75 0.92
Effluent use:	Delivered to recharge basins		

Sahuarita WRF			
Permitted capacity and quality:	3.0 MGD (A+)	2023 inflow (AF): 2023 effluent production (AF): Production ratio:	1,142.80 1,028.50 0.90
Effluent use:	Delivered to recharge basins		

Corona de Tucson			
Permitted capacity and quality:	1.3 MGD (Unk.)	2023 inflow (AF): 2023 effluent production (AF): Production ratio:	482.25 428.66 0.89
Effluent use:	Delivered to recharge basins		

Arivaca Junction WRF			
Permitted capacity and quality:	0.1 MGD (C)	2023 inflow (AF): 2023 effluent production (AF): Production ratio:	39.73 25.40 0.64
Effluent use:	Agricultural deliveries (14.18 AF) and recharge in non-USF basins (11.20 AF)		

Table 14. Permitted capacities and current effluent production for wastewater reclamation facilities in the study focus area. Sources: (PAG, 2020a, 2020b, 2020c; PCRWRD, 2023)

Agua Nueva WRF			
Permitted capacity and quality:	35.2 MGD (A+) (Upgradable to 48 MGD)	2023 inflow (AF): 2023 effluent production (AF): Production ratio:	27,061.46 25,028.82 0.92
Effluent use:	"Purple pipe" reclaimed water deliveries (18,125.66) and delivery to Sweetwater Wetlands USF or in-channel flows via SCRUMUSF (6,795.69), on-site reuse (107.42 AF)		

Tres Rios WRF			
Permitted capacity and quality:	50 MGD (A+)	2023 inflow (AF): 2023 effluent production (AF): Production ratio:	34,048.41 32,771.50 0.96
Effluent use:	In-channel flows via LSCRMRP (32,732.73 AF), on-site re-use (1.02 AF), reclaimed deliveries (37.75 AF)		

Combined regional WRF capacity (Agua Nueva and Tres Rios)			
Permitted capacity and quality:	85.2 MGD (A+) (Upgradable to 98 MGD)	2023 inflow (AF): 2023 effluent production (AF): Production ratio:	61,109.87 57,800.32 0.95
Effluent use:	As described above.		

Table 15. Permitted capacities and current effluent production for regional WRFs in the project context area. Sources: (PAG, 2020b; PCRWRD, 2024; Water Collaborative Delivery Association, 2018)

At all WRFs in the project focus area except for Arivaca Junction, effluent is mainly converted to groundwater via infiltration of constructed basins in a USF. Some of the relatively small amount of effluent produced at Arivaca Junction is delivered to an infiltration basin not designated as a USF, and another fraction is delivered to a third party for agricultural use.

Water infrastructure: CAP delivery

This study focus area is sited at the terminus of the CAP delivery system. Conveyance infrastructure connected to the CAP system allows delivery of Colorado River water into the study focus area (**Fig. 22**, next page). The Project Renews / FICO pipeline extends south from the CAP canal into FICO orchards located within a groundwater savings facility (GSF). The relevance of this pipeline is discussed earlier in the “Methods” section, where it informs selected outfall locations.

CAP delivery on Middle Santa Cruz River

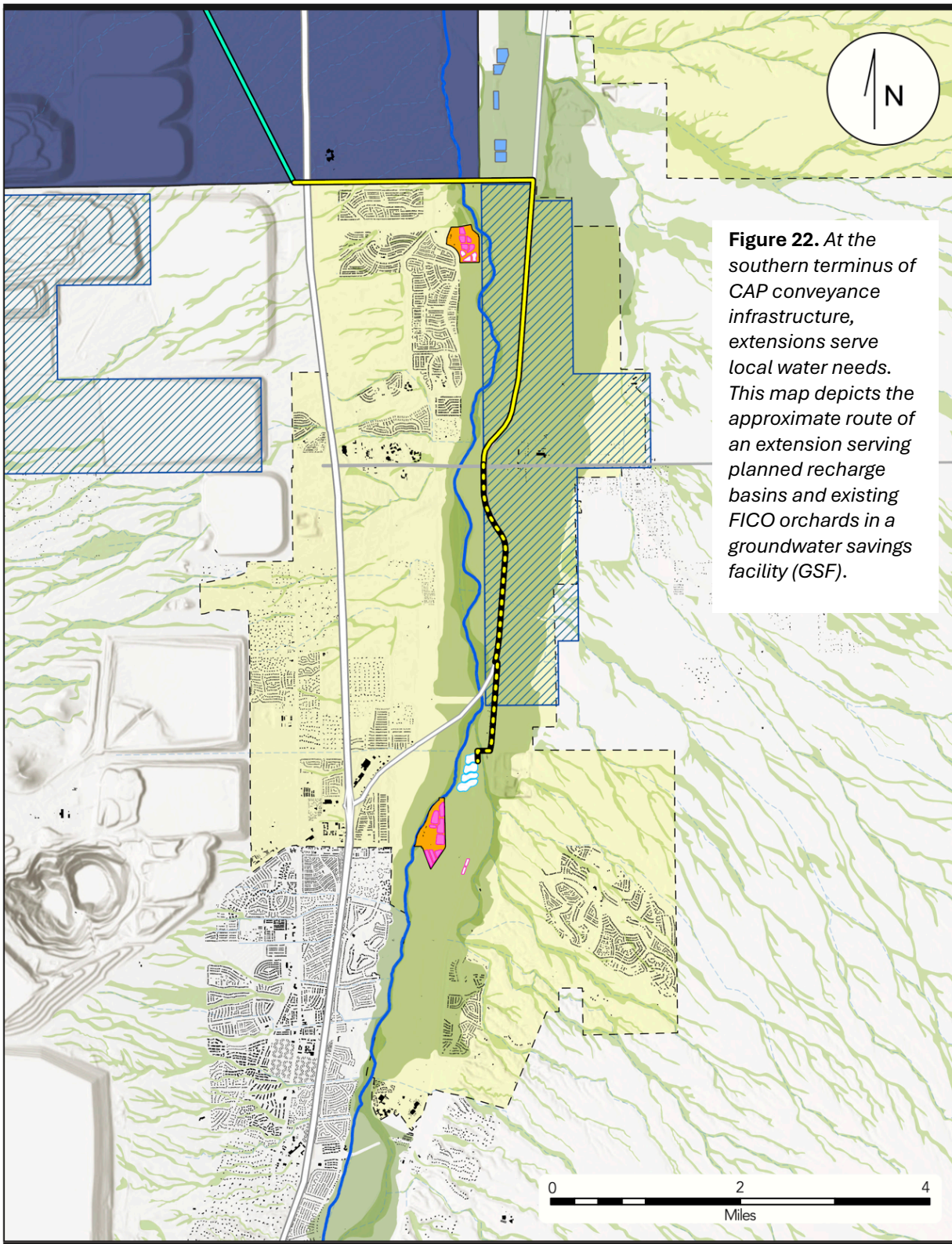


Figure 22. At the southern terminus of CAP conveyance infrastructure, extensions serve local water needs. This map depicts the approximate route of an extension serving planned recharge basins and existing FICO orchards in a groundwater savings facility (GSF).

- | | | |
|-----------------------------|------------------------------------|--|
| Project focus area | WRF footprint | Groundwater savings facility |
| Incorporated community | Recharge basin (effluent) | Central Arizona Project (CAP) |
| Tohono O'odham tribal lands | Recharge basin (CAP water) | Project Renews / FICO extension (approximate) |
| Santa Cruz River | Planned recharge basin (effluent) | Project RENEWS / FICO extension (approximate, planned) |
| Riparian areas | Planned recharge basin (CAP water) | |
| Floodplain (any category) | | |

Projected conditions

Planning context

As part of the conservation opportunity search, we reviewed planning documents and studies relevant to local water systems. Major documents reviewed include the Sahuarita Farms Specific Plan (FICO et al., 2015), PCRWRD facility plan (PCRWRD, 2016), Sahuarita comprehensive plan (Town of Sahuarita, 2022), and the Pima County comprehensive plan (Pima County, 2015).

Broadly, relevant planning documents emphasize the centrality of the Santa Cruz River itself as an essential cultural, recreational, and environmental resource. Existing land use plans suggest that stakeholders will likely realize the greatest benefits if conservation is implemented on the mainstem of the river instead of tributaries.

Additionally, in-channel discharge on the mainstem Santa Cruz River (sufficiently upstream of Tohono O’odham lands) presents the most straightforward opportunity for in-channel discharge. Land ownership here is minimally fragmented, which greatly simplifies the process of pre-project consultation.

The PCRWRD facility plan (PCRWRD, 2016) suggests the likelihood that PCRWRD will eventually consolidate existing subregional WRFs into a regional facility located in the vicinity of Pima Mine Road. Additional information is given in the portion of the Methods section regarding outfall point selection.

Projected effluent availability

Production volumes and service-area population estimates published in PAG’s 208 Plan (PAG, 2020b) show a per capita wastewater generation of roughly 60 gallons per capita per day (GPCD) for study focus area WRFs shown in **Table 16**. Note that WRF service area boundaries do not correspond with jurisdictional boundaries. WRF service area populations therefore differ that from those of their namesake municipalities or census-designated places. We omit the smallest WRFs from this analysis due to the potential for small absolute errors in service area population estimates to disproportionately affect per capita wastewater flows.

Facility	Population (2015)	Inflow (AF)	Inflow (MGD)	Per-capita wastewater (GPCD)
Sahuarita WRF	14,494	1,008	0.90	62.1
Green Valley WRF	31,488	2,061	1.84	58.4

Table 16. Per-capita wastewater flows for the largest WRFs in the study focus area, derived from figures published by PAG (2020b).

Estimated water budgets are based on the 60 GPCD wastewater inflows, service planning area population projections reported in the PAG 208 plan, and a facility appropriate inflow-to-outflow ratio. For a regional build-out scenario with facility consolidation, population estimates are the sum of those published for relevant service planning areas. Projected populations and effluent productions are given in **Table 17**.

Service area	Service or planning area footprints in projected population	Projected population (2045)	Projected inflows (2045, MGD)	Projected effluent production (2045, AF)
Green Valley WRF	Green Valley FPA	48,997	2.95	3,027
Regional WRF	Green Valley FPA, Corona de Tucson FPA, Sahuarita DMA, Joint Planning Area DMA	105,639	6.34	6,745

Table 17. Population and effluent production scenarios used in concept development. FPA: Facility planning area. DMA: Designated management agency. Figures derived from those published by PAG (PAG, 2020b).

Restoration concepts

Overview of concepts

We developed restoration concepts representing four different effluent availability scenarios (**Table 18**). These concepts encompass a mix of near-term and long-term timescales. Some can be implemented under current conditions, others require (and leverage) plans for future infrastructure investments. The particulars of each concept are discussed in greater detail in the sections below.

Concepts that envision the retirement of subregional WRFs and the consolidation of their operations into a regional WRF envision the use of conveyance infrastructure transporting effluent to outfall points where flow would not encroach upon tribal lands. This is necessary due to the likely proximity of a regional WRF to tribal lands.

Concept	Scenario overview	Description	Timeframe	Effluent volume (AF/yr)	Extent of flow (mi)
1	Current GVWRF availability	Present day production from Green Valley WRF, minus existing delivery obligations, discharged from current GVWRF outfall	Near term	873.75	0.78
2	Intermediate	Full production output from Green Valley WRF discharged from GVWRF outfall, or partial effluent production from future regional facility, conveyed to and discharged from GVWRF outfall	Intermediate (2025-2045)	3027	2.7
3	Full future availability	Full production output from regional WRF, conveyed to and discharged from current GV WRF outfall point	Far future (~2045)	6745	6.0
4	Full future availability	Full production output from regional WRF, conveyed to a distributed distribution system with multiple outfall points	Long-term (~2045)	6745	Roughly six miles, distributed across multiple outfalls

Table 18. Overview of concept parameters.

