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Implementing Sustainable Water Management to Balance Water Supply and Demand: Challenges, Opportunities and Solutions

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USCID

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Preface

The papers included in these Proceedings were presented during the **USCID 14th International Conference on Irrigation and Drainage,** held October 1-4, 2024, in Sacramento, California. The theme of the conference was *Implementing Sustainable Water Management to Balance Water Supply and Demand: Challenges, Opportunities and Solutions*.

A note from Randy Hopkins, Conference Chair

> One of the values your membership to USCID provides is an opportunity to network and draw from each other's strengths in creating something greater than we can accomplish on our own. The **USCID 14th International Conference on Irrigation and Drainage** was our opportunity to do just that.
>
> We had an excellent turnout for our conference, with about 100 registered attendees and the vast majority in attendance each day. Our **conference sponsors** provided some much-needed donations, contributing to the conference's success. We had a full exhibit hall with exhibitors representing a wide variety of products and services for our industry.
>
> The tours were a highlight! Thanks to **Eduardo Bautista**, **Therese Ure Stix**, **David Bradshaw**, **Sam Schaefer** and **Amy Johnson** for organizing and leading. Transportation, food, tour content, and speakers were all on time. **Jane Townsend** and **Megan Corcoran** were responsive and 'behind the scenes' working hard to make the conference run smoothly.
>
> Moderators – you all stepped up and made the event possible – you rounded up the audience, rounded up speakers, read the bios, and kept the speakers on time.

The authors of papers presented in these Proceedings are professionals from government agencies, the private sector and academia.

USCID and the conference Co-Chairs express their gratitude to the authors, session moderators and participants for their contributions.

Conference Co-Chairs

Jane Townsend
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WAITAKI WATER MANAGEMENT

Andrew Barton[1]
Morven Glenavy[2]

ABSTRACT

The Waitaki River is a braided river with headwaters in New Zealand's tallest mountain range. It flows via inland lakes and hydropower stations to the coast. This upper catchment water storage provides consistent flows for irrigation downstream of the last dam. Irrigation development was led by the government in the 1970s. Two irrigation schemes were developed to deliver water by gravity to the adjacent land for border-dyke (flood) irrigation. In 1990 the government sold the assets to the farmers. Investment on-farm has converted over 90% of the land to spray irrigation, which has changed the hydrology of local streams. Waitaki River water is very reliable compared to the rest of Canterbury, which encouraged two new pumped irrigation schemes to be developed in the last fifteen years. These pumped schemes utilised the existing irrigation scheme river intakes, which improved the feasibility of new farmer funded irrigation development compared to installing their own new intakes. These new schemes formed separate companies that owned the infrastructure and associated debt. The relatively high amount of debt and energy cost associated with lifting water over 100 metres results in higher water charges. Lower reliability in other parts of Canterbury has driven investment in water storage. While the Waitaki pumped schemes are relatively expensive, there has been no develop storage, which makes total annual costs comparable. The development of the Waitaki River catchment has resulted in a nationally significant power generation scheme and over 90,000 hectares of irrigated land. The inland lakes provide a significant recreational resource for the community. The lower river is a valued salmon fishery and is used to replenish low flows in adjacent catchments. The development of the Waitaki has had an impact upon local Māori and working them to improve outcomes is an opportunity for irrigators.

WAITAKI CATCHMENT

The Waitaki River catchment extends from the mountains of the Southern Alps, including New Zealand's tallest mountain, Aoraki (Mt Cook 12,220 ft), to the South Canterbury coast, as shown in Figure 1. The mountains receive over 8,000 mm (315 inches) of precipitation each year, sourced from prevailing westerly winds from the Tasman Sea that are forced up over the Southern Alps.

This alpine precipitation provides about 80 percent of flow in the catchment. The ice and snow-fed upper catchment has a strong seasonal flow regime with summer peaks produced by heavy rain and snow/glacial melt, and lowest flows in winter (June, July, and August).

Rainfall declines rapidly with distance from the mountains. While Aoraki/Mt Cook village averages about 4,000 millimetres (157 inches) of rain each year, Twizel and Ōmārama (60 kilometres away) receive annual rainfall of 500 millimetres (20 inches).

The glacial lakes of Tekapo, Pūkaki and Ōhau influence flows downstream by dampening flood peaks and modifying flood flows into the lower catchment. These lakes are regulated and their outflows are diverted into the canals of the upper Waitaki hydro-

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electricity system. Downstream of these lakes the tributary rivers form the Waitaki River in a single channel. The Waitaki River is dammed in three locations, creating Lakes Benmore, Aviemore and Waitaki (Waitaki Catchment Water Allocation Board, 2005).

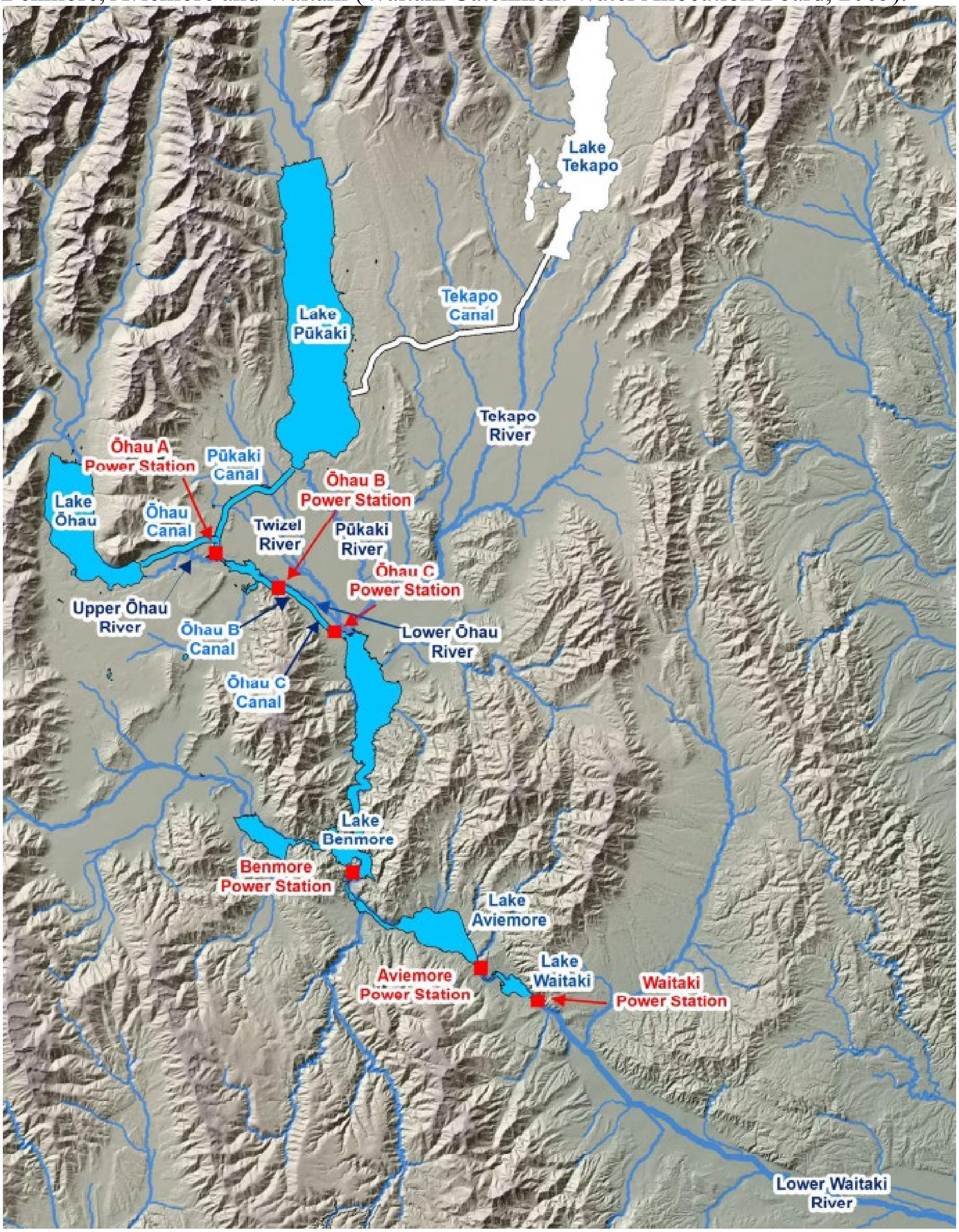

Figure 1 – Waitaki Catchment Power Scheme (Meridian Energy, Ltd 2024)

The Waitaki power scheme consists of a total of eight hydropower stations. The Waitaki power scheme supplies 18% of New Zealand's power (Meridian Energy Ltd, 2024))and

the consistent generation of electricity provides a reliable river flow downstream of the last dam.
The coastal plains and rolling land of South Canterbury and North Otago receives a low average annual rainfall of 500 mm. The Waitaki River has the fourth largest flow of all New Zealand rivers, with a mean flow (1991-2021) at Waitaki Dam of 356 cubic metres per second (Meridian Energy Ltd, 2024) .

IRRIGATION DEVELOPMENT

The Ministry of Works developed a number of run-of-river irrigation schemes throughout Canterbury, which includes over 60% of New Zealand's irrigated area (Dark, 2020). The largest irrigation schemes were developed in North Canterbury (Amuri), mid Canterbury (Rangitata Diversion Race) and South Canterbury (Morven Glenavy Ikawai & Lower Waitaki). These developments harnessed the alpine sourced braided rivers that carry significant flows during warm summer months.
Around 1990 the government made the decision to sell these irrigation schemes to local farmers. The farmers took on debt and formed companies to purchase the assets, with farmers typically being issued one share in the company for every hectare irrigated (Lower Waitaki Irrigation Company, 2014). These companies are governed by a Board of farmer Directors. For the first 20 years of farmer ownership the schemes were operated by racemen. Over time these companies have established professional management structures that reflect the value of the assets and the farmland that relies on irrigation.
The Ministry of Works irrigation schemes were all designed and constructed as border dyke (flood) irrigation schemes. Over time these schemes have been converted to spray irrigation. The drivers for converting to spray irrigation were:

i. Ability to irrigate more land in some schemes

In Mid-Canterbury, the irrigation schemes were developed to irrigate 5/8 of the farm under border dyke irrigation, with 227 l/s supplied with a volume equating to 100 mm/hectare every 17 days. The mid-Canterbury schemes allowed farmers to store their 227 l/s border dyke allocation in a pond, which allowed farmers to spray irrigate additional land at a lower application rate (Duncan *et al,* 1985).
In North and South Canterbury the schemes were designed to irrigate most of the flat land on each farm. Rather than allow farmers to retain the water saved from converting border dyke to spray irrigation, the water saved went back to the Company, and was able to be allocated as new shares to neighbouring dryland.

ii. Reliability of supply

In North Canterbury the rivers are subject to irrigation restrictions. Amuri Irrigation had a policy of turning border dyke irrigators off first when restrictions hit. As river flows fell spray irrigators would face rostered days where they couldn't irrigate but were never totally restricted. The loss of irrigation supply to border dyke farms during periods of low flow created a strong driver for converting to spray.
In South Canterbury, the Waitaki River has highly reliable flows due to the hydropower scheme and irrigation restrictions are extremely rare and have not influenced the rate of conversion.

iii. Soil type

Soil type has played a part in influencing the speed of border dyke irrigation. Stonier soils have lower water holding capacities and are unable to store the high application rate. The 17 day return period for border dyke irrigation means that the soils will have been under stress for as long as week before the next water delivery.

Border dyke irrigation has largely been converted to spray irrigation in North and Mid Canterbury, with less than 1,000 hectares remaining on the Morven Glenavy Scheme and approximately X ha on Lower Waitaki. The water allocation for border dyke was 500 l/s in South Canterbury, which was significantly greater than Mid Canterbury, and may have influenced the rate of conversion to spray irrigation.

WAITAKI CATCHMENT

In Canterbury, water has been allocated on a first come first served basis. The water permits granted earlier in time have priority and are more reliable than later in time permits. These run-of-river water permits are subject to minimum flow conditions that restrict the rate of take during times of low flow and require taking of water to cease at very low flows. The later in time permits often have higher minimum flows than the earlier in time permits.

In the Waitaki River catchment, a monthly minimum flow is specified. The allocation block of 79 cubic metres per second has been subdivided into two blocks bands based on the date that the permit was first granted. Table 1 outlines the minimum flows for the original MGI permit and the newer WDI permit.

Table 1 – Waitaki River allocation example (flow based on Waitaki River @ Kurow

Scheme	Cease flow (m3/s)	Reduction trigger flow (m3/s)
MGI	111	164
WD	164	190

More recently developed irrigation schemes in North and Mid Canterbury have been funded by farmers rather than the government. These schemes have had to invest significantly in storage to supplement less reliable run-of-river supply associated with later in time water permits. The requirement for storage increased the capital cost of the development, which have been debt funded, which results in a higher annual water charge compared to the ex-Ministry of works schemes.

In the Waitaki River, the entire allocation of water that is available is highly reliable on a run-of-river basis due to upstream storage and energy generation. This reliability means an investment in storage is not required. The reliable water has encouraged irrigation of rolling land, outside of the original Ministry of Works border dyke scheme areas. Figure 2 shows a centre pivot on a hill slope.


Figure 2 – Centre Pivot on Waihao Downs Scheme

The avoided cost of storage has encouraged development of new irrigation schemes to supply land located further away from the Waitaki River, North Otago Irrigation Company and Waihao Downs Irrigation. These schemes are piped and require pumping 120 metres to push water over the hill into the next catchment. The higher capital and energy costs of these schemes have been affordable because of the run-of-river reliability means that storage is not required.

As an example, the water charge for the MGI original scheme area is approximately $155 per hectare, including debt servicing plus the farmers own energy costs associated with pumping from the water race ($120-$170/ha). The Waihoa Downs area has a water charge of $1,050 per ha, with the main difference being the higher debt servicing and energy costs associated with pumping water over 200 metres in elevation, although this scheme receives pressurised water with no additional on-farm pumping required.

In the Waitaki catchment the new schemes have been able to share existing irrigation scheme intakes. Further development of the original scheme river headworks has saved capital cost for new schemes and provided ongoing operational cost sharing efficiencies for both the new and incumbent schemes.

Initially the new Waitaki schemes and original ex-Ministry of Works schemes formed a relationship at a commercial arms-length. Over time, as confidence between schemes has developed, the schemes have become more aligned, with Waihao Downs being purchased by MGI. All of the original scheme area and Waihao Downs scheme are MGI shareholders, with debt for each scheme ringfenced. NOIC and LWI forming a combined management company to manage those schemes.

The Waitaki River catchment now irrigates 90,000 hectares of land. MGI (including WDI) irrigates 29,000 ha, with LWI and NOIC irrigating 20,000 ha each. The remaining irrigated area comprises several smaller schemes and individual irrigators adjacent to the Waitaki River.

MORVEN GLENAVY IKAWAI IRRIGATION COMPANY

MGI's origin was the Redcliffs scheme developed in the 1936s to irrigate the area around Ikawai (Benny, 2014). In the 1974 the Bells Pond scheme was developed to irrigate the area around Glenavy and Morven. These schemes were originally developed as border dyke schemes. In the early 2000s the Northern Extension was developed to irrigate land towards Waimate, supplying spray irrigation through a combination of pipelines and open channels. In 2016 the WDI scheme was developed and pumped water via the Redcliffs scheme to 3,500 ha. The layout of the MGI scheme infrastructure is illustrated in Figure 2.

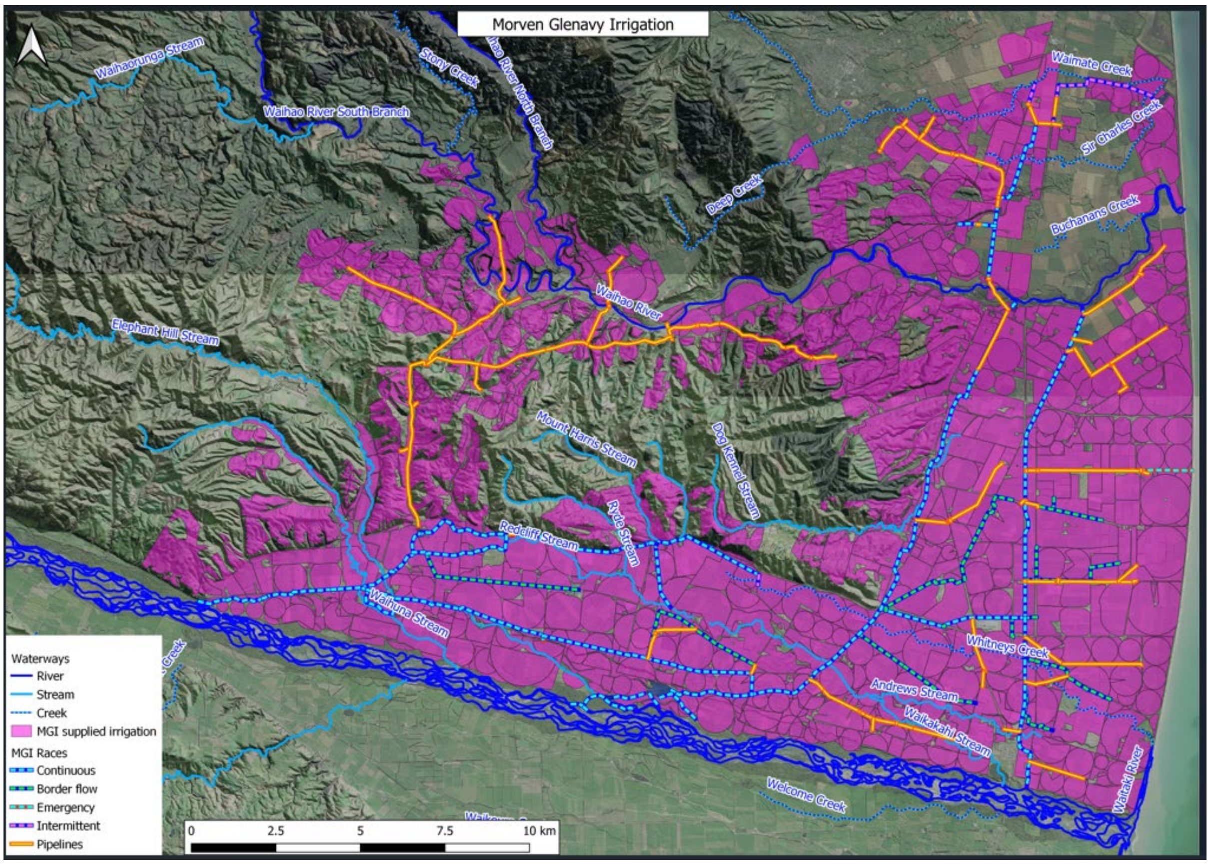

Figure 3 – MGI Scheme

MGI has progressively lined leaky sections of main supply races and has recently replaced lateral supply races in the lower part of the scheme within pipelines. The scheme upgrades have resulted in reduced leakage as part of an effort to improve water delivery efficiency. The scheme has taken on debt to fund the pipelines and race lining and all shareholders contribute to the cost of repaying this debt. The scheme has also invested in pump stations on some pipelines, which provide farmers on these pipelines with water under pressure. The energy costs and debt servicing associated with these pump stations are recovered from the farmers receiving the higher level of service.

MGI has two intakes, one at Stonewall (Redcliffs) and one at Bells Pond (Morven Glenavy). Stonewall has a rock barrier to prevent fish entering the intake whereas the Bells Pond intake is on the few intakes in Canterbury without a fish barrier of some description. 70% of the water supplied is pumped by farmers directly from the water races with the remaining 30% being supplied by pipelines directly to shareholders.

MGI CHALLENGES AND OPPORTUNITIES

Managing run-off

The use of land within most Canterbury irrigation schemes is dominated by dairy farming (MGI has 48% dairy and 20% dairy support). The use of border dyke irrigation on dairy farms created run-off into nearby streams which reduced water quality. The Waikakaki Stream is a spring-fed tributary of the Waitaki River and suffered from high sediment loads and E. Coli and nutrient concentrations. In the early 2000's a committed group of farmers worked through this challenge and improved water quality through improved irrigation practices (Monaghan *et al* 2009*)*.

- Bunding of border ends prevented excessive flow of border dyke wipe-off water into the stream.
- Setting clock timers to avoid applying excessive amounts of irrigation water,
- Improved maintenance of irrigation races to ensure system performance
- Best Practice for the application of fertiliser maintenance P fertilizer
- Re-bordering of old irrigation infrastructure and conversion to spray irrigation

Managing nutrient concentrations

With direct discharges into waterways avoided, the emerging water quality challenge is the increase in nitrate concentrations resulting from reduced aquifer recharge Prior to efficiency improvements, MGI lost 26% of the water taken through race losses. This has been reduced to less than 10% through race lining and piping and has had an impact on down-gradient groundwater levels (Figure 3) because improved water use and conveyance efficiency has reduced recharge to the underlying aquifer. While the improved efficiency reduces the annual mass of nitrogen lost to groundwater, the reduction in recharge is more significant, resulting in increases nutrient concentrations in groundwater (Dench *et al,* 2021)..

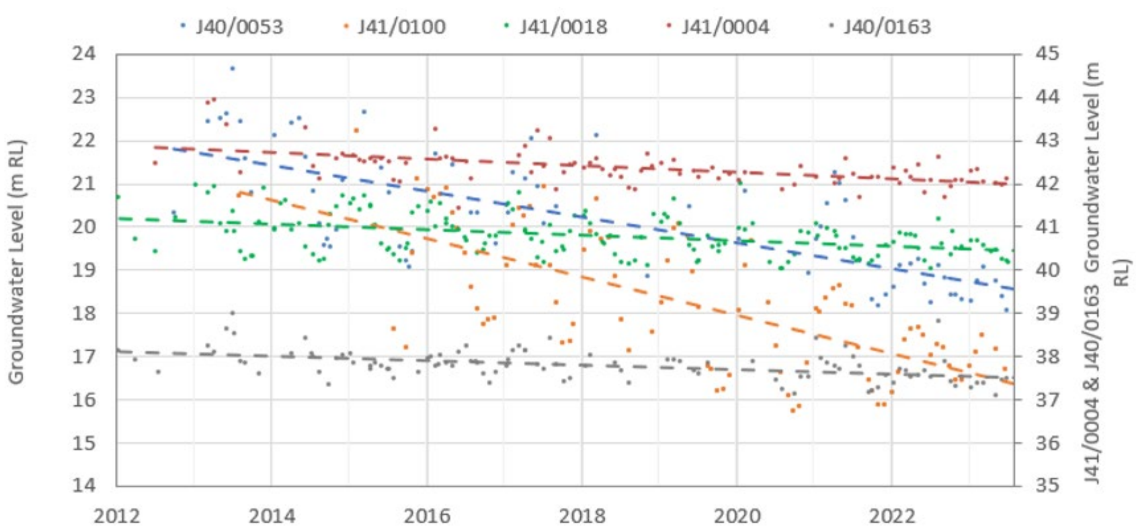

Figure 3 – Groundwater trends over the past 10 years in the Morven Glenavy area. Dotted lines indicate linear regression fitted to the record for each monitoring well.

Farmers under border dyke allocation received 1,000 mm of water per hectare as an annual allocation, but in drier years this limit could be exceeded if water was available. Under spray irrigation the maximum allocation has been reduced to 700 mm per hectare. The 300 mm difference is water that would have drained through to the aquifer under border dyke systems.

MGI was the first irrigation scheme to implement Farm Environment Plans (FEP) in 2010. The FEPs detail the actions required on-farm to achieve industry agreed Good Management Practice (GMP). The FEPs are audited by independent experts and farms who achieve their FEP actions are audited less frequently than those who do not.

The FEPs have improved on-farm practice but further work is required to improve water use efficiency on-farm and to reduce nutrient loss. MGI has invested in weather stations and is working with farmers who have soil moisture monitoring to improve water use efficiency. Efficiency on farms with higher energy costs (WD) tend to be more efficient than within the original scheme area because the cost of each cubic metre is higher.

RIVER AUGMENTATION

The Waihao River is named after the hao eel, with Wai meaning water in Māori. The hao eel is a shortfinned eel that is a delicacy, with the local river and rūnanaka both named after it. The Waihao River has always been used as a bywash site for scheme. Prior to automation and control of scheme gates, the Waihao was a necessary relief point in the event of a power cut or a number of irrigators turning off. The Waihao bywash also provided a buffer because if more irrigators turned on further downstream than anticipated.

When consents were obtained for the Northern Extension the community engagement highlighted an opportunity to augment the flows with reliable Waitaki River water when the flow in the Waihao is low. Over recent years the release of water into the Waihao River has been targeted and managed through scheme controls to replenish flows in the lower River.

For the first 6 months of 2024 the lower river would have been dry if were not for the MGI water release. This release of water has created habitat and sustained the ecology of the lower river until the point that winter rainfall fell in July and allowed the river to flow naturally from its source to the sea.

The Waitaki River Regional Plan is unique in Canterbury because it includes a mahinga kai allocation. Mahinga kai is the Māori term for food and other resources and the gathering of those resources. The allocation provides a flow for use within and outside of the Waitaki River catchment for mahinga kai. The Waihao River augmentation is one such use of that water allocation.

DIDYMO

The clear consistent flowing water of the Lower Waitaki River has become a perfect breeding ground for the invasive diatom didymo (rock snot). Didymo sloughs off rocks and enters the schemes and clogs the screens taking water from the scheme races.

Figures 4 and 5 illustrate the challenge that didymo poses to scheme pipeline intakes from the main canal.

Didymo appears to be growing on the High Density Polyethylene Liner on the first 4 kilometres of the Bells Pond main canal. The didymo sloughs off in patches and floats downstream and clogs intake screens. MGI has invested in improved intake screens that have better capability to self-clean. However, the clearing of the screens requires a significant human resource to maintain supply to shareholders. Investigations into the didymo infestation are scheduled for the 2024/25 irrigation season.

Figure 4 – Image of didymo captured on mechanical pipe intake screen

Figure 5 – Didymo captured on self-cleaning pipe intake screen

WATER PERMIT RENEWAL

Water permit renewal looms for Waitaki River irrigation schemes, with MGI being the first irrigation scheme in Canterbury to face consent renewal in 2028. Under the Resource Management Act (1991) water permits can be issued for a maximum duration of 35 years. The Regional Council, the elected local government, delegates the decision to an appointed panel and submissions can be made by parties who are interested in expressing their views. Upon expiry there is no assurance of renewal, but when considering the application decision makers must consider the value of the investment that has been made.

Regional Plans provide the framework for the decision makers, and include the rules and policy direction that will influence the outcome of the water permit renewal application. The Regional Plans include conflicting objectives of improved water quality and more efficient irrigation conveyance and water use.

The lack of fish screening on the Bells Pond intake will need to be addressed in the renewal application. MGI has commenced a detailed investigation into the performance of the existing rock barrier that has been deployed at the Stonewall intake to assess whether that will be an effective option at the Bells Pond intake.

CONCLUSION

The improved infrastructure and management of water and infrastructure has set up MGI for the future. However, there is considerable further work to do to secure a renewed long term water permit and continuing to improve water quality.

