Agricultural managed aquifer recharge: Cases from the USA and Spain

Feasibility study of manager aquifer recharge for improved water productivity for Australian cotton production

Milestone 2.1 Project report

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NOTE: This is a report briefly describes five managed aquifer recharge schemes from the USA and Spain according to key factors that may be of interest to practitioners looking to implement similar schemes in Australia. While every effort has been made to ensure the accuracy and completeness of this report, no guarantee is given nor responsibility taken by the Australian National University (ANU) for errors or omissions and the ANU does not accept responsibility in respect of any information or advice given in relation to or as a consequent of anything contained herein.

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1.1 Introduction

Managed Aquifer Recharge (MAR) is an increasingly important water storage and supply management strategy, alongside demand management, to secure reliable water supplies while replenishing stressed groundwater systems and protecting water quality. MAR can be defined as the purposeful recharge of water to aquifers for subsequent recovery or environmental benefit. In the 50 years from 1965 to 2015, global MAR capacity has grown from 1000 to 10 000 GL/year (Dillon et al 2019). There are many examples from around the world that demonstrate the advantages of MAR (Ross and Hasnain 2018).

The USA accounts for 26% of the reported global MAR capacity. Annual average MAR in the US has grown from at least 302 GL in 1961-70 to at least 2569 GL in 2011-2015[1]. California accounts for over 70% of reported US recharge capacity, Arizona accounts for 20% and other states, notably New York, Florida and Texas, make up the remainder. Most of the reported recharge capacity is in infiltration basins (Dillon 2018). Although the majority of the MAR schemes in the US have been set up to secure urban water supplies, there are examples of well-established MAR schemes dedicated to supplying water for agriculture and irrigation

This report reviews four selected agricultural MAR case studies from the US and one from Spain, analysing key factors contributing to the feasibility and sustainability of each MAR scheme. These schemes have been selected to represent different MAR scales and technologies. The five schemes are the Arizona water bank, Kern water bank California, Kings River California, Central Platte Natural Resources Management District and the El Caracillo scheme in Spain. A summary of these schemes is given in Table 1.

The first part of the report contains an overview of each case study and factors affecting project feasibility and sustainability. The second part of the report includes further details and analysis of each case study including:

- objectives and evolution;
- physical feasibility; sources of water and recharge arrangements;
- financial and economic feasibility;
- impacts on third parties and the environment; and
- governance, legislation and policies.

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[1] These numbers understate capacity because reported capacity in many USA states is missing, and some projects are missing from the reports of those states who have them (Dillon 2018).

Table 1 Summary of case study qualities.

	Groundwater Active Management Areas, Southern Arizona	**Kern water bank, California**	**Kings Basin, San Joaquin Valley, California**	**Central Platte Natural Resource Management District, Nebraska**	**El Caracillo, Castilla y Leon, Spain**
Purpose	Manage GW overdraft, full utilisation of water from CAP scheme	Obtain reliable supplies	Obtain reliable supplies, manage groundwater overdraft	Enable continued production from irrigated areas	Mitigation of groundwater overdraft
Evolution	AWBA plans, water storage infrastructure	From state to locally managed project	From pilot project to full-scale activity	Rehabilitation of irrigation canals	From state development to locally managed project
Source water	CAP scheme, recycled water	SWP, CVP schemes, Kern River	High flows from San Joaquin and Kings rivers	Seasonal access flows and floodwaters	Diversions from the River Cega
Recharge	Direct recharge in spreading basins, in lieu recharge	75 recharge basins and 88 recovery wells on single site	Recharge on agricultural fields	Rehabilitated irrigation canals	16 infiltration ponds, 3 artificial wetlands, 2 weirs, 4 infiltration canals
Financial and economic viability	AWBA has accrued credits of more than US$1.1 billion	Costs substantially less than reservoir expansion; Member agencies pay user fees for storage and recovery	Costs substantially less than reservoir expansion or dedicated recharge basin	Large net benefits owing to additional agricultural production and increased land values	Net benefits owing to additional agricultural production and employment
Third-parties, and environment	Extensive water quality monitoring program	Habitat enhancement programs, conservation bank	Overall positive impact on nitrate pollution	Improved water quality, flood storage and bird habitat	Water quality targets, natural corridors
Governance	AWBA, LTSCs, accounting	KWB MOU, operational plan, KWBA monitoring committee	Partnership between KRCD, KRWA, KBWA	Partnership between CPNRMD, DWR, irrigation districts and canal companies	Partnership of irrigation farmers and governments, now managed by local council
Current and future Challenges	CAP water supply, water use efficiency, recovery from storage	Continuing availability of water for recharge	Sustainable funding mechanisms, flexible flood capture, water right constraints, risk management	Monitoring and maintenance of return flows	Maintaining support for continued diversions from River Cega

Note: ADWR = Arizona Department of Water Resources, AWBA= Arizona Water Banking Authority, CAP= Central Arizona Project, CPNRMD= Central Platte Natural Resource Management District, CVP= Central Valley Project, KRCD= Kings River Conservation District, KRWA= Kings River Water Association, KBWA= Kings Basin Water Authority, KWB MOU= Kern Water Bank Memorandum of Understanding, KWBA= Kern Water Banking Authority, LTSC= Long-term storage credits, SWP= State Water Project

1.2. Overview of the case studies

1.2.1 Groundwater Active Management Areas, Southern Arizona

Groundwater use in central Arizona increased in the 20th century as cotton acreage boomed and cities grew after World War II. Heavy groundwater pumping far exceeded natural recharge, creating a severe overdraft problem for central Arizona. In 1980 the Arizona legislature passed the Groundwater Management Act – an extensive legal framework for groundwater regulation. Five Active Management Areas (AMAs) were established under the Act and required to draw up management plans to reach safe yield (recharge and extraction in balance) by 2025. Further expansion of irrigated area is prohibited in the AMAs. More than half of Arizona's 3,454 GL annual allocation of Colorado River water is delivered to municipal and agricultural users in the central and southern portion of the state through the Central Arizona Project (CAP) - pumping plants and a 540 km aqueduct. In 1996, the Arizona legislature established the Arizona Water Banking Authority (AWBA) which is responsible for fully utilising Arizona's entitlement to Colorado River water and creating a reserve water supply in case of future Colorado River shortages. Since its creation, the AWBA has utilized MAR to store about 5,500 GL of surface water from the Colorado River. Water is stored in one of 84 direct recharge and 16 *in lieu* recharge facilities that have been permitted across the state. The AWBA primarily obtains revenues through state-wide groundwater withdrawal fees of $2.02 per ML of extracted groundwater and a $0.04 *ad valorem* property tax as well as state legislative appropriations. The impact of recharge operations is extensively monitored by the Arizona Department of Water Resources (ADWR), and MAR facilities are required to routinely sample water quality.

1.2.2 Kern County Water Bank, California

The Kern Water Bank (KWB) was formed by a group of agricultural organisations and water districts in response to a seven year drought which demonstrated that supplies of imported surface water were unreliable. Water is sourced from the State Water Project (SWP), the Central Valley Project (CVP) and the Kern River. The KWB benefits from its location at the confluence of multiple surface water sources and the presence of conveyance infrastructure to transport water. The KWB is situated on 20,000 ha over the highly permeable Kern River alluvial fan which enables relatively fast recharge and recovery. The recharge facilities include 75 shallow recharge basins, 88 recovery wells, 58 km of pipeline, 10 km KWB canal and three pump stations. Member agencies pay an operational cost of between $7.70 and $13 per ML for recharge and between $79 and $124 for recovery. The main benefit of the KWB has been increased water supply reliability for member agencies - surface water allocations have ranged from a low of 5% in 2014 to a high of 70% in 2002. From 1995 to February 2012 maximum annual recovery from the bank was 280 GL. From 1995 to 2006 a total of 1230 GL was recovered. The Kern Water Banking Authority (KWBA) ensures that water recharged and recovered complies with Federal and state water quality regulations. The KWB has programs to provide increased wildlife habitat around its facilities and operates as a conservation bank available for purchase of water to mitigate environmental damages caused by other projects. The KWB is governed by an MOU and an operational plan which includes water sharing rules. The MOU provides for the establishment of a monitoring committee that prevents adverse changes in water levels, water quality or land subsidence. The willingness of KWB members to take on the risk of project development has been a key factor in the success of the project.

1.2.3 Kings Basin, San Joaquin Valley, California

The Kings Basin has been operating under severe overdraft conditions for many years. Diverting flood flows for groundwater recharge, a process known as on-farm flood capture, is considered an important tool for coping with more-variable future precipitation. Recurring floods along the King River lead to high flow conditions when the U.S. Army Corps of Engineers diverts Kings River water into the North Fork-James Bypass channel. Agencies in the Kings Basin maintain over 4,000 ha of recharge ponds and flood control basins with the capacity of recharging over 120 GL of water in a single year. Costs of on-farm capture and application of flood flows are estimated at $US44 per megalitre compared with $US 370-1360 per ML for surface water storage and US$110-1360 per ML for dedicated recharge basins. Strategic implementation of on-farm flood capture could dilute common contaminants such as nitrate and salts and improve groundwater quality. The Kings River Conservation District (KRCD), the Kings River Water Association (KRWA), and the Kings Basin Water Authority (KBWA) have facilitated water management planning, groundwater monitoring and data collection, regional project development and water delivery and recharge. Implementation challenges include providing sustainable funding mechanisms, developing flexible flood capture strategies, working within water rights constraints and managing risks for growers.

1.2.4 Central Platte Natural Resource District, Nebraska

Nebraska has developed more irrigated land than any other state in the USA, mostly producing maize and soybeans. This has led to increasing pressure on water supplies, leading to conflict and legal battles. Nebraska's Natural Resource Districts, government agencies, private irrigation districts and canal companies have increasingly turned to MAR to maintain groundwater and surface water supplies while making use of excess flows and floodwaters. Seasonal excess flows and floodwaters are captured in rehabilitated irrigation canals, and infiltrate from the canals to recharge the underlying aquifer. A proportion of these flows eventually return to the Platte River as baseflow. It is estimated that the annual value of additional agricultural production owing to MAR is US$3.33 million. The additional land value owing to the transformation of 4830 ha from non-irrigated to irrigated land is US$43.7 million. MAR also leads to improvements in water quality and flood storage, and provides habitat for endangered bird species. The Central Platte Natural Resource Management District (CPNRMD) is responsible for groundwater quantity and quality. The CPNRMD cooperates with the Nebraska Department of Natural Resources (who is responsible for surface water administration) to coordinate and deliver sustainable water management under local and interstate water management plans.