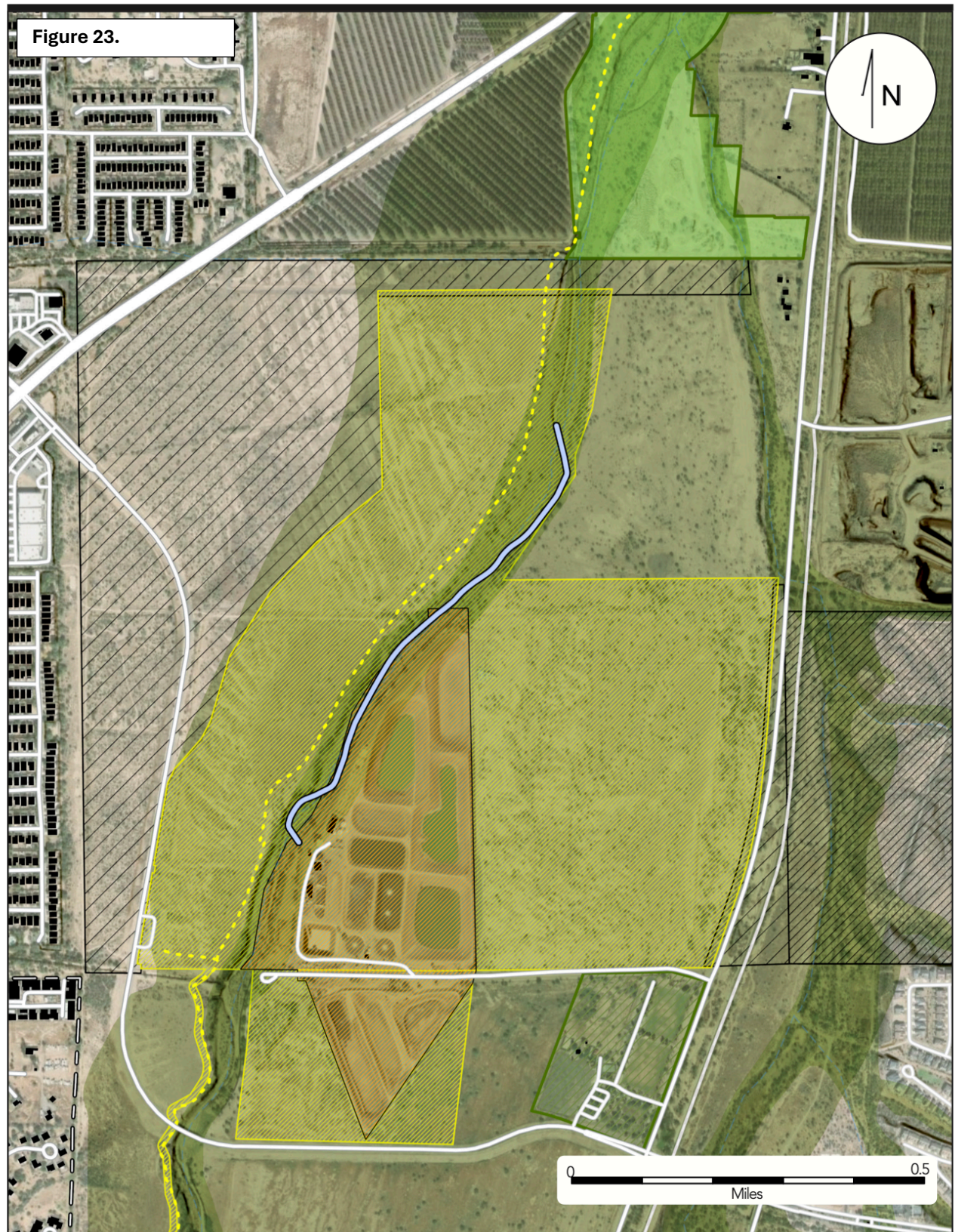
Concept 1

Concept 1 presents a vision for 0.78 miles of surface flow in the MSCR originating from the outfall at GVWRF (**Fig. 23**, following section text). It is designed to be implemented under current conditions. In-channel discharge volumes are derived from current effluent availability at Green Valley WRF, i.e., current effluent capacity less delivery obligations.

This fraction of effluent is currently delivered to PCRWRD recharge basins on site at GVWRF. Because Concept 1 relies on the existing GVWRF outfall point for effluent generated by that facility, no major, new physical infrastructure is required. Implementation requires (a) completion of hydrological studies by PCRWRD necessary to for MUSF designation, (b) MUSF approval by ADWR, and (c) PCRWRD acquisition of a new or modified APP from ADEQ.

The assumptions used in this study project a flow extent of less than one mile. Riparian recovery along this stretch would add value to county-owned lands on the west bank of the Santa Cruz River (opposite GVWRF). The Juan Bautista de Anza National Historic Trail (NHT) has already been completed in this area.

Concept 1: Current availability, Green Valley WRF



- | | | |
|---------------------------------|------------------------------------|--|
| [] Incorporated community | [] Other Pima County parcels | [] Modeled extent of surface flow |
| [] Tohono O'odham tribal lands | [] State trust parcels (unleased) | [] Juan Bautista de Anza National Historic Trail (planned and completed segments) |
| [] Riparian areas | [] State trust parcels (leased) | |
| [] Floodplain (any category) | | |
| [] SDCP CLS lands | | |
| [] WRF footprint | | |

Concept 2

Concept 2 presents a vision for 2.7 miles of surface flow in the Santa Cruz River originating from the outfall at GVWRF (**Fig. 24**, following section text). The modeled extent of flow is derived from a volume of water representing the full production of effluent at GVWRF. It can be implemented under near- to intermediate-term future conditions in which obligated physical deliveries of effluent from GVWRF have been retired or met through alternate means.

Alternate fulfillment of delivery obligations includes the transfer of LTSCs under the state water banking framework, as opposed to the physical transfer of effluent itself. PC RWRD would accrue LTSCs by recharging groundwater through the environmental flows described here. As with Concept 1, these conditions would require PC RWRD to construct no new major infrastructure, as the effluent discharged from the GVWRF outfall would be generated on site.

The extent of flow shown in Concept 2 is also representative of longer-term future conditions (circa 2040) wherein multiple subregional WRFs serving MSCR-area communities have been consolidated into a regional WRF, but only a portion of the overall facility output is available for in-channel recharge. Due to the distance between the GVWRF outfall and a regional WRF, PCRWRD would be required to construct, purchase, or lease conveyance infrastructure under these circumstances.

Under this scenario, inflows from GVWRF's current service area would be processed at a new regional WRF near Pima Mine Road. This would require construction of a new sewer main to move these wastewater inflows downgradient to Pima Mine Road. If conveyance infrastructure could not be leased or purchased, PC RWRD may be able to realize cost savings by constructing an effluent distribution system along the same right-of-way and at the same time as new downgradient mains.

The benefits of riparian restoration accrue across a greater spatial extent than those shown in Concept 1. At this scale, in-channel flows are no longer an isolated feature near the WRF, but a characteristic amenity of this stretch of the MSCR.

As with Concept 1, riparian habitat would develop alongside the planned Juan Bautista de Anza NHT on the west bank of the MSCR. The modeled extent of flow extends downstream beyond previously acquired Pima County CLS, underneath the South Nogales Highway crossing, and a reach that runs through FICO-owned pecan orchards on both the east and west sides of the river.

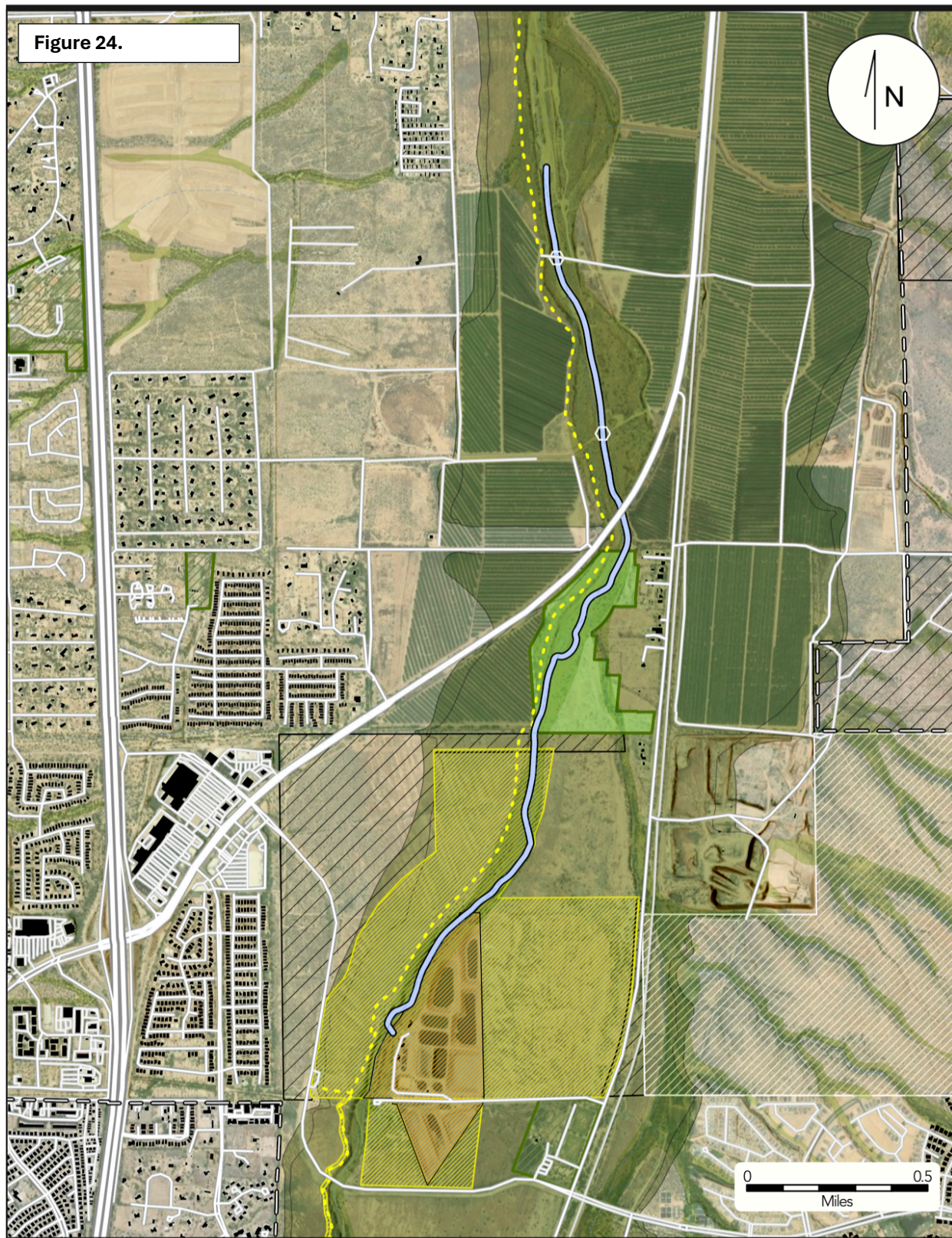
The Sahuarita Farms Specific Plan (FICO et al., 2015), approved by the Town of Sahuarita, is a guiding document that envisions future land-use conversions along portions of the river north of the Old Nogales Highway crossing. The plan calls for the preservation of open

space along a river park, bordered by mixed-use activity centers along existing arterial roads.

Implementation requirements for Concept 2 include all those required for Concept 1, as well as consultation with FICO on matters including in-channel crossing points between orchards on the east and west sides of the river. Long-term operation under a regional consolidation scenario would require PCRWRD to construct or acquire effluent conveyance infrastructure upon cessation of GVWRF operations. This concept also requires PCRWRD to consult with contract holders receiving physical delivery of GVWRF effluent and determine the best route forward.

Concept 2: Intermediate future availability

Figure 24.