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AT THE INTERSECTION OF FARMLAND & WATER MARKETS

Brett Bovee, P.E.[1]

ABSTRACT

There are a myriad of water stresses facing water managers in the Western U.S. that primarily result from declining water supplies to meet growing or hardening water demands. This imbalance between supply and demand is often addressed with a mix of regulatory and market responses. Regulatory responses include water right curtailments, groundwater allocations, conservation mandates, and instream flow laws. Market responses include water right transactions (reallocation), incentivized conservation, infrastructure projects, and new technology development. Both regulatory and market responses serve an important role as we respond to local and regional water stresses.

Management of irrigated farmland should recognize that water stresses and responses present both risks and opportunities. Risks are well documented and include such threats as reduced water supply reliability, stricter administration of water use (diversions and deliveries), reduction in the overall water supply available for use, and increased legal review of water rights and contracts. Setting these risks aside, this paper focuses on the opportunities that water markets, as a form of market response to Western water stresses, present to farm management. Water markets are an established tool to respond to water stress in many parts of the Western U.S. Looking at the last 20 years of water trading activity, it is clear that water markets are very local, typically temporary (in the form of leases), and are dominated by agricultural sellers (lessors). At the intersection of this water market activity and the recurring decisions that agricultural producers make regarding crop selection and rotations, irrigation methods, capital investment, and property management is a set of opportunities. Opportunities explored in this paper include:

- **Innovative water leasing programs** to serve a variety of new uses. Different fallowing programs (rotational, split-season, intermittent) can provide new water supplies to meet environmental, municipal, and agricultural water demands. Examples of successful programs are found in Colorado, California, Arizona, and Washington. A case study in Northern Colorado is presented.
- **Payments for reduced water use** are a growing policy tool, with examples in the Colorado River Basin, Ogallala Aquifer, Columbia River Basin, and other places. These programs are designed to maintain farming and pay growers for using less water. A case study in the Imperial Valley is presented.
- **Water and farm property sales** in certain high-value markets can make sense for shifting agricultural operations. Water right sales have a value premium over

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leases because they can support homebuilding and land development activity. A case study in Northern Colorado is presented.

INTRODUCTION: WATER STRESS & HOW WE RESPOND

There are many contemporary examples of water stress in Western U.S. which are well documented in mainstream media outlets. Many of these examples are somewhat analogous to being stuck on the tracks of a slow-moving train. The stresses result from problems that are decades in the making, the solutions are difficult and slow to take hold, and we continue to see the steady progression of a potential future calamity. Some specific examples include the continued overdraft of multiple groundwater aquifers[1], the potential loss of the Great Salt Lake[2], and the depletion of storage in the Colorado River Basin[3].

These examples of water stress largely stem from a water supply imbalance with supply and demand stressors summarized in Figure 1. We respond to these supply and demand stressors with both regulatory and market responses, also shown in Figure 1. There are many examples in the Western U.S. of how the listed stressors have resulted in the listed responses. Provided below is a short list of examples:

- **Pacific Northwest**: Salmon recovery efforts in response to the Endangered Species Act have created a new demand for water and the response has been regulatory definition of minimum instream flows to support salmon and various water transactions to meet the defined flow objectives.
- **Southwest**: Overdraft of groundwater aquifers has prompted water management districts and state agencies to enact strict groundwater pumping allocations in many locations that reduce water supply. This includes the implementation of the Sustainable Groundwater Management Act (SGMA) in California and the operation of Active Management Areas (AMAs) in Arizona.
- **Intermountain West**: Decline of the Great Salt Lake has created a new demand on Utah's water supplies and has prompted state funding to be used to pay for water transactions to increase lake inflows and to incentivize water conservation actions to reduce demand on local water supplies.
- **Great Plains**: The regional overdraft of the Ogallala Aquifer represents a declining supply. It has motivated some management districts to enact groundwater pumping allocations and has also motivated funding to pay for water transactions and farm buyout programs to reduce pumping.

[1] https://www.nytimes.com/series/uncharted-waters
[2] https://www.pbs.org/newshour/science/the-great-salt-lake-is-rapidly-shrinking-and-utah-has-failed-to-stop-it-a-new-lawsuit-says
[3] https://www.washingtonpost.com/climate-environment/2023/02/05/colorado-river-drought-explained/

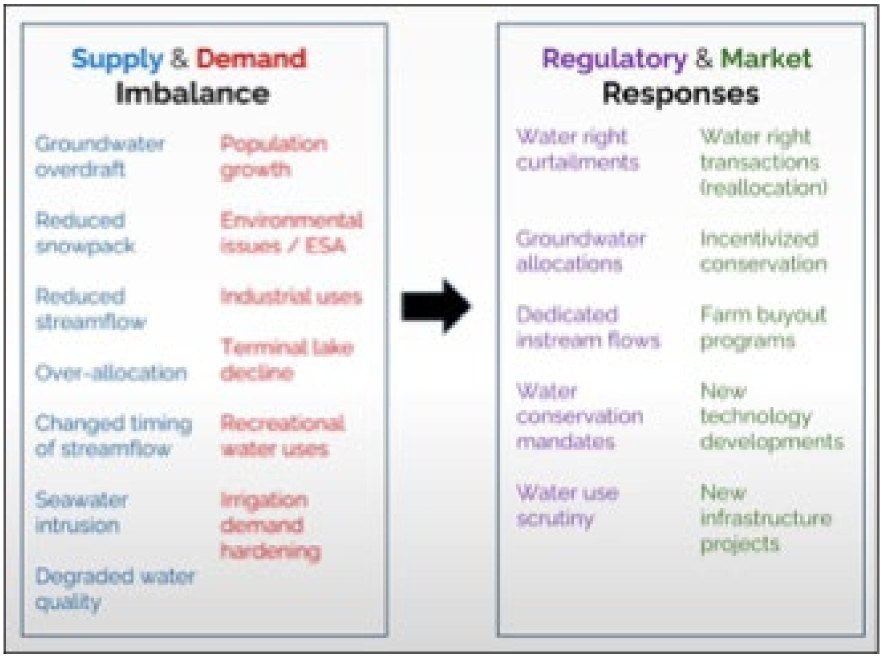

Figure 1: Water Stressors & Responses

FARMLAND: AT THE HEART OF WATER STRESS AND RESPONSE

Irrigation water use is the most significant water use in the Western U.S. region. This fact reflects the local climate conditions, the original economic engines from settlement to today, and government incentives to promote land reclamation and economy building. As a result of irrigation's water use scale and breadth, and because water stresses are so ubiquitous, farmland management will likely have to deal with water stressors and responses now or in the near future. As this takes place, management decisions on irrigated farmland should recognize that water stresses and responses present both risks and opportunities. The risks to farmland are well documented and include such threats as reduced water supply reliability, stricter administration of water use (diversions and deliveries), reduction in the overall water supply available for use, and increased legal review of water rights and contracts. Setting these risks aside, but not diminishing their importance, this paper focuses on the opportunities that water markets present to farm management, as a form of market response to Western water stress.

WATER MARKETS: AN ESTABLISHED TOOL TO RESPOND TO STRESS

Water markets are an established tool to respond to water stress in many parts of the Western U.S. Water markets are comprised of the transaction of water rights and other forms of water entitlements. Generally speaking, we need the ability to reallocate such rights to use shared water resources over time to respond to economic changes, environmental conditions, and political shifts. Providing for such reallocation of the water resource is the role of water markets, and water markets have been active in the Western U.S. for over 20 years. Figure 2 presents a view of water market activity in the Western U.S. over a 10-year period based upon independent research. In total, water market activity is about $1 billion per year transferring over 2 million acre-feet of water entitlements through sales and leases.

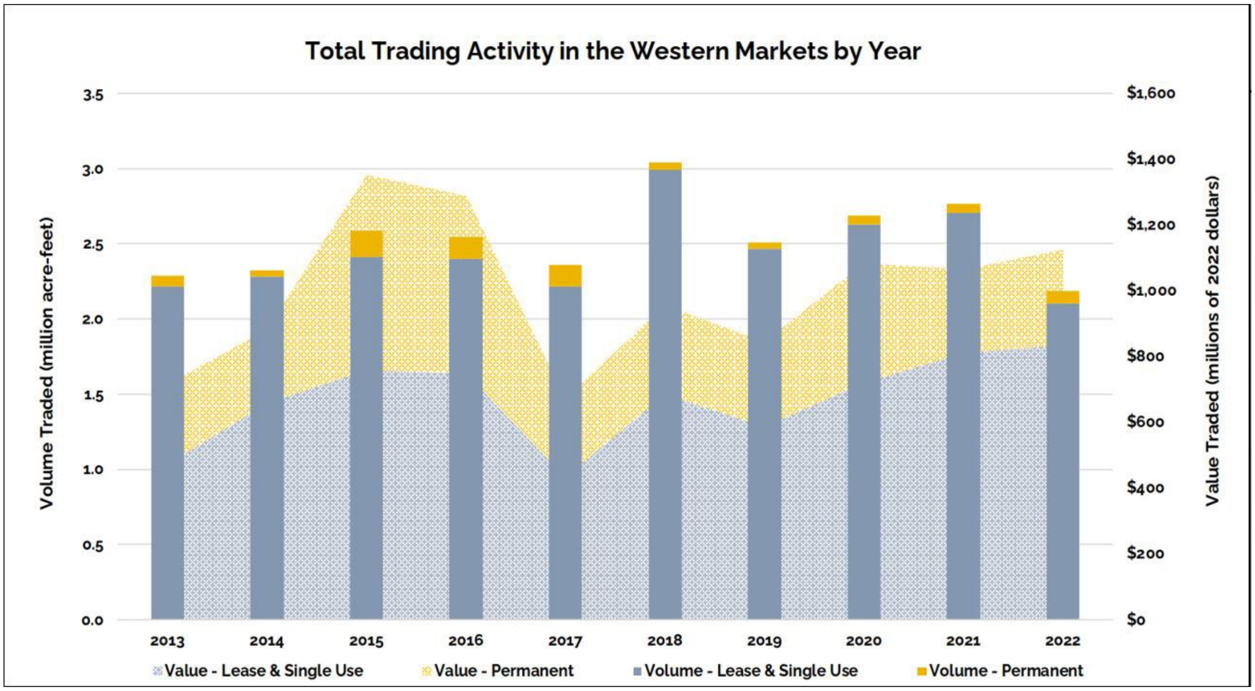

Figure 2: Water Market Activity over 10-Year Period

The transactions that make up water markets are not like stock trade on the New York Stock Exchange or commodity trades on the Chicago Mercantile Exchange. Water trades are like property trades, and water markets are much like real estate markets. Also, like real estate markets, water markets are typically very local. The physical water source has to be accessible by both the seller and buyer. With some exceptions, water rights do not often transact over large distances. Most water trades involve two parties in the same community or county. As such, local conditions often define water market activity and pricing.

As shown in Figure 2, water leases make up the majority of water transaction activity, by both volume and value. Multiple water use sectors are turning to water leases to meet demands. This can take the form of simple water rental contracts or more sophisticated option contracts or multi-year agreements. Some examples of the demand for leased water supplies are listed below:

- **Environmental buyers** often focus on securing water for instream flows to improve habitat conditions. Their demand for water may not be present in all year types as they focus on critically low flows during drought. Also, it usually requires a relatively large flow of water to make a significant impact on streamflow such that available funding makes a bigger impact through leasing.
- **Municipal buyers** have historically focused on permanent acquisitions of water supply to meet a sustained demand and commitment to customers. For various

reasons, municipal utilities are turning to water leases to fill temporary and long-term gaps in their water supply portfolios.

- **Agricultural buyers** are in the water market to either respond to changed conditions or to facilitate new production. Changed conditions could mean temporary droughts, new regulatory restrictions, or commodity changes.

  A growing area of water market activity is conservation payments for reduced water use. Government funding is being used to incentivize the reduction in agricultural water use. Often, the funding is targeted at a goal of long-term water supply sustainability. Some examples of this increasingly common market tool include Federal government contributions in Colorado River Basin[1], Utah's state legislature funding an agricultural water optimization program[2], Nevada water right buyouts[3], and most recently the USDA announcement of water conservation funding for 19 irrigation districts[4].

THE INTERSECTION OF FARMLAND MANAGEMENT AND WATER MARKETS

There is a broad intersection between farmland management and water markets. As a starting point, most water trades involve an agricultural seller. This reflects the fact that most water rights are currently in agricultural use, so it represents the largest seller pool. Local conditions dictate whether a water transaction is a reasonable action for a farmland owner. Some of the prominent factors that influence such a decision include the value of agricultural production, the demand from municipal growth and industrial development, and the relative level of water supply scarcity.

Water market activity involving agriculture is often viewed as permanent sale and permanent retirement of farming. Permanent water sales can have economic ripple effects in the local community if they occur at a large scale and if the sale results in a water transfer out of the community to another location. But as stated above, water markets are primarily leases and involve a growing number of transaction structures that maintain land in agricultural production over the long term. Therefore, water markets can be viewed as an opportunity to maximize revenue in the agricultural sector and can be incorporated into farm management decisions.

Farm management decisions include crop selection and rotations, irrigation scheduling and investment in irrigation technology, soil health practices, property acquisition and divestment, and choices on whether and how to invest in capital improvement projects. These decisions are influenced by multiple factors, but a prominent goal is to maximize profit of the farm operation. Water plays an important role in the profitability of agriculture in the Western U.S. Droughts or regulatory cutbacks in water supply can

[1] https://www.politico.com/news/2023/11/25/biden-climate-cash-water-costs-00128595
[2] https://ag.utah.gov/ag-water-optimization/
[3] https://www.washingtonpost.com/climate-solutions/2024/07/19/water-rights-nevada-pilot-program/
[4] https://www.usda.gov/media/press-releases/2024/08/01/biden-harris-administration-invests-400-million-address-drought

result in significant losses in crop yield and quality, and therefore agricultural investments tend to gravitate to areas with reliable water supplies. Water market opportunities can also play a role in farm profitability by incorporating water transfers into the farm management decisions listed above.

Three examples are provided to illustrate different concepts on how water markets can be incorporated into farm management decisions. These examples do not provide an exhaustive set of concepts and opportunities at the intersection of farmland management and water markets, but they intend to lay the groundwork.

Concept #1: Water Leases While Preserving Farm Operations
As discussed above, water leases are increasingly in demand to meet a variety of water uses and they make up a majority of water market activity. Changes in farm management can produce water for leases while maintaining the farm. Some examples of this that have been put into practice include: (1) rotational fallowing programs: insert water leases into crop rotations, (2) split-season fallowing of forage (hay) crops: provide water leases in critical late-season when crop yields are typically lower; and (3) reducing irrigation demands through changes in irrigation practices or crop selection can provide water for lease in some unique circumstances. There are a large and growing number of examples of these types of water lease agreements dating back 20 years, and a large body of academic and policy research papers on the subject of the agronomic and economic impacts (positive and negative) of farms participating in these types of water leasing programs.

CASE STUDY OF WATER LEASING IN COLORADO

The New Cache la Poudre Irrigating Company operates an irrigation delivery system in Weld County, Colorado serving about 32,000 irrigated acres for the benefit of its shareholders. The Company diverts water from the Cache la Poudre River southeast of Fort Collins, CO and operates a reservoir to provide late-season water supplies. The farmlands served by the Company grow corn, soybeans, and alfalfa hay, along with some specialty crops such as carrots.

Shares in the Company have started to be acquired by non-agricultural owners who have changed the legal use of the shares to serve needs other than irrigation and outside of the Company service area. Approximately 10% of the Company shares are held by municipal and industrial entities. The Company was concerned about this trend and wanted to explore ways to permanently tie Company shares to the irrigated land while also making water available to meet municipal and/or industrial demands that exist because of the development activity along the northern Front Range of Colorado. The Company received grant funding to explore and implement a water leasing program that would achieve these two goals.

The Company found interest from a local municipality in a perpetual water lease agreement. The terms of the proposed agreement were never finalized but the following provides an outline:

- 3 in 10-year call option for the municipality to utilize water supplies associated with Company shares involved in the water lease. The option call would have to be placed by December 31 for the following year.
- Payments by the municipality would include three components: (1) an upfront payment equal to 50% of the enrolled shares' market value, (2) an annual payment each year of $50 per acre-foot of water supply involved in the lease, and (3) a lease payment of $900 per acre-foot in years when the option was exercised, and water was leased.

The economics of this proposed water lease were favorable compared to annual agricultural production returns. Net returns from farming are estimated to yield approximately $150 to $500 per acre, or about $100 to $300 per acre-foot of water use. Despite these favorable economics, the proposed lease did not proceed because Company shareholders were not willing to make a perpetual commitment of their shares to this water lease and thereby sacrifice the future option of selling their land and water. At the time, the permanent sale value of Company shares was rising due to the influence of home-building activity in the surrounding area. While the near-term economics of the proposed water lease looked favorable, there was concern that the long-term economics would not support the perpetual commitment required.

Concept #2: Conservation Payments for Reduced Water Use
As described above, a growing area of economic investment by State and Federal government agencies is for compensated reductions in irrigation water use. The significant influx of government money represents an opportunity for farmland owners who are able to successfully implement water conservation projects and programs. Example activities include canal lining and piping to reduce irrigation conveyance losses, modifying field irrigation practices to employ more efficient techniques, modifying water supply management to allow for new uses of water, and operating on-farm fallowing or deficit irrigation programs to reduce irrigation demands. One important point is that these water conservation programs are designed to maintain farmland in agricultural production over the long term and structurally different than the Conservation Reserve Program (CRP) which commits land to non-irrigation status for many years.

CASE STUDY OF CONSERVATION PAYMENTS IN SOUTHERN CALIFORNIA

The Imperial Irrigation District (IID) started the On-Farm Efficiency Conservation Program (OFECP) as a pilot program in 2013 and has continued to operate the program since the 2014-2015 growing season. The OFECP originated as part of the 2003 Quantification Settlement Agreement (QSA) and a long-term water transfer agreement between IID and the San Diego County Water Authority. The water transfer agreement requires IID to develop 303,000 acre-feet of transferable water through on-farm conservation and delivery system improvements. The OFECP is intended to compensate growers in the IID service area for reducing their water deliveries and using less water. IID runs an annual solicitation and application review process to select conservation projects eligible to receive OFECP funding. There is a strict monitoring and verification process to determine conserved water for each project that compares actual water use to an established baseline. In 2022, IID funded $31 million of conservation payments for OFECP participants.

There are a large variety of crop types in the IID service area. To illustrate the potential payments of OFECP participation, two different crop types are evaluated. The first example is a 52-acre field growing a wheat crop. The field is flood irrigated and has been land-leveled to improve on-farm irrigation efficiency. The estimated annual water savings from land leveling are 0.5 AF per acre. This field received a 2020 payment of $285 per AF of conserved water for a total field payment of $7,400. The second example is a 143-acre lemon orchard. Drip irrigation was installed resulting in estimated annual water savings of 1.45 AF per acre. The 2020 payment rate of $285 per AF resulted in a field payment of $59,100. These conservation payments are not high enough to induce more extensive conservation practices such as fallowing, but they do illustrate the potential revenue gained from improving irrigation water use and can be helpful to incentivize water management activities that have other benefits.

Concept #3: Water and Farm Property Sales in High Value Markets

In certain geographies, land development activity has been high for decades as there continues to be a national push for more new homes. Homebuilding activity often relies upon a permanent transfer of water rights or entitlements such that existing customers of the water utility are not impacted by bringing on a significant number of new customers. This permanent transfer of water is usually a water permanent water dedication by the developer or a permanent water purchase by the utility. The effect of this relationship between homebuilding activity and permanent water transfers is that housing prices are often aligned with water right prices in area of high activity. As housing prices increase, so do water right prices. As a result, areas of population growth and land development activity are seeing value appreciation in water.

The other economic effect of this relationship between land development and water is that water right sale prices have a premium over water lease prices. Water has been shown to have capitalization rates of around 1% in areas with significant demand for water to support land development. Therefore, separate from the water lease discussion above, farmland managers should consider the potential to have significant water right sale values tied to their property. In such instances, there could be an opportunity cost to consider in keeping the water in agricultural production. Also in such instances, the importance and financial benefit of maintaining water rights in productive use should be recognized. For areas that have experienced appreciation in water right values, farmland managers should make a concerted effort to document their water use and to consider options for leveraging the value of growth and reinvesting the proceeds from a sale into another agricultural investment. It should be noted that high sale values are only found in specific geographic areas of growth and for specific types of water assets. These dynamics are not ubiquitous across the Western U.S. region.

CASE STUDY OF WATER SALES IN HIGH VALUE MARKETS

A landowner operated a 150-acre irrigated farm in the northern Colorado Front Range. The land was leased to a farm tenant who primarily grew corn and soybeans with some alfalfa hay production in the past. The tenant was paying approximately $100 to $200 per acre to rent the irrigated farm. Crop returns for the tenant were estimated to be in the range of $200 to $500 per acre depending on yields and crop prices. The property was irrigated with shares in a local irrigation ditch company and with a groundwater well on the property. The irrigation company shares had seen significant price appreciation because of local home-building activity and the general ability to dedicate these types of shares to several municipal water utilities to support water service commitments to new homes. A local homebuilder approached the landowner with an offer to buy the farm property for $6.5 million, which is equal to about $43,000 per acre. The value of the water rights tied to the property heavily influenced this offer price. The landowner was able to realize a value premium of roughly eight times the current value of the water and property in agricultural use and was able to reinvest the funds in another agricultural property at an expanded acreage.

SUMMARY

The Western U.S. continues to experience water stress, which is a combination of the natural hydrology and the significant demands we are placing on available water supplies. Water stresses have varied responses including regulatory action and market reaction. Water markets are an established tool and an outcome of our need to be able to reallocate the available water resources to various demands. Water market activity in proximity to farmlands creates various opportunities for farm managers to consider. The three concepts at the intersection of farmland and water markets that are presented in this paper include: water leases, conservation payments, and water sales.

EVAPORATION FROM GROUNDWATER RECHARGE BASINS

Daniel J. Howes[1]
Luke Nydam[2]

ABSTRACT

Research for open water evaporation measurements has been conducted for many years under various conditions. The results have been variable because of different open water conditions. As an example, energy storage is a major component of the energy balance within an open water system. Water that is cold has the potential to store more of the incoming energy. As the water warms over weeks or months, energy storage decreases and the energy use for the conversion of a liquid to a gas (latent heat of evaporation) increases. It has been shown that deeper lakes have lower evaporation rates in the warmer periods because the water is colder from snowmelt and stores more heat during this period. Conversely, in the winter, the deeper lakes have a higher evaporation rate since the water is warmer because it was heated over the summer. Shallow water bodies, on the other hand, have been shown to have a more consistent evaporation rate because of the limited energy storage.

Groundwater recharge basins are a special case because they have a high turnover rate with substantial amounts of water moving through the basins during the recharge period. Cold water is continuously added and does not have time to warm significantly. The author's hypothesis that the continuous addition of cold recharge water will result in a lower evaporation rate compared to normal shallow water bodies (<2meters) because of the additional energy storage availability.

In this paper and presentation, we will present evaporation measurements made using Eddy Covariance instrumentation during the 2023-2024 recharge seasons in several recharge/open water conditions. The measurements were made at two locations in Kern County of California. The instrumentation will be discussed in a separate paper and presentation. Initial analysis indicates the results to be consistent with the hypothesis. High production recharge basins had substantially lower evaporation rates (crop coefficients) compared to a wetland type habitat with low seepage rates. This data comparison will be presented.

INTRODUCTION

Even with decades of research on open water evaporation, there are significant data gaps and limitations on measuring open water evaporation from remote sensing. In California, a major unknown is the amount of evaporation from groundwater recharge basins. The Sustainable Groundwater Management Act (SGMA) drives sustainable groundwater

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management throughout California. Having an accurate account ofwater entering/leaving the aquifer is becoming extremely important. There are thousands of acres of recharge ponds in the San Joaquin Valley with no accurate estimate of evaporation.

Decades of research show that there are numerous factors influencing evaporation from open water. Two main categories are deep and shallow water bodies. Typically, shallow water bodies are considered two meters deep or less. Depth is a key factor in the ability of the water source to store energy. The uncertainty related to this factor makes it difficult to accurately estimate the evaporation. For deeper water bodies, such as lakes, the fraction of actual evaporation to potential evaporation (evaporation fraction) is higher in the fall and winter because of heat stored in the summer. The cold water after winter can store a significant amount of heat throughout the spring and summer. Mixing also occurs in the late fall and winter, compounding this issue.

For many years, researchers have been studying evaporation rates from open water. Jensen (2010) provides a summary of early research in open water evaporation. Direct measurement of open water evaporation in this summary was only conducted in research settings and therefore has limited ranges of conditions. Typically, a relational estimate is made, such as a Class A pan with a pan coefficient. Pan evaporation relationships have been used for decades as a method to estimate reservoir evaporation from reservoirs of all sizes. However, the level of uncertainty with this relationship is significant (Jensen 2010, Friedrich et al. 2018) and is a major reason why in more recent years, pan evaporation assessment is less common. Additionally, because of the increased warming of standard pans these pans have been found to be a poor method of estimating evaporation from a larger water body (Jensen et al. 2005).

Utilizing open water crop coefficients and weather-based reference evapotranspiration provides a reasonable estimate in some cases but not others. The deeper the water body, the more energy can be stored. In the deeper water bodies, relative evaporation rates (open water "crop" coefficients) tend to be higher in the fall and early winter when the water is warm, and lower in the spring and summer when the water is cold from the cooler winter temperatures. Mixing also plays a significant role since warmer water could be swapped with cold water near the surface during mixing events. These aspects are well-documented, especially in deeper water bodies (Allen and Tasumi 2005, Wang 2014).

Shallow water bodies are considered to be 2 meters (6.5 feet) deep or less. Shallow conditions limit energy storage and therefore studies have shown that wetlands and shallow ponds have relatively constant relative evaporation rates (Jensen and Allen, 2016).

Since recharge basins are generally shallow, it is typically assumed that evaporation would follow a shallow water body. The difference between recharge basins and other shallow pools is that the inflow is relatively high because of the high percolation losses. Therefore, cold inflow is continuously entering the pools potentially providing a source for energy storage, decreasing evaporation (at least in part of the season). Since different basins have different recharge rates, the amount of low temperature water can vary. The cooler the water is, the more ability it has to store energy, lowering the evaporation rate. Our hypothesis is that the relative evaporation rate will be lower than current estimates based on shallow water bodies and that this rate is influenced by recharge rate.

Another unknown is how much evaporation, and evapotranspiration occurs after the water has receded. This would be a function of basin management and soil available water holding capacity. If weeds are allowed to grow, the evapotranspiration may be relatively high since the roots have access to deep water. However, during drought years following recharge the depth of evaporation can be relatively deep, especially if the soil in the basin is tilled.