1.2.5 El Carracillo, Castilla y León, Spain

Since the mid-20th century the expansion of irrigation from "Los Arenales" aquifer, located in Castilla y Leon, Spain, has led to a decline in the groundwater level of more than 20 m. In order to mitigate this impact, the Spanish Ministry of Agriculture (MAPA) initiated MAR demonstration projects and developed MAR facilities including the El Carracillo MAR system. In 1994, farmers from nine municipalities of the region joined in an irrigation association and proposed a water management plan to the political and the river basin authorities. The plan was approved in 1999 with a maximum 14.2 GL water concession diverted from the Cega River yearly between January and April and the total annual water diversion capped at 22.4 GL. The average annual effect of MAR can be measured as 314.3 m^3/ha out of 1,318 m^3/ha extractions, so the MAR contribution to total irrigation is about 23.8%. This important contribution is valued at about €12 million out of the overall value of agricultural production from the El Carracillo system of about 50M €/year. Water quality analysis and groundwater level monitoring have been carried out in a series of sampling points. All the MAR facilities rely on gravity for water infiltration, without any energy consumption. The 16 infiltration ponds provide a recreational facility for the villages' population. Three artificial wetlands and two weirs have been reinstated for ecological reasons and infiltration canals (17 km) provide natural corridors for flora and fauna. The project, building works, tracking and further monitoring are organised by communities of irrigation farmers. El Carracillo Council is responsible for the management and maintenance of the scheme.

1.3 Conclusions

The five case studies demonstrate the capacity of MAR to achieve a range of objectives including management and mitigation of groundwater overdrafts, reliable and consistent supplies of water and continued production from agricultural areas. All of the case studies have experienced considerable evolution of objectives and infrastructure. Two have transitioned from state initiated to locally managed schemes and several have grown from pilot projects into long-term commercial activities.

The physical feasibility of the case studies has depended on reliable supplies of source water and the development of effective recharge facilities. The Arizona and Kern recharge areas have relied on water supplies from large state water distribution schemes, while the others have been able to tap into periods of high flows in local rivers. The case studies display a wide range of recharge facilities including recharge basins, injection and recovery wells, irrigation canals and artificial wetlands.

The financial viability of the larger schemes has been facilitated by revenue raising and user fees. MAR has enabled additional irrigated areas and agricultural production which has provided substantial economic benefits. The schemes have proved capable of meeting water quality standards, and three of the schemes provide environmental benefits such as natural corridors and bird habitat.

All of the schemes have comprehensive governance arrangements involving partnerships by multiple agencies and user groups, strong accountability mechanisms and effective monitoring of recharge outcomes and third party impacts.

The five case studies demonstrate that managed aquifer recharge can make an important contribution to regional water security and stability of supply provided that sustainable water sources, governance and financing mechanisms are in place.

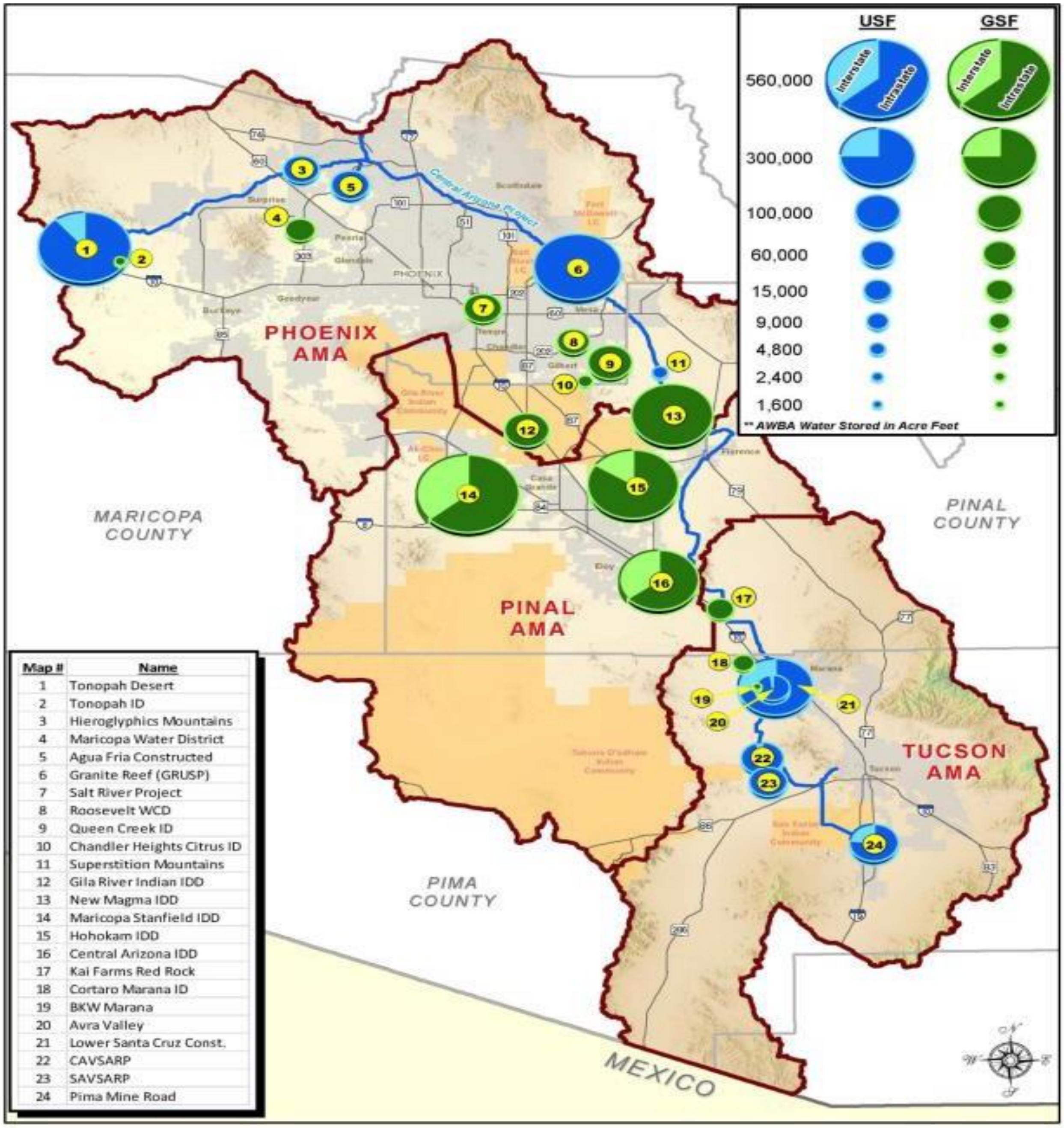
2 Groundwater Active Management Areas, Southern Arizona

2.1 Introduction and overview

Groundwater use in central Arizona increased in the 20th century as cotton acreage boomed and cities grew after World War II. Heavy groundwater pumping far exceeded natural recharge, creating a severe overdraft problem for central Arizona. In some areas well pumping has caused groundwater depressions and severe groundwater overdrafts also caused subsidence. In 1980 the Arizona legislature passed the Groundwater Management Act (GMA) – an extensive legal framework for groundwater regulation. Five Active Management Areas were established under the Act and required to draw up management plans to reach safe yield by 2015 with recharge and extraction in balance (ADWR 2019). The GMA does not permit further development of agricultural land for irrigation. Developers building in the AMAs must demonstrate an assured water supply capable for sustaining residence for at least 100 years (http://www.amwua.org/blog/assured-water-supply-program-protecting-homebuyers-while-ensuring-responsible-growth, Accessed 9 March 2020).

Water supplies include in-state surface water, groundwater, and water from the Colorado River, which is shared with six other states and the Republic of Mexico. More than half of Arizona’s 3,454 GL annual allocation of Colorado River water is delivered to the central and southern portion of the state through the Central Arizona Project (CAP). CAP water is delivered to a variety of municipal and agricultural users, as well as indigenous American Indian communities (Megdal et al 2014). A schematic of the recharge facilities is shown in Figure 1.

In 1996, Arizona legislature established the Arizona Water Banking Authority (AWBA) to make full use of Arizona’s Colorado River entitlement, to address groundwater depletion in central Arizona and to protect Colorado rural water users against future shortages and inter-annual variability of water supply. The AWBA depends on strong state involvement and support, including the financial structure that supports the AWBA. Each year the AWBA pays the cost to deliver any surplus of Arizona’s entitlement to Colorado River water into central and southern Arizona and to store that water underground (ADWR 1999). Since its creation, the AWBA has utilized MAR to store nearly 5,600 GL of surface water from the Colorado River. The legislature also established a centralised state agency, the Arizona Department of Water Resources (ADWR) to implement the GMA and management plans for the AMAs (Silber Coats and Eden 2017).



Map #	Name
1	Tonopah Desert
2	Tonopah ID
3	Hieroglyphics Mountains
4	Maricopa Water District
5	Agua Fria Constructed
6	Granite Reef (GRUSP)
7	Salt River Project
8	Roosevelt WCD
9	Queen Creek ID
10	Chandler Heights Citrus ID
11	Superstition Mountains
12	Gila River Indian IDD
13	New Magma IDD
14	Maricopa Stanfield IDD
15	Hohokam IDD
16	Central Arizona IDD
17	Kai Farms Red Rock
18	Cortaro Marana ID
19	BKW Marana
20	Avra Valley
21	Lower Santa Cruz Const.
22	CAVSARP
23	SAVSARP
24	Pima Mine Road

Figure 1 AWBA Recharge Facilities 2014.

The aquifers of the central and southern part of the state are well suited to MAR, and for many years the available supply of CAP water has exceeded the annual demands of the users with long-term rights to the supply. This temporary mismatch created an opportunity for water banking by a number of entities, including the AWBA. From the year 2000 through 2009, the AWBA stored an average of 342 GL per year.

Without the water stored by the AWBA, the aquifers of central and southern Arizona would be under greater current and future stress. Extensive and regular groundwater level measurements have confirmed the rise in water levels associated with water banking. The success of the AWBA can be traced to factors that include: local political consensus; a large temporary water supply; favorable hydrogeology; supportive regulations; public funding; and institutional innovation.

This case study provides an overview of aquifer recharge and recovery in the southern Arizona AMAs with some additional illustrations from the Tucson AMA.

2.2 Physical feasibility

2.2.1 Availability of water for storage

Aquifers in alluvial basins in South Central Arizona were heavily used and depleted during the last century. By 1980 an estimated 230 GL of groundwater had been abstracted. Maximum declines ranged from 30 to 120 m in different regions. The expansion of aquifer storage capacity is estimated to be one hundred GL, three times the capacity of the largest reservoir in the US (Lake Mead, 32 GL).

Action under the GMA has sought to reduce the groundwater overdraft by substituting other sources of supply for groundwater and by increasing the efficiency of groundwater use. The main alternative supply has been from the 540 kilometre CAP aqueduct with its 14 pumping stations. CAP deliveries totaled 30.5 GL between 1983 and 2013. CAP deliveries for irrigation were 17.4 GL, representing 56% of total deliveries, and peaking in 2000 at 1 GL (Scanlan et al 2016). Water delivered for MAR in Arizona totaled 7.3 GL between 1994 and 2013 with 75% from CAP water and 19% from recycled municipal wastewater. The availability of unused Colorado River water is central to the success of the AWBA. However, the volume of unused Colorado rural water available to the AWBA has been decreasing since 2010 and may become unavailable if shortage conditions occur in the lower Colorado basin. Modelling indicates that this could occur as soon as 2021.

2.2.2 Agricultural water use

Management plans for each AMA established mandatory conservation goals for groundwater users that apply to most non-exempt wells (wells that pump in excess of 160 L/minute or 0.07 GL/year) in the agricultural industrial and municipal sectors. The projected reduction in availability of unused CAP water means that future AWBA operational activities are likely to shift. There will be more emphasis on efficient groundwater use and management, including the distribution of Long-Term Storage Credits (LTSCs; Gelt et al 1999).