- | | | |
|---------------------------------|---|--|
| [] Incorporated community | [] Recreational parcels outside SDCP CLS | [] Modeled extent of surface flow |
| [] Tohono O'odham tribal lands | [] Other Pima County parcels | [] Unbridged crossing |
| [] Riparian areas | [] State trust parcels (unleased) | [] Juan Bautista de Anza National Historic Trail (planned and completed segments) |
| [] Floodplain (any category) | [] State trust parcels (leased) | |
| [] SDCP CLS lands | | |
| [] WRF footprint | | |

Concept 3

Concept 3 presents a vision for 6.0 miles of surface flow in the Santa Cruz River (**Fig. 25**, following section text). The modeled extent of flow represents an effluent volume derived from combined wastewater inflows under a regional consolidation scenario (circa 2040). It can be implemented under a long-term timeframe wherein current WRF operations are consolidated at a single regional WRF constructed near Pima Mine Road.

As with Concept 2, this concept assumes obligated physical deliveries of effluent from GVWRF can be retired or met through alternate means, such as transfer of LTSCs as described above.

Because a regional WRF would also process wastewater from the area currently served by the Town of Sahuarita's municipal facility, Concept 3 further assumes that PC RWRD and Town of Sahuarita will reach an agreement regarding LTSCs accrued from groundwater recharge taking place via in-channel environmental flows in an MUSF. Depending on specific needs and circumstances identified by both parties, the existing intergovernmental agreement between Pima County and City of Tucson may be a useful point.

In addition to consolidating GVWRF and Sahuarita WRF service areas, a regional WRF would likely also process wastewater inflows currently sent to Corona de Tucson and Arivaca Junction WRFs.

Effluent from Corona de Tucson is currently converted to groundwater via soil infiltration in constructed basins with resulting LTSCs allocated according to the above-mentioned intergovernmental agreement. The existing cooperative framework and current deployment of effluent-based environmental flows suggest that both the city and county are amenable, at least in theory, to the concept of environmental flows using the effluent fraction originating from the Corona de Tucson service area.

Although effluent from the Arivaca Junction WRF is currently delivered to agricultural users, PC RWRD planning documents contemplate the possibility that these deliveries may not be accepted in the future (PCRWRD, 2016). PC RWRD also sends a fraction of the effluent from Arivaca Junction to an infiltration pond. However, the facility is located just outside the Tucson AMA (in the Santa Cruz AMA), has no associated USF or MUSF, and accrues no LTSCs.

For reasons described above, including the desire to avoid the extent-of-flow encroachment onto the Tohono O'odham Nation's tribally governed lands, Concept 3 envisions effluent discharge via the existing outfall at GVWRF. This requires construction or acquisition of conveyance infrastructure to move effluent from a regional facility at Pima

Mine Road to the GVWRF outfall. Relevant considerations described in Concept 2 apply here as well.

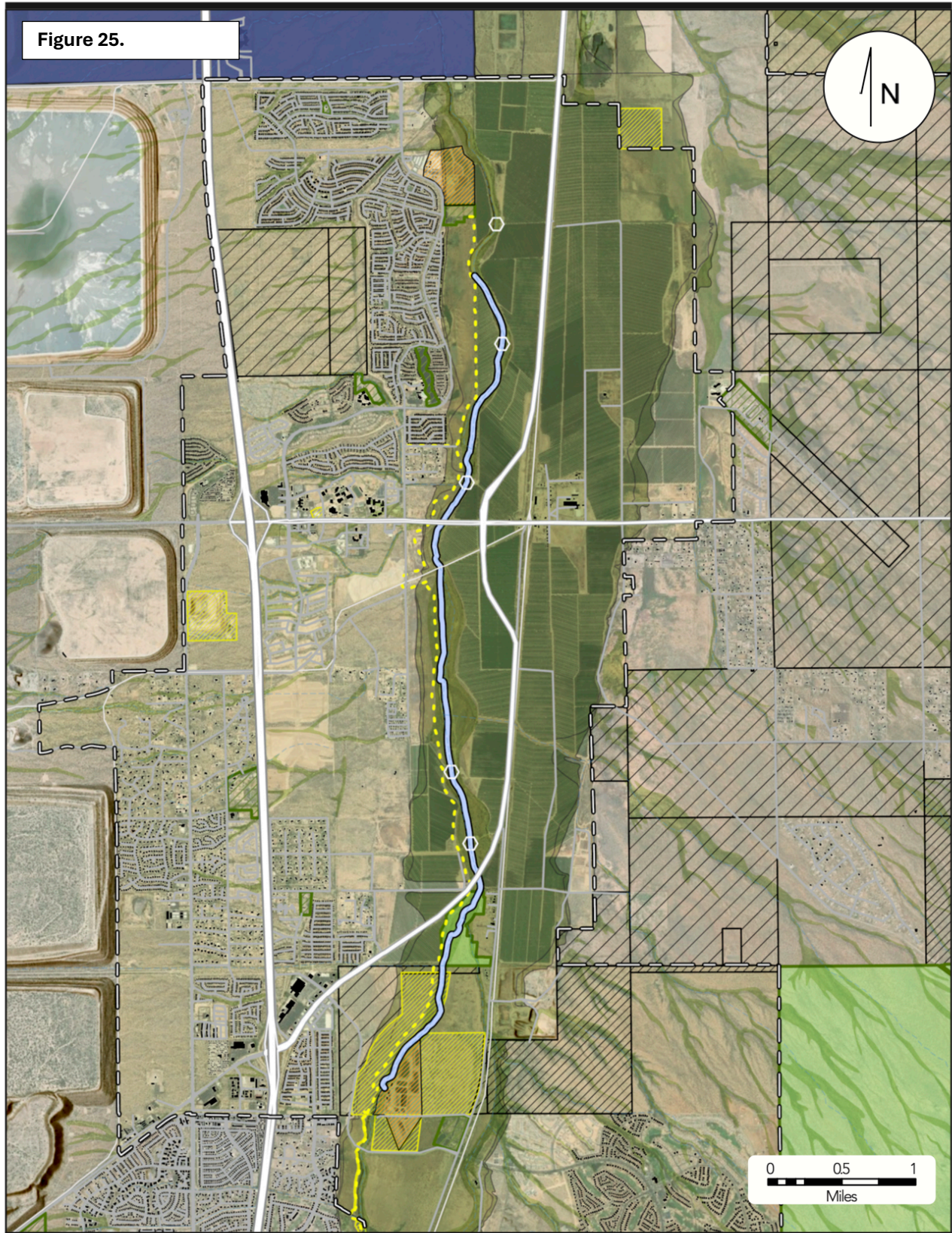
This concept is developed to provide the greatest length of contiguous streamflow, which can result in greater diversity of invertebrate species on downstream reaches. Low-quality effluent favors pollution-tolerant with pollution-tolerant taxa (Mor et al., 2019; citing Arce et al., 2014; Ortiz & Puig, 2007). Researchers have previously observed this phenomenon on effluent-dependent reaches of the Santa Cruz River downstream of NIWTP, with greater diversity of invertebrate taxa observed at increasing distance from the outfall point (Boyle & Fraleigh, 2003). Subsequent upgrades to NIWTP have greatly improved overall chemical indicators of water quality, but the study also reported that water temperatures were greatest near the outflow and decreased as distance downstream increased (Boyle & Fraleigh, 2003). This may benefit temperature-sensitive species.

The modeled extent of surface flow in Concept 3 extends downstream well into FICO Sahuarita orchards. At this scale, riparian flow characterizes not just individual reaches on the MSCR, but also the MSCR valley itself. As with Concept 2, planning documents identify these lands for future conversion into residential and mixed-use space, with natural and open space reserved along the river. The benefits described and attributes described in Concepts 1 and 2 accrue here as well. The issues with unbridged crossings identified in Concept 3 apply here to a greater number of points.

Implementation of Concept 3 requires all actions described for Concept 2. It also requires PC RWRD to consult with the Town of Sahuarita and City of Tucson on the distribution of LTSCs accrued by groundwater recharge using effluent from the Sahuarita and Corona de Tucson WRFs, respectively.

Concept 3: Full production from regional WRF

Figure 25.



- | | | |
|---------------------------------|---|--|
| [] Incorporated community | [] Recreational parcels outside SDCP CLS | [] Modeled extent of surface flow |
| [] Tohono O'odham tribal lands | [] Other Pima County parcels | [] Unbridged crossing |
| [] Riparian areas | [] State trust parcels (unleased) | [] Juan Bautista de Anza National Historic Trail (planned and completed segments) |
| [] Floodplain (any category) | [] State trust parcels (leased) | |
| [] SDCP CLS lands | | |
| [] WRF footprint | | |

Concept 4

Concept 4 presents a vision for roughly six miles of surface flow in the Santa Cruz River distributed across multiple outfalls (**Fig. 26**, at right). Like Concept 3, the modeled extent of flow represents an effluent volume derived from combined wastewater inflows under a regional consolidation scenario (circa 2040). However, rather than being designed to achieve maximum contiguous extent of flow, Concept 4 is designed to maximize the magnitude and spatial extent of restorative benefits by using a linked network of smaller-scale environmental flows. These smaller-scale flows take advantage of existing recreational and conservation resources.

Again, as with Concept 3, it can be implemented under a long-term timeframe wherein current WRF operations are consolidated at a single regional WRF constructed near Pima Mine Road. The same considerations regarding LTSC crediting from areas currently served by Corona de Tucson and Sahuarita WRFs apply to Concept 4 as well.

As with Concept 2 and 3, Concept 4 also assumes obligated physical deliveries of effluent from GVWRF can be retired or met through alternate means, such as transfer of LTSCs as described above.

Concept 4 envisions outfalls and discharge volumes at the locations described below in **Table 19** (next page).

The distributed outfall system is designed to allow Concepts 1 and 2 to serve as initial flows in a phased implementation.

Concept 4: Full effluent production from regional WRF, distributed outfall system

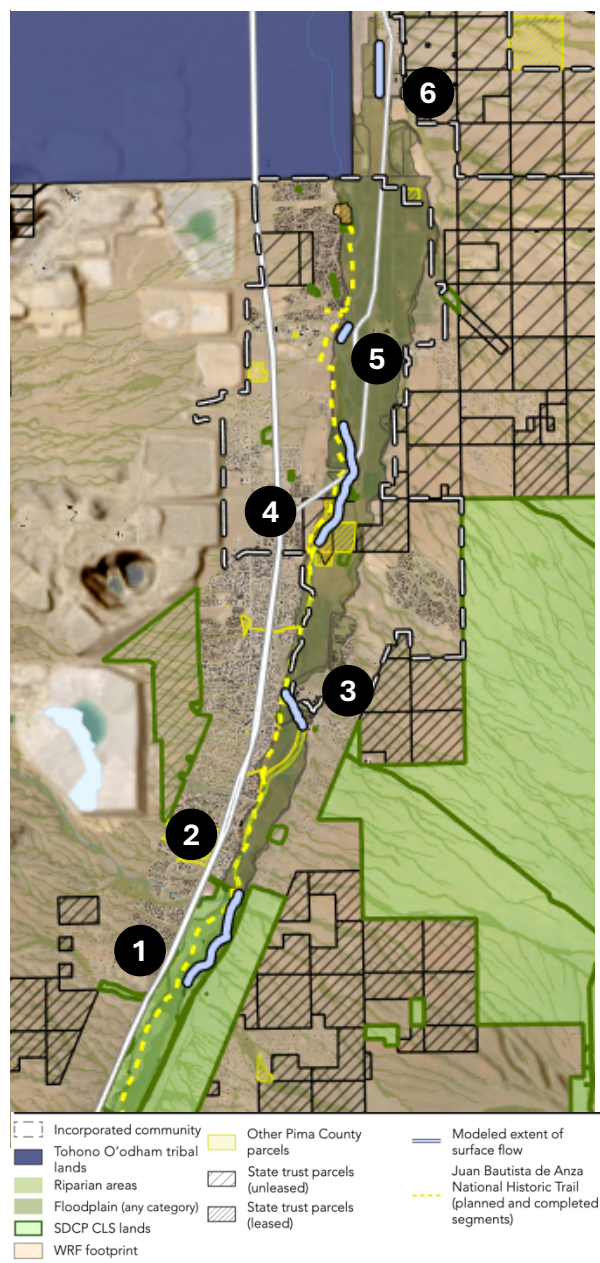


Figure 26. Concept 4 presents a design for a distributed outfall system. Overlaid numbers correspond to the outfalls in **Table 19**.