Currently, recharge basin managers in the San Joaquin Valley utilize a set percent loss evaporation estimate. For example, some water banks in Kern County use a set 6% of the total inflow to account for non-recoverable losses, the majority of which would be evaporation. There are over 10,000 acres of recharge ponds in Kern County California. If current estimates are off by only 10%, that would translate to an error of over 4,000 AF of recharge, which is worth more than $2 million or more during a normal year in a single subbasin. We propose four methods to measure and estimate evaporation from two groundwater recharge ponds in Kern County. Our partner Buena Vista Water Storage District (BVWSD) and a supporting water agency, Rosedale-Rio Bravo Water Storage District (RRBWSD), have agreed to provide access to their recharge facilities.

This paper will discuss the initial results from 1.5 years of this study in several shallow water conditions. Data collection is continuing, and future analysis will include development of remote sensing models to accurately determine the evaporation from recharge basins regionally.

METHODOLOGY

An eddy covariance (EC) system to directly measure evaporation and other energy balance components was selected for this study. The EC equipment is expensive and requires careful maintenance but have been successfully used to measure open water evaporation (Blanken 2000, Coonrod et al. 2001, Allen and Tasumi 2005, Pérez et al. 2020). The details of the EC system can be found in a companion paper (Nydam and Howes, 2024)

Briefly, the EC system include 3D sonic anemometer for sensible heat flux (H), sonic anemometer and infrared gas analyzer for direct evaporation measurement (latent heat flux (λE_{EC})), and a net radiometer for net radiation (R_n). Additionally, independent wind speed and direction, air temperature and relative humidity probe, and precipitation gage is installed.

The evaporation computed using the energy balance is computed using (Jensen and Allen 2016):

$$\lambda E_{EB} = R_n - H - Q_t + Q_v \quad (1)$$

Where λE_{EB} is the latent heat flux, Rn is the net incoming radiation, and H is the surface heat flux. Qt +Qv replaces the energy storage term typically identified as G. Q_t is the water energy storage and Q_v is the net energy advected into the basin. Q_t is computed as (Jensen and Allen 2016):

$$Q_t = C_w \rho_w \frac{\left[\left(\int_B^Z T(z)dz\right)_{t2} - \left(\int_B^Z T(z)dz\right)_{t1}\right]}{t2 - t1} (2)$$

Where we are integrating the temperatures across the profile from the bottom (B) to the water surface (S) at time 1 (t1) and subtracting that from the integrated temperature at time 2 (t2). C_w is the specific heat of water in $MJkg^{-1}K^{-1}$ and ρ_w is the density of water in kg m^{-3}. Q_v is computed as:

$$Q_v = (V_p T_p + V_i T_i) \frac{\rho_w C_w}{A} \qquad (3)$$

Where V_p and T_p are the volume and temperature of precipitation entering the basin, V_i and T_i are the volume and temperature of the water entering the basin, and A is the surface area of the water in the basin.

Finally closed energy balance system is:

$$\lambda E_{EC} = \lambda E_{EB} \quad (4)$$

However, the full closed energy balance is still being evaluated. This paper will present the direct measurement of evaporation (λE_{EC}) from the sonic anemometer and infrared gas analyzer to evaluate the hypothesis that the evaporation rates in recharge basins is lower than predicted using the crop coefficient method for shallow basins.

The results will be presented as normalized evapotranspiration values, normalized based on the grass reference evapotranspiration measured at a nearby weather station. This is also known as the grass reference-based ET fraction (EToF) or actual crop coefficient (Kco). The Kco is computed as:

$$K_{co} = \frac{\lambda E_{EC}}{ET_o} \qquad (4)$$

Grass reference (short crop) evapotranspiration (ETo) data was obtained from two nearby California Irrigation Management Information System (CIMIS) weather stations in Kern County. Belridge station (#146) and Shafter station (#5) are the closest stations to the measurement locations. The Belridge station is west of the sites and Shafter is northeast of the sites.

SITES

Measurements have been taken at two sites since the project began in May 2023, using the same sensor equipment. Both sites were located in Kern County California, west of Bakersfield. The first site was located in a shallow pond (Chicca Pond) that had been a wetland habitat in the past. The vegetation was mowed before wetting up but towards the end of the measurement period in late summer 2023, tules and other wetland vegetation were growing in this pond. While this site was not a recharge basin, the cooperator guaranteed water availability throughout the measurement period regardless of water year. When this site was initially selected, the availability of water for recharging was unknown. The cooperators were Buena Vista Water Storage District (BVWSD) and Terry Chicca, a grower in BVWSD.

Instrumentation was installed prior to the field flooding up. The site was selected based on surrounding fetch and likely water depth. The depth was approximately 1.5 meters at its deepest and varied throughout the site. The pond area was approximately 50 acres with the measurement site located in the southeastern portion, downwind of the prevailing wind.

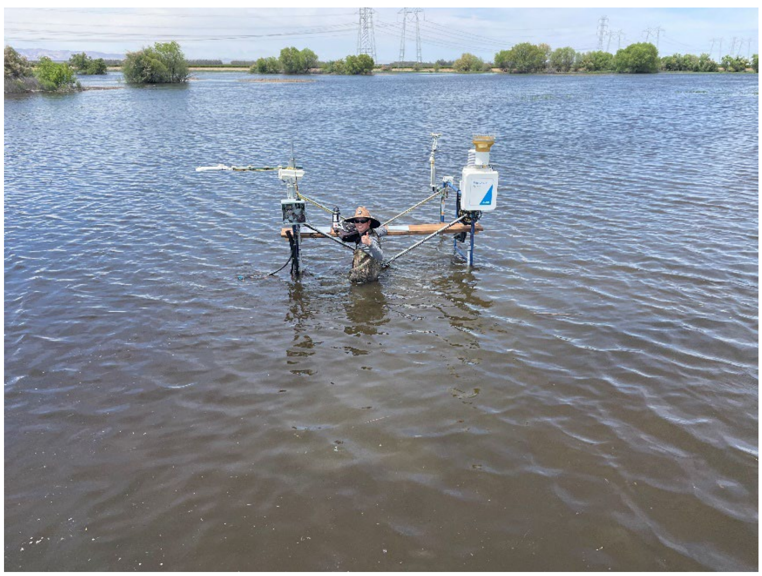

Figure 1. Chicca Pond measurement site looking from the southeast towards the northwest.

The wetland tule vegetation was significant by late July 2023 in the Chicca Pond. However, because some recharge basins are managed with wetland vegetation it was decided to continue the testing through October 2023. Figure 2 shows the tule growth in the wetlands from emergence in July through full growth in September. Sensor height was adjusted monthly in August and September to account for the increased vegetation growth.

In mid-October 2023, the pond was dried so that the equipment could be moved to the next site. Standing water was visible until November 3. The soil was dry enough to remove the equipment on December 3, 2023.

The sensor equipment was moved to a more traditional groundwater recharge basin in Rosedale-Rio Bravo Water Storage District. The recharge area was over 580 contiguous acres split into multiple cells (Figure 3). With prevailing winds from the northwest, the station was installed in the southern portion of the site with significant open water surrounding the measurement site.

Figure 2. Vegetation surrounding the Chicca Pond from July 3 (top left), August 9 (top right), and September 1, 2023 (bottom).

Measurements were taken at the RRBWSD recharge basin from December 20, 2023, through June 2, 2024. Standing water was continuously entering the basin maintaining a depth between 2-3 feet from December 2023 through March 3, 2024. Dry down began on March 3, 2024, and by March 7, 2024, there was no standing water. After March 7, the EC station measured bare soil evaporation and evapotranspiration (ET) of weeds growing as the basin dried.

Figure 3. RRBWSD groundwater recharge basin used for evaporation measurements (oriented top is north).

RESULTS

The results are discussed in three distinct categories. The first is open water evaporation from the two sites without vegetation impacts. The second will be the evaporation and transpiration with aquatic weeds (tules) once these emerged in the Chicca Pond. The third category will be the bare soil evaporation and weed ET measured after pond dries down in the RRBWSD recharge basin.

Recharge Basin Evaporation

Open water evaporation occurred over different periods of time in each site. The Chicca Pond evaporation occurred from May through mid-July 2023. The open water evaporation for RRBWSD basin was measured from December 2023 through mid-March 2024.

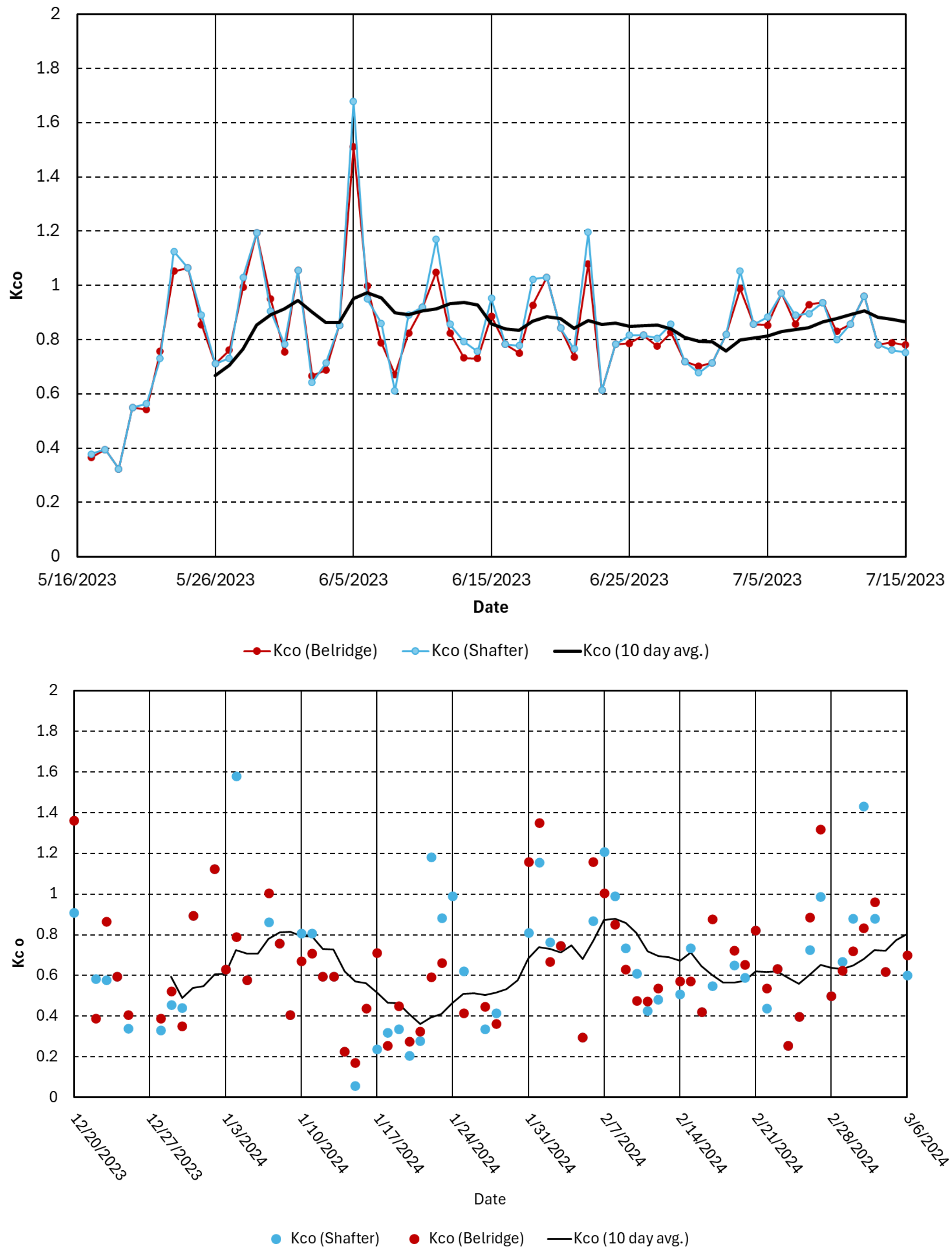

Figure 4. Crop coefficient for open water evaporation at the Chicca Pond (top) prior to vegetation emergence and RRBWSD basin (bottom) with daily values based on the two ETo weather stations and the 10-day moving average of both stations.

The open water Kco values are shown in Figure 4 for the two sites. The Kco for the individual CIMIS stations is shown along with the 10-day moving average with the stations combined. The average Kco at the Chicca Pond ranged between 0.8 and 1.0 but generally was closer to 0.8. Individual days ranged between 0.6 and 1.2 over the time period. Because this site did not have high recharge rates, higher Kco's were expected. However, to mimic a recharge basin, flows were continuously delivered to the ponds. Therefore, the water temperatures would be lower than a static shallow water body, likely causing the Kco values to be lower than the traditionally assumed 1-1.05 (Allen et al. 1998).

The Kco values from the RRBWSD recharge basin had more variability and overall were significantly lower than traditional evaporation estimates for shallow water. The RRBWSD recharge basins have remarkably high recharge rates, exceeding 0.5 acre-feet per acre per day. Water inflow exceeded 250 cfs throughout the study period into this basin. The 10-day moving average varied between 0.39-0.85, averaging 0.5-0.55 over this period.

Both measurement sites show evaporation rates below traditional shallow water evaporation. This suggests that the hypothesis is correct. Recharge basins with high inflow rates of lower temperature water have lower evaporation rates. The Kco difference between the two sites indicates that evaporation will be proportional to the recharge rates. This possibly means that the higher the recharge rate the less evaporation during the recharge period.

Wetland/Aquatic Weed Evapotranspiration

The EC sensors were used to measure the evaporation from the drying recharge basin and the evapotranspiration from the weeds growing in the recharge basin (Figure 5). On March 7, 2024, standing water was no longer visible in the recharge basin. The EC station continued to measure the evaporation and ET until the site was moved on July 2, 2024. When the soil was wet the Kco remained at the level of evaporation when there was open water. However, the evaporation rate decreased rapidly until a rainfall event near the end of March increased the evaporation rate again. It declined rapidly again until it started to level out by the end of April.

The bare soil evaporation dropped rapidly between 3/7 and 3/23, as expected in a two-stage drying model (Allen et al. 1998, Mutziger et al. 2005). Approximately 0.75 inches of precipitation occurred on 3/23 and 3/24, and 0.5 inches occurred over 3/29 and 3/30, both showing an increase in Kco after these events. Two more precipitation event occurred on 4/5 and 4/13, also coinciding with a slight increase in Kco for a period after these events. No additional precipitation occurred after 4/14/24 during the study period.

Figure 6 shows the drying and weed growth at the site over the study period. Weeds grow became prevalent by mid-April. Groundcover continued to expand into early June. The Kco levels out in mid-May and stays around 0.2 until the end of the study period. This indicates that the weeds continue to use soil moisture left over after the recharge and spring rains into mid-summer.

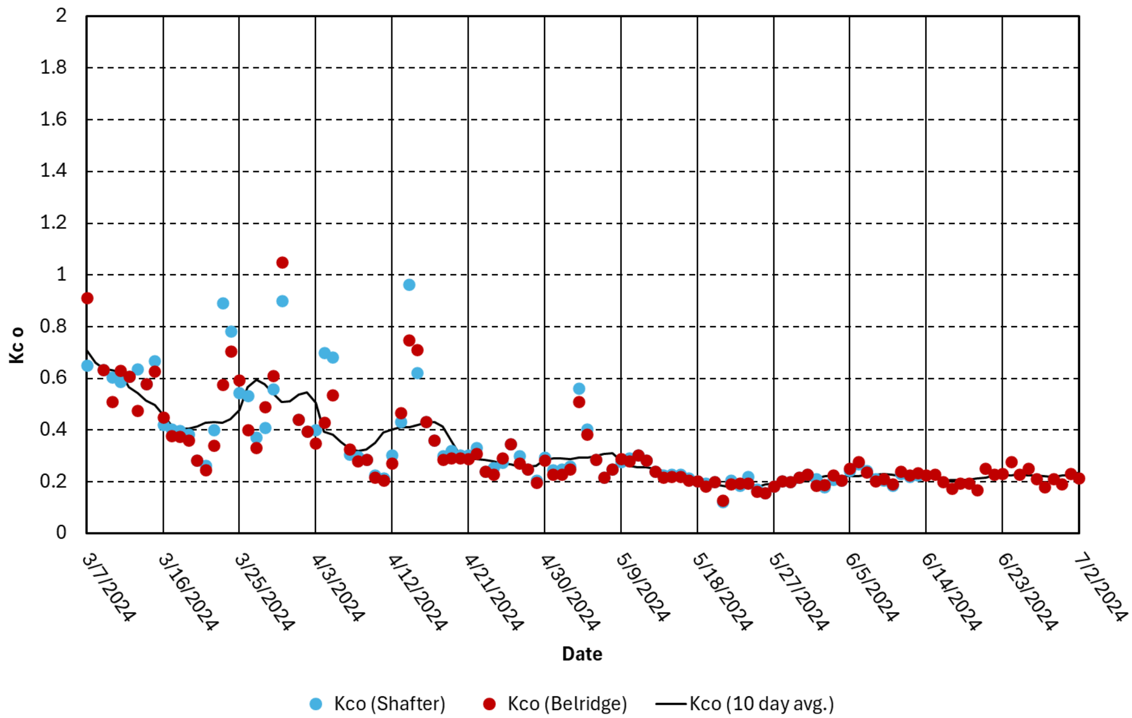

Figure 5. Bare soil evaporation followed by weed evapotranspiration from the RRBWSD recharge basin after the open water receded.

Figure 6. Bare soil and vegetative growth in RRBWSD recharge basin after water receded between March and the beginning of July 2024.

Wetland Evapotranspiration

The final set of data was measured by the EC station after significant tule growth in the Chicca Pond. The pond is traditionally a wetland but was mowed before wetting up so that open water evaporation could be measured. Figure 7 shows the ET from the wetland area after the vegetation emerged from the water around the EC station. The Kco was slightly higher with vegetation than without, with the 10-day average, ranging between 0.8 and 1.0. Average daily ET reached 1.3 on several days as would be expected.

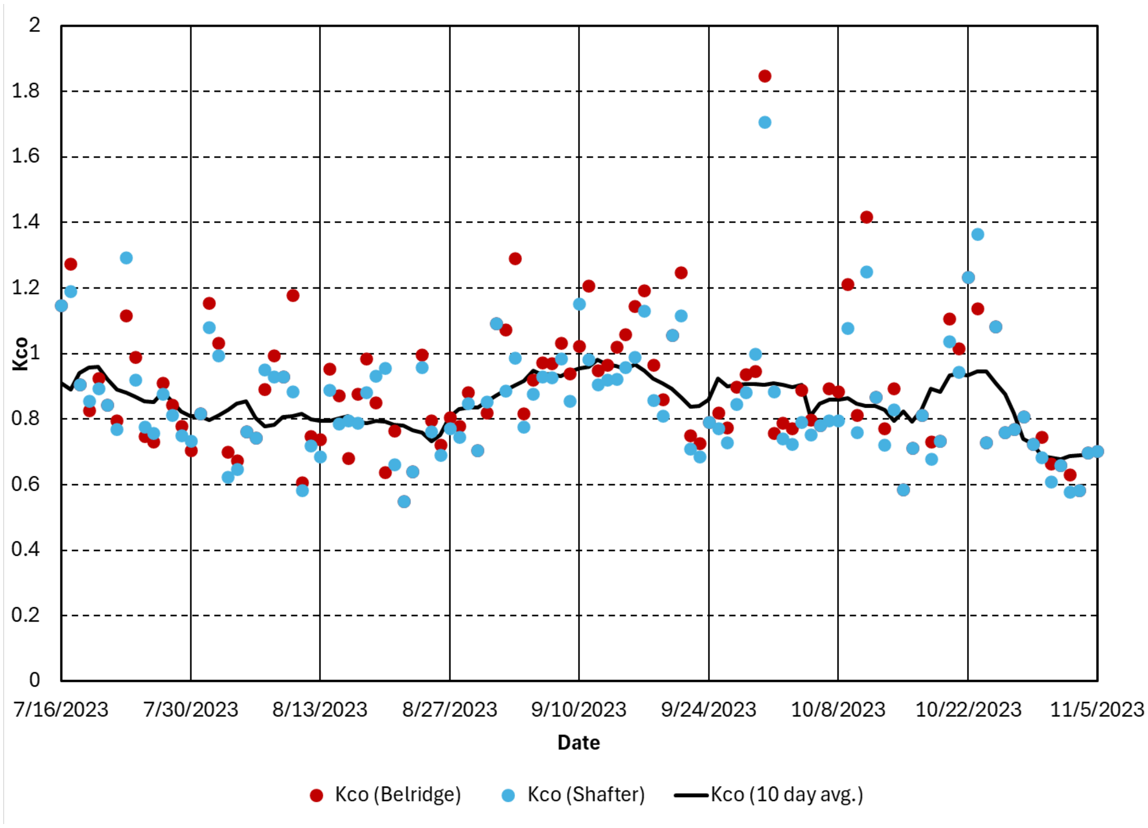

Figure 7. Relative evapotranspiration (Kco) for the Chicca Pond with tule growth within the wetland habitat.

The wetland ET is lower than would normally be expected (Howes et al. 2015). While research from Howes et al (2015) shows some measurement locations where the Kco (Kv in that paper) was below 1, Kco values between 1.1 and 1.2 are more typical. One plausible reason for the lower Kco could be that the sensor height was not adjusted until September 1, 2023. By the end of August, the tule height was nearly level with the sensor height. On September 1, the EC sensors were raised 39 inches. It is possible that the open path sensor was not measuring the full transpiration of the tule vegetation through the end of August. It is surprising that with the increase in vegetation from mid-July to the end of August, the Kco did not increase, it actually seemed to decrease slightly.

After the sensor was raised the Kco increased over time. There was not an immediate increase in Kco at or just after the platform was raised.

CONCLUSION

The initial analysis of open water evaporation indicates that the continual influx of cool water into recharge basins results in a lower evaporation rate compared to a normal shallow pond. While the number of sites and conditions are limited, the initial comparison between a high recharge rate and lower recharge rate shows that recharge rates may be a variable in the rate of evaporation. The results suggest that the overall hypothesis is correct.

Evaporation from the ponds post dry up shows that a significant amount of water may be lost. While soil surface evaporation drops rapidly, weeds accessing deeper water supplies continue to deplete the soil reservoir. How this affects the amount of potential recharge water lost depends on the length of the recharge period and the recharge rate.

The initial results suggest that using a single percentage of total recharge water inflow to account for losses is likely not accurate for any particular recharge basin. The results suggest that both infiltration rates and recharge duration are important variables in the loss computations. Future data analysis will attempt to derive a loss equation. However, more data is needed to fully account for the range of conditions where groundwater is recharged.

Statistical evaluations were not yet made in this preliminary paper. Future analysis includes comparing the open path direct ET measurements with the traditional open eddy covariance energy balance to better understand the water energy storage mechanism. The EC station is currently measuring the evaporation in a water district regulating pond used for short-term water storage. Recharge is sporadic and finding alternative measurement conditions when recharge basins are not in use is critical. The current measurement site is deeper than most recharge basins but the high flow through water supply should provide an interesting test case.

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ORLAND-ARTOIS WATER DISTRICT ANNEXATION AND INFRASTRUCTURE EXPANSION PROJECT

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Jenny Scheer[2]

ABSTRACT

The Orland-Artois Water District's Class II Lands Annexation Project is an example of an innovative and collaborative approach between a water district and surrounding agricultural landowners to address local declining groundwater levels. Orland-Artois WD (District) is a Central Valley Project water service contractor located in Glenn County, California. The District and surrounding region is primarily used for agricultural production of permanent crops such as almonds, olives, and walnuts. While the District delivers Sacramento River surface water to in-District lands, there are thousands of acres of irrigated farmland adjacent to and intermingled with the District that rely solely on groundwater for irrigation. Historical groundwater use has led to declining supplies in the region surrounding and including the District. However, in certain wet year types, there are surface water supplies available for irrigation use. This Project accomplished the annexation of approximately 10,000 acres into the District facilitating the possibility to purchase and irrigate with additional available surface water and reducing reliance on groundwater. The Project also evaluated the feasibility of using existing District infrastructure to deliver water to annexed lands and where not feasible, new infrastructure was designed to 30% completion level. The District recently applied for and received USBR WaterSMART Grant funds for design completion and construction of proposed infrastructure improvements. This presentation will discuss project concept development, policy decisions and agreements between the District and Class II landowners, benefits to the District and its existing landowners, and design process and criteria for infrastructure improvements.

INTRODUCTION

The Orland-Artois Water District (District) Infrastructure Expansion Implementation Project (Project) is located within Glenn County, California, 90 miles north of Sacramento. This project will make it possible to deliver supplemental surface water supply, through voluntary transfers, to land within the District that will result in a reduction of groundwater pumping by approximately 10,000 to 20,000 acre-feet/year. It will also allow for Central Valley Project (CVP) contract water or flood water to be delivered to a recharge basin for groundwater storage. New infrastructure will consist of 4 new turnouts off the Tehama-Colusa Canal (TCC), two booster pumps to increase flows on existing pipelines, and expansion of its buried pipeline conveyance system to deliver supplemental surface water to approximately 10,000 acres of adjacent established farmland within the United States Bureau of Reclamation's (Bureau)

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Central Valley Project (CVP) Place of Use (see Figure 1). This Project increases drought resiliency by providing a secondary source of water supply for 10,000 acres of land which provides flexibility, decreasing groundwater pumping in normal to wet years which ensures groundwater supplies will be available in dry years, and increasing groundwater supplies through groundwater recharge. California recently experienced consecutive years of drought. These dry years caused groundwater levels to decline, had negative impacts on household wells, and are threatening the nearby infrastructure of the TCC and Interstate Highway 5. This project aligns with the goals of multiple local and regional water management plans to address water resiliency such as the District's Ag Water Management Plan, the Colusa Subbasin Groundwater Sustainability Plan, and the North Sacramento Valley Integrated Regional Water Management Plan. The project has the support of the landowners, the City of Orland, Artois Community Services District, Colusa Basin Drainage District, Glenn County Board of Supervisors, Glenn Groundwater Authority, Tehama- Colusa Canal Authority, and North Valley Community Foundation.

BACKGROUND & NEED

The District was formed in 1954 and began water deliveries in 1977. Today the District serves approximately 29,664 acres. The District is a CVP contractor whose water originates in the Sacramento River, is stored behind Shasta Dam and is conveyed to Glenn County via the TCC before entering the District's distribution system.

The District has a CVP contract with the Bureau for 53,000 acre-feet (AF) annually. Additionally, the District contracts with local landowners and water districts for another 10,000 AF of transfer water each year and has two groundwater wells. The amount of available deliverable water can be reduced in drought years. The 10- year average annual water supply is 38,090 acre-feet, which includes four years of 0% allocation due to droughts in 2014, 2015, 2021, and 2022. In unconstrained years, the total amount of available water is 63,000 acre-feet per year (AF/YR). In the ten years from 2013 to 2022, the District delivered an average of 39,617 AF in years when their CVP allocation was greater than 0%. Thus, in years when the District receives water from the Central Valley Project, they have over 23,000 acre-feet of unused water that would be available to newly annexed lands.

Because the District historically has excess supplies in average to wet years, infrastructure improvements to deliver water to newly annexed lands will enable the District to beneficially use their full CVP contract water while protecting local groundwater supplies. By constructing new water distribution infrastructure and improving existing conveyance capacity, this Project will allow for an additional 10,000 acres of newly annexed established farmland to access supplemental surface water supplies. Newly annexed lands will have access to annual excess CVP supplies, CVP transfers, or other non-project water that will be conveyed by the TCC. This project does not put new land into agricultural production.