Increased attention on recovery of water will be required. 25% of water stored in Underground Storage Facilities (USFs) is located in areas where no wells or other infrastructure exists to recover or transport water. In this situations, either additional infrastructure is needed to allow recovery or indirect recovery can be achieved through the exchange of Long-Term Storage Credits (LTSCs) that allow for the storage and recovery of water. LTSCs are created when a recharging entity stores water in an aquifer, and grant a right to withdraw groundwater at a later date. LTSCs can be used by recharging entities or sold or transferred by those same entities to other water users (Silber Coats and Eden 2017). In some areas, recharged water was stored in aquifers that had high levels of arsenic and fluoride. Water recovered from those storage facilities will require treatment prior to use.

In the Tucson AMA no new agricultural land can be developed for irrigation. Farms have been given a maximum annual groundwater allowance for irrigation. This is based on the historic irrigated area on a farm in the five years before the GMA and an amount of water to be used per acre called a water duty. The irrigation water duty is being reduced over time as increasing water application efficiencies are required. Cotton is the predominant crop grown in the Tucson AMA accounting for 75% of planted acreage. CAP deliveries to the Tucson AMA are primarily for MAR (1.5 GL [69%]; Gelt et al 1999). Agricultural water users are important stakeholders of the AWBA, and with together with other major users, make an important contribution to the success of the organisation.

2.2.3 Aquifer storage

Arizona law recognises two primary types of MAR; direct recharge and *in lieu* recharge (Megdal et al 2014). Water is stored in one of 84 direct recharge and 16 *in lieu* recharge facilities across the state. Since its creation, the AWBA has utilized MAR to store nearly 5,600 GL of surface water from the Colorado River.

- Direct recharge occurs through state-permitted USFs. There are three recognized forms of USF's under state law: (1) *managed USFs* refers to direct recharge by percolation through a stream channel; (2) *infiltration basins* refers to recharge via percolation of water through a constructed basin (Figure 2); and (3) *injection recharge* refers to recharge through an injection well into the aquifer. USFs are owned and operated by municipal and third party entities. To establish a USF, entities must obtain a permit from ADWR[2]. The USF permitting process includes a description of facility characteristics, an analysis of unreasonable harm and hydrologic feasibility, a monitoring plan, the proving of technical and financial capability, and establishment of legal access.
- *In lieu* recharge occurs through Groundwater Savings Facilities (GSF)[3]. These facilities are irrigation districts that utilize Colorado River water, effluent, and other surface water instead of pumping groundwater to which they are legally entitled under the 1980 GMA. In the Tucson AMA irrigators have groundwater saving facilities but they do not have underground storage facilities.

Figure 2 CAP aquaduct and Agua Fria Recharge Basins, Phoenix AMA

Farms using less than their groundwater allowance are given a credit for the difference between the actual groundwater use and the groundwater allowance. These credits are accumulated in a flexibility account and can be used in future years. Annual groundwater allotments were set near the historic peak of irrigation acreage, thus much more groundwater than is needed is legally available to farmers each year. With increasing irrigation efficiencies and significant amounts of farmland leaving production many farms have accumulated large flexibility account balances (Gelt et al 1999).

2.3 Financial and economic feasibility

The Arizona Water Banking Authority manages aquifer recharge and water banking operations. Operation of the AWBA is financed through a variety of means. The AWBA primarily obtains revenues through state-wide groundwater withdrawal fees of $2.03 per ML of extracted groundwater, and a $0.04 *ad valorem* property tax collected in Maricopa, Pinal, and Pima counties[4]. AWBA funding also comes from state legislative

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[2] https://waterbank.az.gov/water-storage

[3] https://waterbank.az.gov/water-storage/storage-facility-types

[4] http://www.azwaterbank.gov/Background/Funding.htm

appropriations from the Annual General Fund for water banking and for groundwater replenishment purposes. Lastly, the AWBA receives monies from authorized interstate banking entities in California and Nevada. In carrying out its operations, the AWBA can also request that its GSF partners, as recipients of *in lieu* water, pay a share of the water delivery costs. Funding for the operation of USF's and GSF's is the responsibility of owners who obtained funding through user permits and user fees.

Through 2018, the AWBA has expended $US 393 million to purchase and store water, and it holds 5311 GL of storage credits (AWBA 2018). In 2019 dollars, those expenditures equate to $US 490 million, for an average cost of $US 0.092 per m^3 recharged. It is possible to value the AWBA credits based on market transactions. In addition the credits held by the AWBA, there are approximately 9000 GL of credits held by others, including cities, American Indian communities, and private companies. While most of those credits are held for later use by the storers, some are available for purchase and a market with a number of transactions has emerged. Average purchase prices in 2017 and 2018 were in excess of $US 0.20 per m^3, which suggests that the in-place value of the AWBA's accrued credit balance may exceed $US 1.1 billion USD.

Farms in the Tucson AMA declined to take contracts for CAP water because it was more expensive than the cost of native groundwater. However they have had access to CAP water from GSF facilities at a cost below the cost of pumping groundwater, and they can get pumping credits to meet state water pumping restrictions (Gelt et al 1999).

2.4 Third party impacts

ADWR has an extensive monitoring program, including both automated and field measured water levels. Statewide groundwater data are available online[5]. There are also specific water level monitoring requirements for MAR facilities[6]. MAR facilities in Arizona are required to routinely sample water quality in monitor wells adjacent to spreading basins. The quality of the source CAP water is also regularly monitored, and falls well below nationally established drinking water quality standards[7].

The energy requirements for recovery wells varies by location, but reported pumping energy for irrigation wells in the central portion of the state range between 0.48 kWh/m^3 and 0.91 kWh/m^3, with costs of $US 0.02/m^3 to $US 0.04/m^3.

2.5 Governance, legislation and policies

Legislation, including Arizona's 1980 Groundwater Management Act (GMA), 1986 Underground Water Storage and Recovery Act and the 1994 Underground Water Storage and Replenishment Act set the stage for storing and recovering water in the state's five Active Management Areas (AMAs). The GMA created a system of rights and permits for the AMAs, and prohibited new agricultural land. The 1986 and 1994 acts included provisions for underground storage and set up a system for tracking and accounting for water.

The AWBA stores the state's unused Colorado River entitlement. That stored water is accounted for as LTSCs. During shortage conditions in the Lower Colorado River basin, Colorado River water is allocated according to priority. Shortages of Colorado River water significantly impact CAP subcontractors. When shortages in the availability of CAP water affect entities for which the AWBA has stored supplies, the AWBA will distribute LTSCs to those entities, generally free of charge. Entities receiving a distribution of LTSCs from the AWBA can then exchange the LTSCs for groundwater, in essence substituting an entitlement to pump groundwater in place of surface water deliveries (Silber-Coats and Eden 2017).

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[5] https://gisweb2.azwater.gov/gwsi

[6] https://new.azwater.gov/recharge/applications

[7] https://www.cap-az.com/departments/water-operations/water-quality

There is a thriving market for the recharge of water and subsequent sale of LTSCs in central Arizona and the cost to purchase a LTSC has fluctuated over the past ten years between $36 and $324 per ML. For each megalitre of water stored via direct recharge in an USF, the user receives an equivalent LTSC minus a 5% deduction, known as “a cut to the aquifer,” which is intended to represent water lost through evaporation and provides a net gain of water to the aquifer. The 5% cut to the aquifer assigned when calculating LTSCs at USFs was a negotiated number that may inadequately represent the true losses from storage. For the bank to stay in balance, long-term deposits need to match withdrawals and there will need to be adjustments if “paper water” does not match physical supplies (Silber-Coats and Eden 2017).

The AWBA is housed at ADWR, which provides administrative and technical support. ADWR performs its managerial duties in coordination with the Central Arizona Water Conservation District (CAWCD), which manages and operates the CAP. ADWR is responsible for the allocation and regulation of the use of Colorado River water. ADWR also is responsible for the permitting of USFs, GSFs and the management of LTSC accounts. CAWCD serves as the chief manager and operator of the CAP, and contracts delivery of Colorado River water to AWBA storage facilities. GSFs and USFs are regulated by ADWR but managed by their respective permittees; these permittees must manage and maintain their recharge facilities in order to assure safe conditions for future usage (Megdal 2012).

3 Kern Water Bank, California

3.1 Introduction: objectives and evolution

Kern Water Bank (KWB) is located 19 km west of Bakersfield in Kern Co, California (Figure 3). The county has a dry climate and receives an average of only about 165.1 mm of rain (ICF 2018). The KWB was formed by a group of agricultural organisations and water districts in 1995 in response to a seven year drought which demonstrated that supplies of imported surface water were unreliable. Banked water can be withdrawn from the bank at the request of participants, mostly agricultural users. The infiltration ponds used for recharge also provide environmental benefits by providing a wetland habitat for migrating birds and protected species

Water stored in the bank comes from the three different water sources and is stored in the aquifer via irrigation ponds. The KWB is situated over the Kern River alluvial fan, made up of gravel and sand from ancient streambed channels. The alluvial fan is highly permeable and physically well suited for aquifer recharge. There are more than 11 other groundwater banking operations in the region. The main source of water for the region and the KWB is the State Water Project (SWP), other sources are the Central Valley Project (CVP) and the Kern River. 87% of the stored water goes to agricultural uses (Tiedeman et al 2016). Agriculture accounts for 20% of the exports from the county, valued at over US$7 billion in 2017.

There is a temporal and spatial mismatch between the demand and supply of water in California. Most of the demand is from Southern California in summer while most of the supply comes from Northern California in winter. The SWP was constructed in the 1960s to provide a reliable and secure water storage and delivery system. The SWP transports water from Northern California to 29 long-term contractors throughout the state[8]. DWR retains legal rights to SWP water, while contractors hold annual entitlements. These annual allocations are based on current water conditions, and in most years these are less than the full contract amount.

DWR initiated the development of a groundwater bank in Kern Co in 1986 and subsequently purchased 8093 ha of land from Tenneco West, which had constructed 320 recharge ponds in partnership with the Wheeler Ridge-Maricopa Water Storage District. In 1993 the development of the bank was halted owing to high costs, Endangered Species Act habitat regulations, uncertainty over water available for storage and negotiations over

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[8] https://water.ca.gov/Programs/State-Water-Project

local use of the bank (Thomas 2001). During the drought from 1987-1994 SWP allocations for agriculture were cut sharply and agricultural SWP contractors suffered from a lack of reliable surface water supply. Water users increased their reliance on local groundwater but were unwilling to pay the cost of stored water estimated at between US$490-550/ML.

Figure 3 Location of Kern Water Bank.

In 1994 DWR and SWP contractors negotiated the Monterey Agreement which included a provision that transferred KWB Lands to several Kern Co agricultural entities in exchange for permanent retirement of 56,000 ML of their contractual entitlements to SWP water. The KWB was transferred to the Kern Water Bank Authority (KWBA), which was formed by the contractors whose SWP contracts were reduced. The KWB has been in operation since 1995 despite several legal disputes following from the transfer of the KWB from state to local control (Miller et al 2014).