No.	Outfall name	Description
1.	Madera Canyon	Good upland connectivity via Madera Canyon Wash. Located on Canoa Ranch (existing conservation lands). Somewhat close to Demetrie Wash, which has a bridged crossing of I-19. Assume 2000 AF/yr discharged from upstream outflow point, augmented by and joining with a low-volume outflow located downstream, off Camino de la Canoa, opposite of Demetrie Wash.
2.	Camino de la Canoa / Demetrie Wash	A low-volume outflow (200-500 AF/yr), perhaps capable of supporting a small stand of cottonwoods and 100 yards of reliable flow. Camino de La Conoa is on the opposite bank of the Demetrie Wash / MSCR confluence. Demetrie Wash carries high peak flows, so it is large and has a bridged crossing of I-19. The bridged crossing allows Demetrie Wash to provide good east/west permeability. Discharge volume would be 200-500 AF/yr.
3.	Continental Road	Serves the Green Valley area. From a recreational perspective, it's easy for trail users to get across I-19 and access the river in this area. Would require incorporation into future development and conservation plans. Western lands are generally blocked by mines, but there is a very small amount of permeability in the corridor where W Continental Road, Duval Mine Road, and S Mission Road converge. This site provides better connectivity to the wildlands to the east where the central Santa Rita Experimental Range and more distant uplands are accessible to wildlife via washes. This is a sensible place to close the gap between outfalls on Canoa Ranch and those located farther downstream. Outflow volume of 500 AF/yr.
4.	GVWRF outfall	This outfall would provide a centralized reach of environmental flows and riparian habitat, providing north-south habitat connectivity along the MSCR. Depending on the pathway to implementation for Concept 4, this outfall may use either the outflow volumes assumed for Concept 1 or Concept 2. As with Concepts 1 through 3, this outfall provides recreation benefits along the planned Juan Bautista de Anza NHT.
5.	Sahuarita Rd	There is no outstanding connectivity here to off-channel habitat, but outflows here would break up an otherwise long stretch of ephemerally flowing river. Small, low-volume outflow, mimicking a baseflow-supported seep, at perhaps 500 AF/yr.
6.	Lee Moore Wash at Old Nogales Highway	This site presents an opportunity for gap closure between Martinez Hill reach and upstream restoration sites. This discharge point is not on the Santa Cruz River, but it is nearby and located within the study focus area. Lee Moore Wash runs parallel to the SCR on this reach, to the east of the Tohono O'odham Nation's San Xavier District. This wash conveys peak flood flows above 10,000 cfs. Although off-channel from main SCR, it provides a restoration opportunity in an otherwise dry area. Concept 4 proposes a 500 AF/yr outflow, perhaps enough to support small cottonwood stand and very short surface flow. As with other low-volume outflows, it would be constructed more like a seep than a spring. This is not a prime location for habitat connectivity there is a large solar field to the west, but it punctuates a long and otherwise ephemerally flowing reach between Mine Road and Martinez Hill.

Table 19. Outfall locations and discharge volumes for Concept 4.

Effluent-based flows that support hydroriparian habitat near Demetrie Wash may facilitate its use as a crossing point beneath I-19, enhancing habitat connectivity (**Fig. 27**). As noted in **Table 19**, Demetrie Wash conveys high peak flood flows to the Santa Cruz River, where the two streams converge on the north end of Canoa Ranch. These high flows mean that I-19 crosses over Demetrie Wash on a pair of bridges. Elsewhere in the area, ephemeral flows on smaller washes pass through culverts under I-19.



Figure 27. Bridged crossing over Demetrie Wash.

This bridged crossing facilitates relatively easy wildlife movement across the barrier presented by Interstate 19. The nearest underpasses of I-19 with natural land cover are 17 miles to the south at Rock Corral Canyon and 19 miles to the north at an unnamed wash near the northern end of the San Xavier District. Two other underpasses are located on these reaches. However, they are paved roads conveying traffic flow, and Denneboom et al. (2021) report that humans use of crossings reduces the odds of their use by wildlife. Ephemeral flows on other washes are conveyed under I-19 via culverts that are likely too small to be useful.

Anderson et al. (2023) catalogue lands in and around the Demetrie Wash / MSCR confluence as having high value for species flow that preserves biodiversity in spite of climate change.

If camera traps are not already in use at Demetrie Wash, conservation groups may wish to deploy them to assess baseline conditions.

Management concept: LTSC reserves to mitigate drought and mimic natural flow variability

Drought planning is an ongoing concern in the Santa Cruz River watershed. Indeed, improved drought planning was the motivating theme of the Spring 2025 SCWC symposium. New approaches to MUSF management can help the region better prepare for and respond to drought. Concept 4 proposes the creation of a reserve of account of LTSCs to be used for drought response and adaptive management (“DRAM” credits), explained below. DRAM credits would allow Pima County to mitigate the environmental effects of drought and, to an extent, recreate some of the variability seen in natural flow regimes. Although this study proposes the introduction of DRAM credits on the MSCR, it is broadly applicable across Arizona’s MUSFs.

Reporting on the predictive value of seasonal forecasts in the Upper Santa Cruz River Basin, Shamir (2017) finds that extreme El Niño Southern Oscillation (ENSO) conditions are predictive of unusually dry La Niña winters and unusually dry El Niño summers. In response to such forecasts, managers of engineered environmental flows can plan on increased seasonal flows that meet riparian transpiration needs during a period of reduced natural inputs.

Because groundwater recharge via effluent-based flows creates recovery rights, Pima County can create a reserve account of accrued LTSCs for drought response and adaptive management of environmental resources. By withholding, for example, 20% of accrued LTSCs as DRAM credits, Pima County would create a water reserve equivalent to an additional year of baseflow that could be distributed over any five-year period.

DRAM reserves have environmental uses beyond drought planning and response. Although it is impractical to reproduce channel-scouring peak-flow events, managers can plausibly reproduce other important variations seen in natural flow regimes. For example, the extent of snowmelt-fed groundwater recharge and the frequency of low-intensity precipitation events will likely decline due to climate change (Meixner et al., 2016; Robinson, 2021). Increased flow volume during spring months would mimic the changes in stream reach and volume seen in streams fed by snowmelt. Shorter increases in flow, on the order of hours or days, would mimic streamflow response to lower-intensity precipitation.

It is important to note that a 20% DRAM reserve does not result in a 20% loss of recovery volume. Recall that evapotranspirative use on MUSFs may be as low as 3-5% of discharged water volume. A rough calculation might assume heightened ET during periods of water stress (say, 10%). Under this scenario, 90% of the DRAM reserve volume would be converted back into groundwater via infiltration — meaning that a 20% DRAM reserve results in only a 2% loss of *physical* water.

The overall loss of *paper* water (groundwater recovery rights) is influenced by MUSF siting, operations, and ADWR determinations. In an MUSF where effluent-based flow benefits a park or monument, a 0% cut to the aquifer (100% crediting) results in a paper loss of 2%, the same as physical loss. For effluent-based flows in an MUSF established after the DCP, a 50% cut to the aquifer (50% crediting) results in a paper loss of 11%.

The use of DRAM credits could be hampered by concerns over whether in-channel discharge is considered a beneficial use under Arizona law. To mitigate these concerns, DRAM credits could be exchanged for an equivalent amount of CAP water. Existing and planned delivery infrastructure (the Project Renew's / FICO orchards pipeline) could convey CAP water to outfall points on the MSCR, where its delivery would accrue recharge credits.

Assuming trade parity, exchanging DRAM LTSCs for an equivalent volume of CAP water would have the same effect on outflow volume as physically recovering and discharging the DRAM groundwater reserve. However, it is not clear whether or how the differences in water chemistry would impact riparian species. Under a CAP-for-DRAM exchange scenario, it seems prudent to blend effluent baseflow with the additional water volume from CAP. In the long-term, Tucson Water may wish to study how effluent-dependent ecosystems respond to alternate water chemistries.

ADWR credits CAP water stored via in-channel recharge at the same rate as CAP water stored via constructed basin infiltration.

Discussion

Concept viability and likelihood of implementation

Toward the end of the project, PCRWRD submitted to ADWR a formal application to create an MUSF in the MSCR downstream of GVWRF (PCRWRD, 2025). The facility proposes a maximum annual storage of 4,595.6 acre-feet per year.⁹ This volume allows the complete discharge of effluent produced by GVWRF into the MSCR, similar to the scenario described in Concept 2.

Total in-channel releases remain to be seen, but the project represents a viable on-ramp (if not outright implementation) for any of the concepts presented here. PCRWRD's commendable decision to create the MUSF reflects long-standing interest in the project both within the agency (Greeley and Hansen, 2007) and among stakeholders (SCWC, 2022)

The project aims to achieve 100% LTSC accrual for effluent returned to the aquifer due to its location within the Santa Cruz Valley National Heritage Area (PCRWRD, 2025).

⁹ The current permitted capacity of GVWRF is 4.1 million gallons per day, which works out to 4,592.6 acre-feet per 365-day year — three acre-feet less than the proposed maximum annual storage volume of 4, 595.6 acre-feet.

Extremely literal-minded readers may wonder if this is a typo in the application. For fun, I re-ran the unit conversion using what I first thought was the average length of a year — 365.25 days, you know, one leap year every four years. But I was still off by about 0.1 acre-feet. Then I remembered: some “would-be” leap years are regular years (e.g. the year 2100 will have 365 days).

The actual average number of days per calendar year is closer to 365.2425 (Richards, 2013, p. 598). However, for every revolution about the sun, Earth completes only 365.2422 rotations about its axis (Royal Belgian Institute for Space Aeronomy, n.d.). These measures differ by only 0.0003 days. When rounding to five significant digits, calculating maximum annual discharge volume using either figure in conjunction with a 4.1-million-gallon daily discharge volume will return an annual volume of 4,592.6 acre-feet.

However, it makes more sense to calculate the maximum annual discharge volumes using 366 days per year, since that is the maximum number of days in a calendar year. (I presume that ADWR uses calendar years and not, for example, solar or sidereal years.) By submitting new paperwork and a \$25,000 application fee (12 AAC 15, R12-15-103B) PCRWRD can amend their application at any time. *Nevertheless, I do not formally recommend that PCRWRD make this change.* My reason is that I already have a hard time making friends, and I am not looking to make things more difficult.

GVWRF effluent delivery obligations and pricing

At Green Valley WRF, a long-standing contract¹⁰ with Robson Ranch Quail Creek, LLC stipulates that Pima County will provide at least one million gallons per day (1,120 acre-feet per year) to Robson's recharge basins. In practice, PCRWRD can deliver more than the minimum amount to Robson, and in 2023 delivered 1,863.51 acre-feet of effluent (PCRWRD, 2024). In exchange, Robson contributed \$1.2 million to the construction of the current GVWRF facility and agreed to a long-term pricing scheme for ongoing deliveries (Pima County, 2001a).

Because Robson relies on the LTSCs, and not the effluent itself, a straightforward solution is to amend the agreement between Pima County and Quail Creek/Robson to reflect the sale of LTSCs rather than effluent. Arizona Administrative Code provides an avenue for ADWR to issue an updated certificate of assured water supply if necessary (12 AAC 15, R12-15-704(G); see also ADWR, 2019).

Alternately, Robson may be amenable to retaining physical ownership of effluent but accepting delivery to a shared, in-channel MUSF (Baeza, 2025). The most recently available information suggests that in-channel infiltration can realize efficiency gains due to clogging that has built-up within constructed basins over their operational lifespan (Baeza, 2025).