The annexation of this land provides established farmland with an alternative source of irrigation water other than groundwater to support long-term sustainability and drought resiliency. 95% of the newly annexed lands are planted to tree crops, which cannot be fallowed and require water every year regardless of water year type. This Project will build drought resiliency by supplying 10,000 to 20,000 AF of surface water each year to these lands, which will reduce groundwater pumping by an equal amount and protect groundwater supplies for use during dry years when District surface water is not available. This offset of groundwater pumping within the District boundary will benefit all District landowners and groundwater users in the surrounding area.

Offsetting groundwater pumping and undertaking groundwater recharge will allow the Colusa Subbasin groundwater basin to meet its goals and objectives of groundwater sustainability by Water Year 2042 as mandated within California's Sustainable Groundwater Management Act (SGMA). The District has taken a leadership role in effectively managing the local groundwater resources that they and their current landowners conjunctively manage to sustain agricultural production in Northern California. Implementation of this Project will allow for management of an additional 10,000 acres that are currently outside of the District boundary and solely rely on groundwater to meet crop demand.

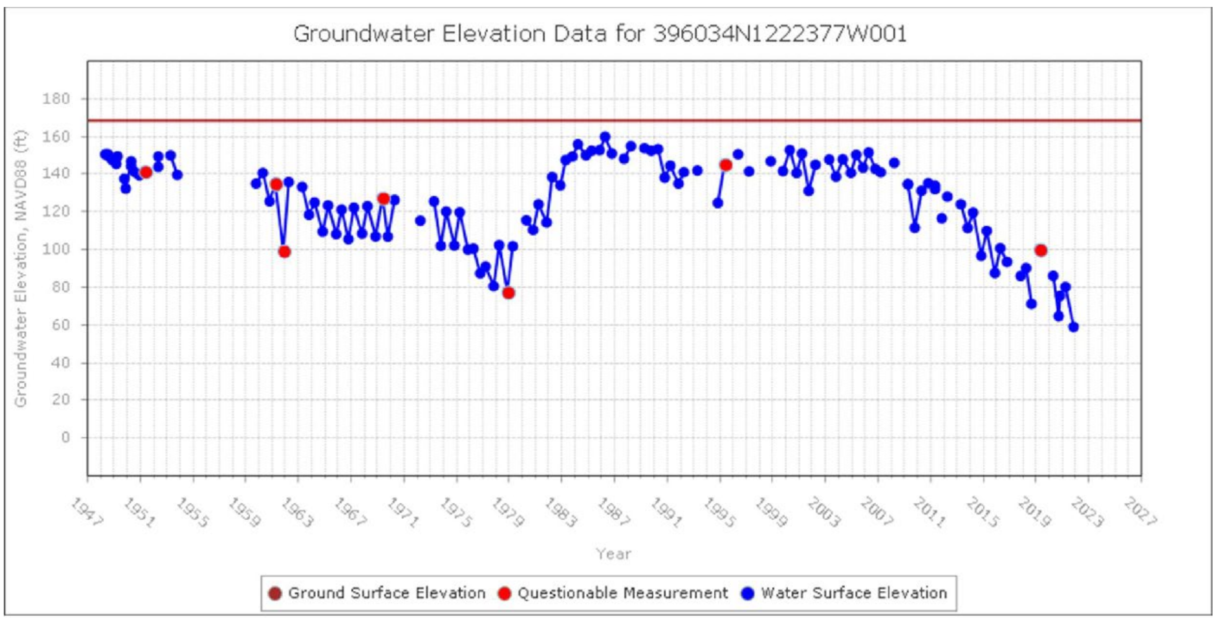
The newly annexed landowner group, in conjunction with the District, has already made a substantial investment to see this Project come to fruition. Roughly $1 million was spent by the landowners for design, environmental documentation, agency reviews, and project management to complete the annexation.

Uncertainty in surface water deliveries has increased significantly since the District first received water from Reclamation's CVP over four decades ago. Groundwater pumping increases when surface water deliveries are curtailed in an area dominated by permanent plantings of orchards. Farmers in the Orland-Artois area are facing a dual threat of smaller and less frequent surface water allocations and declining groundwater levels. This Project helps ensure two sources of water for thousands of acres and a multitude of families. For orchards that are currently irrigated with only groundwater, they gain access to surface water. For their neighbors who are already in the District, groundwater supply reliability is increased by decreasing groundwater pumping in Normal to Wet years on Project lands.

To comply with temperature and flow requirements to protect endangered fish, in recent years Reclamation has been unable to deliver historical levels of water to their water service contractors like the District. More water needs to remain behind the dam at the CVP's Lake Shasta to keep water temperatures lower for migrating salmon and other species. This effectively shrinks the capacity of Lake Shasta, California's largest reservoir. At the same time, minimum flows required to be released into the Sacramento River out of Lake Shasta have increased, so the lake is draining faster each year. Taken together, these operational restraints have seriously hampered surface water deliveries. In the decade from 2014-2023, CVP allocations for the District averaged 56%. The decade prior, from 2004-2013, allocations averaged 86%, a full 30 percentage points higher.

Droughts make matters worse and California experienced five years of serious drought in the decade from 2014-2023 and 2020-2022 was the driest three-year period on record in California. Unfortunately, California's climate is notoriously variable and highly susceptible to droughts. Climate change is expected to exacerbate this feature, resulting in wetter wet years and dryer dry years as well as longer stretches of dry years. Reservoirs help buffer the effects of drought by carrying over water supplies from wet years to dry years. However, given the restrictions in place for California's reservoir operations, their benefits have become more limited, and farmers have become more vulnerable to California's yo-yo weather patterns.

Under SGMA, there has been an increased emphasis on fully utilizing available surface water supplies. As groundwater pumping becomes less certain, surface water supplies are increasingly sought to maintain current levels of agricultural production. The graph below shows just how valuable surface water supplies are for protecting groundwater. As shown below, groundwater levels were slowly declining from 1950 to 1980, particularly in the drought years of 1977-1978. Groundwater levels began to rise with the introduction of surface water supplies in the region from the Tehama-Colusa Canal, as groundwater pumping was curtailed in lieu of surface water and flood irrigation helped aquifers recharge. However, after about 30 years of stability from the early 1980s to the late 2000s, groundwater levels began to decline again, and at an even faster rate. At the well shown on the hydrograph, groundwater levels are now at an all-time low.



Since 2010, there has been a shift toward a preference for groundwater supplies among local farmers, as shown on the well hydrograph, which has been driven by surface water supply uncertainty, efficient irrigation systems such as drip and micro sprinklers that many feel are better suited to groundwater, a concern about phytophthora in surface water supplies among orchardists, and the lower cost of groundwater relative to surface water. In the decade from 2000 to 2009, the District delivered an average of 54,718 acre-feet in 100% allocation years. In the following decade from 2010 to 2019, the District delivered an average of 40,422 in 100% allocation years. To increase surface water deliveries and reduce groundwater pumping, the District is annexing 10,000 acres with landowners eager to use surface water.

When more groundwater is pumped from an aquifer than enters the aquifer in a given period of time, the aquifer is in overdraft. Average annual overdraft in the immediate vicinity of the District has been estimated at 2,900 AF. This number was developed using the C2VSimFG-Colusa groundwater model developed for preparation of the Colusa Subbasin GSP. Cumulative overdraft from 1990-2015 was 74,600 AF in the District area.

Dry wells and land subsidence reflect a trend of declining groundwater levels exacerbated by drought. From spring 2020 to fall 2022, 279 dry wells were self-reported in Glenn County, California. These all represent households and farms who have been negatively affected by groundwater overdraft. In the disadvantaged city of Orland, a municipal well went dry within city limits and hundreds of households were affected in the surrounding unincorporated area. The City of Orland received a grant from the California Department of Water Resources to extend its water delivery pipelines into the unincorporated area to serve 190 of these households. The Artois Community Services District received a similar grant to extend water service to 25 households. Both projects help households access deeper public supply wells, however, they do not reduce overall groundwater use since the City of Orland and the community of Artois use groundwater for their sole source of water supply. On the contrary, this Project would bring additional water supplies into the area and offset groundwater use with surface water use.

By reducing groundwater demand, this Project will increase groundwater levels and groundwater storage in the Orland/Artois area where 14,000 people are solely dependent on groundwater. This will decrease the likelihood that other Glenn County residents will face the hardship that hundreds of their neighbors recently faced when their wells went dry. Dry wells lead to great challenges in the affordability and accessibility of water as homeowners fill tanks with hauled water for hygiene and sanitation and buy bottled water for drinking and cooking.

Land subsidence in the District service area was measured at 0.6 feet (7.2 inches) per year in the five-year period June 2015 to June 2020 by InSAR (Interferometric Synthetic Aperture Radar) (see same map). The Tehama-Colusa Canal, Interstate 5, and the Union Pacific Railroad run through the Project area and are threatened by land subsidence, as are the City of Orland's water supply and wastewater pipelines.

The Project is one of just a handful of projects described in detail in the Colusa Subbasin GSP and is included as a Project and Management Action. The Colusa GSP covers the 1,130 square mile (733,000-acre) Colusa groundwater subbasin in Colusa and Glenn counties in Northern California and is the largest groundwater subbasin in California's Sacramento Valley. Although projects are not ranked in the GSP, this project was recently ranked by the two groundwater sustainability agencies in the Colusa Subbasin as the second most important implementation project and was characterized thus:

"*This project is a priority for the Colusa Subbasin because it provides significant near- and long-term benefits to raise groundwater levels, re-water domestic wells, and reduce land subsidence. Without this keystone conjunctive use project, it will be difficult to stabilize groundwater levels in the area and achieve groundwater sustainability in the largest subbasin in the Sacramento Valley. If this project had been in place 10 years ago, this area would not have experienced such groundwater decline and its attendant negative impacts. The Project helps the Colusa Subbasin address groundwater* *challenges related to three undesirable results: declining groundwater levels, land subsidence, and reduction of groundwater storage as well as address impacts to domestic wells, which is a major goal of California's Sustainable Groundwater Management Act [SGMA].*"

GROUNDWATER RECHARGE

The Project will also include a new connection to an existing basin within and adjacent to the District's boundary for the benefit of replenishing the groundwater aquifer through managed groundwater recharge. The basin cannot currently receive water, but deliveries on a new pipeline will enable recharge of voluntary transfer water, excess flood water, and excess District CVP supplies.

The site is an existing basin that is the result of gravel removal for building the railroad and Interstate 5 and does not require additional excavation. The basin had a Feasibility and Preliminary Design Report prepared to evaluate groundwater recharge potential. According to that study, "the basin was quarried to a depth of 15 to 25 feet below ground surface and the bottom area of the basin encompasses about 20 acres. The total design volume capacity of the basin is about 200 acre-feet."

In the event of excess storm water in wet years this new infrastructure can be used to convey flood water via the Bureau's 3F floodwater provisions in the newly approved WIIN Act contract with the District. This Project will create a conjunctive use program designed to increase surface water supplies, improve water management operational flexibility, sustain local groundwater levels, improve District operational efficiencies, and achieve long-term sustainability goals for all users within the District boundary. Conjunctive use provides drought resiliency for District water users because they can use District surface water in normal to wet years and rely on groundwater in dry years.

As groundwater levels have declined in Glenn County due to recent droughts and lack of access to surface water, the impacts have included hundreds of domestic (household) wells that have gone dry and land subsidence that threatens the Bureau's TCC and the State of California's Interstate 5. Management of recharge basins connected by this Project will speed up the recovery of groundwater levels, re-water domestic wells, and reduce land subsidence as they all share connectivity within the same groundwater aquifer.

ENGINEERING

Designs are based on topographical site surveys completed in October and November 2022 and March 2023. For each site, a local title company provided conditional title reports, which were reviewed by a registered land surveyor who mapped all easements in the path of new infrastructure to ensure there would be no conflicts with existing infrastructure including electrical and telecommunications.

Hydraulic analyses were prepared for 3 of the District's 5 laterals using computer modeling of the District's existing water delivery system to determine available capacity in existing pipelines and identify areas where new infrastructure is needed. Designs are based on projected peak demands, which are calculated using historical data and increasing future demand by 30%. The 30% demand increase is based on a survey mailed to District landowners where landowners reported they expect to increase their use of District water by 30% over the next 5 years in order to reduce reliance on groundwater.

The project includes 2 phases, with the first phase consisting of infrastructure that is lower cost per acre and can be implemented more quickly, and a second phase of higher cost infrastructure that can only be completed with assistance from grant funds. Construction is expected to last approximately 21 months. The project timeline was extended to 36 months to allow for all required reviews and approvals in addition to any potential weather delays during construction. Refer to Figure 2 for proposed infrastructure locations.

Phase I components:

<u>33.6E Extension</u> – Extend the pipeline with an additional 1,500 feet of new pipe to serve two additional landowners with two 10-inch farm turnouts and two road crossings. A new easement will be granted for the 1,500 feet of new pipe. The new easement will be granted by one of the landowners at no cost to the project.

<u>0.6 Booster Pump</u> – Install a 90-horsepower (HP) booster pump on an existing Reclamation-owned pipeline (OAWD sublateral 35.2-0.6) to increase flow from seventeen cubic-feet-per second (CFS) to thirty CFS. The booster pump provides more pressure and velocity to deliver supplemental surface water to 1,800 acres of newly annexed lands. Adding a booster pump on an existing pipeline is an economical and environmentally neutral way to increase acreage served while avoiding the larger cost and greater disturbance that would be required from a new pipeline. An easement will be granted by one of the landowners served by the extension at no cost to the project. Booster pump designs include a fenced gravel area surrounding the pump that is large enough for a crane to enter for maintenance and repair of the pump.

<u>Hart 342 Tie-in</u> – Approximately 81 feet of 12-inch PVC pipe connecting into an existing Reclamation-owned pipeline (OAWD Lateral 41.2) with a 12-inch on-farm turnout, and one road crossing of a county-owned gravel road. No easements are needed, as all work will be in the existing USBR right-of-way or on the annexing property.

<u>Knight 27 Tie-in –</u> One connection to an existing Reclamation-owned pipeline (OAWD Lateral 35.2) with 291 feet of 14-inch PVC pipe and one 14-inch farm turnout. The infrastructure includes one road crossing and .02 acres of easement acquisition. The easement will be granted by a neighboring landowner who is also involved in the project.

<u>Knight 33 Tie-in –</u> One connection to existing Reclamation-owned pipeline (OAWD Lateral 41.2) with 184 feet of 14-inch PVC pipe and one 14-inch farm turnout. An easement of 0.1 acres will be granted by a neighboring landowner.

<u>33.6N Tie-in</u> – One connection to existing Reclamation-owned pipe (OAWD Lateral 33.6) with 55 feet of 8- inch PVC pipe and one 8-inch farm turnout. One road crossing is needed, and no easements are needed since all work will be in existing USBR right-of-

way or on the annexing property.

Phase II components:

99W Pipeline – One all new lateral to serve lands in an area where no existing District water delivery system exists. The lateral begins with a 75-horsepower pump on the Tehama-Colusa Canal. The pump discharges into a pipeline that begins with 9,668 feet of 24-inch PVC pipe, reduces to 18-inch PVC pipe after the first on-farm outlets and continues an additional 5,402 feet before reducing further to 10-inch PVC pipe the last 237 feet of the pipeline to serve the final on-farm outlets. An additional 291 feet of PVC pipe of varying sizes is needed for the on-farm outlets, bringing the total length of pipe to 15,598 linear feet. The pipeline includes 6 new on-farm turnouts for irrigation (ranging from 8-inch to 14-inch outlets) and two new turnouts to deliver water to existing basins for groundwater recharge. 6 road crossings are needed along with a 0.93-acre easement from a neighboring landowner. All other easements needed will be granted at no cost by landowners served by the pipeline.

2.6 Booster Pump – Install a 70-horsepower booster pump on Reclamation-owned OAWD sublateral 35.2-2.6- 2.0LT to add 20 feet of head at 22 CFS to serve four properties downstream. The booster pump design includes a small, fenced gravel area surrounding the pump. Crane access for maintenance and repair of the pump will be provided on the adjacent private road. An easement will be granted by a neighboring landowner.

The proposed infrastructure would be constructed on either newly annexed private landowners' property, existing District landowners' property, Reclamation land adjacent to the TCC, on other private lands, and adjacent to and across several Glenn County roads. Spoil from excavation will be managed on site and used as pipe backfill. No spoiled material will be exported. Pipeline diameters will range from eight (8) to thirty (30) inches. Steel casing pipe will be used in areas where the exposed pipe passes through the TCC bank. The maximum depth of ground disturbance for pipelines and farm turnouts will be nine (9) feet, while the booster pump stations would have a maximum depth of eighteen (18) feet.

Planning for the OAWD Infrastructure Expansion Project began in February 2020 and all work to date has been entirely funded by private landowners whose lands would be served by the expanded infrastructure. Extensive infrastructure feasibility analysis has been completed including evaluating alternative alignments, locating existing electrical utilities to serve new pumps, determining the amount of flow each property needs, and consulting with Reclamation and the Tehama-Colusa Canal Authority on design requirements. Existing site-specific 30% engineering designs have been completed for all infrastructure expansion sites in the Project. These plans were developed to be consistent with USBR As-Built plans for the Reclamation-owned Tehama-Colusa Canal and the existing Reclamation-owned OAWD distribution system. All designs for improvements to Federal facilities undergo engineering design review by Reclamation through MP-620 forms (Request for Review and Acceptance of Design Drawings and Specifications) and a license request for the new pump on the Tehama-Colusa Canal. The Tehama-Colusa Canal Authority, which operates and maintains the TCC, will also review the designs.

An extensive hydraulic analysis was developed for the District's Lateral 35.2, which identified two locations for booster pumps to be installed to increase flow in the existing system and thereby increase the flow that can be delivered to serve additional acreage. This hydraulic analysis was even peer-reviewed by another local engineering consulting firm who concurred with the findings of the consulting engineers. Hydraulic analyses were also prepared by the consulting engineers for Lateral 33.6, which identified a pipeline extension to serve annexed lands, and for Lateral 41.2, which identified sufficient capacity to serve 2 new on-farm outlets.

Site topographical surveys have been completed and title reports have been reviewed to identify and address other easements or infrastructure that could impede plans for infrastructure expansion. This work generated the necessary inputs to develop 30% designs which were submitted to the Bureau for engineering review. Designs are now proceeding to 60% for Phase 1 projects.

Easements are needed on 3 parcels outside the lands owned by the District or Project proponents on a total area of 1.13 acres. Landowners have been approached at all three parcels and negotiations with private landowners have resulted in verbal agreements for all easements needed for infrastructure expansion. All easements will be granted to the District.

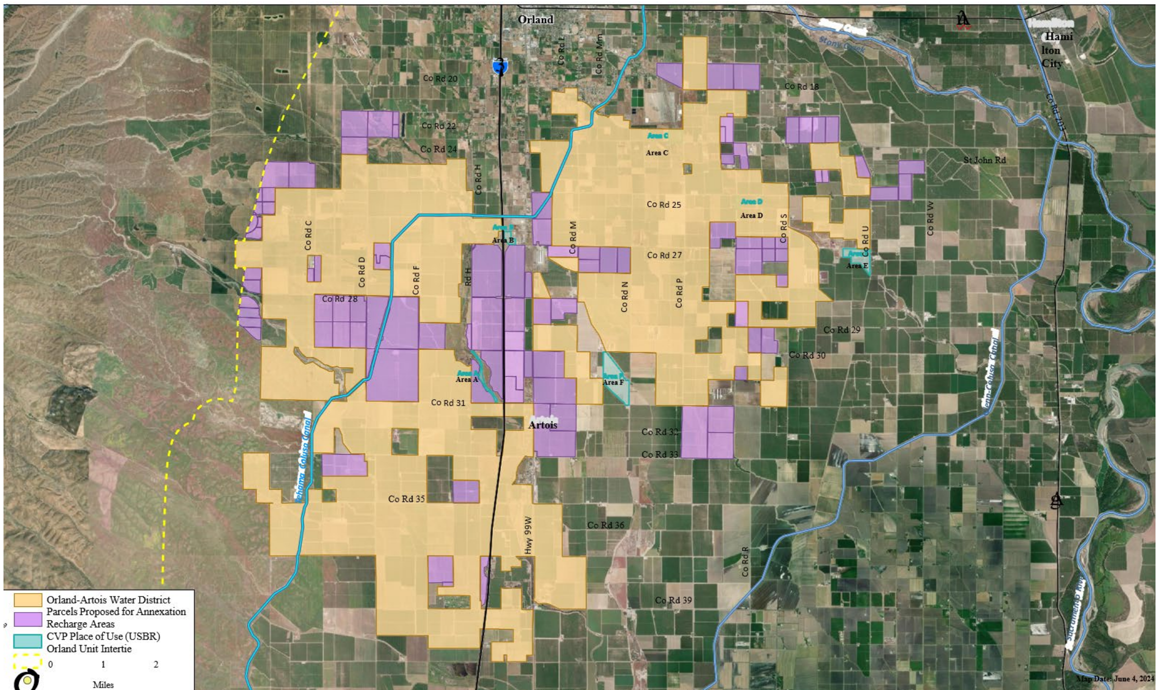
MEASUREMENT

The Project benefits will all be quantifiable utilizing metered diversions and monitored groundwater elevations. This new data will be compared to historical data to substantiate the Project's benefits. The information will be accessible to the public on the Orland-Artois Water District website under "District Projects".

These benefits will be quantified in the following manners:

- All new Project TCC turnouts will be metered
- All new Project field level turnouts will be metered
- The new connection to the recharge facility will be metered
- The new recharge facility will incorporate additional groundwater monitoring wells located adjacent to the basins.
- All current groundwater monitoring wells will continue to be monitored, measured, and recorded, both within the District boundary and the Colusa subbasin
- All supplemental voluntary water transfers will be duly agreed upon and approved by the various agencies (Bureau, TCCA, and the District) and documented in contract form and in board meeting minutes.
- The District's annual water budgets will be amended to show annual water use projections and actual deliveries through the newly constructed Project facilities.
- The District will continue to improve their website, www.oawd.com, to allow the District landowners, water users and members of the public access to all recorded data.

- The District will work closely with the Glenn Groundwater Authority to share all common groundwater elevation data and updated District water balance information to comply with SGMA goals and objectives.



Orland-Artois Water District

Figure 1: Annexation Support - Lands Proposed for Annexation

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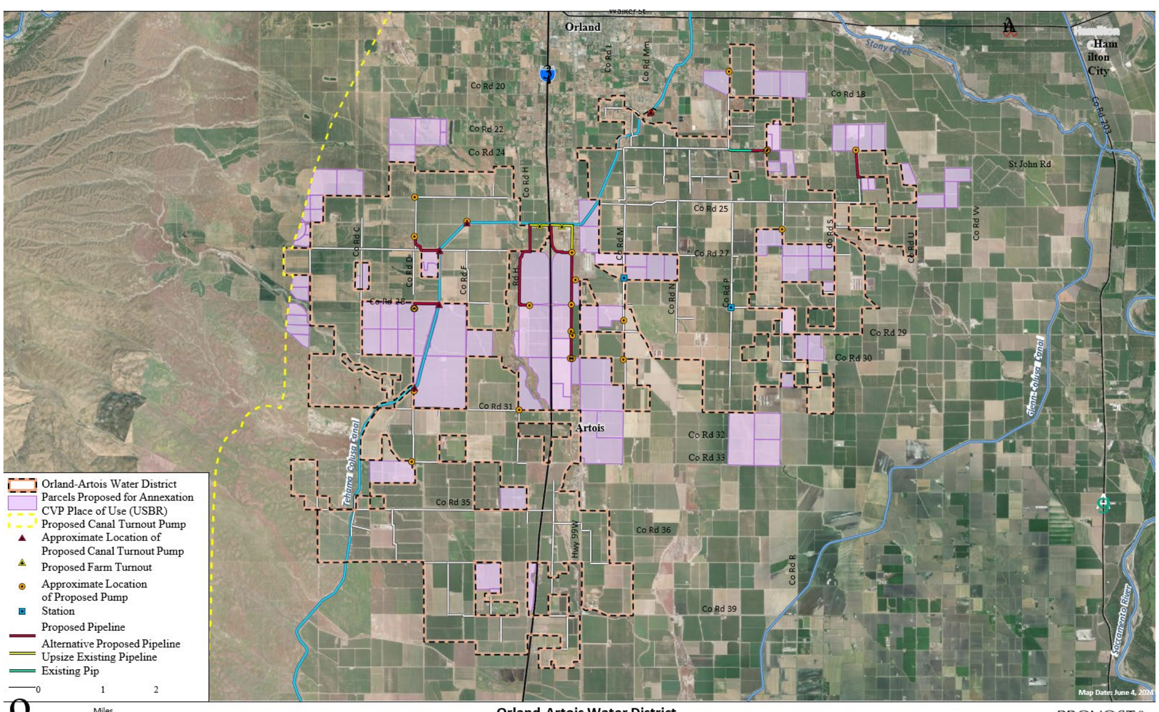

Orland-Artois Water District

Figure 2: Annexation Support - Proposed Infrastructure

PROVOST& PRITCHARD

FLOOD WATER DIVERSION IN ALISO WATER DISTRICT

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ABSTRACT

Aliso Water District (AWD) is located in western Madera County. AWD encompasses approximately 26,000 acres. AWD's main water supply is groundwater since the District does not currently have surface water supplies. With the passage of the Sustainable Groundwater Management Act (SGMA), AWD recognizes a need to import surface water into the district to balance its overdraft. Fortunately, a state flood bypass system, the Chowchilla Bypass (CBP), passes directly through the district. Unfortunately, floodwater is only available 1 in 4 years based on recent hydrology. Therefore, AWD needs to divert, utilize and recharge as much of this floodwater as possible to mitigate their overdraft in non-flood years. One project to accomplish this goal is the Chowchilla Bypass Turnout (Project).

The Project is anticipated to divert up to 10,000 acre-feet (AF) during high flow events on the San Joaquin River to a 75-acre recharge basin. AWD will construct a turnout with a fish screen from the CBP that will send water through a pipeline 1.5 miles east to the recharge site. The Project will allow the District to implement groundwater recharge, in-lieu recharge, and flood relief.

Challenges with this project include funding, environmental permitting, water rights permitting, and landowner coordination. Once complete, this Project will demonstrate that taking advantage of wet years, such as Water Year 2023, to divert unappropriated high-flow waters from the Bypass will allow AWD to operate sustainably. This presentation will discuss the general background, design, permitting, and lessons learned.

BACKGROUND AND INTRODUCTION

Aliso Water District (AWD or District) encompasses roughly 26,000 acres. The District was formed in 1978, with the intent to obtain surface water. The District was essentially inactive until the Sustainable Groundwater Management Act (SGMA) in 2014. After the passage of SGMA in 2014, the District became the Groundwater Sustainability Agency to represent the landowners within the District boundary. SGMA motivated the District to protect its ability to pump groundwater. The District land is predominantly agricultural with a majority of the crops in the District being permanent crops; the bulk being nuts and vines with some annual row crops. The District's main water supply is from pumping groundwater since the District currently has no surface water supplies of its own. The District is pursing appropriative water right to divert water from the Chowchilla Bypass (CPB), which is tributary to the Lower San Joaquin River. The District will be able to

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divert up to 10,000 Acre-Feet (AF) of surface water for on-farm recharge practices (Groundwater recharge basins).