3.2 Physical feasibility

3.2.1 Source of water

The majority of water banked in the KWB comes from the SWP (58.5%). The SWP water is crucial for supplying the scheme and motivating local stakeholders. SWP water travels to Kern Co through the 715-km-long California Aqueduct and is delivered to the KWB's recharge ponds via local canals (Miller et al 2014). The Kern County Water Authority (KCWA) is the local SWP contractor, which is responsible for distributing SWP water to

13 local water districts. These include Kern Water Bank Authority (KWBA) members Tejon-Castac Water District, Wheeler Ridge-Maricopa Water Storage District, Semitropic Water Storage District, and KCWA's Improvement District No. 4.

About 27% of KWB banked water comes from the 164 mile long Kern River, which is fed by snow melt from the southern Sierra Nevada mountains (ICF 2018). In most years the river is dry downstream of Bakersfield owing to diversions for irrigation and municipal water supply. KWB has not received water from the Kern River for over half of the years that the bank has been in operation. Kern River water can be diverted to the KWB through several channel facilities including the KWB canal. In wet years flood flows from the river may be diverted to the bank at the request of the Army Corps of Engineers. Kern River floodwater is supplied to members of the KWB at the cost of conveyance.

CVP water makes up the remaining 14.5% of water entering the KWB. CVP is the Federal water storage and delivery system operated by the US Bureau of Reclamation (BOR) and CVP water enters the Kern River through the Friant-Kern canal. The KWB acquires CVP water through short-term arrangements with the BOR (AECOM 2016).

The KWB benefits from its location at the confluence of multiple surface water sources and from the presence of conveyance infrastructure that can transport water. The greatest challenge faced by the bank is to ensure continued supply of water to the bank through prolonged droughts.

3.2.2 Recharge

The Kern Water Bank Covers 8,288 ha which is mostly located over the highly permeable Kern River alluvial fan. The bank is also located at the intersection of several conveyance structures that already existed when the bank was created including the Friant-Kern canal and the California Aqueduct. These allow the KWB to obtain water from a variety of sources, depending on availability. The recharge facilities include 75 shallow recharge basins, 88 recovery wells, 58 km of pipelines, the 10 km KWB canal to the Kern River and three pump stations (ICF 2018; Figure 4). Recharge basins make up a total of 3035 ha of KWB property, arranged in rows with small canals connecting neighbouring ponds. The basins have an average water depth of 0.61 m. Recharge is relatively fast, between 46 mm/day and 122 mm/day, with slower recharge rates at the end of a long recharge cycle. The bank has the ability to recharge 49,000 to 74,000 ML per month.

Recovery wells are located on the northern two thirds of the area. These wells are spaced at 0.54 km intervals, average 229 m deep and can yield up to 19000 litres per minute. Water is recovered from the bank by pumping at the request of KWB members subject to KWB control measures to protect water levels. KWB members may also exchange surface water intended for a nearby groundwater banking project for the accounting transfer of KWB water to that project. They may also sell banked water to nonparticipant agencies but must first offer other KWB members the opportunity to purchase their water. Currently a total of about 1120 GL is stored in the bank. From 1995 to February 2012 maximum annual recovery from the bank was 280,000 ML. From 1995 to 2016 a total of 1850 GL was pumped with an annual average of 84 GL per year.

Water used for recharge is tracked by several entities. The DWR and KCWA track water diverted from the SWP and the DWR measures diversions. Sales of water from the bank and recharge accounting are governed by the KWB[9]. A loss factor of 10% is assumed for all water banked in the KWB. Bank participants can sell the stored water to third parties. If water is sold to an entity outside of Kern County an additional 5% loss factor is included in the sale (ICF 2018). Water going out of the bank is jointly accounted by KCWA and DWR and transported in the California Aqueduct.

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[9] http://www.kwb.org/store/files/109.pdf;

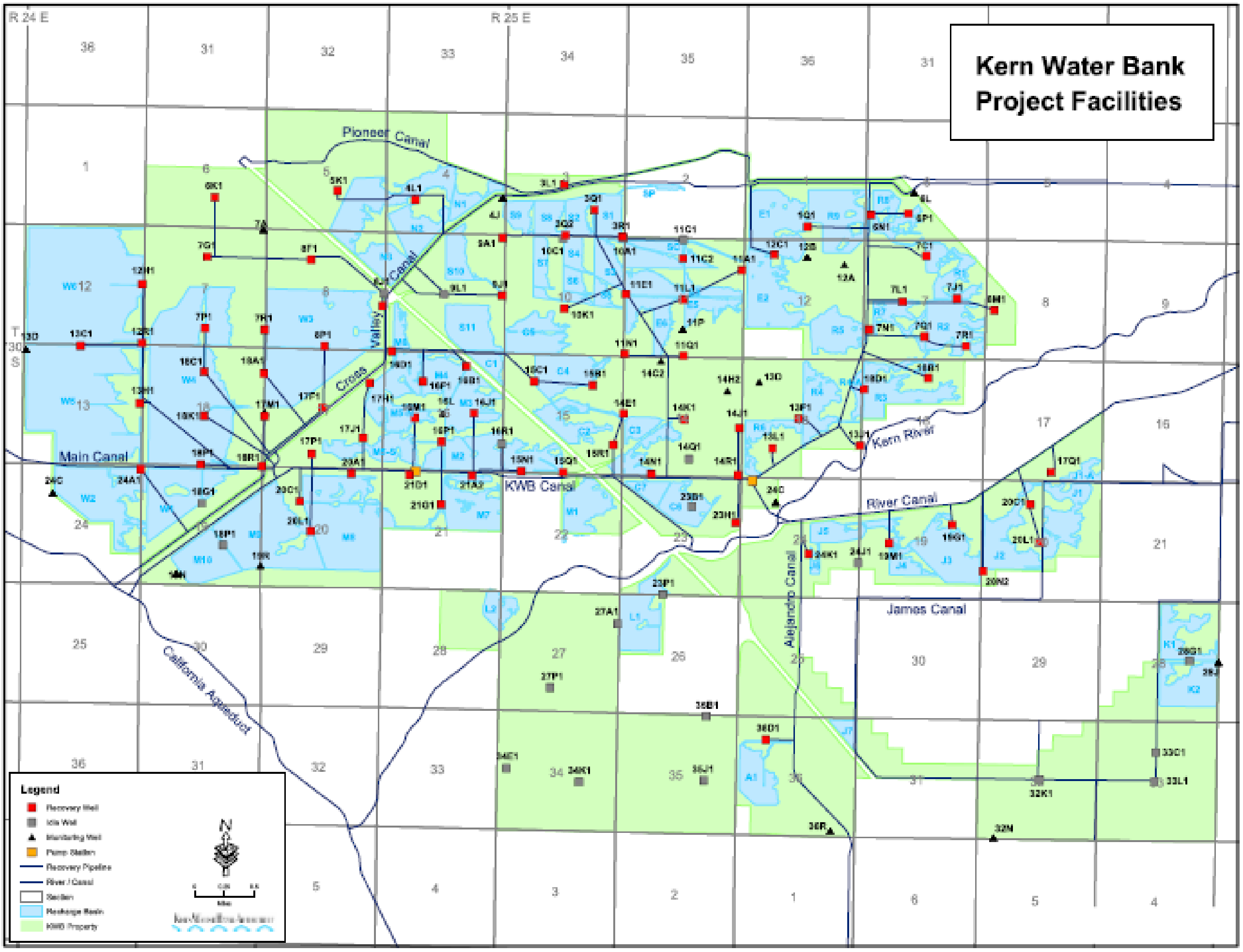

Figure 4 Kern Water Bank Project Facilities.

3.3 Financial costs and viability

The capital cost of the KWB Infrastructure the KWB Canal totalled about US$35 million. US$27 million came from private loans, US$5 million from a proposition 204 loan (Null and Viers 2013) and US$3.4 million from a proposition 13 grant[10]. Member agencies pay the operational of between $7.70 and $13 per ML for recharge and between $79 and $124 per ML for recovery[11]. Member agencies also pay for the operation and maintenance of banking facilities through assessments based on their share in the project.

At the end of each financial year KWB reconciles actual operating costs with charges to members, and may refund any overpayment to members (Thomas 2001). However, a relatively small number of landowners control member agencies which in turn collectively influence KWB operations. These landowners are ultimately the direct beneficiaries of KWB water deliveries and of resulting profits from beneficial use of water for agricultural purposes or from the sale of stored water.

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[10] https://www.waterboards.ca.gov/water_issues/programs/grants_loans/propositions/prop13.shtml

[11] Personal Communication, KWBA.

The main benefit of the KWB is the increased water supply reliability for its member agencies. During dry years SWP allocations have been below 100%, for example a low of 5% in 2014 and a high of 70% in 2002[12]. Banked water is allotted to bank members to keep crops alive and maintain production and profit. Groundwater recharge and recovery is substantially cheaper than alternatives, for example it is estimated that the cost of groundwater recharge is between $US74 and $US900 per ML whereas the cost of reservoir expansion is between $US1390 and $US2200 per ML (Choy, McGhee and Rohde 2014).

3.4 Impacts on third parties and the environment

Water recharged and recovered by the KWBA must comply with federal and state water quality regulations. The Central Valley Regional Water Quality Control Board implements the Tulare Basin Plan which covers the Kern County sub-basin. The Basin plan specifies allowable levels of pollutants in surface water and groundwater. KWBA monitors groundwater quality through testing of both dedicated monitoring wells and the recovery wells. DWR determines if water meets criteria needed for discharge into the California Aqueduct for delivery to KWBA members.

In addition to benefiting its members by providing water during shortages, the KWB also benefits the local environment by providing increased wildlife habitat. The KWB has re-established 4856 ha of grassland habitat and 3035 ha of aquatic or semi-aquatic habitat around recharge ponds. In 2011 and 2012 35,000 individuals of 66 species of water birds were estimated to have utilised the KWB during their winter migration (ICF 2018). Land withdrawn from agricultural production to accommodate the ponds also provides benefits of a carbon sink.

1538 ha of the project operate as a conservation bank, available for purchase for the mitigation of environmental damages caused by other projects. Companies and organisations with projects that impact threatened or endangered species in the Kern Co area can apply to purchase off-site mitigation credits.

The Environmental Water Account (PWA) was a source of income for the KWB from 2000-2007. The EWR was designed to reduce conflicts between environmental needs and other water users in the Sacramento-San Joaquin Delta. The EWR allowed fisheries managers to purchase from contractors water that would otherwise have flowed out of the Delta in order to protect endangered fish species. Up to $50 million per year of federal and state taxes was available to the EWA[13]. From 2000-2005 the KWB sold 390,000 ML of water to the EWA.

3.5 Governance: legislation, policy and operations

The KWB is governed by an MOU and operational plan (Miller et al 2019). Both state water contracts and the Endangered Species Act (ESA) play an important role in the regulation of the bank. State water contracts establish allocations to each SWP contractor. If KWBA action has potential to impact a threatened or endangered species it must obtain an incidental take permit from the US Fish and Wildlife Service. These permits are often conditional on development and approval of a Habitat Conservation Plan. The KWBA has created a Natural Community Conservation Plan under California's NCCP Act with the goal of contributing to species recovery.