The initial 20-year contract provided for effluent delivery beginning at \$40 per acre foot. Future pricing was tied to the CAP excess rate. The contract also stipulated four renewal terms of an additional 20 years each, for a total 100 years obligated delivery (Green Valley News staff, 2001; Pima County, 2001a).¹¹ When Pima County and Robson renewed the contract in 2023, the price per acre-foot was tied to the CAP excess rate (Pima County, 2023).

The new pricing reflects future-pricing language from the original contract, not any renegotiation (Pima County, 2001a). The CAP excess rate in 2023 was \$280 per acre-foot and the rate in 2025 varied between \$313 and \$406 per acre-foot (CAWCD, 2022, 2024).¹²

Before the contract extension was approved, Pima County Procurement Department projected annual revenues of \$516,000 from effluent delivery, with a "potential revenue of

¹⁰ Pima County procurement contract 11-03-R-128617-0201 (Pima County, 2001a).

¹¹ Under Arizona law, a development must demonstrate a 100-year supply of water before ADWR will issue a certificate of assured water supply.

¹² The CAWCD price schedules shows that the excess rate varied with Drought tier in 2024 and varied with delivery volume in 2025. When the contract was renewed, Arizona was experiencing Tier 2a drought conditions, indicating an excess rate of \$280 per acre-foot. In 2025, the excess rate was tied to delivery volume. Delivery volumes were tiered at every 100,000 acre-feet between 700,000 and 1.1 million acre-feet. The highest CAP excess rate per acre-foot is \$406 for the 700,000-acre-foot tier; the lowest is \$313 per acre-foot. The mid-tier rate, given for 900,000 acre-feet, is \$349 per acre-foot. The text above presumes that the lowest-volume tier is appropriate, but additional work is required to verify this.

\$10,320,000 over the 20-year term” (Pima County, 2023). The first estimate appears to assume annual delivery to Robson of 2,000 acre-feet at the then-current rate of \$280 per acre-foot. The second estimate appears to assume that delivery volume and pricing will remain fixed over the 20-year contract term.

Neither assumption is accurate, though it is unclear whether this has any significant effect on PCRWRD operations or Pima County financial projections. Both price and demand are, if not volatile, variable. This begs the question of whether Pima County (as well as City of Tucson and other municipalities) have incurred any unrealized risk exposure due to accounting assumptions around long-term water contracts. Future research could perhaps shed light on the question.

Robson’s delivery rate is favorable compared to that charged by Tucson Water for effluent delivery through their “purple pipe” system (**Table 20**). Tucson Water realizes \$698.64 of revenue per acre-foot of effluent delivered in 2023, while Robson has paid less than half that amount in 2023. While PCRWRD deliveries to Robson do not rely on an extensive distribution system like Tucson Water, and do not incur significant pumping costs, Tucson Water’s average pumping costs across the purple pipe system are only about 30% of effluent revenue. Future work might examine a larger dataset of past budgets and price schedules to more thoroughly compare retail effluent deliveries against CAP water.¹³

Robson does not use the effluent directly.¹⁴ Rather, the effluent is delivered to a USF (constructed recharge basins) owned by Robson, where it is converted to groundwater. Robson then accrues LTSCs that enable groundwater recovery throughout the Tucson AMA.

Delivery volumes and costs for reclaimed water in Pima County	
Tucson Purple Pipe System	
2023 total reclaimed water (“purple pipe”) deliveries by COT	12,870.7 acre-feet ^a
COT revenue from reclaimed water deliveries	\$8,992,031 ^b
Pumping costs for reclaimed water delivery	\$2,701,280 ^b
Revenue per acre-foot of reclaimed water delivered	\$698.64 ^c
Pumping costs per acre-foot of reclaimed water delivered	\$208.88 ^c
Purple pipe revenue per acre-foot, less pumping costs	\$489.76 ^c
PCRWRD effluent delivery to Robson Ranch Quail Creek LLC	
2023 delivery volume	1,863.51 acre-feet ^d
2023 Cost per acre-foot	\$280 ^e
2023 Total revenue realized	\$521,782.80 ^c

Table 20. Volumes and costs for reclaimed wastewater in Pima County Sources: *a.* (City of Tucson, 2024). *b.* (City of Tucson Business Services Department, Accounting Operations, 2023). *c.* Calculated. *d.* Volume reported by PCRWRD (2024) *e.* Derived from published CAP rates (CAWCD, 2022)

¹³ When reporting purple pipe delivery volumes from 2003, Megdal (2007) notes that Tucson Water delivery rates of \$610 per acre-foot. Twenty years later, Tucson Water realizes revenues of only \$699 per acre-foot.

¹⁴ However, Robson retains the right to do so under item 16 of their pre-annexation development agreement with the Town of Sahuarita (Town of Sahuarita & Robson Ranch Quail Creek, LLC, 2000)

As of December 31, 2018, Robson Ranch Quail Creek, LLC had accrued 19,586.05 acre-feet of LTSCs (ADWR, 2020c), suggesting deliveries in excess of need. LTSCs accrued by the Robson Ranch Quail Creek LLC long-term storage account (LTSA) have previously been transferred to the LTSA for Robson Ranch Mountains LLC (ADWR, 2025). The Robson Mountain community is in Pinal County, at the opposite end of the Tucson AMA, nearly 50 miles away.¹⁵ It is not at all clear how or when Pima County came to believe that one million gallons of water per day — 36.5 billion gallons (112,000 acre-feet) of water over the hundred-year life of the contract — was a reasonable estimate of need. Future research might clarify this.

¹⁵ The effluent use agreement was approved by the Pima County Board of Supervisors on February 20, 2001. The minutes record Supervisor Bronson's belief that "it was imperative ... to begin the process of moving golf courses from groundwater use" (Pima County, 2001b). Whether the contract facilitated that outcome may depend on how one views the transfer of LTSCs to Robson Ranch Mountains LLC.

Allocation of effluent and recharge credits under a regional consolidation scenario

As described above in the introduction, crediting parity for effluent-based groundwater recharge, regardless of facility type (MUSF or USF), is the single greatest determinant of project success that lies outside the control of local jurisdictions.

Pima County and Tucson Water both support effluent-based in-channel flows, at least in theory, and would likely agree to in-channel discharge for effluent fractions originating in the Corona de Tucson and GVWRF service areas. Sahuarita, however, may hesitate.

Sahuarita has adopted policies to “continue the construction of recharge basins at Sahuarita WRF,” augment those basins with public amenities, study reclaimed water delivery, and to “consider market value of effluent credits” (*Study Session: Water — Do We Have Enough?*, Sahuarita, AZ). Time constraints prevented deeper research into the subject, but it seems likely that Sahuarita’s interests would prevent a full realization of Concepts 3 and 4 absent some mechanism to eliminate the crediting disparity.

Design and operation of engineered components

As described above, riparian communities on effluent-dependent reaches of ephemeral streams are influenced by factors like water quality and colonizing species (M. T. Bogan et al., 2020; Eppehimer et al., 2020; Hamdhani et al., 2020, 2023). Site visits also revealed obvious differences in outfall channel characteristics and habitat quality. Some of these differences obviously derive from the engineered environment: riparian forest cover will not grow on an intact soil-cement bank (Fig. 28).



Fig. 28. Soil cement bank at Agua Nueva restricts woody riparian habitat to one side of the channel. See also cover photo for top-down view. (Photo: Rudy Malusa)

Other differences are plausibly, but not definitively, related to the engineered environment but require further study. This study identified several topics that warrant further research:

Factors affecting effluent temperature at outfall and feasibility of passive cooling mechanisms. Temperature is a dimension of water-quality, and it has potentially profound impacts on the viability of any given aquatic species. Boyle & Fraleigh (2003), examining effluent-based flows below NIWTP, found that temperature improved with distance downstream from the outfall. This begs the question: how does effluent conveyance and outfall design affect the temperature of discharged water? Is it possible to incorporate buried cooling loops or other forms of passive cooling into future effluent conveyance systems and outfall designs?

Tucson Water has an extensive “purple pipe” system that is already delivering reclaimed water for non-potable uses like irrigation. By sampling water temperatures at different points in the system, Tucson Water may be able to characterize heat transfer as a function of pipe length, diameter, and depth. Serving distant outfalls in concept 4 with a cluster of small mains, rather than one large main, would result in a greater surface-area to volume ratio for conveyance infrastructure. This, in turn, could perhaps result in significantly lower outfall temperatures.

Effect of outfall design on channel geometry and riparian habitat. On site visits to existing outfalls, it was apparent that the engineered environment greatly influenced the natural environment. For example, there are significant difference between the two highest-volume outflows at Agua Nueva and Tres Rios WRFs.

The outfall design at Agua Nueva WRF sets the discharge point high up a soil cement bank, resulting in a “plunge pool” below. Downstream of the outfall, the channel is “locked” against the soil cement bank, where riparian habitat can grow on only one side of the stream. At Tres Rios, the high-volume outflow is set relatively low into the bank, resulting in an intense and narrow stream that extends relatively far from the bank before turning downstream.

At Santa Cruz River Heritage Project, the outfall is relatively low-elevation and low volume. There, the water appears to spread widely (especially given the relatively low volume discharge) before eventually forming a thin stream.

Clearly, there is a relationship between discharge volume, outfall placement, and existing features in the channel. It seems reasonable to discourage cascading outfalls capable of scouring out plunge pools, but beyond that, there is much to learn.

Effect of stormwater outflows on channel alignment. It is plausible that stormwater outfalls affect channel alignment. When placed high above the channel, these outfalls may convey flows capable of scouring holes in the channel below. These localized depressions can then capture streamflow and cause channels to “migrate” toward soil cement banks. The extent and nature of this tendency requires further characterization.

Effect of grade control structures on channel alignment and stream width. It is not clear whether and how grade control structures affect channel geometry and riparian habitat. PCRFCFCD has recently “notched” the center of some grade control structures with the intent of better centering streamflow mid-channel (i.e., relieving the tendency of flows to migrate toward one or the other soil cement bank). Future work might evaluate the effectiveness of this intervention. Newer grade-control structures are built with slopes that converge mid-channel. These slopes are typically a 4:1, pitch but can be a 12:1 pitch if designed for maintenance vehicle crossing (PCRFCFCD, personal communication).

It is possible that grade control structure might function as “sand storage dams” like those described by Standen et al. (2020). Burying a low-permeability substrate behind grade-control structures (e.g., at the depth of the structure itself) could facilitate shallow groundwater storage that hydriparian species could exploit. This is a potential method that managers can use to mimic gaining-reach habitat. (Other methods for creating localized instances of perched groundwater are discussed below.)

Feasibility of engineered methods to selectively reduce hydraulic conductivity below effluent-based flows. The creation of locally perched groundwater volumes could result in bankside riparian habitat that more closely resembles the broad cover found on gaining reaches characterized by shallow groundwater. Where rising water tables are locally problematic reduced hydraulic conductivity could allow flows to preferentially infiltrate downstream reaches.

An example case can be found nearby the A-Mountain Landfill on the Santa Cruz River Heritage Project, where managers have reduced outflows to avoid the possibility of rising groundwater contacting buried landfill contents. The water table on downstream reaches is lower, and reduced hydraulic conductivity near the landfill could perhaps facilitate the originally envisioned flow volumes.

Another use scenario would be at sites where channel downcutting in recent centuries has incised through clay layers that once held perched aquifers supporting groundwater-dependent riparian species.

Potential methods for reducing hydraulic conductivity include permeation grouting, wherein a thin cement solution would fill channel sand void space before hardening. Time constraints precluded further investigation that would reveal whether this technique is viable without sustained flow interruption on rewatered streams.