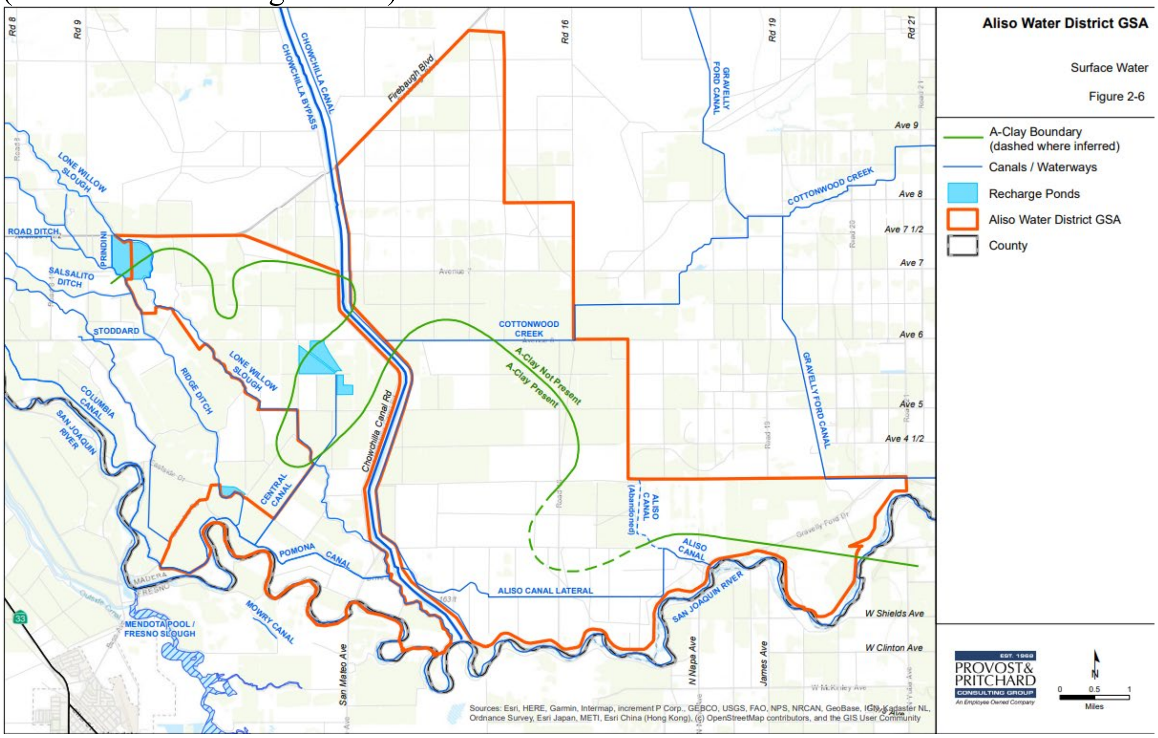

Figure 8. Aliso Water District Vicinity Map

The District is proposing to construct a 100 cubic feet per second (CFS) diversion structure (Project) along the Chowchilla Bypass (CBP) to divert water to a groundwater recharge basin located approximately 1.5 miles east of the diversion structure. The Project is composed of a low water level channel, a reinforced concrete vault to support two (2) 168-inch diameter conical fish screens, a 72-inch pipe, and a concrete control box with a 72-inch control gate, a 100 CFS pump station and approximately 1.5 miles of 48-inch HDPE into a 75-acres recharge basin. The District estimates it has an annual groundwater deficit of roughly 2,500 AF per year. If the District secures the appropriative water right to divert water from the CBP and divert 10,000 AF, the District should be able to correct their groundwater deficit and achieve sustainability.

The project consists of excavating a roughly 320-foot long channel from the invert of the pilot channel and terminate 15 feet away from the inside toe of the levee. At the terminus of that channel, a concrete vault will be constructed to support two (2) 168-inch cone shaped fish screens. The fish screen concrete vault has the following measurements 37' (L) x 20' (W) x 13’-5 1/2" (D). The fish screens will be protected from scouring during flood flows with an 18-inch thick apron of Class II Rip Rap. A 72-inch pipe would connect from the fish screen concrete vault to the control gate box. The control gate box shall be located about 5 feet off the inside top of bank of the Chowchilla Bypass. The control gate box shall be furnished with a 72-inch canal gate to isolate flood system. After the gate control box, the pipe shall pass through the levee and continue until it is outside Central Valley Flood Protection Board property/jurisdiction. Outside of the floodway, the pipeline will terminate into a pump station. The pump station will convey flood water through a 48-inch pipeline to the recharge site. The 72-inch pipeline shall be installed through the floodway and levee using the open cut method.

DESIGN CONSIDERATIONS

The Project design took into account a number of factors such as how quickly water could be placed into the basins and offset the groundwater deficit since the District does not have access to surface water and is dependent solely on groundwater wells to irrigate approximately 26,000 acres. In addition, the District wanted to make the best use of funds available after the passing of a Prop 218 to begin collecting groundwater extraction fees from landowners. The District intent with the Project is a proof-of-concept due to the close proximity to the Chowchilla Bypass. The District recently entered into a long-term lease to develop an approximately an 80-acre groundwater recharge basin. The basin is located 1.5 miles east of the Chowchilla Bypass.

The San Joaquin River bifurcation to the Chowchilla Bypass allows for the diversion of high flows to prevent flooding in urban areas. The San Joaquin River is rated for a maximum flow rate of 4,000 CFS and the Chowchilla Bypass bifurcation structure is rated for 5,500 CFS.

Due to the ever-changing climate pattern in California, the Project facilities were design to act as temporary flood relief system to Chowchilla Bypass. The District will mobilize and demobilize the self-priming centrifugal pumps to the turnout location when California experiences a wet year, which appears to be in a pattern of once every 4 years. The CBP is operated and maintained by Lower San Joaquin Levee District and falls within the District boundary. CBP is a potential source of flood water to Aliso WD as the result of an appropriative water right permit. CBP is primarily a flood-release stream diverting water originating from the Millerton Lake, and is primarily active and contains flow when flow rates in the San Joaquin River are greater than 4,000 CFS. The CBP has a bifurcation structure at the San Joaquin River rated for 5,000 CFS. The District is able to divert flood water from the CBP when the flows in the CBP are above roughly 1,300 CFS.

In 2023 the District installed a temporary diversion system under the California Governors Executive Order N-7-22; during 2023, the District was able to divert approximately 1,300 AF. The District lack of permanent groundwater recharge facilities did not allow the District to divert to the full extent of the Project design. In Water Year 2023 a wet year, there were over 100 days of flood releases from Millerton Lake, The District would have been able to divert close to 20,000 AF at a 100 CFS rate.

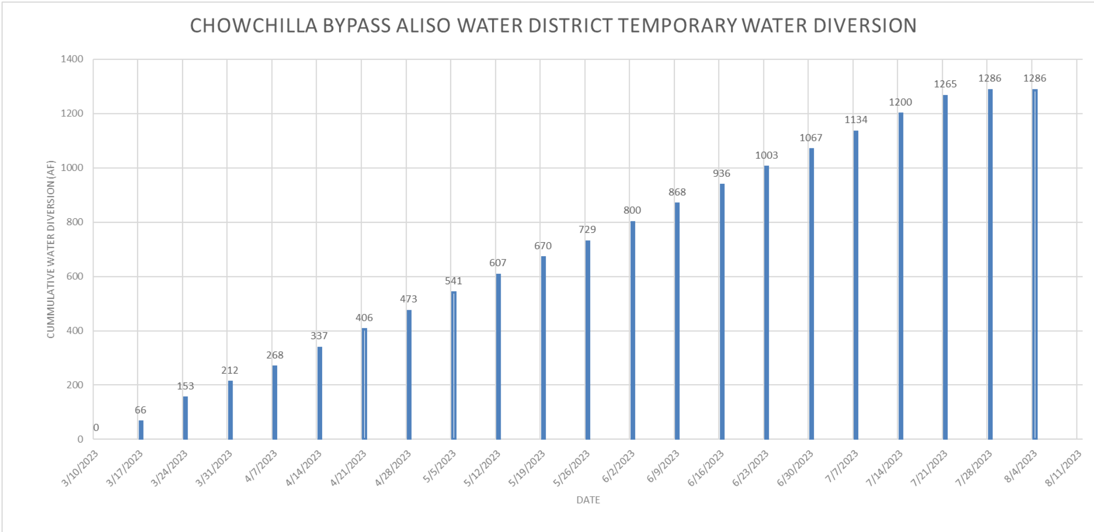

Figure 9. Temporary Water Diversion System by Aliso Water District

One of the Project design challenges is the fluctuation of flows and water levels in San Joaquin River and Chowchilla Bypass. In order to combat the fluctuating water level at the Project turnout intake, the District investigated three (3) different alternatives:

1. Vertical Turbine Pump Station Sump that matches the height of the Chowchilla Bypass Levees to prevent overtopping (The pump station sump would be approximately 12 feet above existing ground).

2. Underground Common Suction Header (Requires for pump to be able to prime and bring water up to eye of the impeller).

3. Aboveground Common Suction Header (At high flows and water levels, the pumps will have flooded suction).

The District opted out of Alternative 1 due to the cost to construct a pump station sump of approximately 30 feet (18 feet underground, and 12 feet aboveground). A pump sump with the depth mentioned above was not a feasible option especially when the high flood flows are not guaranteed to run every year.

The District opted out from Alternative 2 since the varying water level in the Chowchilla Bypass did not allow for favorable hydraulic operation of the pumps. Due to the varying water level in the suction header, the pump Net Positive Suction Head Required was greater than the available diminishing the operating range of the pump system. Additionally, the pumps will experience greater wear and tear and reduce the service life of the equipment resulting in a greater investment from the District.

The District is currently analyzing the feasibility of alternative 3. This alternative will allow for the pump to have flooded suction at high flows and high water levels in the Chowchilla Bypass. A check valve will be installed upstream to prevent any backflow allowing for pumps to lose prime and stop pumping. Additionally, the District will be installing an Air-Operated Double Diaphragm (AODD) pump to bring water up to the above ground common suction header in order to have flooded suction for the pump

during low to average water levels in the Chowchilla Bypass. This alternative allows for the most flexibility and robust operation of the diversion system by the District.
The Project was sited such that they would:

1. Have geology favorable to groundwater recharge.

2. The turnout to be located in one of the proposed Point of Diversion in the Districts water right application.

3. Be strategically located to divert water from the Chowchilla Bypass and alleviate the flood system from any strain due to high flood flows.

The site's primary purpose is offset of groundwater overdraft and flood system strain relief as a secondary benefit. A geologic exploration was conducted along the Project and critical location such as the Chowchilla Bypass levee, pump station location, discharge pipeline alignment, and groundwater recharge basin. At the Chowchilla Bypass levee and pump station, the borings holes had a depth of 35 feet to determine levee stability and structural reinforcement required for the structures. Along the discharge pipeline alignment, the boring holes had a depth of 6 feet to determine trench slope requirements and backfill requirements. At the groundwater recharge basin, four borings holes were conducted to verify if the shallow soil profiles would be conducive to recharge. The geologic investigations and infiltration tests have shown the site could sustain recharge rates between 0.75 ft per day. For example, the recharge goal for the Project is 10,000 AF (in anticipation of above average conditions) in the ground in approximately 221 days, or an average of 1,400 AF per month (0.75 feet per day).

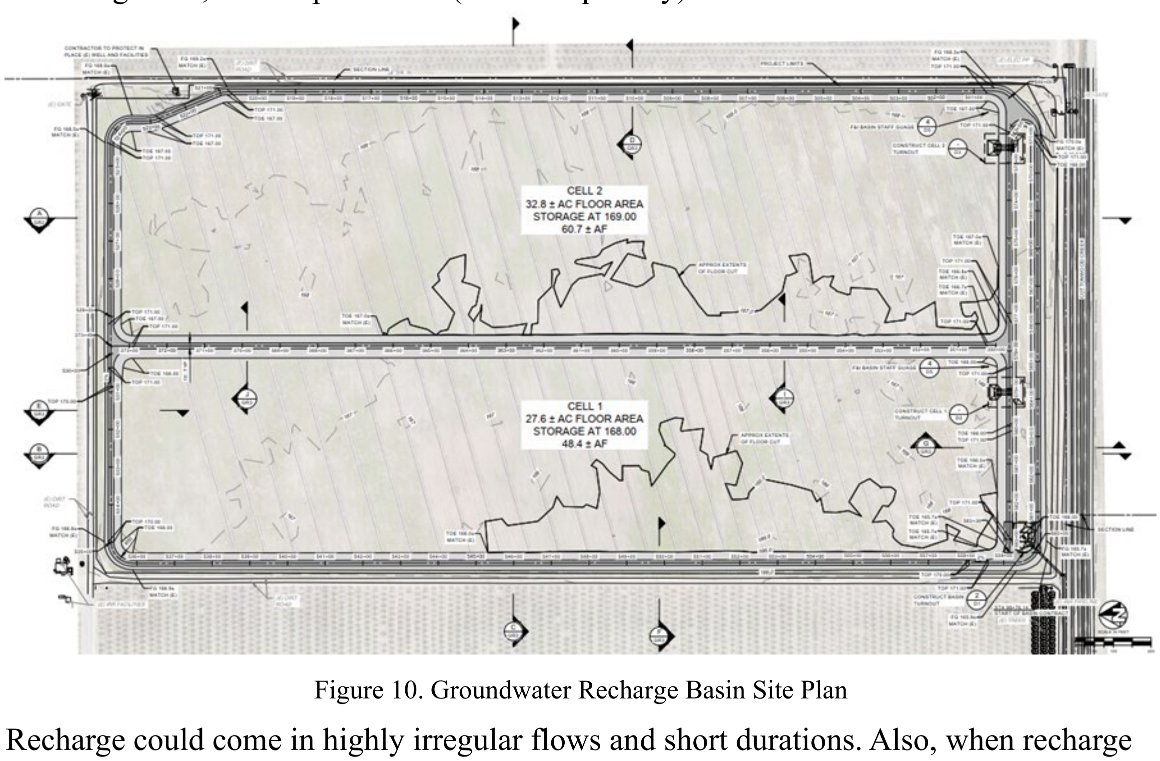

Figure 10. Groundwater Recharge Basin Site Plan

Recharge could come in highly irregular flows and short durations. Also, when recharge basins are being filled for the first time, they will percolate at much higher rates. Recognizing the potential need to take high flows in short time frames, many design features were incorporated. The turnouts to each site were designed for relatively high flows and sediment handling. The site was divided into smaller cells to help manage spreading and evaporation.

Table 1 below lists the sustainable recharge rate, acreage, and delivery inflow for each site. As the table shows, the design inflows are about four times higher than the sustainable recharge flow.

Table 1. Summary of Recharge and Inflow Rates

Site	Sustainable Recharge Rate (ft/day)	Acreage	Sustainable Recharge Inflow (cfs)	Design Inflow (cfs)
Site 1	0.75	80	30	100

DISTRICT WATER RIGHTS

The District is in the process of obtaining an appropriate water right of 10,000 AF from the State Water Resources Control (SWRCB). The District has taken a multi-pronged approach, pursuing both a Standard Right as well as a Temporary Right. The Standard Right can take 7-10 years to complete, and the threshold to demonstrate availability of water is much higher. A temporary right takes 4-5 months to complete and was used to flesh out issues with the SWRCB and protesting parties. The District continues to pursue a temporary right on an annual basis. The temporary right only provides 180-day to access the water and has to be done annually as a provision just in case flood water is available, so the District may divert water.

Obtaining both the Temporary and Standard right has proven to be much more difficult that one would expect. Especially considering this is flood water that would otherwise flow to the ocean. On the temporary right, the terms and conditions placed on the permit to satisfy protesting agencies, make the timely response to flood diversions nearly impossible. On the temporary right, the high level of protests (both sincere and obstructive) demonstrates the political challenge of obtaining rights to this river system.

PROJECT PERMITTING

The District is required to secure a variety of State and federal permits to be allowed to construct the Project. The District was required to secure a Minor Alteration Request & Encroachment Permit from Central Valley Flood Protection Board (CVFPB), Lake and Streambed Alteration (Section 1602) from California Department of Fish and Wildlife (CDFW), and compliance with the California Environmental Quality Act (CEQA). The Project must also demonstrate that is exempt from Section 401 Permit from Regional Water Quality Control Board, Section 404 and Section 408 Permits from U.S. Army Corps of Engineers.

California Environmental Quality Act

The District understands the importance of compliance with the California Environmental Quality Act (CEQA). The primary goal of the District with this Project is to ensure that environmental factors are considered in decision-making processes.

Consistent with the March 28, 2023, Drought Executive Order N-7-22 Action 13, the California Department of Water Resources (DWR) developed a process to allow local agencies to submit their proposed recharge projects to DWR for CEQA suspension, which meet the objectives of the Executive Order (EO). Based upon the unpredictable and severe circumstances created by the state's increasingly hotter and drier climate, Governor Newsom enacted EO 13 to suspend CEQA for groundwater recharge projects that capture available water for the purposes of recharging groundwater basins through the application on open and working lands to help mitigate drought impacts on groundwater conditions. DWR determined that the Chowchilla Bypass Project meets the criteria and is consistent with the requirements and concurred with project eligibility.

Central Valley Flood Protection Board Minor Alteration Request & Encroachment Permit

The Central Valley Flood Protection Board (CVFPB) establishes, maintains, and enforces standards for the construction, maintenance, and operation of the flood control system to protect life, property, and habitat for the Chowchilla Bypass. The District applied for an Encroachment Permit and Minor Alteration Request.

The Minor Alteration Request allows the District to perform a geotechnical investigation along the CBP to determine levee stability and other information required to construct the Project. The District performed three (3) geotechnical borings to get a broad understanding of the CBP levee. The findings of the geotechnical investigation will be used to design structures such as the fish screen concrete vault and gate control box.

The CVFPB Encroachment permit allows the District to construct the Project on the State property. The encroachment permit required endorsement from the Lower San Joaquin Levee District (LSJLD). The endorsement received by LSJLD District Engineers allows for the District to move with the Project permitting phase.

California Department of Fish and Wildlife – Lake and Streambed Alteration

The District will apply for a Lake & Streambed Alteration (1602 Section) Permit with CDFW to construct the project. CDFW requires the permit requires any person, state or local governmental agency, or public utility to notify CDFW prior to beginning any activity that may do one or more of the following:

- Divert or obstruct the natural flow of any river, stream, or lake;
- Change the bed, channel, or bank of any river, stream, or lake;
- Use material from any river, stream, or lake; or
- Deposit or dispose of material into any river, stream, or lake.

Temporary and Permanent impacts on the Chowchilla Bypass and Cottonwood Creek were quantified and exhibits were prepared to submit to CDFW and facilitate the permitting process. Although the 1602 permit is not based on impacts but on construction costs; the Agency still requires a visual of the impacts. This additional work to prepare the exhibits is time-consuming and it does not aid the District to obtain the permit. During a pre-filling meeting, CDFW will provide guidance to prevent back-and-forth between the Client and Agency for a streamlined permit process.

U.S. Army Corps of Engineers – Section 404 Clean Water Act

Typically, a Section 404 permit is not required for the Project since the Chowchilla Bypass is not a Water of U.S. and no discharge of dredge or fill material will take place during the construction of the Project. The Project falls under multiple exemptions of Section 404(f) of the Federal Clean Water Act.

Relative to the Project all the impacted waters are accurately characterized as "irrigation ditches" and involve the construction of the various components listed in the regulations. Therefore, the Project is exempt from Section 404 of the Federal Clean Water Act and the Porter- Cologne Water Quality Control Act.

U.S. Army Corps of Engineers – Section 408

Typically, a Section 408 permit is required for any project constructed that alters USACE Civil Works project. The Lower San Joaquin Levee District received a letter from the USACE stating that the Chowchilla Bypass levees are not recognized as a federal levee. Hence, the Project being exempt from Section 408 Permit.

Regional Water Quality Control Board – Section 401 Water Quality Certification

Typically, a Section 401 permit is required for projects that actively discharge any dredge or fill materials into the Waters of the State. The proposed Project by the District is exempt from the Section 401 permit and discharge any dredge or fill material will take place during the construction of the Project.

Since the Project is exempt from U.S. Army Corps of Engineer Section 404 permit, it allows for the Project to also be exempt from Section 401 permit issued from Regional Water Quality Control Board.

PROJECT FUNDING AND COST

The District elected to be the GSA for the lands within its service area. As a GSA, the District is authorized under Water Code Section 10730 et seq. to impose fees to fund the costs of a groundwater sustainability program, including, but not limited to, preparation, adoption, and amendment of a groundwater sustainability plan, and investigations, inspections, compliance assistance, enforcement, and program administration, including a prudent reserve. The District is authorized to collect these fees in the form of real property assessments.

The District also has general authority to levy assessments to fund improvements under Water Code Section 36455 et seq.

The District recently approved a land base assessment and a groundwater extraction fee to fund on-going compliance with SGMA, District Administration, District Consulting Services, Monitoring, and Capital Improvement Projects (CIP). The District recognizes the need to groundwater recharge and achieve sustainability by 2040. The need for groundwater recharge and ambitious sustainability goals from the District led the District to proposed for the construction of the Project. The District received a grant for the Construction of Project from the Department of Water Resources (DWR) under the State Budget Act of 2021. The District is currently securing funds from other agencies such as United States Department of Agriculture (USDA) and/or Natural Resources Conservation Services (NRCS), and California Infrastructure and Economical Development Bank (IBank).

The NRCS launched a Groundwater Recharge Pilot Program where public agencies such as irrigation and water district were encouraged to apply. The NRCS was not ready for the influx of additional work and legal hurdles when dealing and assisting a water management entity to apply and secure funds appropriately. The District submitted all documentation required and was unsuccessful in securing funds from NRCS due to the hurdles that the District had to endure to prove Tax Exemption status.

Capital Cost. Initial capital cost to develop the Project are significant. The Engineers Opinion of Probable Construction Cost for the Project is approximately $10 million. This includes the cost to construct the infrastructure in the Chowchilla Bypass, pump station, furnish and install approximately 8,000 lineal feet of pipeline, construct an 80-acre recharge basin, inter-basin structures, and construct monitoring wells. With the average net yield of 10,000 AF of groundwater recharge every 4 years, the capital cost to develop this new supply calculates to approximately $4,000 per AF. The following table breaks down the capital cost into the major cost components.

Table 2. Proportions of the Major Capital Cost Components

Item	Portion of Cost
Chowchilla Bypass Infrastructure	17%
Pump Station	22%
Discharge Pipeline	44%
Recharge Basin	17%

Flexibility in Design and Permitting. The AWD project demonstrated the necessity of incorporating flexibility into both design and permitting processes. The fluctuating water levels in the CBP, and the infrequency of high-flow events required the AWD to evaluate multiple alternatives for the pump station design. The chosen design allows for effective operation during varying flow conditions by using an aboveground common suction header, which provides a more flexible and robust solution.

Moreover, the permitting process underlines the importance of engaging with regulatory agencies early and thoroughly understanding the environmental and legal requirements to avoid delays. AWD had to navigate various state and federal permits, learning that clear and early communication with agencies can streamline the process and mitigate challenges related to environmental impacts and water rights.

CONCLUSION

The results of this Project show that the District will continue to work to achieve sustainability under SGMA. The Project will demonstrate that taking advantage of wet years, such as Water Year 2023, to divert unappropriated high-flow waters from the Bypass will allow AWD to operate sustainably. A Project of this magnitude and scale will not only allow the District achieve sustainability, but it will demonstrate that there is a need for adaptive strategies in water resource management, especially in the face of climate variability and stringent regulatory landscapes. Flexibility in both design and permitting can ensure the sustainability and success of similar projects in the future.

EDDY COVARIANCE EQUIPMENT FOR EVAPORATION MEASUREMENTS ON GROUNDWATER RECHARGE PONDS

Luke Nydam[1]
Daniel Howes[2]

ABSTRACT

The Cal Poly Irrigation Training and Research Center (ITRC) began investigating evaporation values for groundwater recharge basins using the Eddy Covariance (EC) method in 2023. While data does exist for evaporation (E) from open water surfaces, groundwater recharge basins pose a unique set of conditions, namely a higher flowthrough rate that keeps water temperatures cooler than would otherwise be expected in ponds of a comparable size and depth. Obtaining accurate E values for these recharge ponds is important for accurately measuring groundwater recharge.

The ITRC chose the Eddy Covariance (EC) method to measure (E) as it provides the most direct method of measurement under real-world conditions. By measuring the vertical wind speed and the gas concentration of eddies in the atmosphere, the flux of those gases can be determined. To measure this, the EC station relies on two key components of instrumentation, a sonic wind anemometer and a gas analyzer. The sonic wind anemometer uses ultrasonic frequencies to measure wind speed in three dimensions while the gas analyzer measures the concentration of the gases of interest.

In addition to these, other environmental monitoring instrumentation is used to give context to the E readings. These include the following: net radiometer, temperature and humidity sensor, rain gauge, camera, water temperature sensors, soil moisture and temperature sensors, and soil heat flux sensors. These sensors allow the analysis of the environmental factors affecting E, check for errors, and perform energy balance calculations.

Instrumentation for the EC system was installed on a scaffolding tower. Solar panels and batteries to power the station were placed on a separate scaffolding tower to not interfere with the wind field that the station is measuring. For accurate readings, the station must be placed in the recharge pond of interest, which can often prove to be a challenging task. In addition, the pond of interest must also have appropriate site conditions for accurate readings. In addition, recharge ponds are typically not filled for the entire year, meaning that the station must be moved on a somewhat regular basis to obtain meaningful data. This paper will present the instrumentation details, why it was selected, how it was installed relative to the wind directions and recharge basin orientation and size, power requirements, and other critical installation considerations. Our hope is that others will find this information valuable for future open water measurement sites.

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This is the first part of a companion paper. The companion paper (Howes and Nydam 2024) discusses the sites examined and the preliminary results from the study. This paper describes the sensors used.

INTRODUCTION

The eddy covariance method is a widely used technique for measuring and analyzing the exchange of gases and energy between the Earth's surface and the atmosphere. The core principle of eddy covariance is that air does not travel across earth's surface in a laminar fashion, but rather it travels across the ground in turbulent eddies. These eddies transport gases and energy between earth's surface and the atmosphere.