The KWB is governed by the KWBA, a joint powers authority (JPA) with six member agencies: two California water districts (WDs), two California water storage districts (WSDs), the KCWA and the Westside Mutual Water Company (WMWC). The WDs and WSDs supply water for agricultural purposes. The JPA dictates that each KWBA member agency has rights to the project proportional to the amount of SWP water the member agency retired in the agreement that transferred the KWB from the DWR to the KWBA (Miller et al 2019). 55,500 ML of

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[12] http://www.mwdh2o.com/PDF%202016%20Background%20Materials/Chart%20-%20MWD%20Water%20Sales%20and%20SWP%20Conditions%20-%20All%20Years%20(1990-2015).pdf

[13] http://www.calwater.ca.gov/content/Documents/new_final_framework.pdf

the members' SWP water allocations were retired as part of this transfer. Each member of the KWBA has a seat on the board of directors which governs the KWBA.

The Kern Fan Monitoring Committee oversees water banking in the KWB to prevent adverse changes in water levels, water quality or land subsidence (ICF 2018). The KCWA and all water districts adjacent to the KWB are members of this committee. The monitoring committee is also responsible for suggesting resolutions to disputes before any legal action may be taken. The KWBA has two recovery operations plans aimed at avoiding adverse impacts on nearby landowners from KWB pumping. The Long-Term Project Recovery Operations Plan creates a groundwater model to evaluate the impacts of project operations and mitigate any negative impacts. Several KB entities[14] have established a separate joint project recovery operation plan to cover their operations.

4 Kings Basin, San Joaquin Valley, California

4.1 Introduction and overview

California's Central Valley accounts for roughly 10% of U.S. agricultural production: valued at $45 billion in 2014. The region faces two major hydrologic issues: severe and chronic groundwater overdraft, and flood risks from winter storms with an increased frequency of extreme run-off events owing to climate change (Hayhoe et al 2004). The Kings Basin, a sub-basin of the San Joaquin Valley Groundwater Basin, covers 4000 km^2, including parts of Fresno, Kings and Tulare Counties (Figure 5). The basin is in chronic overdraft. On average, it loses between 123 and 200 GL of groundwater each year from an estimated total storage capacity of 115,000 GL (Kings Basin Water Authority, 2012).

Two major sources of surface water are the San Joaquin River and the Kings River. Both provide water for irrigation and groundwater recharge, distributed through an extensive canal network maintained by federal and local agencies.

The Kings Basin supports significant agricultural production, with crops ranging from grapes and figs to nuts and stone fruit. Irrigated lands are the largest source of water demand in the basin and comprise roughly 75% of the total basin area; 12% is in urban use and the remaining 13% is undeveloped.

The Kings Basin has been operating under severe overdraft conditions for many years. California's five-year drought, as well as operational changes to statewide water delivery systems resulting from endangered species protections in the Sacramento-San Joaquin River Delta and pumping actions in adjacent basins, has exacerbated this rate of depletion. Groundwater quality, closely tied to water availability, is another ongoing challenge for the Kings Basin. In several areas, declining water tables have resulted in the migration, infiltration, or concentration of contaminates—in particular, Total Dissolved Solids (TDS) and nitrates (KBWA, 2012). Diverting flood flows for groundwater recharge, a process known as on-farm flood capture, is considered an important tool for coping with more-variable future precipitation (Langridge et al 2012).

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[14] The Joint Project Recovery Operations Plan Regarding Pioneer Project, Rosedale-Rio Bravo Water Storage District, and Kern Water Bank Authority Projects

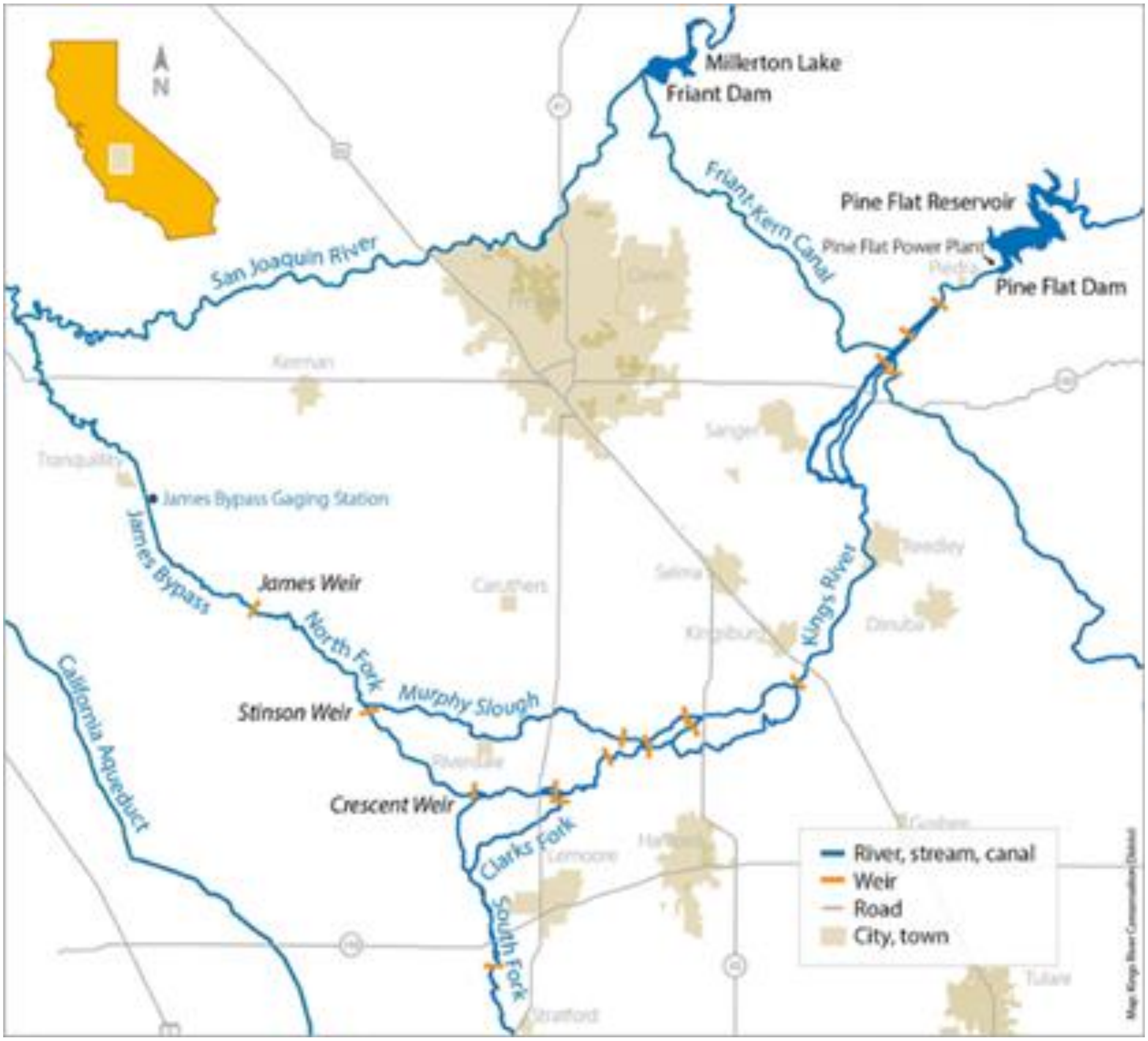

Figure 5 The Kings Basin.

4.2 Physical feasibility

4.2.1 Source water

The Kings River Basin requires 3330 GL to meet irrigation demand. WRIME (2007) calculated a water budget for the Kings Basin from 1964 to 2004. Surface water deliveries to this area varied annually, ranging from about 370 to 1850 GL. Groundwater supplied 1230 to 2710 GL, or about 60% of total water demand, resulting in an average 200 GL annual overdraft. A more recent study found that, from 2003 to 2013, groundwater storage decreased 284 GL annually (KRCD 2013).

Ironically, recurring floods along the Kings River corridor also impact the area. Over 44-years, 10,480 GL of surplus flood flows passed through the James Bypass, a man-made flood channel with a design capacity of 168 L/s. These surplus flood flows are defined as unclaimed flood flows that are both hydrologically and legally available. Under normal operation the James Bypass is dry and hydrologically disconnected from the San Joaquin River. Under high flow conditions, the U.S. Army Corps of Engineers diverts Kings River water into the North Fork-James Bypass channel at Crescent Weir.

Irrigation districts are contemplating or have invested in dedicated recharge basins to capture available flood flows to increase groundwater resources. Over the last two decades, Kings River Basin growers and landowners have worked with the Kings River Conservation District (KRCD), Kings River Water Association (KRWA) and other water agencies to explore and develop recharge strategies and facilities. Currently, agencies in the Kings Basin maintain over 4,000 ha of recharge ponds and flood control basins with the capacity of recharging over 120 GL of water in a single year. Engineered recharge basins covering a dedicated 27 ha area were proposed near the James Bypass that would be designed to capture up to 1000 ML of flood flows monthly, providing roughly 2,450 ML annually of in-lieu recharge (groundwater conserved by surface water being used instead of pumping groundwater) and dormant flooding (flooding when crops are dormant) (KRCD 2000).

4.2.2 Recharge

In 2011, KRCD and Sustainable Conservation, an NGO, initiated a pilot project to spread high-flow floodwaters across farmland. A 405 ha pilot study at the Terranova ranch included fields with green tomatoes, wine grapes, alfalfa and pistachios (Bachand et al. 2012). Infiltration rates averaged around 20 cm per day (up to 63 cm per day on one field), decreasing to about 10 cm per day after two days and 5-6 cm per day after sustained flooding for up to 20 days. This infiltration rate is attributed to soil preparation including deep preparing and crop establishment practices.

A simple mass balance model was developed to describe salinity and nitrate concentrations and it was calculated that about 12 m of water would be needed to displace legacy salts and nitrates. Further applied flood flows would improve groundwater salinity levels over time.

Based on a 30 year record of Kings Basin surplus flood flows it is estimated that 12,000 ha operated for on-farm flood recharge would have had the capacity to capture 80% of available flood flows and potentially offset high overdraft rates in the Kings Basin (Bachand et al 2016).

4.3 Financial viability

On-farm irrigation and distribution systems help reduce overdraft when surface water intentionally delivered in excess of demand seeps through unlined ditches or fields to replenish groundwater. Both local water agencies and landowners have a strong incentive to manage available water resources conjunctively because capturing flood flows for recharge can be a much less expensive source of water to replenish groundwater supplies than water purchased in dry years from the state water market at premium prices.

Trials included diversion of 400 ha of flood flows for about two weeks in January and then from April to early July. Wine grapes were flooded with sufficient water for direct recharge during April and May, and one pistachio field and one alfalfa field with sufficient floodwater in April for direct recharge of 32 and 19 cm, respectively. Flood flow diversion was timed to not interfere with necessary land preparation practices for crop management. Vineyards showed no reductions in 2010 or 2011 crops, and no significant yield reductions were observed for either pistachios or alfalfa.

Costs of on-farm capture and application of flood flows are estimated at $44 per ML. Costs included labour, land preparation, fuel and farm scale infrastructure. Some applied water went to direct recharge for future benefit and some to in-lieu recharge for current benefit. In comparison, large-scale surface water storage can cost from $370 to $1360 per ML (DWR 2013), and dedicated recharge basins cost from $110 to $1,360 per ML (Choy et al 2014). For the project study site (Figure 6), it was calculated that if 25% or more of the captured flood flows can be used for in-lieu recharge, then the savings in groundwater pumping costs can support an active on-farm flood capture program by individual farmers (Bachand et al 2012).