Alternately, a “natural” clogging layer could be artificially induced through the injection of clogging-layer analogues or precursors. Recall that these clogging layers are typically found at or near the channel surface, and, as described elsewhere in this report, intermittent high flow events will periodically scour the channel and remove them. Biological clogging layers are typically composed of polysaccharides; physical clogging layers are typically composed of settled fines.

Biological clogging layers could be created through the injection of innocuous thermoresponsive polysaccharides that are soluble at high temperature but gel at ambient temperatures. These compounds, especially those based on semisynthetic derivatives of naturally occurring carbohydrates, are the subject of active research (Graham et al., 2019; Nishimura et al., 2020; Otto et al., 2021). However, pectin is a widely known example of a naturally occurring thermoresponsive polysaccharide with a long history of human use. It is not clear whether it is sufficiently stable to create a long-lived (i.e., cost-effective) aquiclude.

Alternately, creating a sufficiently well-buried biological clogging layer may be as simple as injecting warm, nutrient-rich water. This would introduce a temporary period of bacterial growth and polysaccharide build-up before the system re-equilibrated to ambient temperatures and nutrient density. Physical clogging layers could perhaps be created through high-pressure injection of slurried fines.

Future study might carefully consider the lifespan of these clogging layers and their long-term consequences. A long-lived clogging layer is undesirable if it persists longer than the rationale for its existence. (If the city excavates A-Mountain Landfill and reburies its contents elsewhere, the clogging layer would serve no purpose.) Future study might also characterize an “ideal” clogging layer with consideration of root-zone depths and desired hydraulic conductivity.

Unbridged channel crossings require stakeholder consultation

Grade control structures and phased flow implementation are possible solutions for maintaining use of unbridged channel crossings downstream of discharge points. Several of these crossings are found downstream of the Green Valley WRF outfall (**Fig. 24-26**). They presumably facilitate movement of agricultural equipment, workers, and products between orchards on opposite sides of the MSCR. Stakeholder consultation is a prerequisite to any releases that might affect these crossings.

Grade control structures may help meet existing needs while still allowing effluent-based flows. PCRFGD currently builds grade control structures with a center-channel low point and a maximum 4:1 slope (horizontal:vertical). When intended for use as a crossing point by maintenance vehicles, the slope is only 12:1. However, users report that even the 4:1 grade control structures are readily crossed by heavy equipment (like that seen on farms). Due to construction methods, each grade control structure is at least as wide as a grader (PCRFGD, personal communication).

Because Concepts 2 through 4 are suitable for phased implementation, environmental flows that do not extend past Old Nogales Highway can be implemented while existing crossings remain in use. As orchards are converted to new land uses as described in the Sahuarita Farms Specific Plan (FICO et al., 2015), crossings would no longer be required for agricultural use. Discharge volumes (and extent of flow) could then be increased.

Local news media have covered at least one instance of effluent flow across agricultural crossings. When the City of Tucson began discharging effluent from a newly completed treatment plant in 1951, Cortaro Cotton & Cattle Company partner-manager Albert Oshrin alleged that downstream crossings were destroyed (“Fireworks, Sewage, Garbage Disposal on Council Agenda,” 1951). By 1955, Oshrin was purchasing effluent from the City, and had paid to construct a pipeline for conveyance (Harrington, 1955).

Crossings were also affected in the early 1970s, when effluent-based flows downstream of Tucson increased as a result of Dow Chemical's refusal to accept ongoing effluent deliveries ("Oshrin No Longer Defendant," 1971; USGS, 1969, 1972b, 1972a). Aerial imagery shows built-up crossings in the vicinity of the modern-day locations of Quarry Road and El Rio Preserve (USGS, 1972a), both of which are near the Avra Valley Road exit on Interstate 10. The latter crossing (**Fig. 29**) shows accumulation of surface water on the upstream side, the former shows accumulation in what appears to be a separately constructed basin on the upstream side.

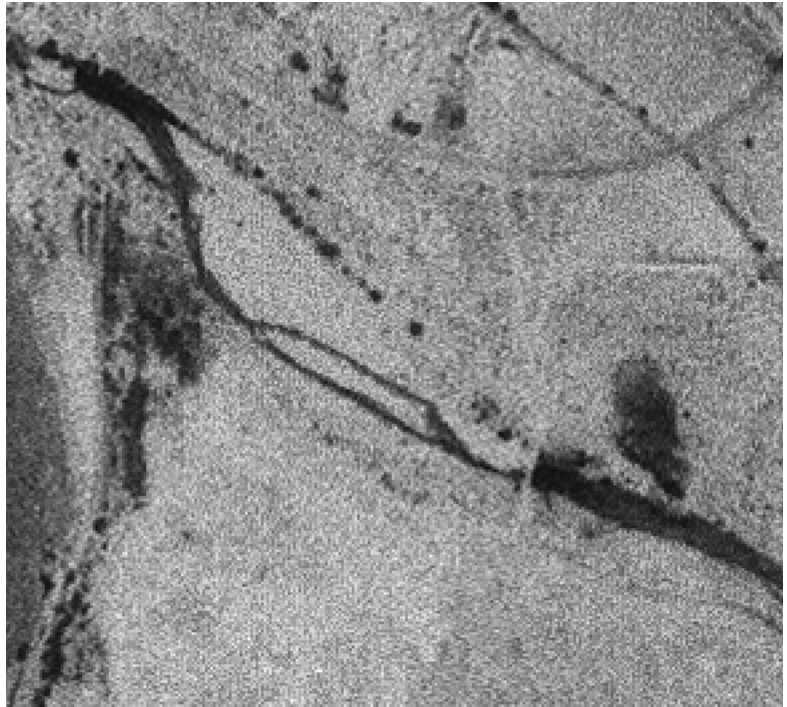


Figure 29. An informal crossing (right-hand side of image) is visible near the modern-day location of El Rio Preserve (USGS, 1972a). This image was taken in 1972, after cessation of effluent delivery for agricultural use resulted in extended flow reach.

Environmental considerations: Past flow regimes on the MSCR

Presenting on their exhaustive history of the Santa Cruz River in the Tucson area, Webb and coauthors (Webb et al., 2014a) criticize the concept of restoration ecology: “‘Restoration’ is a euphemism for creation of designer ecosystems with little or no relation to what resources once were present ... If you hear the word ‘restoration’ applied, immediately ask: ‘Restore to what and when?’”

The idea of “restoring” hydriparian habitat on the MSCR can initially seem like a strange concept, as cottonwood-willow forest is characteristic of flowing desert rivers, and conventional wisdom holds that this stretch of the Santa Cruz River has “always” been dry. However, there is archaeological, historical, climatological, and geophysical evidence to suggest the past presence of hydriparian habitat on the MSCR, especially before the 1770s.

Moreover, perennial or even intermittent flows are not actually a prerequisite for hydriparian habitat. Fonseca and List (2012) report that 56% of riparian cottonwood-willow woodlands in Pima County are found on ephemeral reaches, while another 21% are found on intermittently flowing reaches.

At any rate, the current flow regime of the MSCR is not a complete and meaningful history of the river. The most readily available records of MSCR flow — those produced by modern gauging equipment — contribute to the perception that the MSCR is a “dry” river. The hydrograph for even the famously soggy 2021 monsoon season (**Fig. 30**) shows periodic cessation of flow between storm-related pulses (USGS, 2025).

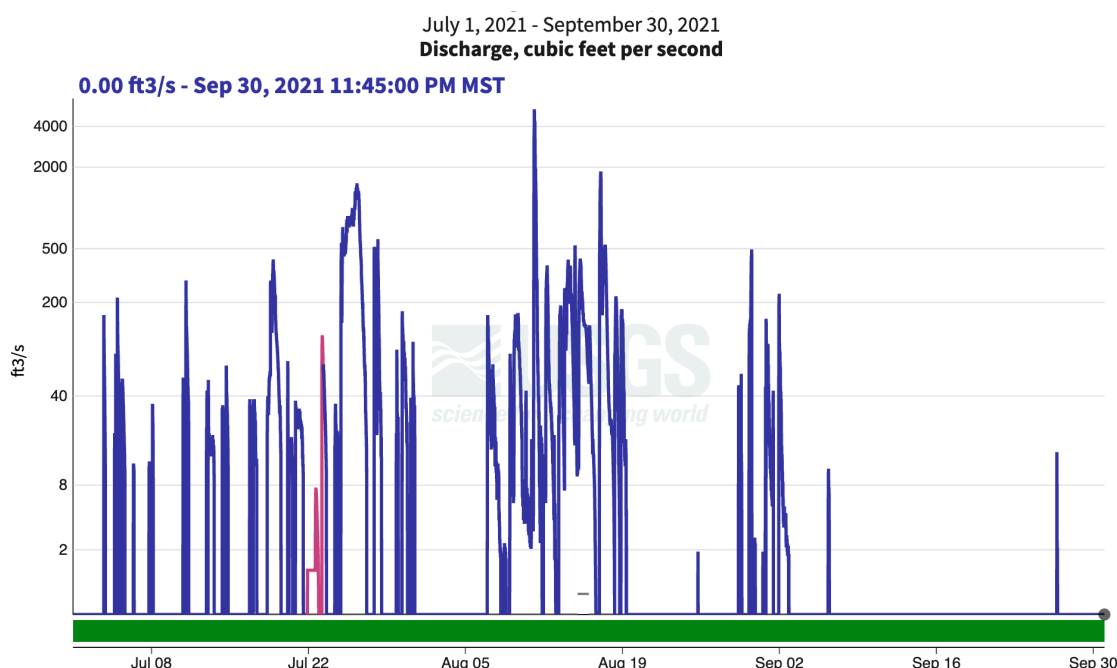


Figure 30. This hydrograph shows monsoon-season flow on the MSCR, July 1 – September 30, 2021. (Data from the Continental (Green Valley), AZ station, station ID 09482000, USGS (2025a).) The graph shows discrete storm-related flows and intervening cessations. No other months in 2021 showed flow events.

The lack of perennially occupied indigenous villages on the MSCR during the Spanish Colonial era likely also contributes to the perception of a “dry” river.

However, two maps produced during this period depict different extents of surface flow (Seymour, 2020; Seymour & Rodriguez, 2020), hinting at a flow regime with significant interannual or interdecadal variability (**Fig. 31**). This makes intuitive sense: the climate of the southwest between 1400 and 1850 was characterized by heightened hydrodynamic variability. And indeed, the timings of these specific renderings in 1769 and 1780 comport well with climate reconstructions (Griffin et al., 2013, **Fig. 31**).

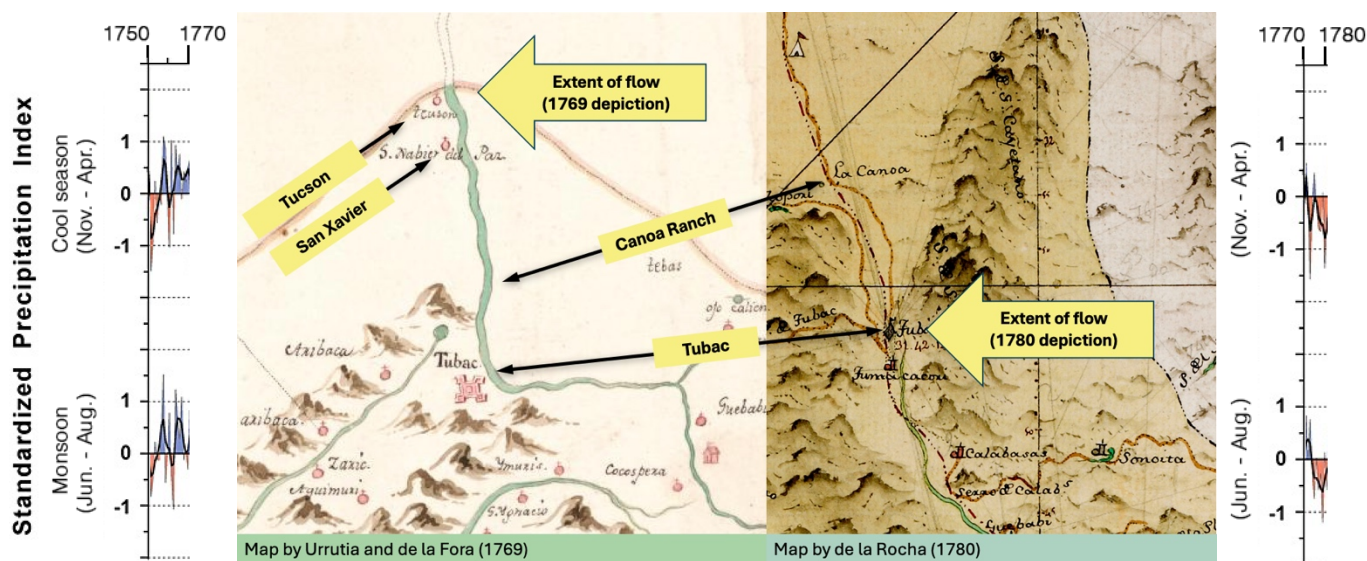


Figure 31. Urrutia and de la For (left, 1769) depict the Santa Cruz River conveying surface flow north past Tucson. De la Rocha (right, 1780) depicts surface flow only as far north as Tubac. These depictions comport with decadal-scale precipitation trends reported by Griffin et al. (2013). Precipitation indices are adapted from Griffin et al. (2013). De la Rocha map is reproduced from Seymour (2020) with annotations added.