The eddy covariance method relies on precise measurements of vertical wind speed and gas concentrations, which are obtained using a 3D sonic anemometer and a gas analyzer, respectively. The 3D sonic anemometer captures all three components of wind velocity—longitudinal (u), lateral (v), and vertical (w)—to fully characterize the wind field. This is crucial for calculating turbulent fluxes, as it allows for the direct measurement of vertical wind speed fluctuations that drive gas exchange between the surface and the atmosphere. The gas analyzer, on the other hand, detects concentrations of key trace gases such as H_2O, CO_2, and CH_4. Gas analyzers can be configured as either open-path or closed-path systems. Open-path analyzers measure gas concentrations directly in the atmosphere, while closed-path analyzers draw air through a sampling tube for analysis. At the ITRC, an open-path gas analyzer is used to measure CO_2 and H_2O concentrations. For accurate flux calculations, both the anemometer and gas analyzer must operate simultaneously at high frequencies (typically 10-30 Hz) and with a high degree of precision, ensuring that the rapid fluctuations in wind speed and gas concentrations caused by both large and small eddies are captured effectively.

The term "covariance" in the eddy covariance method refers to the statistical correlation between vertical wind speed fluctuations and gas concentration fluctuations. Simplified, the flux of a gas is calculated as the mean product of the vertical wind speed fluctuation (w') and the gas concentration fluctuation (c') over a given period. This relationship is represented by the equation (Burba and Anderson 2005)

$$\text{Flux} = \overline{w'c'} \quad (1)$$

Flux quantifies how much of something, such as energy or a specific gas, passes through a unit area per unit time. In eddy covariance, the primary focus is on the flux of energy and gases between the Earth's surface and the atmosphere. Energy flux, which measures the rate of energy transfer per unit area, is typically expressed in watts per square meter ($W\ m^{-2}$). Gas flux, on the other hand, quantifies the transfer of specific gases between the Earth's surface and the atmosphere. It can be expressed either as the rate of mass flow per unit area (e.g. $g\ m^{-2}\ s^{-1}$) or as the number of moles transferred per unit area (e.g. $\mu mol\ m^{-2}\ s^{-1}$).

Additional instrumentation on the eddy covariance station provides valuable context to the H_2O flux data and enables the ITRC to perform an energy balance analysis. This includes instruments such as a net radiometer, temperature and humidity sensor, soil temperature & moisture sensors, soil heat flux sensors, a camera, and more.

Assessing the energy balance is crucial for validating the accuracy of the system's data. The principle behind energy balance is that the energy entering a system should equal the energy leaving the system plus any change in the system's internal energy. By accurately accounting for all energy inputs, outputs, and storage terms, the energy equation should balance. If there is a significant imbalance in the equation, the discrepancy may indicate that some energy components are unaccounted for or that there may be errors in the data. The energy balance at the Earth's surface is typically described by the equation (Jensen and Allen 2016)

$$R_n = H + LE + G + S \qquad (2)$$

Where:

- $\boldsymbol{R_n}$ is the net radiation (the difference between incoming and outgoing radiation).
- $\boldsymbol{H}$ is the sensible heat flux (the transfer of heat from the surface to the air).
- $\boldsymbol{LE}$ is the latent heat flux (the energy used for evaporation and transpiration).
- $\boldsymbol{G}$ is the ground heat flux (the heat transferred into the soil).
- $\boldsymbol{S}$ represents other minor storage terms, such as heat stored in biomass or water bodies.

In the context of the ITRC’s study, which focuses on groundwater recharge ponds rather than the Earth's surface in general, the energy balance equation will differ. For example, energy associated with incoming and outgoing water flows must be accounted for. However, understanding the general energy balance equation is fundamental to grasping the overall concept and applying it to specific contexts like groundwater recharge.

By measuring these components, quality control checks can be conducted on the data collected by the station. Ideally, Rn should equal $H + LE + G + S$. In practice, some discrepancies are expected due to measurement errors, unaccounted for storage terms, and other factors. However, a significant imbalance may signal a problem with the data quality. One common method to assess data quality is the energy balance ratio (EBR), where an EBR closer to 1 indicates more accurate and reliable data.

The primary goal of using the eddy covariance method in this study is to obtain accurate and reliable evaporation data, which is crucial for understanding water dynamics in groundwater recharge ponds. To ensure the validity of this data, additional measurements and quality control checks are essential, as they help to identify and correct potential errors.

INSTRUMENTATION

This section provides an overview of the sensors deployed by the ITRC on the eddy covariance station. Each of the sensors listed below has been or is planned to be used; however, not all instruments listed are currently in use. The ITRC EC station has been operated in a few different test locations, each with its own unique conditions and challenges. While some sensors are key for the eddy covariance process and must be used, others are not always needed. For each instrument, a discussion is made on its general purpose, operation, and maintenance considerations. For detailed technical specifications and more comprehensive guidance on usage, readers should consult the Data Acquisition System manual, the LI-7500DS manual, and/or the respective manuals provided with each sensor.

Wind Anemometer: Gill Windmaster Pro

A critical component of the eddy covariance method, the sonic wind anemometer measures the three components of wind velocity—longitudinal (u), lateral (v), and vertical (w)—by emitting and measuring ultrasonic sound waves across three axes. The anemometer takes measurements with both a high degree of accuracy and a high frequency (up to 32Hz). The specific model used by the ITRC is Gill's Windmaster Pro, which also measures air temperature, humidity, and air pressure.

To protect the instrument, bird repellent devices are essential. These are installed atop the anemometer to prevent birds from perching and potentially obstructing the ultrasonic transducers with droppings. The current setup includes three Bird Barrier repellent trays and three strands of fishing line wrapped once around the anemometer to deter birds without disturbing the wind measurements.

When cleaning the anemometer, care must be taken to not damage transducers. A gentle wipe with a damp cloth is sufficient in most cases; harsh chemicals or aggressive scrubbing should be avoided to prevent damage. The wind anemometer with installed bird deterrents along with the gas analyzer can be seen in Figure 1.

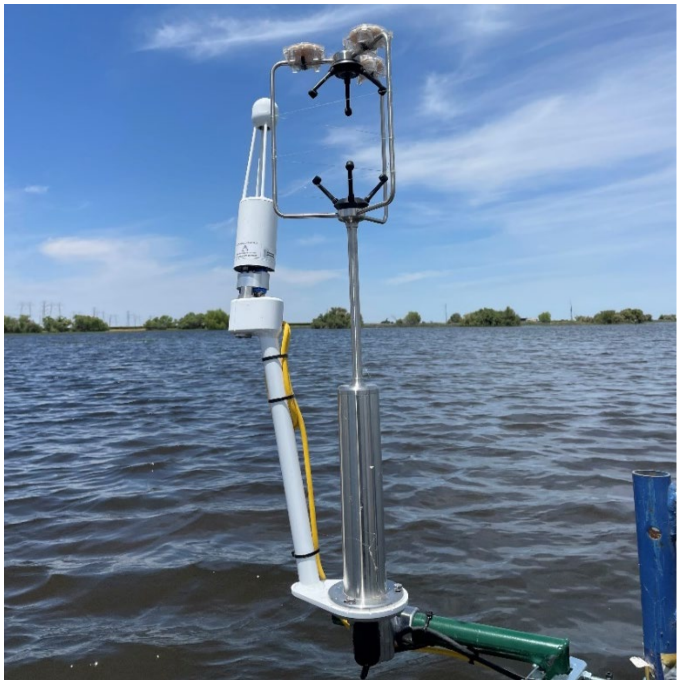

Figure 11. Wind Anemometer and Gas Analyzer Setup

Gas Analyzer: Licor LI-7500DS

Along with the wind anemometer, the LI-7500DS gas analyzer is a crucial sensory component for implementing the eddy covariance method. Gas analyzers are generally categorized into two types: closed-path and open-path. Closed-path analyzers draw air samples through a tube using a pump for analysis. In contrast, the ITRC employs an open-path analyzer, as shown in Figure 1. This type measures gas concentrations using an infrared beam that travels between the sensor's upper and lower windows. For accurate readings, the analyzer also incorporates an air temperature thermistor and pressure sensors. Accumulation of dust, pollen, chemical residues, and other contaminants on the sensor windows can lead to measurement drift and data gaps. Regular maintenance and cleaning should be performed to prevent this. Although the windows are made from scratch-resistant sapphire, they should be cleaned gently using a damp microfiber cloth or disposable shop towel to prevent damage. The use of overly harsh chemicals should be avoided (LI-COR 2023 Using the LI-7500DS).

Net Radiometer: Kipp & Zonen CNR4

The net radiometer used by the ITRC, shown in Figure 2, is the Kipp & Zonen CNR4, which measures net radiation by capturing both incoming and outgoing longwave and shortwave radiation. Net radiation measurements are critical for eddy covariance studies as it provides data on the energy exchange between the Earth's surface and the atmosphere. Equipped with a thermistor for temperature measurement, the CNR4 also includes a ventilator and a heater to optimize its operation under varying environmental conditions. The ventilator aids in maintaining the radiometer at the ambient air temperature. This ensures that radiation measurements are not affected by the temperature of the device itself. The heater is useful during the mornings, especially in winter, to prevent dew formation on the sensor glass, which can interfere with accurate radiation measurement.

Figure 12. Net Radiometer

It is important to keep the radiometer level to ensure that the sensors are properly aligned, allowing for accurate readings. The bubble level on top of the sensor aids with this process and should be checked during maintenance visits to ensure the instrument remains level. In addition to leveling, the sensor should also be cleaned regularly. As with other sensors, cleaning should be performed with a damp microfiber or shop towel while avoiding the use of harsh chemicals to prevent damage.

Humidity and Temperature Sensor: Vaisala HMP155

The temperature and humidity measurements at the station are taken using the Vaisala HMP155 sensor. While temperature and relative humidity are also measured by the wind anemometer, a purpose build temperature and humidity sensor helps to increase the accuracy of the measurements. In addition, some redundant measurements help to improve the reliability of the station by allowing temperature and humidity readings to be made even if one sensor were to fail. The sensor is housed in a solar shield, as shown in Figure 3, which guards against direct sunlight while allowing sufficient airflow. This ensures that the probe accurately records ambient temperature and humidity levels. The sensor should be cleaned if the vents are observed to be clogged.

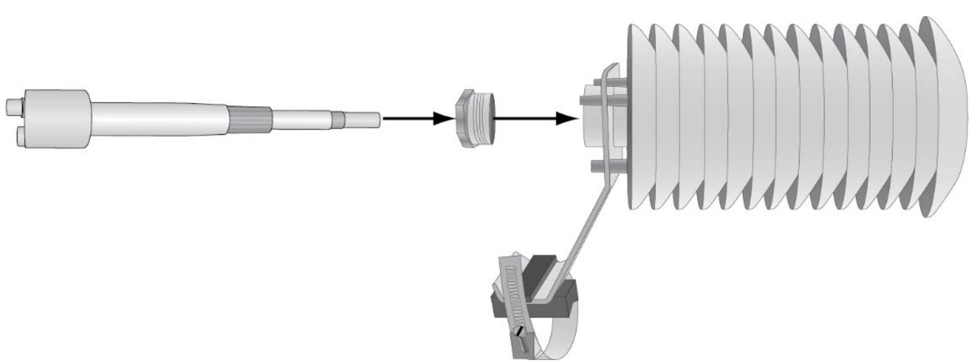

Figure 13. Vaisala HMP155 humidity and temperature sensor (*courtesy of Vaisala*)

Rain Bucket: Texas Electronics TR-525M

The rain bucket used is the TR-525M rain gauge. The gold portion of the rain gauge functions as a funnel to direct water into a tipping mechanism. Although the funnel includes a screen to help prevent clogging, debris will occasionally obstruct the funnel. During maintenance visits the bucket should be checked to ensure that water can freely flow through the funnel and into the tipping mechanism. The screen, as shown in Figure 4, can be detached by removing the retaining ring above it. Additionally, the funnel can be removed from the body by loosening the screws on the sides of the bucket. A 'crown of thorns' attached to the top of the rain bucket acts as a bird repellant.

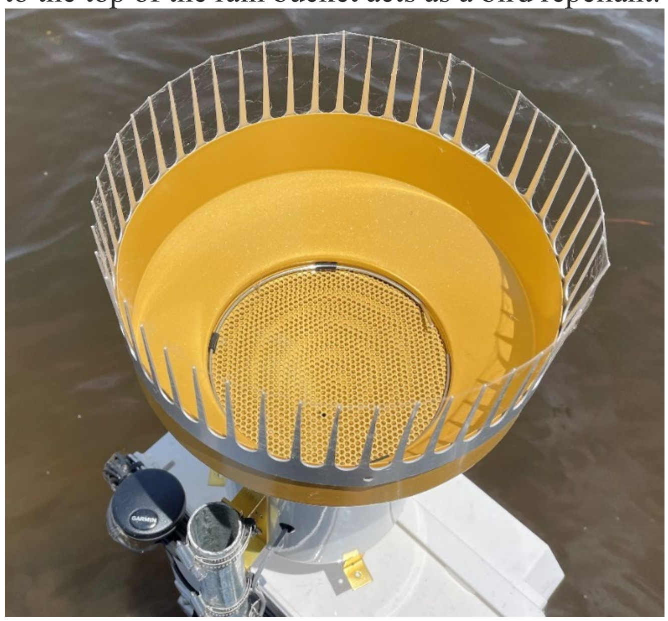

Figure 14. Rain Bucket Top View

The tipping mechanism is calibrated to tip once a certain amount of water has filled one side of it. The tipping action passes a magnet over a sensor. This sends a signal to the data acquisition system. It is important to check that the tipping mechanism has not accumulated an excessive buildup of dirt or contaminates as this will interfere with the balance of the tipping mechanism. In addition, the tipping mechanism will not function properly if stuck in a neutral position; it must lean to one side or the other to function correctly.

Self-Calibrating Soil Heat Flux Sensors: Hukseflux HFP01SC

The Hukseflux HFP01SC self-calibrating soil heat flux sensors are used to measure the amount of energy entering or leaving the ground, an integral component for energy balance calculations. Each sensor is a disk approximately 3 inches in diameter, featuring a red top and a blue bottom. It is equipped with two cables: one for analog data transmission and the other to provide power for self-calibration.

To install the sensor(s), a shallow pit should be dug with a smooth undisturbed side. A slit should be made in the undisturbed soil 5 cm from the surface into which the sensor should be placed with the red (top) side facing upward. Soil temperature and moisture sensors can be placed in the same pit.

Note: *<u>Make sure to mark the location of the installed sensors and burry the cables in a straight/predictable manner. It is easy to damage the sensors and/or sensor cables especially if their location is unknown, and the ground dries out and becomes hard.</u>*

<u>Soil Moisture Content and Soil Temperature Sensors: Stevens HydraProbe</u>

The soil moisture and temperature sensors used are the Stevens HydraProbes, part number 7900-170. Soil temperature readings are another important factor for energy balance calculations, particularly in studies involving groundwater recharge ponds where water inflows and outflows carry a significant amount of energy into and out of the system. Accurate soil temperature readings help estimate the temperature of water percolating into the ground, which is assumed to be equivalent to the surrounding soil temperature. This data is particularly important in scenarios where the volume of percolating water is significant, as it provides an estimate of the outflow temperature through percolation.

Soil moisture data may not be particularly useful when the test site is flooded, and the ground is continually saturated. However, soil moisture readings are helpful when gathering evaporation data during dry-up periods for recharge basins.

The HydraProbe sensor features a short cylindrical body with four prongs extending from one flat end. To install the sensor(s), a shallow pit should be dug with a smooth undisturbed side (like the soil heat flux plates). Heat flux plates and soil moisture sensors can be installed in the same pit. Prongs should be fully pressed into the undisturbed soil approximately 5 cm below the surface of the soil. The pit should then be filled in.

Note: *<u>Make sure to mark the location of the installed sensors and burry the cables in a straight/predictable manner. It is easy to damage the sensors and/or sensor cables especially if their location is unknown, and the ground dries out and becomes hard.</u>*

<u>Infrared Thermometer: Apogee SI-411</u>

To measure surface water temperature, an infrared thermometer was used at the eddy covariance station. All objects above absolute zero emit electromagnetic radiation. The wavelength and intensity of the radiation are indicative of the object's temperature. Terrestrial surfaces such as soil, plant canopies, and water bodies emit radiation primarily in the mid-infrared portion of the electromagnetic spectrum. The infrared thermometer reads the wavelength and intensity of this emitted infrared radiation and determines the surface temperature of the water.

Surface water temperature is an important factor in eddy covariance and energy balance studies as it influences the exchange of heat and moisture between the water surface and the atmosphere. This has a large influence on both the sensible and latent heat flux of the test site. Accurately measuring this data is key for understanding the energy dynamics of a system.

One of the advantages of using an infrared thermometer in test sites with varying water levels is its ability to measure temperatures from varying distances without needing to reposition the sensor. This is beneficial as it allows for continuous temperature readings despite fluctuations in water levels.

Water Depth and Temperature Sensors

Sensor: *Endress + Hauser, Waterpilot FMX167*:
At the time of the writing of this report, the Waterpilot FMX167 sensor is installed at ITRC's EC station. This sensor measures water depth using a pressure transducer but does not record temperature. It was selected from the ITRC sensor inventory as a temporary solution until another sensor, capable of measuring both depth and temperature, could be acquired. The FMX167 provides depth data by detecting changes in pressure which correspond to changes in water depth. The sensor's output voltage varies with the depth: upon installation, voltage readings were taken with the sensor both out of the water and at a known depth. These data points were used to establish a calibrated relationship between voltage output and water depth.

Sensor: *Solinst 301Water Level Temperature Sensor*:
The Solinst 301 sensor has been selected for the eddy covariance (EC) station to measure both water temperature and pressure. This sensor is a vented type, as opposed to an absolute sensor, which offers advantages for accurate measurement under varying atmospheric conditions.

To differentiate between the two types of sensors, it is important to understand the components of pressure at a certain depth underwater. There are two primary factors: the atmospheric pressure exerted above the water and the pressure from the weight of the water. An absolute sensor measures the total pressure, which combines both these elements. However, this means any change in atmospheric pressure can affect the readings, making it difficult to discern whether changes in pressure readings are due to shifts in atmospheric conditions or actual changes in water depth.

In contrast, the vented design of the Solinst 301 includes a tube extending above the water surface, allowing it to separate atmospheric pressure from water pressure. This setup ensures that changes in atmospheric pressure do not impact the water depth readings, leading to more precise measurements. Two or three sensors will be deployed at the site to create a more detailed water temperature profile and provide redundancy in depth measurements.

Camera: Stardot PhenoCam

Figure 15. PhenoCam Installed at EC Station

A Stardot PhenoCam is installed at the ITRC EC station to capture qualitative visual information. Although this camera does not yield quantitative data like other sensors, it provides insights into site conditions and phenological changes. Typically, the camera is positioned on the corner of the station that is downwind of the prevailing winds. This placement allows it to capture images of the upwind fetch area, offering a visual record that is valuable for understanding the environmental context. Additionally, the camera can monitor any instrumentation within its field of view, providing a visual check that can be helpful for maintenance and data validation.

GPS

A Garmin GPS unit is used at the eddy covariance station for providing accurate location and time data. While GPS coordinates could manually be measured and entered in during the initial configuration of the system, the integrated GPS unit is typically more accurate and convenient. Additionally, the GPS helps synchronize the SmartFlux system's clock, ensuring all data is accurately time-stamped.

DATALOGGER BOX COMPONENTS

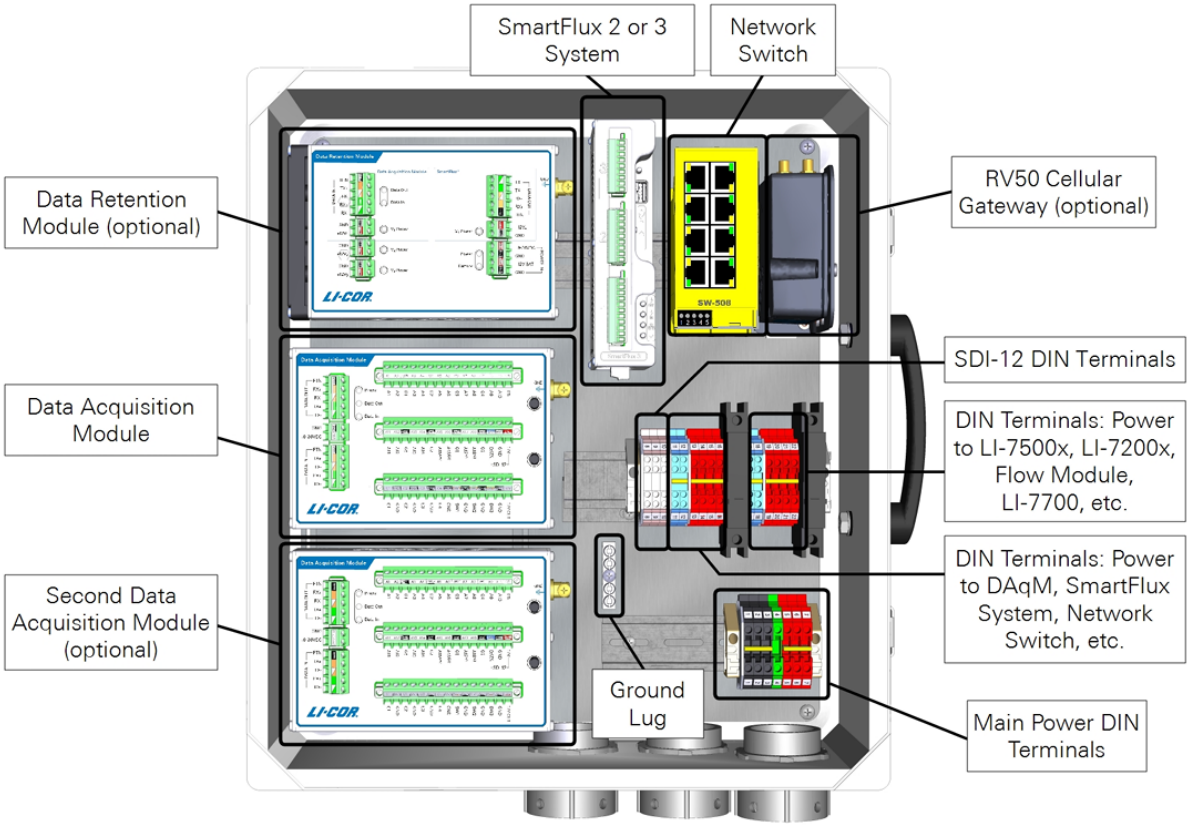

Figure 16. LiCor Datalogger Box

The datalogger box is the central hub of the station, managing power distribution to the sensors and handling data collection and storage. Key components housed within the box, as illustrated in Figure 6, include the SmartFlux system, the Data Acquisition Module (DAqM), the Data Retention Module (DRM), a network switch, modem, and power distribution DIN terminals. Unlike the configuration depicted, the system used by the ITRC features only one DAqM. Not visible in Figure 6 is the backup battery located behind the upper DAqM, which provides power to keep the system operational in the event of a main power supply failure.

At the heart of the datalogger box is the SmartFlux System 3, which serves as the central processing unit. It utilizes EddyPro software to process real-time data from the wind anemometer and gas analyzer, while also collecting and storing data from other sensors onto a connected USB hard drive. The Data Acquisition System manages inputs from various environmental sensors through components like the DAqM and the DRM. The DAqM collects data from the sensors and sends it to the DRM or directly to the Smartflux. The DRM is an optional component that offers features such as temporary data storage, power regulation, and battery backup to ensure continuous operation during power outages. Additionally, network connectivity is facilitated by the BrainBoxes SW-508 which features 8 ethernet ports. Remote access to the station is enabled by a Sierra

Wireless/Semtech RV50X cellular modem. The modem itself requires a subscription for full functionality and data monitoring via its portal. The data plan can be supplied by the cellular provider of one’s choice (LI-COR 2023 Using the Data Acquisition System).

SOLAR POWER TOWER

Figure 17. Tower for Solar Power System. The displayed configuration shown has a double stack of scaffolding and twin solar panels.

The ITRC utilizes solar to ensure reliable power delivery for the Eddy Covariance station even in remote locations. To avoid affecting the wind field, the solar tower is placed at least 30 feet from the station and away from the direction of prevailing winds. The solar system is comprised of two primary components: solar panels and batteries. The panels are sized to meet the average power demands of the station, while the batteries are large enough to sustain power during periods of low or no output from the panels. The system was sized by analyzing solar data from local CIMIS stations to make sure power demands could be met even during periods of minimal solar irradiance. Figure 7 shows an ITRC solar tower installation. Batteries are housed inside the white jobsite toolbox.

Panel and Battery Sizing

For the solar power system, two Rec N-Peak 370-watt panels from NAZ Solar Electric were selected, forming a 740-watt array. This configuration intentionally oversized the panels relative to the system's needs. Two routes were possible when designing the system: size the battery for more days of autonomy or to increase the panel capacity to ensure sufficient charging even during periods of low solar input. In this case, the latter was chosen. Adding an extra panel proved more economical than expanding battery storage to increase days of autonomy. It should be noted that the wattage specified on a solar panel is a nominal output based on ideal conditions such as optimal sunlight (1000 watts/meter²) and perfect alignment with the sun.

Installation of these solar panels is typically done in series to achieve a higher output voltage from the array. This is done to achieve the minimum voltage required to start charging the batteries with lower light conditions. For installations in the northern hemisphere, panels should face south with their tilt angle adjusted to match the latitude for balanced year-round energy production. For a summer optimized system, the angle should be reduced by about 15 degrees while a winter optimized system should increase the angle by about 15 degrees. Since worst case charging scenarios are typically in the winter, a winter optimized configuration was chosen for the ITRC's station.

The system utilizes four Concord SunXtender AGM 104 Ah batteries, totaling 416 Ah of storage for the system. When sizing battery storage, days of autonomy must be considered. This is a measure of how long the system can operate on stored energy during periods of low solar activity, such as during cloudy or foggy conditions. Although fewer autonomy days were chosen to reduce costs, this is compensated for by the larger solar panel array, which allows for charging in lower levels of solar irradiation. It should be noted that battery capacity tends to decrease over time with each charge-discharge cycle. A decreased storage capacity should be accounted for when sizing the solar system. Details of capacity loss are typically outlined in a battery's product documentation.

MISCELANEOUS HARDWARE

While the sensors, dataloggers, and solar power system are the main components for collecting data and powering the system, other miscellaneous hardware is crucial for keeping everything working properly.

Scaffolding

Scaffolding units measuring 5'x 5' x 7' were used as a framework for mounting the eddy covariance equipment. Two scaffolding towers were erected for a test location, one for the instrumentation and one for the solar power system. The primary reason for having two separate towers is so that the solar panels will not interfere with the sensors on the instrumentation tower. Additionally, the datalogger box, instrumentation, and the solar power system would overcrowd a single tower. Depending on the conditions of the test site, multiple scaffolding units may need to be stacked on top of each other to mount equipment sufficiently high. Care should be taken to properly secure scaffolding towers to the ground to prevent the towers from tipping over.

Grounding

Proper grounding is important for the system to work properly and avoid grounding loops. A grounding loop can occur when there are multiple ground connections. Differences in voltage between different ground points can cause noise and interference with instrumentation. Another way to think of this is that the ground serves as a zero-volt reference for the system. Two different reference points will throw off measurements. To avoid this, the eddy covariance station uses a single grounding point at the instrumentation tower.