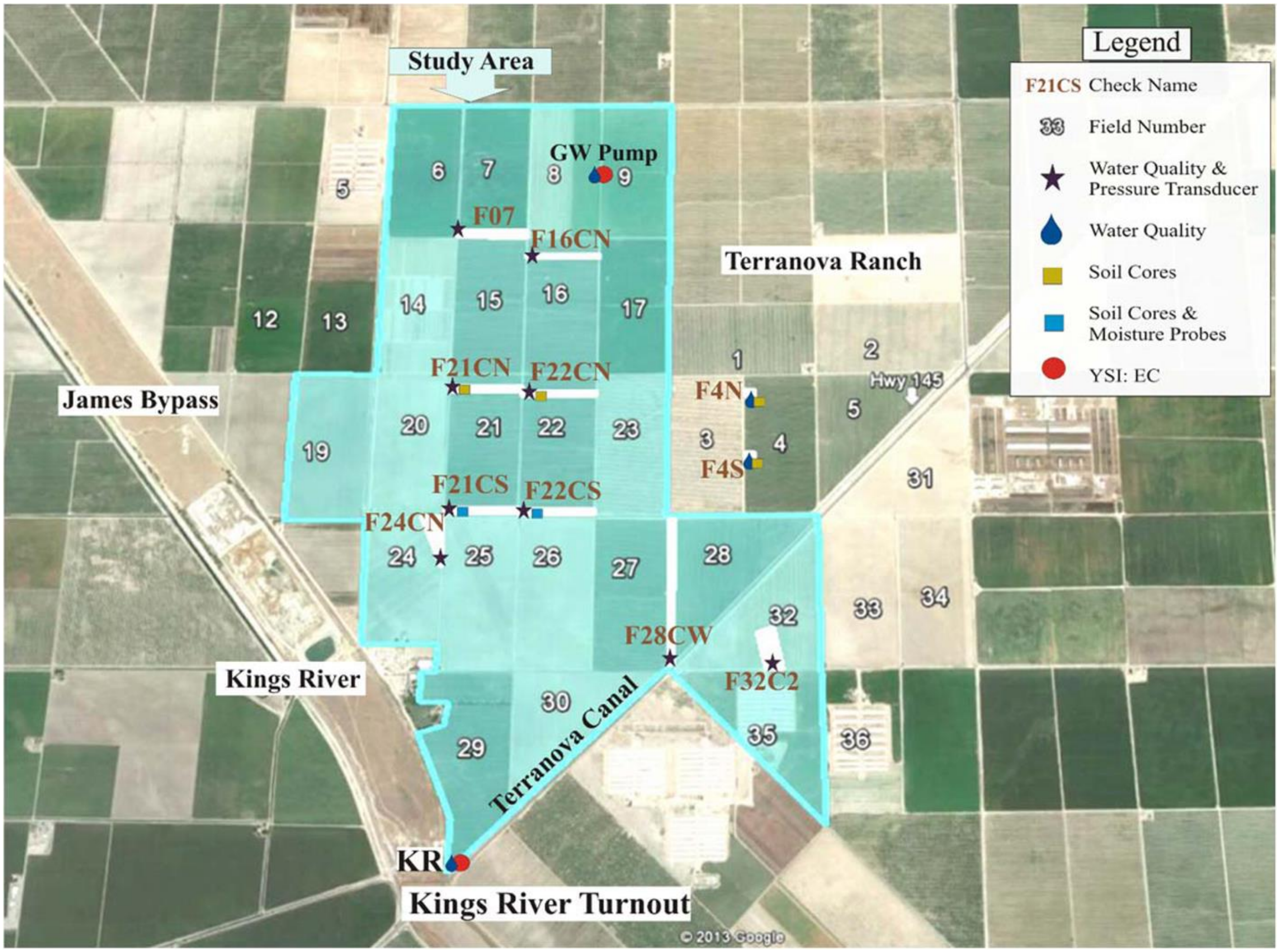

Figure 6 Project site.

4.4 Impacts on third parties and the environment

King River flows are derived from Sierra's snow melt, with salt and nitrate concentrations one or more orders of magnitude lower than groundwater at this study site. The surface water applied on-field flushes salts and nitrate from the root zone to groundwater.

Nitrate levels in many groundwaters in the Kings Basin have increased over the past several decades due to the expansion of agricultural practices and other human sources like wastewater treatment plants. Some irrigation districts in the region are concerned about applying floodwater on farmland due to the potential to infiltrate nitrates from agricultural soil into the water table and consequently further degrade water quality. However, sstrategic implementation of on-farm flood capture could dilute common contaminants such as nitrate and salts and improve groundwater quality (Bachand et al 2014).

4.5 Governance

Groundwater management efforts by several agencies and private entities in the Kings Basin have been underway for some time prior to SGMA. Among many others, the Kings River Conservation District (KRCD), the Kings River Water Association (KRWA), and the Kings Basin Water Authority (KBWA) have facilitated water management planning, groundwater monitoring and data collection, regional project development, water delivery and recharge. But local agency efforts were not well aligned as each managed only for the water resources within their respective boundaries. This lack of coordinated data collection and planning efforts limited the potential for meaningful solutions to the shared issues threatening groundwater resources

While many areas in the Central Valley appear suitable for on-farm flood recharge, implementation challenges include providing sustainable funding mechanisms for system operation and maintenance, developing flexible flood capture strategies, working within water rights constraints and managing risks for growers. For participating growers, challenges include integrating flood flow capture infrastructure and practices with farming operations and developing methods of funding such as selling easements and irrigation cost savings. Appropriate cropping mix and nutrient management strategies have to be developed to facilitate the flood flow program, promote dual-purpose use (i.e. flood capture and agriculture) and manage water quality risks. Finally, central to implementing on-farm flood capture is the question of how it integrates into California's water rights, which provide the legal framework for distributing water in California (Bachand et al 2016).

5. Central Platte Natural Resources District, Nebraska

5.1 Introduction and overview

The Platte River stretches for 1,400 km in Colorado and Nebraska, USA. The river is primarily by snowmelt from the Rocky Mountains, has many tributaries and is hydrologically connected with underlying aquifers. This connection of surface water and groundwater provides opportunities to re-distribute and re-time water supplies that support over 60,000 ha of irrigation.

Irrigation has been used to enhance yields since the late 1800s, first using surface irrigation from privately managed canal companies and later through groundwater pumping from the alluvial and High Plains aquifers. The relatively abundant supply of both surface and groundwater sources has led Nebraska to develop and irrigate more land than any other state in the USA, mostly producing maize and soybeans. This has led to increasing pressure on the water supplies, leading to conflicts and legal battles despite Nebraska not having suffered steep declines in groundwater storage (McGuire, 2017). Nebraska is required by interstate compacts to mitigate streamflow depletion caused by groundwater pumping in order to protect habitats for endangered species and/or ensure adequate surface water supplies for downstream users. These pressures have led to multiple strategies to manage the water system including allocations, reservoir restructuring, reduction of irrigated land, and MAR projects under the Platte River Cooperative Agreement (PRCA) and the Platte River Recovery Implementation Program (PRRIP).

Nebraska’s Natural Resources Districts, the Nebraska Department of Natural Resources (NeDNR), private irrigation districts and canal companies have increasingly turned to MAR as a means to ‘make use’ of excess flows and floodwaters to maintain linkages between groundwater and surface water supplies. The Central Platte Natural Resources District (CPNRD) MAR scheme captures seasonal excess flows and floodwaters in leaky irrigation canals. Water from the canals recharges the underlying aquifer. A proportion of these flows eventually return to the Platte River as baseflow. In 2015, these canals were rehabilitated for multiple purposes, including surface water irrigation, re-timing of excess flows, reducing flood risk, and aquifer recharge (GRIPP 2017).

Groundwater underlying the canals is hydrologically connected to the Platte River via the alluvial aquifer. Groundwater recharged from the canals eventually contributes to base flow that is essential for maintaining groundwater-based irrigation and drinking water supply. It also supplies stream flow that supports multiple endangered species that rely on river habitat, especially during dry periods. The project benefits current and future local farm families who use irrigation, rural households and communities that use the aquifer for drinking water, and wildlife that uses the river by helping to maintain adequate aquifer supplies. The project is a partnership of the locally-organized private irrigation canal companies, the regional government agency

Central Platte Natural Resources District (CPNRD), State of Nebraska Department of Natural Resources (NeDNR).

5.2 Physical feasibility

5.2.1 Source water

CPNRD and the local canal companies negotiated purchases or leases to form irrigation districts, an official political sub-division. Local agreements were signed for the maintenance and delivery of surface water, NeDNR granted excess flow water rights to hold diverted Platte River flows in the canal during the off irrigation season. Between 2011 and 2018 over 49.41 GL of excess flows of surface water and floodwater were diverted into three major canals. Between 2015-17 the average annual diversion was 16.47 GL.

5.2.2 Recharge

The canals were in major disrepair after nearly a century of providing irrigation but recharge from leaky canals is essential to provide aquifer recharge to mitigate groundwater declines from groundwater irrigation, and to maintain baseflows. So, in 2011, CPNRD approached the canal companies to increase aquifer storage by rehabilitating canals and diverting excess river flows. Canal rehabilitation included new water control structures, monitoring equipment, clearing excess vegetation and installing bank protection (Figure 7). The projects were funded through a partnership of CPNRD, NeDNR, private canal companies, and the Nebraska Environmental Trust. Between 2011 and 2018, annual groundwater recharge averaged 11.11 GL of average (CPNRD 2016). It is estimated that over 150,000 m^3 of water per month was returned to the Platte River as base flow. In 2015-17 the average annual amount of water returning to the river was 2.34 GL.

Figure 7 Canals used in the Central Platte MAR, prior (left) and after (right) rehabilitation.

5.3 Financial viability and economic benefits

The capital cost of the canal rehabilitation was US$14.4 million of which US$7.2 million can be assigned to MAR, US$4.8 million for project preparation and US$2.4 million for construction and water conveyance. Annual operating costs total about US$20,000. The levelised cost of recharge is estimated to be US$0.044 per m^3 while the levelised cost per m^3 of water returned to the river is estimated to be US$0.212 per m^3.

Monetary benefits of the Central Platte MAR can be assessed by comparing the value of irrigated agriculture production or land valuation. Water allocations in this catchment exceed inflows, therefore it can be assumed that many irrigated fields would become non-irrigated without the aquifer recharge program. Without recharge it is estimated that there would be a loss of 4,830 ha of irrigation. In 2018 in Central Nebraska the average yield for irrigated maize 15.1 metric tons/ha, while the average non-irrigated production was 10.1 metric tons/ha (USDA 2018). Assuming a market price of $138 U.S./metric ton, this extra irrigated area leads to an average annual value increase of $690 US/ha with an annual value is $3.33 million US dollars. The levelised cost of annual infiltration is about US$0.5 million which implies a benefit cost ratio of 6.7:1.

The impact of irrigation on land values provides an alternative perspective on the benefits of the Central Platte MAR. In 2018, non-irrigated land in Central Nebraska was on average $6,793/ha, while irrigated land is valued at $15,833/ha, due to expected crop yield differences, a ratio of 2.33:1 (Jansen and Stokes 2018). The additional land value caused by the transformation of 4830 ha from non-irrigated to irrigated land is $43.7 million dollars.