A map produced by Urrutia and de la For (1769, **Fig. 32**, left) shows continuous flow on the Santa Cruz River through the MSCR. It depicts surface flow that terminates after passing through San Xavier del Bac and Tucson. Urrutia accompanied Marqués de Rubí and Nicola de la For on an expedition to inspect Spanish presidios between 1766 and 1768 (Texas State Historical Association, 2020). Presumably, this map reflects surface flow conditions they encountered during their journey. The climate reconstruction of Griffin et al. (2013) shows that Urrutia and de la For’s observations coincide with the latter years of a decade-plus interval of consistently wet winters and monsoons.

Another map, made by Geronimo de la Rocha and based on observations made in 1780 (Seymour, 2020; Seymour & Rodriguez, 2020, **Fig. 32**, right) depicts cessation of flow at Tubac. It too comports with tree-ring reconstructions of climate by Griffen et al. (2013), which show a decade-long succession of dry winters and dry monsoon seasons.

Settlers complained to the territorial government in 1780 that the Santa Cruz River no longer reached Tubac, citing diversions from upstream users (Seymour, 2020). De la Rocha's own written account confirms these reports and adds additional details. Writing of his visit to a spring called Ojo del Zopori on May 12, 1780, and to Aribaca (Arivaca) on May 13, 1780, he describes both as unusually if not historically dry (Seymour & Rodriguez, 2020). On May 17, he passes through La Canoa, the site of modern-day Canoa Ranch, noting that "the spring could not supply enough water for the people" (Seymour & Rodriguez, 2020). De la Rocha camped along the MSCR, apparently in the vicinity of modern-day Green Valley, and writes that "in the place we slept there was no water" (Seymour & Rodriguez, 2020).

During decade-long wet periods, the maximum seasonal extent of flow was likely many miles more than what was observed during drought periods.

This interpretation — that the different maps depict climatically dependent flows — is buttressed by Juan' Nentvig's description of the river in the *Rudo Ensayo* (Nentvig, 1980). Relying on either his own observations or other information received during his long tenure in colonial Sonora (1752 to 1764), Nentvig describes a river with a variable reach:

The fifth river [the Santa Cruz River] emerges about a league northeast of Santa María Soamca and flows south to San Lazaro then turns west to San Luis and Buenavista. From there it turns northwest to Guebavi, Calabazas, and Tumacacori, finally reaching the Tubac presidio where it ordinarily ends *except when the rains are abundant. Then it flows farther north*, skirting the Santa Rita Mountains, to *San Xavier del Bac*.

Nentvig (1980, p. 12, emphasis added)

Nentvig's description of wet- and dry-period flows matches the respective maps from 1769 and 1780. The illustrated record agrees with written record, which agrees with the climatological record.

Archaeological findings from the Continental Site (AZ EE:1:32(ASM) and others nearby) further support the idea of historically variable flow regimes on the MSCR. The Continental Site is in Green Valley on the MSCR floodplain near Continental Road.

The Continental Site provides physical evidence of long-term human presence, including diversion canals, catchment or impoundment basins, and irrigated agriculture (Dart, 2014). Excavations have recovered the remains of Sonoran mud turtles (Dart, 2014) and a mat made of "reeds collected from the nearby river banks" (Associated Press, 2009). Site sediment has yielded abundant pollen from cattail, a hydriparian species that depends entirely on persistently saturated soils (Dart, 2014). The site's "discoverer" attributes its inhabitation to the river's formerly "consistent" flow (Associated Press, 2009).

Undoubtedly, water resources at the Continental site were sufficiently reliable to support irrigated agriculture and persistent settlement. Describing a rounded cobble found at the site (Arizona State Museum identifier AP-2001-200-14), archaeologists cast it as an item of cultural or ceremonial significance, presuming that it must have been imported “for some purpose” (Moreno, 2022). However, archaeologists found the cobble years before finding evidence of irrigated agriculture. It is possible that site inhabitants simply moved it a short distance from a nearby channel meander that remains unexcavated.

If it does not reflect a perennially flowing river, the Continental Site may at least reflect the presence of shallow groundwater contained within an underlying perched aquifer. Various ADWR reports have mentioned perched groundwater in the area (Mason & Bota, 2006; Mason & Hipke, 2013), and plans for a nearby groundwater recharge project have raised concerns that the perched aquifer could inundate a pecan orchard rootzone (Davis, 2014).

It is difficult to know exactly what the MSCR looked like during past climatic intervals, but clearly, new hydriparian habitat is not a radical departure from past conditions.

Pathways to achieve crediting parity for effluent-based in-channel flows

Legislative action: Full crediting parity

The most straightforward route (if not the easiest route) is for the state legislature to establish crediting parity for effluent-based groundwater recharge in USFs and MUSFs. The City of Tucson and Pima County should advocate for such legislation. The Town of Sahuarita and other jurisdictions may also wish to advocate for it.

Legislative action: Recreational corridor channelization districts

Recreational corridor channelization districts were a previously authorized means of obtaining credit parity on an MUSF, but the authority to create new districts has lapsed. It is not clear whether any of these districts — technically, they are special taxation districts under state law — even exist in Arizona.¹⁶ New legislation could lift the sunset provision on the creation of these districts. However, this option is inferior to full crediting parity, as described above.

Delivering effluent to new or existing state parks, national parks, or national monuments

State law provides for 100% recharge when MUSFs benefit certain public lands, namely, a state park, national park, or national monument (45 ARS 852). This can guide MUSF siting in other parts of the Tucson AMA: Cañada del Oro flows through Catalina State Park, Rincon Creek flows through Saguaro National Park, and Brawley Wash flows through Ironwood Forest National Monument. The floodplain along Tanque Verde Creek overlaps with the east unit of Saguaro National Park.

Catalina State Park is not far removed from Tucson Water's purple pipe system; discharge there would require a short extension. Rincon Creek is farther removed. Avra Valley WRF is located a short distance upgradient from Brawley Wash, but it is separated from Ironwood National Monument by tribal lands.

Establishing state parks on county conservation lands — namely, Canoa Ranch — provides an obvious pathway to qualification for Concept 4. However, this would require state legislation, and it is not clearly superior to the other changes to state law described in above.

Adding value to parks and monuments without colocation

If the GVWRF MUSF permit application (PCRWRD, 2025) is approved as one that benefits an existing park or monument — namely, Santa Cruz Valley National Heritage Area — this

¹⁶ There may be one on the Agua Fria River, but I was unable to locate an authoritative list of special taxing districts in Arizona.

will effectively set a precedent to authorize crediting parity within the Tucson and Santa Cruz AMAs. The National Heritage Area is administered by the National Park Service, but it remains to be seen whether ADWR will consider it a park unit.

The GVWRF is squarely and unambiguously within the borders of the National Heritage Area. However, there is a defensible argument that MUSFs may qualify as beneficial facilities *without* physical colocation.

45 ARS 811 provides guidance on when a party may request that ADWR designate an MUSF as one that “adds value” to these public lands: if the park or monument “includes any portion of a natural channel of a stream or adjacent floodplain that would benefit from the facility.”

The wording does *not* clearly state that a “flowing portion” of the stream or its adjacent floodplain must intersect the park or monument. It only stipulates that the “*any portion*” of the “stream or adjacent floodplain” must intersect the park or monument. It does *not* say “any benefitting portion” of the stream. And it does not say *how* the MUSF must add value to a national park or monument.

An implicit subtext here is that the MUSF may indirectly add value can to the public lands, e.g., by providing a seed bank or habitat for flora or fauna found on those lands. Parks and monuments are created by enabling legislation or executive orders that often state the conservation values that motivate its creations. These are the very values that an MUSF can support. The species that add value to a park or monument are inherently mobile (especially over sufficiently long timescales, when their ranges can expand or contract), and they can move between a park and an off-site stream.

The Santa Cruz River channel or floodplain crosses the Tubac Presidio State Historic Park in the Santa Cruz AMA, Ironwood National Monument (at its northernmost reaches in the Tucson AMA, and in the southernmost region in the Pinal AMA), and, arguably, Picacho Peak State Park in the Pinal AMA. Any entity applying to create an MUSF on the Santa Cruz River anywhere in these AMAs has a defensible case for 100% recharge credits.

Long-term viability: Price signals

As described in the Introduction, existing literature contains few price points that assign a dollar value to each acre-foot of in-stream flow. Loomis (2012) reported a value of \$242 per acre-foot (2025 dollars) for streamflow in an urban river. This value was derived from a contingent valuation survey that asked about a fractional decrease in streamflow, but not absolute cessation. Because an acre-foot of flow in a wetted river channel has less marginal value than an acre-foot of flow in a dewatered river, the value is presumably higher in arid lands — though the exact amount remains uncertain. Hence, the value reported by Loomis may understate the actual value of instream flow. While instream flows are valuable, economic benefits are realized indirectly.

New price signals suggest that heightened supply-demand imbalance can imperil the long-term viability of new effluent-based in-channel flows. **Table 21**, below, gives recent indicators. These costs approach that of desalinated water and are rising more quickly (**Table 22**).

Recent costs per acre-foot for water conservation in the Lower Colorado River Basin			
Year	Cost per acre-foot	Project / agreement	Water volume
2018	\$250	Colorado River Indian Tribes (CRIT) Drought Contingency Plan (DCP) compensated transfer	150,000 AF (50k AF/yr over 3 years)
2022	\$260	Compensated reduction in CAP deliveries to Tucson (rejected by M&C)	30,000 AF
2023	\$400	Compensated reduction in CAP deliveries to Tucson, funded by Inflation Reduction Act (IRA)	110,000 AF (multiyear through 2025)
2025	\$1,554	Funding for Advanced Water Purification (AWP) plant in exchange for CAP delivery reductions to Tucson	56,000 AF (over ten years)
2025	\$2,000	Funding for infrastructure and metering to support water conservation, in exchange for CAP delivery reductions to Gilbert	8,500 AF (over ten years)
2025	\$3,080	Funding for CAP/Salt River Project (SRP) interconnects, in exchange for CAP delivery reductions	50,000 AF (over fifty years)

Table 21. Cost per acre-foot for water conservation projects. These costs begin to approach that of desalinated water (San Diego County Water Authority, 2025).

Wholesale cost of desalinated water in San Diego	
Year	Cost per acre-foot
2016	\$2,123 ^a
2022	\$2,815 ^a
2024	\$3,400 ^b
2026	\$3,736 ^a

Table 22. Wholesale purchase price for desalinated water in San Diego. Sources: *a.* Smith (2022) *b.* San Diego County Water Authority (2025).