Bird Repellant

Bird repellant is used on the station to prevent birds from landing on instrumentation and defecating on it. While bird spikes are used on the rain gauge, optic bird gel is used for the wind anemometer and net radiometer. These gel trays deter birds by serving as a multi-sensory repellant, meaning that birds don't like the look, smell, or feel of the repellant. The repellant is easy to install; however, instrumentation with the repellant installed on or near them should be cleaned regularly. The repellant is sticky and can build up on instrumentation if not cleaned regularly.

Temperature Stations

As of this report, the ITRC is working on accessory stations to monitor water temperature at various points in a test pond. These would ideally gather water temperature data at all inlets and outlets of the test area. This will improve the accuracy of energy balance calculations by providing temperature of both inflowing and outflowing water, which is a critical factor influencing the system's energy dynamics.

SITE CONSIDERATIONS FOR EDDY COVARIANCE

When choosing the location for an eddy covariance station, careful consideration must be given to ensure accurate and representative measurements. Since the eddy covariance method relies on wind and atmospheric conditions, many of the primary considerations deal with finding a location with suitable wind conditions.

Prevailing Wind direction

Most test locations will have one or two general directions where the wind comes from most of the time. The direction that the wind comes from most frequently is known as the prevailing wind direction. To determine the prevailing wind direction(s), a wind rose should be consulted. If a wind rose cannot be found for an area near the test location, one can be made in excel using local CIMIS data from a station nearby. Both daily and seasonal wind variations should also be considered. Creating wind roses for each month or season can help to show these seasonal variations.

Since the eddy covariance station measures the area upwind, the station should be installed in a location where it will be downwind of the location of interest most of the time. Ideally, the station would be installed in a location where the surface to be measured surrounds the station. Since other considerations such as access and fetch make this option infeasible in many places, a location must be chosen where the station will be measuring the appropriate surface for a high percentage of the time.

When placing the instrumentation on the scaffolding tower, the gas analyzer and wind anemometer should be placed on a corner where it will be most exposed to the prevailing winds. For example, if the prevailing winds are coming from the northwest, the gas analyzer and wind anemometer should be installed on the northwest corner of the tower.

Fetch/footprint
Fetch refers to the upwind area where the eddy covariance station is measuring flux. A site location should be chosen where the prevailing winds create a fetch area that is representative of the terrain that is desired to be measured. A general rule of thumb for the upwind fetch distance is 1:100, meaning that for every unit of distance the instrumentation is above the ground/canopy, it will be measuring 100 units of distance upwind of the instrument. For example, if the wind anemometer and gas analyzer were placed 10 feet above the surface of the ground, it would be estimated that the station is measuring the area up to 1000 feet upwind of the station.

Consideration should also be given as to how the height of the instrumentation will change over time. When measuring open water surfaces, fluctuations in water level will affect the instrumentation height and therefore the footprint of the station. Vegetation growth can also change the instrumentation height. Adjustments may need to be made to keep the wind anemometer and gas analyzer within the desired height range.

It should also be noted that LiCor recommends that the wind anemometer and gas analyzer should not be lower than 1.5 meters above the ground or vegetation canopy. This is so that the instrumentation is in the correct atmospheric boundary layer for flux readings.

Representativeness
After considering the prevailing winds and the footprint that the station will be measuring, care should be taken to ensure that the area being measured is representative of the desired surface to be measured. Alternative sights should be considered if a portion of the estimated footprint falls on surfaces not applicable to the study.

Terrain and obstructions
The ground surface around the station, and especially in the prevailing wind direction, should be even and homogeneous without any large obstructions such as trees, buildings, or hills. Obstructions like these could cause turbulence and affect the accuracy of the measurements. A general rule of thumb for obstacles is that the distance to the obstacle should be at least 10 times the height of the obstacle. If the terrain is sloped, the station should be positioned to minimize the effect of the elevation gradient on the vertical wind readings.

Accessibility
Another consideration for an EC installation is how difficult it will be to install and access the station in a given location. Installing a station takes considerable effort and typically requires good vehicle access to bring all the tools, hardware, and equipment to the location. After the EC station is installed, regular maintenance trips are required for troubleshooting problems, cleaning instrumentation, and other regular maintenance. Considerable time and headache can be saved if a location is chosen where access for these things is relatively easy.

Vandalism/Security
Accessibility must be balanced with the risk of vandalism. Often, places that are highly accessible for maintenance are highly accessible to vandals. Factors that can help reduce the risk of vandalism are installing the station in a more remote location where people are less likely to travel. Another option is to install the station in a location maintained and/or secured by a local irrigation district. The station should also be placed in a location to prevent inadvertent damage to the station. Avoid locations where the station could easily be hit accidentally by vehicles or equipment. If situated by a roadway, make sure that the station is easily visible and that there is enough room to easily drive around.

Vandals will typically try and steal items that have more apparent value to them such as copper wire, batteries, or solar panels. While the data logger and instrumentation are the most expensive parts to replace, that equipment is specialized enough that the average person would not know what they are. It was recommended by our contacts at Land IQ not to lock the datalogger box. Typically, vandals will cause more damage trying to open the datalogger box when it is locked. If someone does try and steal things, the hope is that they will open the datalogger box, not realize what it is, and just steal some of the wires rather than damage the expensive dataloggers.

Vandals often target items like copper wire, batteries, or solar panels due to their apparent value. Although the data logger and instrumentation within the datalogger box are the most costly components to replace, their specialized nature means they are unlikely to be recognized by the average person. It has been recommended to not lock the datalogger box. Locking the box can result in more damage when thieves try to break in. The hope is that if the intruders open the box, they will not recognize the equipment's value, and only take some wires without harming the more valuable dataloggers.

MAINTENANCE

To keep an EC station operating well, regular maintenance is required. This includes routine tasks for maintaining smooth operation and addressing issues as they emerge. Summary data and images should be downloaded from the station on a daily to weekly basis to monitor its performance. Monthly site visits are needed to inspect and clean sensors and solar panels, download raw data, and perform other necessary tasks. The frequency of these visits may increase if additional issues arise. The specific maintenance tasks and their frequency can vary based on the test location and the equipment in use. The list below provides an example of typical maintenance activities for an EC station.

- ***Clean Solar Panels:*** Keeping panels clean helps to increase panel power output.
- ***Raw data download/USB swap:*** To save data on the cellular data plan, only summary and image data is downloaded over cellular data. The rest of the data should be downloaded when at the station via a direct ethernet connection or by swapping out the USB on the SmartFlux unit.
- ***Changing desiccant***: Desiccant in the datalogger box absorbs moisture to protect electronics. Once saturated, it requires recharging or replacement. Desiccant can be recharged using a microwave or oven.

- ***Rain gauge funnel check:*** Although the rain gauge has a screen, the funnel will get clogged at times. The funnel should be removed to check and clear out any obstructions and to check the tipping mechanism.
- ***Net radiometer cleanliness/pictures:*** When visiting the station, the initial cleanliness of the net radiometer should be documented. Readings from the net radiometer are affected when there is an excess buildup of dirt and grime on the sensors. Rating the cleanliness and documenting with pictures helps to show how much the readings may have been affected.
- ***Clean and level Net radiometer:*** As mentioned above, excessive dirt and grime can affect the accuracy of the net radiometer, and it needs to be clean for proper readings. In addition, the net radiometer should be leveled to get proper readings of incoming radiation from the sky and outgoing radiation from the ground. If the instrument is not level and pointing directly at the sky and ground, measurements will be off.
- ***Hardware Check:*** Perform a general check of other instrumentation and hardware for anything that could be causing problems.
- ***Site Observations:*** Perform a general check of the surrounding area for things that could affect station readings such as tractor work or other perimeter work.
- ***Vegetation Observations:*** Check the surrounding area specifically for vegetation growth. Vegetation growth at or near the location of interest impacts the rates of evapotranspiration.
- ***Other Notes:*** Write notes for additional observations or work done to the sensors. Was anything amiss with the station? Was anything fixed? Were any sensors installed or taken off?
- ***Site Pictures:*** A picture is work a 1000 words and observations can often be more clearly documented with pictures than with notes. Pictures should be taken of the upwind fetch area, the station itself, the surrounding area, in the data logger box (as a reference for the wiring configuration), and of anything else of interest.

SOFTWARE

While the proper hardware, instrumentation, and site selection is needed for good eddy covariance measurements, it would be difficult to impossible to run the system and process the data without the complementary software. While other software solutions may exist, the ITRC chose to use the full software package from LiCor to simplify operating the system. While other sensor specific software exists for initial calibration and bench testing, the following outlines the major software components for operating the eddy covariance station and processing the data.

LI-7x00 A RS DS

A software frequently used is the LI-7x00 software. With this live data can be viewed from the smart flux and biomet systems, station and site parameters can be configured, the system can be rebooted, and the download application can be launched. With a cellular connection, this functionality is available via a remote connection. Downloading and viewing data is often the simplest way to check the status of the EC station.

Blueprint Utility
The data acquisition system can read inputs from numerous sensors; however, the system must be configured correctly so that it knows where to look for a signal and what signal to look for. This can be done using the Blueprint Utility software.

The blueprint utility software is a graphical interface to configure sensors attached to the data acquisition system. Sensors are represented as blocks that can be dragged into the configuration file. From there port channels and variables can be assigned. Additional blocks can be added for calibration and other calculated outputs. Configurations are saved as .daqm files.

Using an IP address, the software can connect to an eddy covariance station remotely or by a direct ethernet connection. Once connected, configuration files can be uploaded (pushed) to the station. To see the current configuration file being used by the station, the software can download (pull) the existing configuration file from the station.

Eddy Pro
The EddyPro software processes raw data collected by the eddy covariance station. It is optimized for handling data collected by LiCor gas analyzers. This software runs on the Smartflux 3 unit installed at the station, where it computes flux data that can be reviewed in summary files downloaded from the system. Initially, EddyPro processes data according to parameters set through the LI-7x00 software during station setup. It is important to note that while site parameters can be updated, Smartflux does not retroactively reprocess past data based on these changes.

Additionally, EddyPro software is available for download, allowing users to independently process raw eddy covariance data. This downloadable version offers increased flexibility in data processing, allowing raw files to be processed with dynamic metadata, various filters, and numerous other adjustments. This ensures that users can tailor data analysis to meet specific research needs.

CONCLUSION

Eddy covariance is a powerful technique for measuring gas and energy fluxes, but its success depends on careful selection and configuration of instrumentation, hardware, and site location. Core components like the wind anemometer and gas analyzer are fundamental to the method, yet the choice of additional sensors is dependent upon the specific objectives and conditions of each study. Additionally, these instruments must be supported by well-suited hardware and a reliable power supply.

Proper site-selection must also be considered for optimal data collection and to allow sensors to accurately monitor the intended test surface. Factors such as prevailing wind patterns, fetch, vegetation, and topography play significant roles in determining the best placement for a station and its sensors. Furthermore, practical issues like site accessibility and potential vandalism require consideration and impact the overall design and maintenance of the station. By addressing these requirements, researchers can maximize the effectiveness and reliability of an eddy covariance system.

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ODE TO THE BUREAU OF RECLAMATION'S DRAINAGE MANUAL

Michael J. Day, P.E.[1]

ABSTRACT

The U.S. Bureau of Reclamation first published its Drainage Manual in 1978. The author began his training and practice in consulting irrigation and drainage engineering four years later and was trained to do agricultural drainage investigations and designs according to the methodologies prescribed in the Drainage Manual. Now after over forty years of irrigation and drainage consulting engineering experience, mostly in California, the author reflects on how drainage needs have changed in California due to the forces of water scarcity, improvements in irrigation efficiency, plus environmental concerns including water quality. With updates in 1984, 1991, and 1993 The Drainage Manual remained an important "go to" resource through the years to help diagnose and treat agricultural drainage problems. Some limitations in the Drainage Manual have been found and some workarounds have been developed to address the limitations that are discussed. Some project examples are given to illustrate applications of The Drainage Manual to solve on-farm drainage problems using a "wholistic approach" where rainfall, irrigation, surface drainage, soils, geology, agronomy, and subsurface drainage sciences were applied. Lastly there is a brief discussion of possible research needs and additions to the drainage manual to make it even better.

INTRODUCTION

The United States Bureau of Reclamation (Reclamation or USBR) first published its Drainage Manual in 1978. Four years later I was trained by my employer at the time, J.M. Lord, Inc., to utilize the Drainage Manual to do agricultural drainage investigations and designs. Reclamation updated The Drainage Manual in 1991 and 1993 but hasn't since.

After over forty years of utilizing the Drainage Manual as a reference on more than forty different sites (see Table 1 for a list below), mostly in California, and about thirty constructed drainage systems, I can testify to what an amazing resource it has been for diagnosing and treating agricultural drainage problems. I have also used its principles in some subsurface investigations and dewatering system designs for urban developments that had shallow groundwater problems.

With this technical paper I'd like to discuss many of my "takeaways" from utilizing the Drainage Manual (i.e. the most important things I have learned), discuss some limitations with the Drainage Manual along with some workarounds for those limitations, and briefly discuss possible research needs and additions to the Drainage Manual to make it even better.

The Drainage Manual introduces both surface drainage and subsurface drainage but focuses more on subsurface drainage. Similarly, I have worked on both surface and

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subsurface drainage projects, but many more subsurface drainage projects. Thus, I'll focus this paper more on subsurface drainage. Generally, I have found many helpful publications from the National Resource Conservation Service (NRCS) for surface drainage, but I have found the Drainage Manual to be superior to NRCS publications on subsurface drainage.

I'll use the Drainage Manual's outline to organize the order of this technical paper and comment related to on-farm drainage because most of my experience is on-farm rather than district or regional drainage collector systems.

Table 1. Drainage Project Site List

Year(s)	Closest City	Investigation	Design	Interceptor	Relief Drains	Drainage Wells
1982-83	Mendota, CA	X	X	X		
1982-83	Firebaugh, CA	X	X	X		
1983-1985	Cartago, CA	X			X	
1986	Lemoore, CA	X	X	X	X	
1986-87	Manteca, CA	X	X		X	
1987	Stockton, CA	X	X		X	
1987	Newman, CA	X				X
1988	Turlock, CA	X	X	X		
1988	Los Banos, CA	X				
1989-1993	Napa and Sonoma, CA*	X	X	X	X	
1994	Manteca, CA	X	X		X	
1995	Manteca, CA	X	X		X	X
2004	La Vegas, NV	X	X		X	
1993	Lost Hills, CA	X		X		
2006-2007	Riverdale, CA			X		
2011-2016	Mendota and Firebaugh, CA**	X	X	X		
2015	Watsonville, CA	X		X	X	
2017-18	Firebaugh, CA	X			X	
2017-2018	Galt, CA	X		X		
2017-2019	Walnut Grove, CA	X	X		X	
2024	Delano, CA	X	X	X		

*Included more than twenty different sites
**Included six sites for the San Joaquin River Restoration Program

Drainage and The Environment

The Drainage Manual mentions the importance of considering the importance of the environment and water quality concerns, perhaps prophetically, though maybe this was added in 1990's revisions. Salts, Boron, and specific ion toxicity concerns in some areas of the San Joaquin Valley were recognized as problems during plans for a San Joaquin Valley Master Drain in the 1960's. And those concerns remain today. Selenium was discovered in many areas of the San Joaquin Valley that have subsurface drainage problems in the late 1980's. And that problem also remains today (in spite of many millions of dollars of research and planning for solutions).

Water quality concerns have greatly limited the number of subsurface drainage systems constructed in the San Joaquin Valley since the 1980's and have necessitated many operational changes in drainage water management areas including shutting down Westlands Water District's drainage collector system, restrictions on the use of evaporation ponds, and The Grasslands Bypass Project. Integrated Farm Drainage Management (IFDM), not mentioned in the Drainage Manual, has been developed after the last revision as an alternative for managing subsurface drainage water but adoption of IFDM has been limited.

In California's San Joquin Valley widespread water shortages in areas with subsurface drainage problems has led to widespread water transfers (and land retirement) from areas with subsurface drainage problems to areas without those problems. Improved water management and water conservation measures, including wide-spread adoption of micro-irrigation, has also contributed to a reduction in areas that have shallow groundwater and subsurface drainage problems. Westlands Water District in western Fresno and Kings Counties, Dudley Ridge Water District in southwestern Kings County, and Lost Hills Water District in northwestern Kern County, CA have experienced these effects dramatically.

Topography, Water Sources, and The Relationship Between Surface and Subsurface Drainage

The Drainage Manual speaks of the importance of getting basic information about topography and understanding how topography influences drainage on pages 13-15. I have found this to be an important basic truth. A great example of this occurred on a project Provost & Pritchard Consulting Group (P&P) did for Nees Farms in Panoche Drainage District near Firebaugh, CA. Nees Farms had planted pistachios on property purchased from a landowner who made no mention of shallow groundwater problems during the land sale. After a very rainy winter, the leaves of the trees were showing leaf-burn and backhoe pits filled with shallow groundwater. P&P performed an investigation of soils and shallow groundwater conditions including a topographic survey. Depths to shallow groundwater were found to be too shallow for healthy root zone aeration (Figure 1 below) so initially it appeared that a subsurface drainage system was needed.

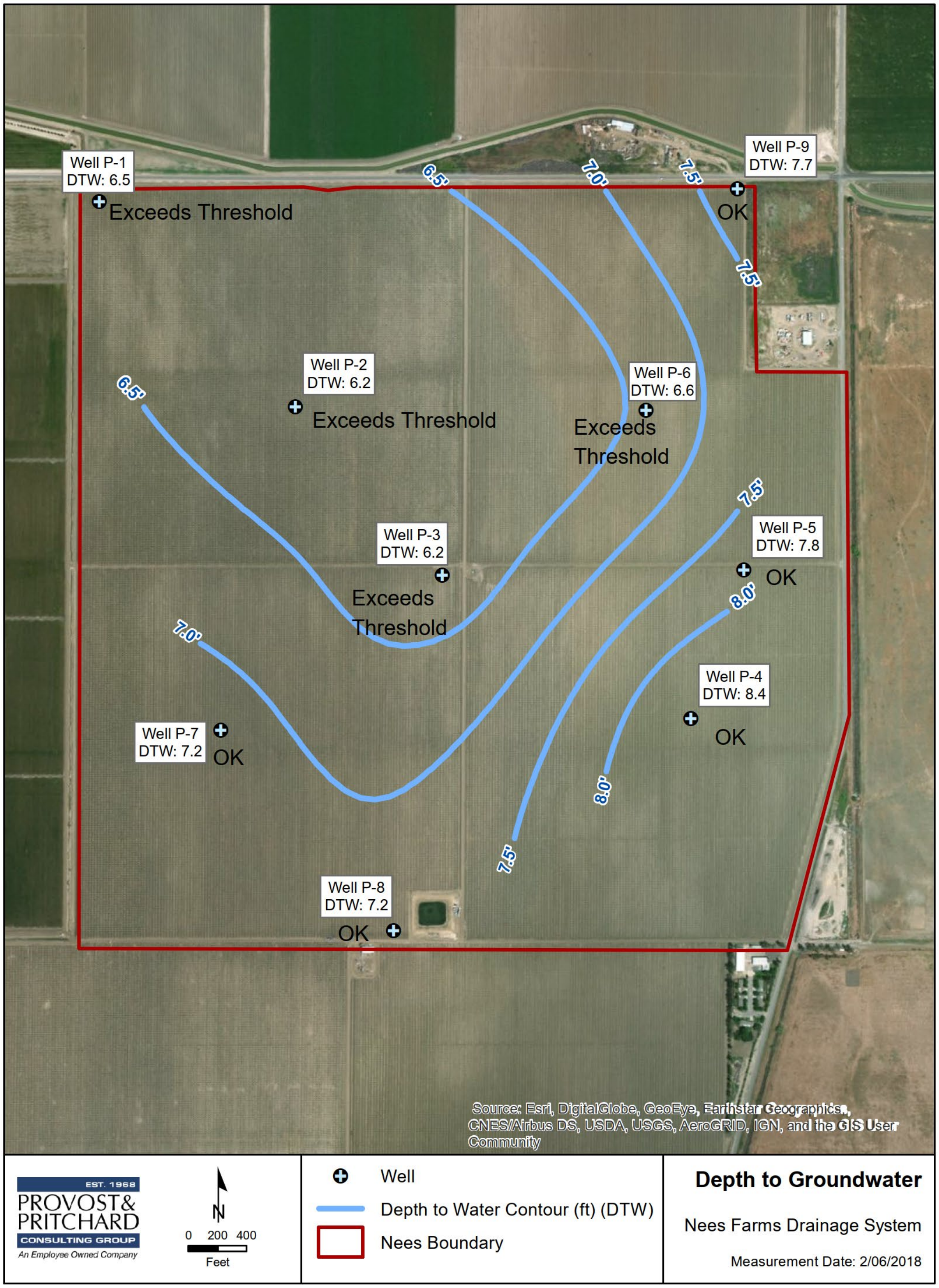

Figure 1. Depth to Groundwater Map Nees Farms February 6, 2018

During field work I noticed that a tailwater drainage system had been blocked off during the orchard's development. Observations of ponding after rain events and interpretation of a topographic survey map (see Figure 2 on the next page) highlighted that water ponding on the ground surface after rains increased rainwater infiltration.

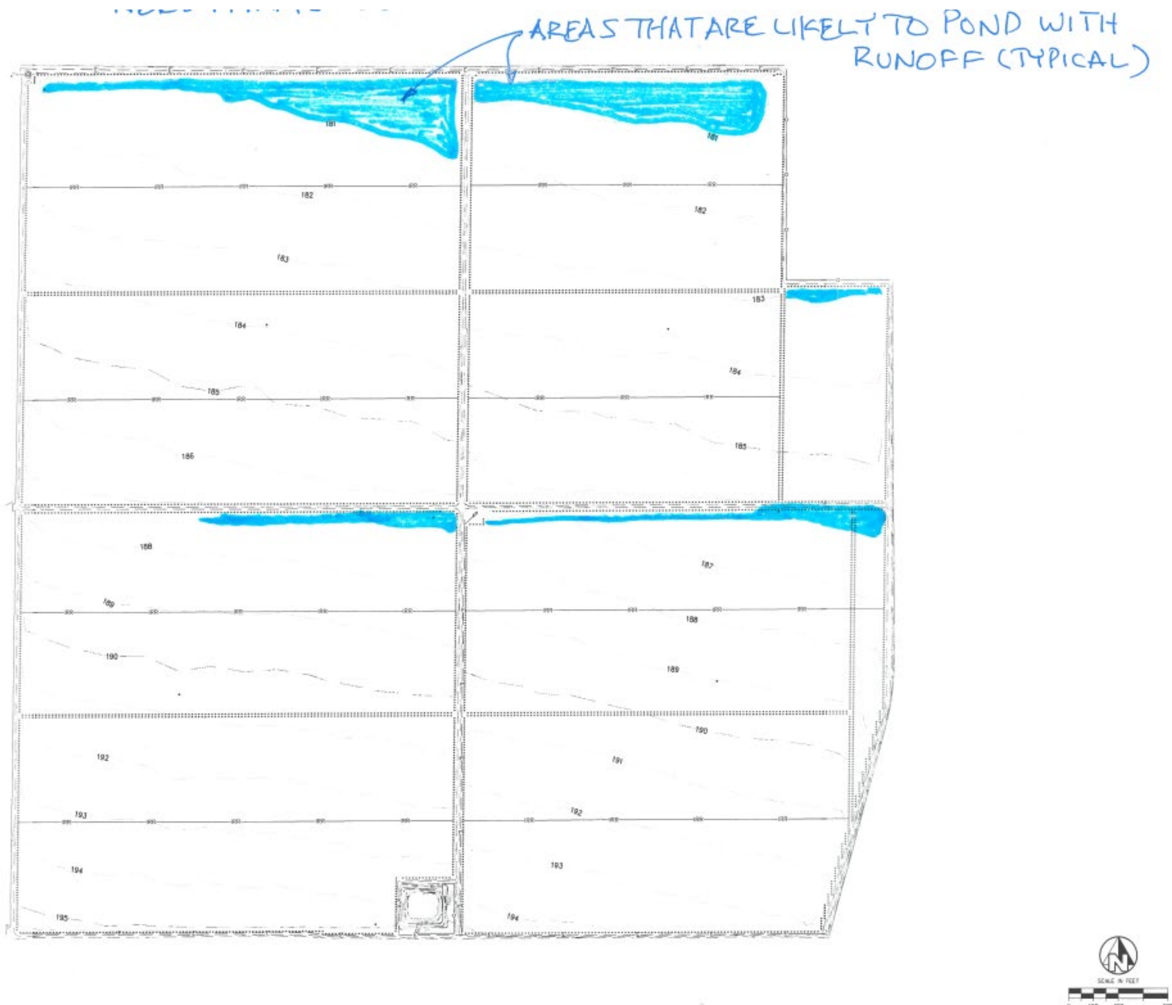

Figure 2. Nees Farms Topographic Map with Ponded Areas

While doing a water source study on the property following procedures discussed on pages 127-128 of the Drainage Manual, I noted that the farm manager mentioned the reservoir on the south end of the property seemed to have excessive leakage. P&P recommended, and farm staff performed a simple pond-drop test on the reservoir. P&P estimated leakage at 0.9 acre-feet per day based on that test.

Pursuant to P&P's recommendations, the farm manager restored the tailwater drainage system and lined the reservoir with geomembrane liner. The result was that Nees Farms did not need to install a subsurface drainage system after those changes were made. Nees Farms' staff performed on-going monitoring of shallow groundwater levels in monitoring wells P&P installed and found those changes lowered groundwater sufficiently for the trees to become healthy again, even when heavy rains returned a few years later.

Another example of the connection between topography and subsurface drainage occurs frequently in vineyards of the Napa and Sonoma "wine country". The areas with shallowest water table are usually found in "swales" (small topographic "valleys") and other low areas where surface water runoff accumulates. Therefore, subsurface drains are usually located in those areas. I learned this from Brian True, whose father George True designed many subsurface drainage systems in the Napa and Sonoma area. P&P continued this practice during the design and construction of more than 20 drainage systems for vineyards from 1989-2003. An employee purchased P&P's Napa office and continued drainage investigation and design work on many other vineyards utilizing the same methods P&P employs.

Geology and its relationship to Subsurface Drainage

Pages 15-18 and parts of pages 126 and 127 of the Drainage Manual speak of the importance of understanding the geology of a site while investigating its needs for drainage and designing drainage systems. I have personally learned the value of understanding an area's geology and frequently utilize geologists on P&P's staff and geological references to better inform P&P project teams who are assessing drainage problems and/or designing drainage systems to solve them.

I believe it is particularly important to know when faults in the earth, aquicludes, and aquifer configurations alter water flows below the earth, affecting shallow groundwater problems. I was involved in a drainage investigation of some property next to Owens Lake in eastern California early in my career for J.M. Lord, Inc. A consulting geologist and geophysicist was also part of the project team, and he helped to steer our project teams' understanding of the shallow groundwater problem in the area proposed for a dude ranch development. His input to the team performing the drainage investigation was very helpful. Ironically the dude ranch development was never done, but springs on the site were developed for a major bottled-water operation.