There are also several external benefits that are hard to monetize, including improvements in water quality, drinking water supply, flood storage, and wildlife.

5.4 Third-party and environmental impacts

The Central Platte MAR has been providing alluvial aquifer recharge and subsequent river returns since 2011. These returns vary depending on annual climate and crop water use. The diversions and returns back to the river are measured and the MODFLOW groundwater modelling package is used to estimate recharge. Groundwater levels have risen across most of the project area since the inception, even with an extreme drought in 2012 (Table 2, Figure 8).

Nebraska has obligations from several interstate compacts to mitigate streamflow depletion caused by groundwater pumping in order to protect habitats for endangered species and/or ensure adequate surface water supplies for downstream users (Platte River Cooperative Agreement/Platte River Recovery Implementation Program (PRRIP) (Kuwayama et al 2016). Also the recharge project site lies within the critical habitat reach of the Platte River Program, which is a species recovery program for the least tern, piping plover, and whooping crane. River returns contribute to streamflow targets for each species.

Table 2 Annual diversion, recharge, and river returns.

Year	Diversion (Mm^3)	Recharge (Mm^3)	River Return (Mm^3)
2011	23.72	20.09	1.27
2012	1.75	0.00	0.00
2013	9.30	5.28	0.77
2014	1.42	0.00	0.00
2015	15.61	11.18	1.66
2016	21.64	11.96	2.25
2017	12.16	10.19	3.10
Total	85.59	58.69	9.05

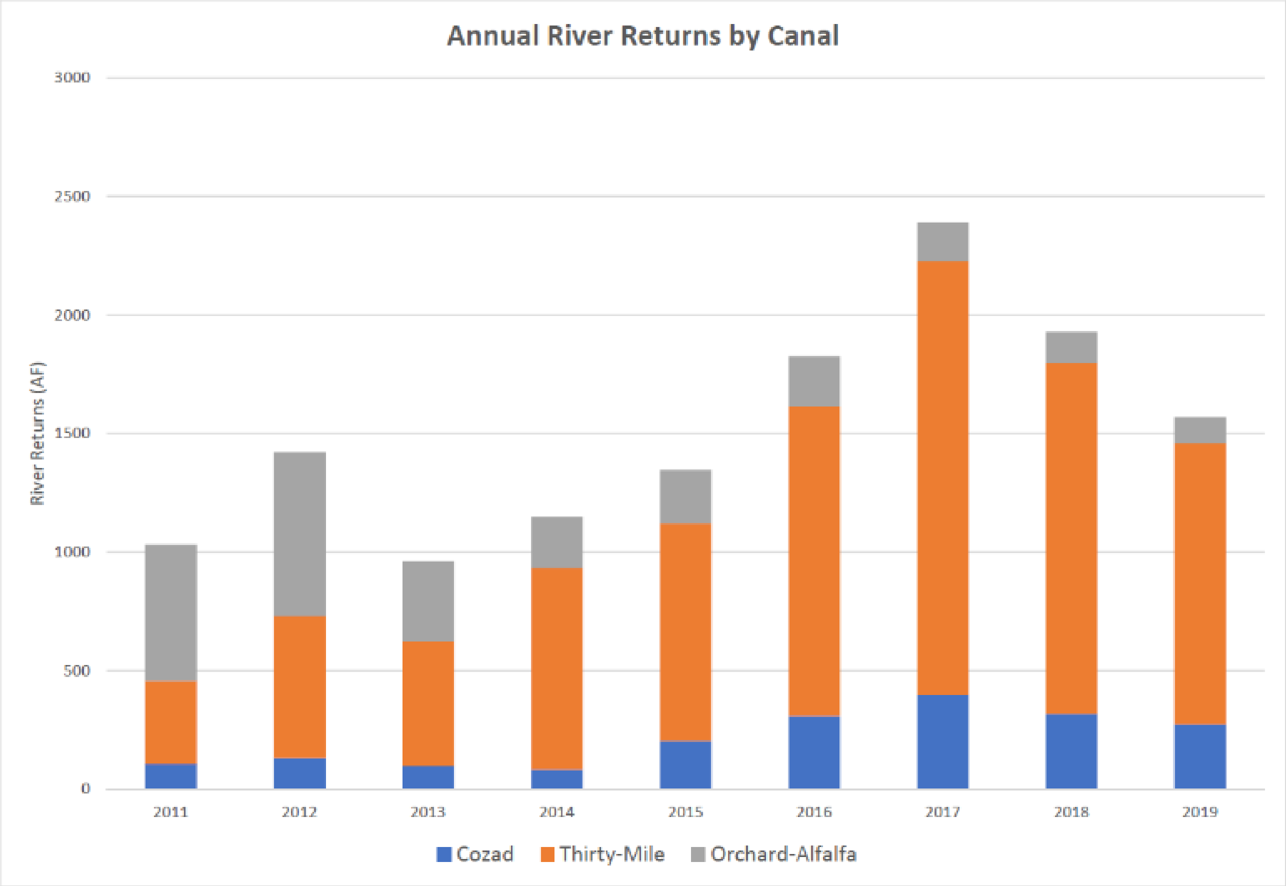

Figure 8 Annual diversion, recharge, and river returns.

Groundwater nitrate testing in the project area has found 90% of the wells below 7.5 mg/l with only one sample exceeding the safe drinking water standard of 10 mg/l.

As a passively operated MAR system, there are negligible energy requirements to infiltrate, with the only energy uses being monitoring & operating the flows and gates. To recover the water, there are no additional energy requirements.

The PRRIP monitors endangered bird and fish species on an annual basis, and preliminary results indicate that numbers have increased since PRRIP began their conservation efforts (Baasch and Keldsen 2018).

5.5 Governance

Local irrigation districts are local government entities, with a locally elected board, who set taxes and fees, and hire staff to manage canals that provide surface water to member irrigators. Nebraska's NRDs are the entities primarily responsible for groundwater management, under the state's conjunctive use law. They have sole authority to regulate groundwater extraction and to enforce violations of district rules and regulations. The NRDs are given taxing authority to provide financial security. The NeDNR is a state agency responsible for registering groundwater wells and permitting induced groundwater recharge in the state as well as overseeing surface water quantity and water rights. Surface water and groundwater quality (point-source pollution) is monitored by the Nebraska Department of Environment and Energy, while the NRDs are responsible for groundwater quality related to nonpoint source pollution (GRIPP 2017).

The CPNRD MAR scheme is organized under the local Central Platte Integrated Management Plan (IMP), the basin-wide Platte River IMP, and the inter-state PRRIP which aims to increase streamflow in the Platte River in order to improve habitats for endangered fish and bird species. 30-year interlocal management agreements were negotiated between MAR project owners. Water appropriations are leased from private Irrigation Districts to the CPNRD who are MAR project owners with 50% leased interest in real and personal property and 50% leased interest in water delivery system, including operations & maintenance

The agencies involved used a public stakeholder input process throughout development of IMPs, PRRIP, and the MAR projects. These included monthly public meetings and providing project updates through print and digital media.

6 Managed Aquifer Recharge System for Rural Development in Castilla y León, Spain

6.1 Introduction, objectives and evolution

Los Arenales aquifer is a large groundwater body that occupies 2,400 km^2 of Castilla y León, Spain with 46,000 inhabitants in 96 villages. Since the mid-20th century the expansion of irrigation from Los Arenales aquifer has led to a decline in groundwater level of more than 20 m. In order to mitigate this impact, the Spanish Ministry of Agriculture (MAPA) initiated MAR demonstration projects and developed MAR facilities in three pilot zones: Santiusta basin area (2002), El Caracillo (2003), and Alcazaren-Pedrajas (2011)[15].

According to the Spanish Water Law (Ley 29/1985), Art. 40, each aquifer with an exploitation index exceeding 0.80 requires an urgent intervention from Water Authorities. Between 1972 and 2002 the groundwater level at Los Arenales aquifer registered a decline of 24 m in a sector of the aquifer (La Moraña). The Spanish Government responded by establishing a set of limitations for the use of water, the compulsory constitution of farmers associations as water management bodies with central administration, and the development of artificial recharge facilities to reduce the water level decline.

In 1994, farmers from nine municipalities of the region joined in an irrigation association, and proposed a management plan to the political and the river basin authorities. The plan for El Carracillo MAR system was approved by the central government under Decreto-Ley 9/1998, of August 28th[16], to approve and regulate hydraulic constructions for the “General Interest of the Nation”. The plan was approved in 1999 with a maximum 1,370 L/s or 14,204 m^3/yr water concession diverted from the Cega river yearly between January and April, with the total annual water diversion capped at 22.4 Mm3 (Escalente et al 2016).

El Carracillo MAR site is located in the northern part of Segovia province, in an area around 150 km^2 wide surrounded by pine woodlands between the Cega and Pirón rivers. At the Caracillo basin site, river water is diverted for recharge by gravitational flow through 40 km of pipes to the recharge facilities; including 3 infiltration ponds, an artificial wetland, and infiltration field. Water is distributed for irrigation using uncontrolled spreading of floodwater, and a riverbank filtration scheme. Recharge is also promoted through irrigation return flows and inter-dune filtration ditches.

The scheme includes exchanges of arable land, change in crops, improved efficiency of irrigation, extension of the energy supply and reduction of energy consumption. The scheme also includes environmental features such as the recovery of degraded wetlands (La Iglesia and El Señor lagoons) and dry springs, dilution of nitrates

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[15] http://www.marsol.eu/15-0-Arenales-.html

[16] Published on 29/01/1999.

and of other pollutants. The plan was modifed in September 2015 establishing the environmental minimum flow rate for the Cega river[17].

Figure 9 shows MAR canals (purple lines) and infiltration ponds (pink diamonds), monitoring networks (yellow and blue crosses) and regional ground water flow directions (blue arrows).