The comparison is reasonable: both water conservation and desalination reflect the cost and value of bringing *new* sources online. Notably, they appear to be converging. These prices not only suggest that demand for effluent might imperil in-stream flows, they show a specific example.

In **Table 20**, the Advanced Water Purification (AWP) plant is intended to reduce the flow of effluent out of the Tucson AMA and into the Pinal AMA. This happens when effluent released into the Lower Santa Cruz River Managed Storage Facility (LSCRMSE) results in flows that extend past Trico Road (the last metered point on that reach of the Santa Cruz), and continue past the county line, then further past the boundary between Tucson and Pinal AMAs. Effluent that flows out of the AMA cannot be converted into recoverable LTSCs.

Under the ten-year agreement, USBR will result fund an \$87 million AWP facility. This facility is intended to process 5,600 acre-feet of effluent for direct delivery to Tucson Water customers. In exchange, Tucson Water will reduce annual orders of CAP water by 5,600 acre-feet per year for a period of ten years. Inflow to the AWP facility will require a corresponding reduction in effluent delivery to the LSCRMSE.

Converting this effluent into potable water does not generate any new LTSCs, but it does create a new supply of reliable “wet” water. This arrangement diversifies Tucson’s water portfolio and enhances the region’s water security — but does so at the cost of robust riparian habitat downstream of Trico Road.

Because effluent represents a potential source of “new” potable water — especially given the USF/MUSF crediting disparity for effluent — recent price signals suggest a possible threat to future effluent-based flows.

Inter-basin agreements between stakeholders in the Tucson and Pinal AMAs can achieve both parties to achieve full use of outbound effluent flows

The USBR-funded AWP facility is not the only way to recover water “lost” by effluent flowing out of the Tucson AMA. This report proposes an alternative mechanism that can be implemented using existing state policy:

- 1.) Tucson Water establishes a new flow gauge at the boundary between Tucson and Pinal AMAs.
- 2.) Tucson Water submits paperwork to ADWR, enlarging the LSCRMSF and placing its downstream perimeter at the boundary between the Tucson and Pinal AMAs.
- 3.) Tucson Water submits paperwork to establish a new MUSF in the Pinal AMA. The upstream perimeter is located at the Pinal-Tucson AMA boundary. Its downstream perimeter is sufficient to covering the maximum extent of surface flow under anticipated conditions.
- 4.) When applying to create the new MUSF, Tucson Water requests its designation as one that adds value to Ironwood Forest National Monument, whose boundaries include floodplain along effluent-watered reaches of the Santa Cruz River. This would qualify the new MUSF for 100% recharge credits under ARS 45-811(B).
- 5.) After the MUSF is created, the rights for recovery of stored water in the newly created MUSF would be transferred to holders of CAP water rights in the nearby Central Arizona Irrigation and Drainage District (CAIDD) GSF. In exchange for accepting LTSCs from the MUSF in the Pinal AMA, the CAIDD rightsholders would transfer a corresponding volume of their CAP allocation to the Tucson AMA.

A mildly complicating matter is whether ADWR would proportionally credit recharge in the Pinal AMA’s new MUSF to all parties discharging into the LSCRMSF, or if ADWR would credit all recharge in the Pinal AMA to the party discharging the greatest volume. The latter option would simplify accounting, and it is justifiable under a “but-for” scenario (but for discharges belonging to Tucson Water, flows would not cross the AMA boundary). However, from a hydrological point of view, the boundary-crossing flow includes the commingled discharge of all parties using the LSCRMSF for storage.

Data availability

This study was possible only because of public-facing data reported by planning organizations and regulatory agencies. It was also hamstrung by the limited availability of additional data on water resource management and use. Greater data availability can significantly empower small organizations performing similar work in the future.

ADWR provides abundant public-facing information on water rights and use but makes relatively little available as geospatial data. That which is available may be no more complicated than point features with links to PDF records. (Many of those files are scanned versions paperwork completed by hand.) I was unable to locate, for example, geospatial time-series data of CAP deliveries, recharge volumes at USFs and MUSFs, groundwater pumping volumes, or projected aquifer levels used to issue certificates of Assured Water Supply. Nor could I find public-facing geospatial data on effluent production volumes, effluent delivery obligations, CAP delivery obligations, or LTSC accrual and “spending.”

This is understandable. Public agencies have limited budgets and statutory obligations. However, improved public-sector data curation could municipal and private-sector dividends.

Fragmented management regimes can result in disaggregated and unused data whose consolidation would enable better water management (Gallaher & Heikkila, 2014; Jury & Vaux, 2005). What data is available often reflects jurisdictional rather than hydrological boundaries (Gallaher & Heikkila, 2014). For example, before the late 2010s, differing hydrologic modeling tools prevented an “apples-to-apples” comparison of Colorado River projections performed by scientists at the US Bureau of Reclamation and their counterparts in Mexico (Rivera-Torres et al., 2021).

Missing data also precludes accurate water accounting. A complete sector-by-sector accounting of Colorado River water was not published until 102 years after the signing of the Colorado River Compact (Richter et al., 2024). The authors attribute the prior impossibility of such an analysis to missing data from Mexico and disjoint system boundaries between Colorado River Compact water allocations and Lower-Basin tributaries whose diversions are not governed by the Compact. In other studies, missing groundwater data has led researchers to model an unlimited supply (Averyt et al., 2013).

In some cases, missing data may simply represent the difficulties of relying on self-reporting from myriad private rightsholders. An undated ADWR document lists four dozen community water systems in Pima County for which the agency is missing annual reports or water system plan updates (ADWR, n.d.). Community water system (CWS) records examined in this study, especially those of smaller water systems, sometimes exhibited unlikely or frankly implausible trends in water usage.

Ambiguous system boundaries, inputs, and outputs can lead to double-counting errors, especially regarding exchange between surface and groundwater (Evans et al., 2017; Lustgarten, 2015). When ADWR corrected a double-counting error, it nearly tripled their calculated volume for cumulative groundwater overdraft in the Phoenix AMA over a 32-year period (Ferris & Porter, 2021). CWS reports examined in the course of this work were sometimes ambiguous.

Ultimately, the state would be well-served by a significant investment in water-data infrastructure. Implementation of the Open and Transparent Water Data Act in California may provide lessons for Arizona.

Conclusion

Concluding remarks

Ultimately, there is enough effluent physically available to support environmentally beneficial hydriparian habitat creation via in-channel flows on the MSCR. The project would comport with the “linked, local, and leveraged” framework that describes successful riparian restoration projects elsewhere in the Colorado River Basin. Planners and non-specialists can use this framework to guide decision-making.

However, effluent availability depends not only on the physical availability of water, but also its legal availability for future use as groundwater. This is directly affected by the lack of crediting parity for effluent storage in MUSFs vs USFs. Stakeholders should aggressively pursue crediting parity in the state legislature.

Almost all engineered flows on the Santa Cruz River originate from outfalls near the facility generating the source water (WRFs or the TARP project). Santa Cruz River Heritage Project is the first on the river to convey reclaimed water to an off-site outfall, which realizes social, cultural, economic, and environmental benefits not otherwise possible.

The preferred concept, Concept 4, builds on the success of the Heritage Project. It envisions effluent conveyance to a distributed system of outfalls that best realizes the goals of the linked/local/leveraged framework.

It further benefits from proposed management tools, like DRAM credits and variable flow regimes, that rely on physical infrastructure and state water policy to help the project realize maximum environmental benefit. These benefits include the creation of hydriparian habitat that emulates recurrent, if not persistent, historic conditions on the Santa Cruz River.

Recent price signals suggest macro trends can threaten the viability of new in-channel flows. Jurisdictions should take proactive steps to ensure that supply-demand imbalance does not imperil the viability of new and existing in-channel flows.

Finally, this work identifies numerous knowledge gaps and areas of potential future investigation and recommendations for future actions. These are collected in the numbered lists below.

Collected questions for possible future research

- 1.) What is the baseline tendency for species movement across I-19 at Demetrie Wash? Conservation groups may wish to deploy camera traps in this location (if not already present). Species may show relative preferences or aversions to different crossing types (Denneboom et al., 2021); camera traps at nearby culverts that cross I-19 could help to clarify these preferences for local species.

- 2.) What passive cooling methods are possible for improving water temperature at effluent outfalls, and how viable and cost-effective are they? This work may be informed by sampling water temperatures across Tucson Water's purple pipe system, where the diameters, depths, lengths, and flow volumes of mains are well-characterized.
- 3.) How does outfall design affect riparian habitat near the outfall point? These questions may be translated into design guidelines, e.g., a maximum height restriction that avoids flow from creating plunge pools and channelization.
- 4.) How do other components of the engineered environment affect riparian habitat and channel geometry? These include factors like stormwater outflow placement and design, the tendency or ability of grade control structures to impound shallow water and guide channel alignment, and other factors that "losing-reach" habitat and "channel lock" against soil cement banks.
- 5.) Is it possible and practical to induce locally perched regions of groundwater using engineered clogging layers? This may include studies on permeation grouting, injected thermoresponsive polysaccharides or other biological methods, and injected slurried fines. Researchers may ask how best to determine injection depths, extents, and desired hydraulic permeability.
- 6.) To what extent do long-term financial projections at the City and County level rely on assumptions about long-term water pricing? To how much risk does this expose budgets?
- 7.) By what process did Pima County determine that delivery of 112,000 acre-feet of water over one hundred years (the total delivery obligations to Robson Ranch Quail Creek LLC) was a reasonable obligation to incur?
- 8.) How can jurisdictions modify future water delivery agreements to ensure that they do not inadvertently incentivize new instances of hydrologic disconnect? Does the transfer of LTSCs between Robson Ranch Quail Creek LLC (Green Valley) and Robson Ranch Mountains LLC provide an informative case study?

Collected recommendations

- 1.) Pima County's deal with Robson delivery is favorable to Robson. Although the county Board of Supervisors wished to begin "moving golf courses from groundwater use," the LTSCs accrued by Robson in Green Valley have been transferred to an account affiliated with golf course development in a Pinal County portion of the Tucson AMA. Future water-delivery contracts should be considered in view of their potential to exacerbate hydrologic disconnect.
- 2.) Tucson Water should study whether and how effluent-dependent ecosystems respond to alternate water chemistries, such as the augmentation or replacement of effluent discharges with Colorado River water conveyed by CAP.
- 3.) Stakeholder groups should catalogue existing riparian restoration projects on the Santa Cruz River and its tributaries. The inventory can build on previous accountings (Fabre & Cayla, 2009; Zugmeyer et al., 2015). No single organization is responsible for riparian conservation and restoration projects. The Santa Cruz Watershed Collaborative, which coordinates among many responsible agencies, may wish to lead this initiative.
- 4.) ADWR should revise CWS reporting forms to better clarify the following: (1) type of water right(s) (e.g., Type 1 vs Type 2 groundwater right) and corresponding file number(s) permitting groundwater withdrawal during the reporting period, (2) the volume of water withdrawn under each right during the reporting period, and (3) the wells assigned to each right. These changes should be made in such a way that surface water banked in the aquifer (e.g., CAP water, effluent) can be easily disambiguated from other types of groundwater.
- 5.) Researchers may wish to compile a more an inventory of the effluent management practices and environmental outcomes along effluent-dependent watercourses in Arizona. These watercourses are identified in GIS assets extracted from ADEQ data sets during background investigation for this study.
- 6.) RFCDD and environmental management agencies should identify areas where infiltration of runoff and other flows are undesirable, for example, along channel reaches that overlie contaminant plumes or reaches adjacent to landfills. Agencies should consider whether it is sensible to reduce hydraulic conductivity in these areas, and whether it further makes sense to do so (e.g., via permeation grouting) during channel grading projects.
- 7.) Tucson Water should initiate discussions with CAIDD to gauge interest in mechanisms to continue effluent-based flows into Pinal AMA.

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