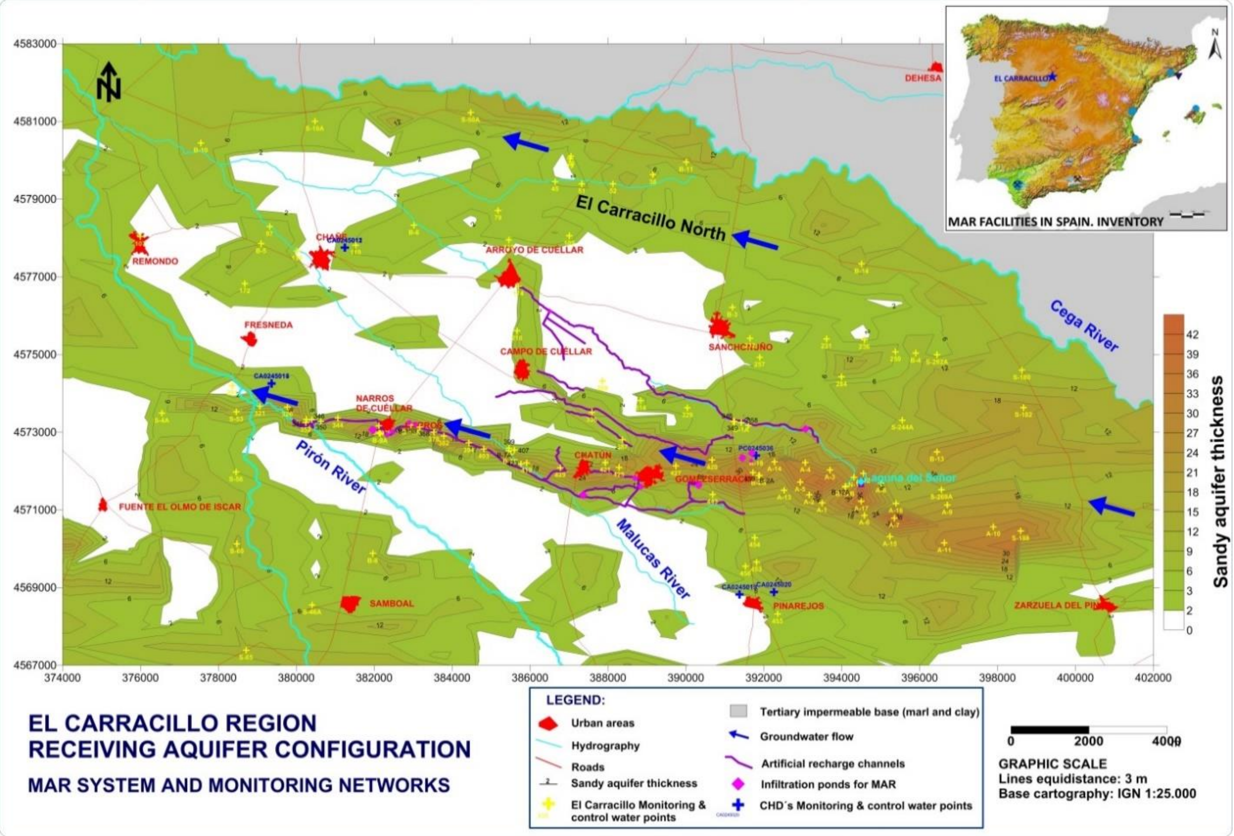

Figure 9 MAR systems in El Carracillo region, Spain.

6.2 Physical feasibility

6.2.3 Source of water

The plan approved in 1999 allowed a maximum 1,370 L/s or 14,204 m^3/yr water concession diverted from the Cega river yearly between January and April, with the total annual water diversion capped at 22.4 GL. By 2000, Phase I of the MAR project construction was completed, to transport water by gravity inside a pipeline over 19.6 km from the Cega river to Lastras de Cuéllar and Gomezserracín Villages for MAR activities. This phase became operational in 2003. By 2005, Phase 2 of the project was completed with the inclusion of four additional villages in the irrigation community - Chatún, Campo de Cuéllar, Narros de Cuéllar and Fresneda de Cuéllar - and the construction of 14 extra km of ditches for MAR (Figure 9).

Total recharged volume for the period 2002-2015 amounted to 31.47 GL and this has resulted in a small trend increase in the water level. Water availability varies substantially over time. There have been two dry periods with no diversion at all, and one wet period with 7.18 GL diverted for MAR in one hydraulic year 2012-13. Evaporation losses are negligible as infiltration takes place primarily during the rainy season (Escalente et al 2016).

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[17] https://www.boe.es/buscar/doc.php?id=BOE-A-1998-20676

6.2.4 Recharge

El Carracillo MAR aquifer recharge system is “opportunistic”, passive and intermittent. The MAR system targets the shallow Quaternary shallow which consists of a fine sand dune layer, alluvial deposits and clay with a 20-m-average depth and a maximum depth of 45 m (Macías et al., 2014). Infiltration generally takes place during the rainy season (winter-spring) when most surplus water is available. The system integrates a fish-bone pipeline working as an aqueduct from the Cega river to 14 points of distribution. Several MAR techniques are used, including 16 infiltration ponds, 17 km of MAR canals, 2 spreading basins, 3 artificial wetlands, reuse of abandoned wells and reuse of sand-pits (Figure 10 and Figure 11). Due to variable river flows annual volumes recharged ranged between 0.5 and 5.5 GL between 2002 and 2008.

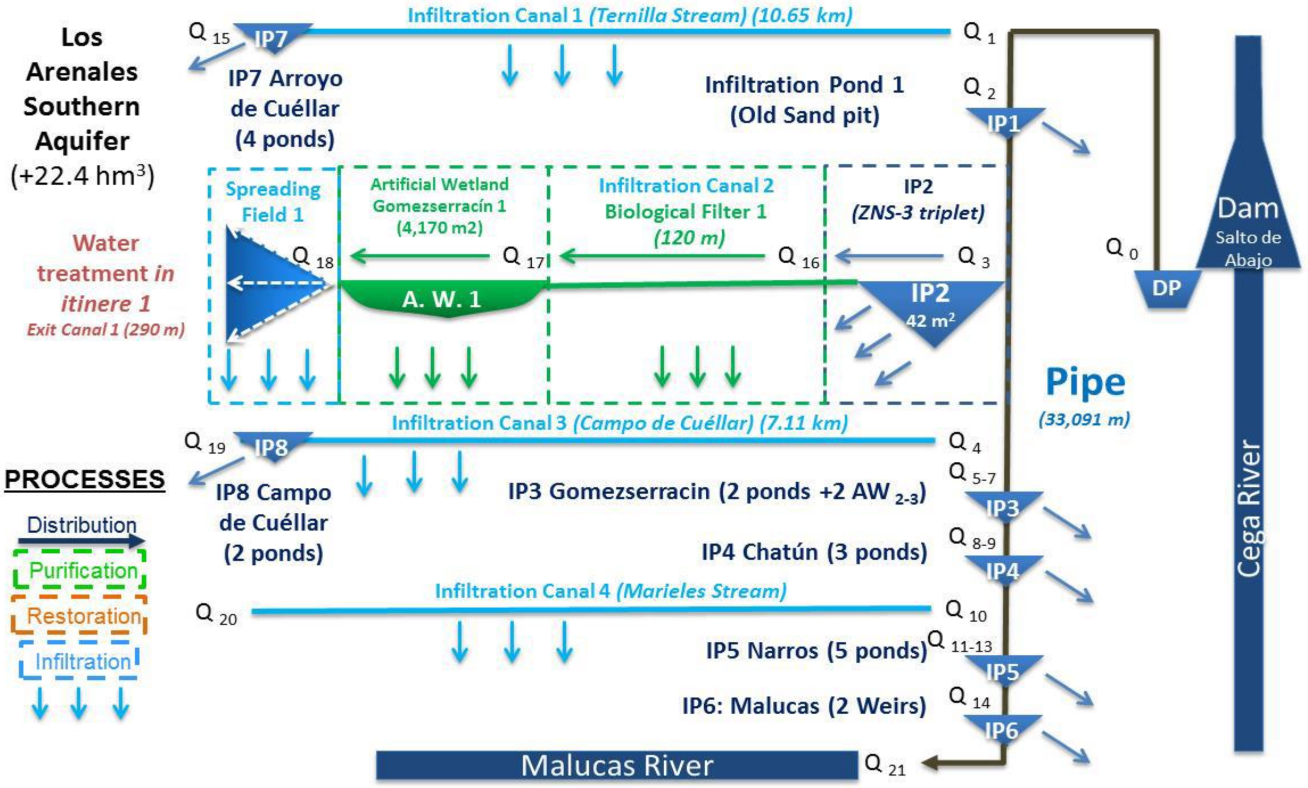

Figure 10 Operational sketch of El Caracillo MAR scheme.

Groundwater extraction averaged about 8 GL/year based on data collected from 314 inventoried wells, with an average pumping rate about 9,957 m^3 per well per year. The irrigated area is 3,500 ha. On average each hectare receives 1,318 m^3 of irrigation water supplied from groundwater, of which 314 m^3 is from MAR.

6.3 Financial viability and economic benefits

The capital cost of the project was €5,274,000 with an operating and maintenance cost of €40,000 per year. The estimated levelized cost of recharge is US$0.21 per m^3.

El Carracillo district ranks highly in the Spanish agriculture for its production of horticultural products (80% of vegetable production of Segovia province and 30% of Castilla y León Autonomous Region). Horticultural industries stand out with a turnover of about 45 M€/year. Important industries apart from horticulture are milling, spirit beverages and meat. The region is the premier producer of strawberry mother plants in Spain, with 60 million units produced per year on only 600 ha (ITACYL 2015).

Figure 11 Gomezserracin infiltration pond in dry and wet season, and sandpit reused as infiltration pond.

MAR increases water availability allowing the transformation of rain-fed lands into irrigated lands, leading to greater production. 713 farmers make up the association supplied by the MAR system with a mean annual aquifer extraction about 8 GL/ year. The effect of MAR can be measured as 314.3 m^3/ ha out of 1,318 m^3/ ha extractions on average, so the MAR contribution to total irrigation is about 23.8%. This is an important contribution, valued at about €12 million, out of the overall value of agriculture production from the El Carracillo system of about 50 M€/year. Yields per hectare are doubled in most cases (e.g. garlic, rye), and even tripled e.g. for sweet melon (Junta de Castilla y León (JCyL) 2015).

6.4 Impacts on third parties and the environment

Water quality analysis and groundwater level monitoring have been carried out at a series of sampling points. Fourteen water quality parameters were tracked. Water quality standards for nitrate have been exceeded at a few measurement points in these areas, and have been declared as "vulnerable" for nitrates contamination by river basin authorities, namely the Duero Hydrographic Confederation (CHD). Farmers are now required to fertilize with less than 3 kg/m^2 of manure and less than 20-10-15 gr/m^2 for nitrogen, phosphorus and potassium respectively. Water quality fulfils Spanish standards for salinity (https://www.boe.es/buscar/pdf/2007/BOE-A-2007-21092-consolidado.pdf, Accessed 9 March 2020).

All the MAR facilities rely on gravity for water infiltration, without any energy consumption. Regarding water extraction and on average for 314 inventoried wells, total energy consumption for pumping is estimated to be 49,737 Kw-h for the irrigation period pumping about 8 hours per day. For total annual extractions about 8 GL, the mean is calculated to be 0.165 Kw-h/m^3.

El Carracillo system includes 16 infiltration ponds that are also a recreational attraction for the villages' population. In addition three artificial wetlands and two weirs have been reinstated for ecological reasons. Infiltration canals (17 km) provide natural corridors for flora and fauna among the cultivated areas as vegetation grows in their beds and banks.

6.5 Governance, legislation and policies

The project, building works, tracking and further monitoring are based on the organization of communities of irrigation farmers. Once constructed and commissioned, the works were transferred to the El Caracillo Council, which is responsible for the management and maintenance, under the advice of specialists of the CHD and the Tragsa Group (Escalente et al 2016).

According to the Environmental Statement published in September 2015, an environmental minimum flow rate of 6,898 l/s must be met, while a maximum rate of diversion of 1,370 l/s from January to April is allowed. These water rights are revised every 6 years with the next revision due for 2022-2027. Public consultation is conducted and ruled by Chapter IX of Annex IV of the Water Basin Plan.

Despite the benefits of the project the proposed phase 3 (MAR and extra irrigation at El Carracillo north) has been resisted by groups opposed to further diversion of water from the river Cega. This proposal has required the mediation of river water authorities and started a legal conflict that requires final decision made by courts.

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