Areas of the San Joaquin Valley that have shallow groundwater problems are strongly related to areas with extensive clay layers laid down in former lake beds, now buried by younger alluvium, that "perch" groundwater. Such clay layers can be seen in Figure 3 which is a geologic cross section through the San Joaquin Valley south of Fresno from USGS Water Supply Paper 1999H. In some cases, the layers are 100 feet or more deep, but in most areas, they are shallower than that. The "A" Clay has been identified as a culprit for perched groundwater conditions in many areas of the central and western portions of the San Joaquin Valley from Mendota to Bakersfield. Portions of Merced County have shallow groundwater perched above the Corcoran "E" Clay and/or "A" Clay that rise to near the ground surface in wet years.

I have learned through the years that alluvium often is better understood by thinking about it in terms of "lenses" than layers. Furthermore, soil variations in alluvium are often extreme, sometimes varying greatly within just a few feet, making it extremely difficult to assess and design drainage solutions. The use of geophysical methods, cone penetrometers, and permeameters are ways to more economically gain an understanding of soil and geology variations. None of these are currently discussed in the Drainage Manual but are now widely used by universities, private consultants, and government agencies for a variety of purposes in better understanding subsurface conditions. Figure 4 is one of several geophysical transects commissioned by Reclamation to better understand where "paleochannels" of the San Joaquin River are located on a property that may be affected by increased River flows associated with San Joaquin River Restoration. Figure 5 is a conceptual cross section of a portion of the San Joaquin River Levee aided by cone penetrometers. Figure 6 is a picture of the Aardvark Permeameter, one of several commercially available permeameters. P&P now uses the Aardvark Permeameter on some of its projects for more rapid assessment of soil permeability. While these technologies increase our understanding of subsurface conditions there is still a need for basic research to compare and contrast data from these newer methods versus Drainage Manual bore hole logging and hydraulic conductivity tests.

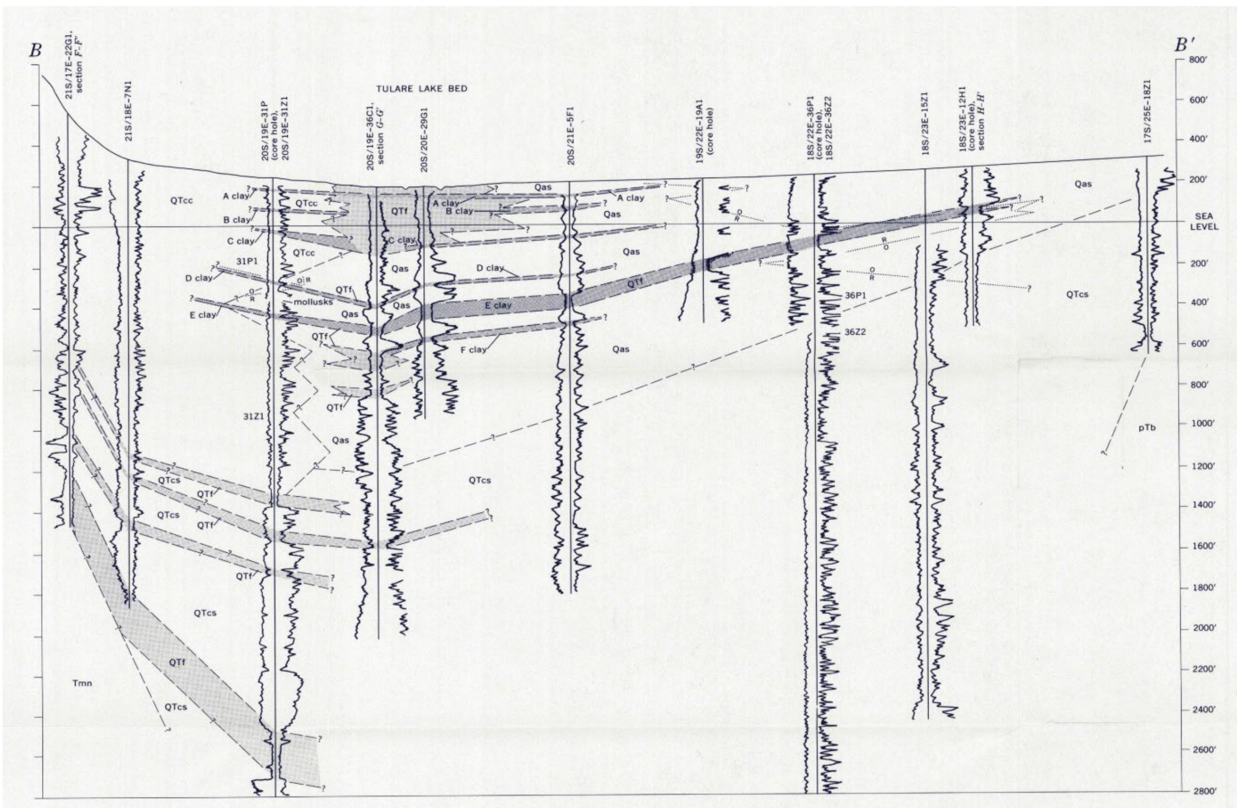

Figure 3. Geologic Cross Section of San Joaquin Valley South of Fresno from USGS Water Supply Paper 1999H.

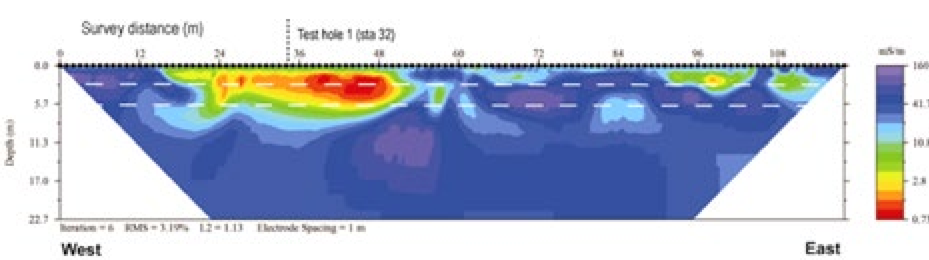

Figure 4. Geophysical Cross Section on a Property Adjacent to the San Joaquin River

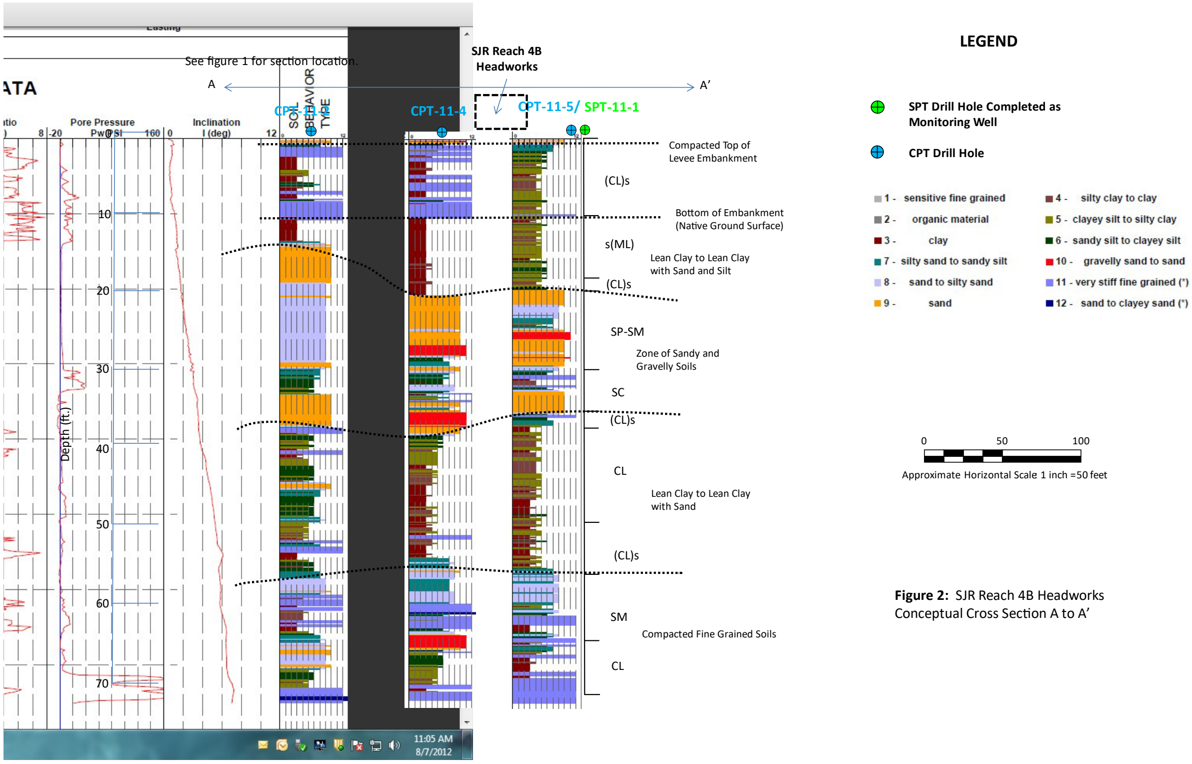

Figure 5. Cone Penetrometer Test Results and Conceptual Cross Section of Portion of San Joaquin River Levee for San Joaquin River Restoration Program

Figure 6. Aardvark Permeameter

Soil Characteristics

Pages 18-28 of the Drainage Manual describe soils assessments to describe their various properties. I have logged soils on projects and trained other P&P employees to do the same according to this methodology. “Determining Soil Texture by The Feel Method” by Steve J. Thein of Kansas State University has also been an excellent aide. While working together with Ron Brase of Crop Care Associates on vineyard projects we began to factor consolidation (soil density) and cementing into our estimates of hydraulic conductivity and developed graphical representations of the soil logs to help clients understand them better. I also learned to look for mottling as a sign that soils have been saturated at some time in their history. This is important for logging soils when water table conditions are not present as mottling can indicate sustained water table conditions. In recent years Reclamation has commissioned studies of the capillary zone and how to factor capillary rise above the water table into the San Joaquin River’s Seepage Management Program. Findings from those studies should be added to The Drainage Manual.

Through the years it has become clear that hydraulic conductivity, both horizontal and hydraulic conductivity are the most important properties to assess, and it is essential to conduct field tests to obtain numbers for design purposes. Having a great description of soil properties is helpful but estimates of hydraulic conductivity that factor all other soil properties, even if done by a veteran, lead only to very approximate results. Tests have often proven initial estimates based on other soil properties wrong; either too high or too low.

Another lesson learned is one should not use soil texture alone to judge a soil’s hydraulic conductivity unless it is single grained. The size of soil particles dictate porosity in single-grained soils which is strongly related to hydraulic conductivity. Thus, hydraulic conductivity is very related to grain size. But once a soil has enough silt and/or clay to be considered a loam, clay loam, or clay its other properties, including the strength of a soil’s structure, consolidation, and cementing, governs the “secondary porosity” or “preferential flow” and therefore its hydraulic conductivity. I encountered a great example of this on Ryer Island in California’s Delta when a backhoe pit dug into extremely heavy clay soils had streams of water pouring in from large cracks. Occasionally hydraulic conductivity test results on clay loams and clays are in the medium high or high range. This is contrary to some NRCS references that predict medium low and low hydraulic conductivity for those soils.

Often geotechnical engineering consultants are involved in drainage projects that employ drilling methods, log and sample soils, test and prepare soil reports according to the Unified Soil Classification system and ASTM standards that are not consistent with The Drainage Manual. Since such geotechnical methods, tests, results, and reports provide relevant and useful information, P&P has developed ways to “translate” soil test reports for the Unified System into the USDA Soil Classification System and work together with geotechnical engineering firms on drainage projects. It would be helpful to add a section to the Drainage Manual addressing this topic.

Salinity and Alkalinity

Pages 28-37 of the Drainage Manual cover salinity and alkalinity. While this section provides excellent information on this topic, it is now outdated. More recent research and information on soil salinity and alkalinity has been developed by researchers and university extension experts. P&P keeps and utilizes more current references salinity and alkalinity. Boron is often found in parts of the western San Joaquin Valley's soils and groundwater. Most commercially grown crops are sensitive to Boron yet research and results on crop sensitivity and leaching requirements for Boron is very limited. This is a major research need for San Joaquin Valley agriculture and for other farming areas affected by Boron.

Rethinking "The Barrier"

Determining which soil or geologic layer should be considered as "the barrier" for drainage design purposes can be very difficult. Page 126 of The Drainage Manual discusses identifying the barrier zone and defines it as a layer which has a hydraulic conductivity of one-fifth or less of the weighted hydraulic conductivity of the strata above it. Often the barrier layer is deeper than bore holes performed during the investigation and borings or well logs from prior work in the area are inconclusive.

Sometimes there really isn't a single layer "perching" water. Rather the layering of soils and the geologic formation impede the downward movement of water sufficiently to cause a shallow water table. This is especially true when the rate of downward flowing water is relatively high. High rainfall totals, deep percolation, seepage, and/or groundwater recharge rates result in shallow groundwater problems. At some locations, rather than thinking a barrier is perching groundwater I think "the aquifer is full and can't take more".

On several drainage study and designs in recent years I have found it is important to recognize that "the barrier leaks" when performing transient-method drainage calculations or the drainage design won't match real field conditions and will be overly conservative (and expensive).

Surface Runoff

Pages 37-45 of the Drainage Manual describe methods for factoring surface runoff into drainage system designs. When designing surface drainage systems or combined surface and subsurface drainage systems I prefer using the NRCS' TR-55 Urban Hydrology for Small Watersheds method rather than what is presented in The Drainage Manual. It would be helpful to see a comparison between these methods. Also, the National Oceanic and Atmospheric Administration (NOAA) has updated data and methods for determining storm intensity and return periods for the western USA (see https://www.weather.gov/owp/hdsc_noaa_atlas2). It is also important to recognize and factor climate change and its impact on precipitation in the future for drainage design purposes.

Rainfall and Deep Percolation Schedule

Pages 46-55 of the Drainage Manual describe how one can develop a schedule for rainfall and deep percolation from irrigation. I have put together or supervised the preparation of such a schedule many times for projects and utilized computer spreadsheet programs, including Excel, for the calculations and charting of results.

California's Department of Water Resources' California Irrigation Management Information System (CIMIS) operates, maintains, and manages weather data for a network of weather stations in California useful for rainfall and evapotranspiration data. CIMIS also maintains an on-line library of resources for irrigation scheduling that is more current than the Drainage Manual.

Field and Laboratory Procedures

Pages 61-107 of The Drainage Manual describe various field procedures for testing horizontal and vertical hydraulic conductivity of soils in the field. Both companies I worked for (JMLord, Inc. and P&P) utilized the methods described in the Drainage Manual successfully many times to obtain field data and designed many successful drainage systems with that data. At times however, both companies developed and used alternative tools and materials to make testing easier. For example, 4" diameter polyethylene non-perforated septic system pipe is perfect for casing 4" auger holes when it is slotted with a hack saw before use. The pipe fits perfectly in holes augured with 4" hand augers and 3¼" hand augers fit well inside it when one needs to auger deeper than the casing and "sink the casing" if the hole is collapsing. Figure 7 is a picture taken when a P&P employee used the septic system pipe for that purpose.

Figure 7. Polyethylene Septic System Pipe Used to Case 4" Auger Hole at Nees Farms

Other examples of variations from The Drainage Manual include the use of small electric driven pumps that run off 12 Volt car batteries (instead of bailers or hand pumps).

Pressure transducers and data loggers now eliminate the need for the equipment shown on page 65 to record water level recovery versus time in auger hole and piezometer tests. Figure 8 is a chart made with transducer and data logger data for a piezometer pump out test. Also, as previously mentioned, Aardvark permeameters are being used to make permeability tests easier.

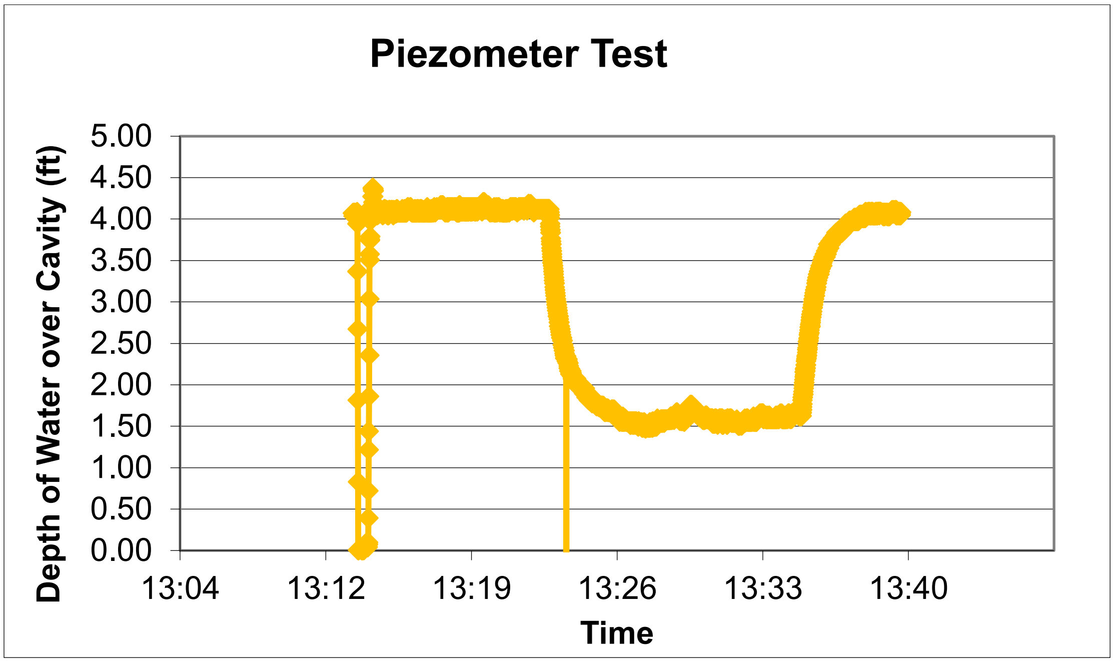

Figure 8. Example Chart of Data from a Pressure Transducer and Data Logger

<u>Ground-Water Studies and Economic Considerations</u>

Pages 128-35 of The Drainage Manual describe studies to map depth to groundwater and groundwater elevation. Such studies are foundational for drainage studies. I recall following these procedures on a large farming operation within the Yolo Bypass of the Sacramento River just west of Sacramento. Farm management was convinced the property had a subsurface drainage problem but an investigation found shallow groundwater levels were deeper than ten feet below ground surface everywhere beneath the farm; not shallow enough to affect the annual crops farmed there. This was a surprising and happy finding for that farm.

A different result was found by P&P a few years ago while performing a groundwater study for a blueberry grower considering buying land a few miles from the Kings River in Centerville, California. The investigation, which utilized water level data from existing wells in the general area and backhoe pits dug by the grower's agronomist, suggested that shallow groundwater levels would be too shallow for blueberry production. P&P estimated the costs of installing a subsurface drainage system and worked with the grower to estimate benefits similar to what is described on Pages 137-140 of the Drainage

Manual. The grower opted not to purchase the property and was grateful to know about and avoid the subsurface drainage problem.

Spacing of Drains

P&P developed Excel spreadsheets to perform the Transient Flow Method of Drain Spacing described on Pages 147-167 of The Drainage Manual to aid with selecting depth and spacing of relief drains on its subsurface drainage design projects. Figure 9 is a chart generated by the Excel Spreadsheet when it was used a few years ago

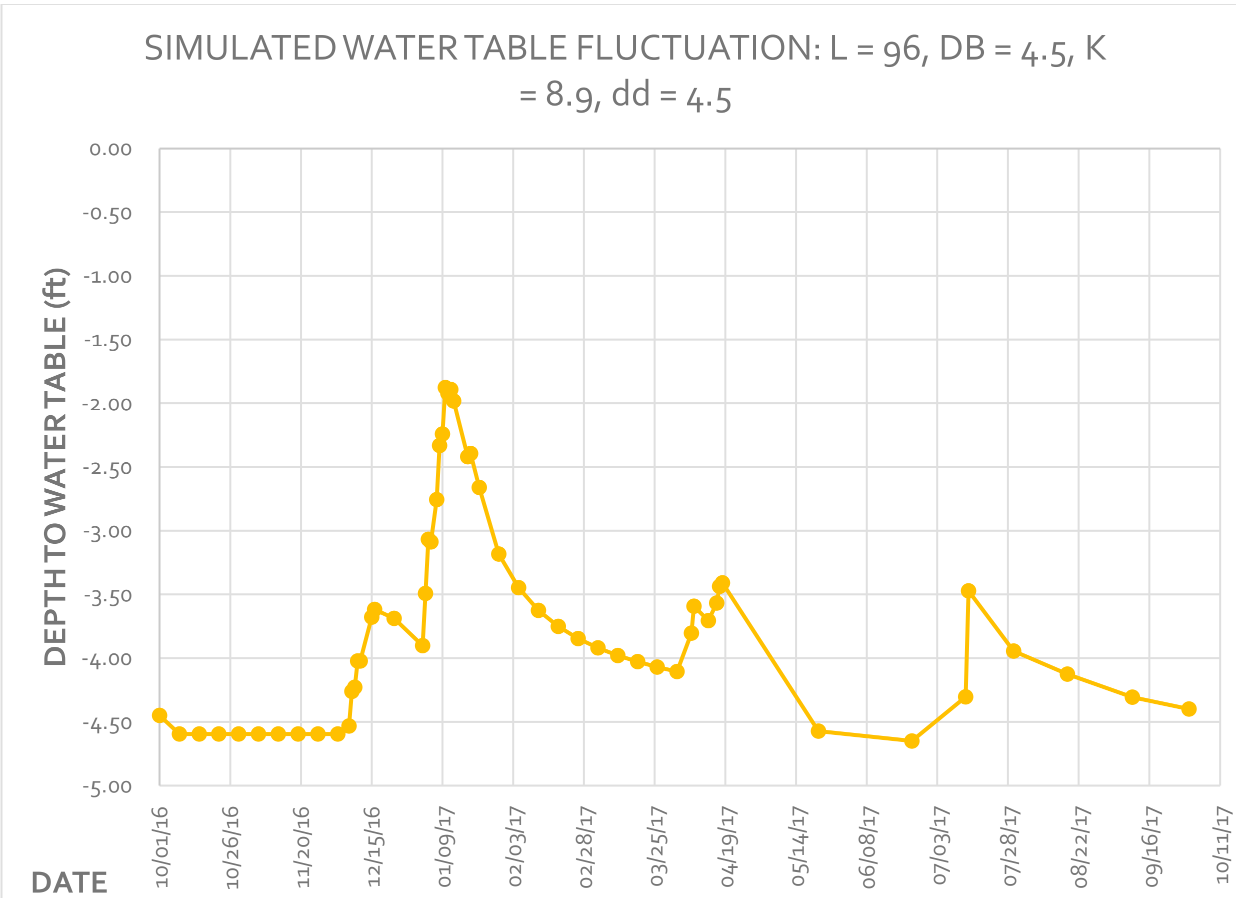

Figure 9. Graph of projected variations in depth to water table (Excel spreadsheet chart) for relief drains in California's Delta region.

Interceptor Drains

The method described in The Drainage Manual for interceptor drain design on pages 175-180 has been used successfully for many years. But an adjustment in equation 12 is needed when the interceptor is adjacent to a relatively wide water body like a river, instead of a narrow water body like a canal. The formula is obviously derived from Darcy's groundwater flow equation, so the R (distance from channel centerline to required first drain) is adjusted based on a flow-net analysis that factors the width of the source of water and curved pathways that water takes to flow from the water source to the interceptor drain.

In recent years P&P has been utilizing SEEP\W - 2D by Geo Studios to aid in designing interceptor drains. Figure 10 shows an output from SEEP\W on an interceptor drain design for an interceptor drainage system that was installed to protect an orchard from high water levels in the Cosumnes River. Use of SEEP\W helped determine that a second parallel drain was necessary to insure sufficient water table depths beneath the orchard. SEEP\W has also been used to evaluate and rule out slurry walls to protect lands adjacent to the San Joaquin River.

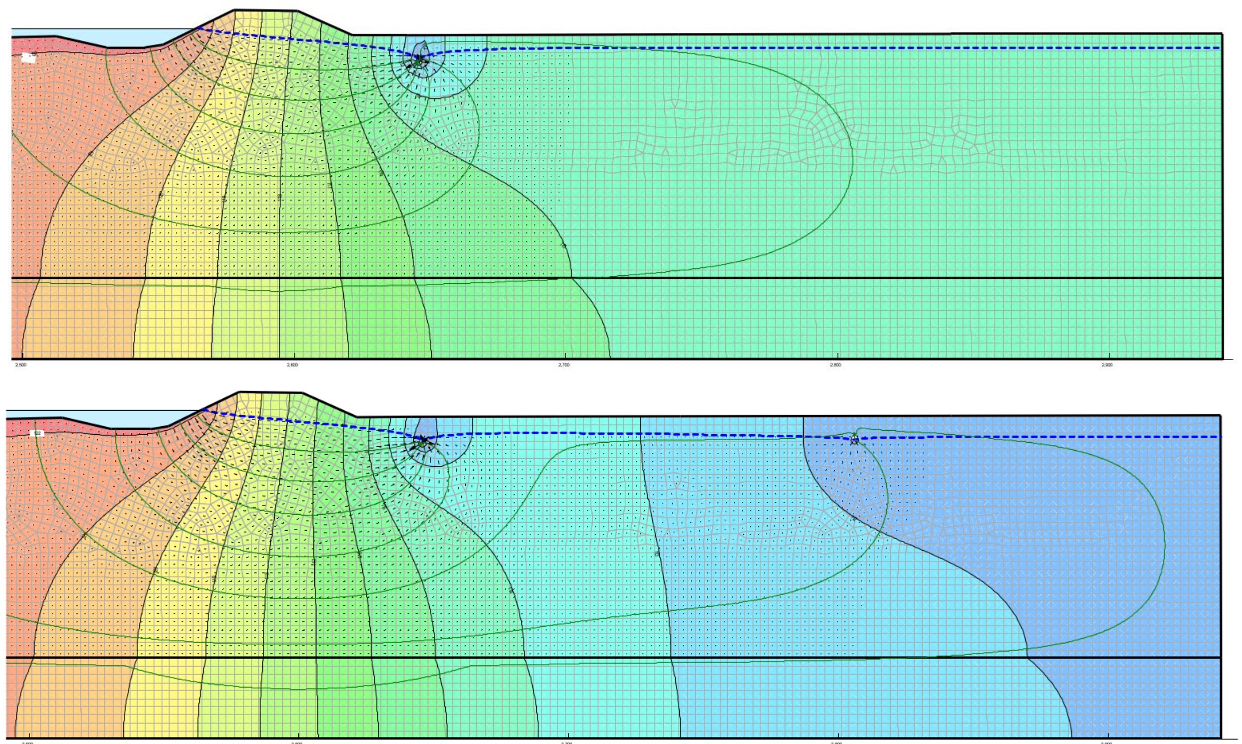

Figure 10. SEEP\W 2D Model Output for Interceptor Drain Design. One Open Drain Above, Two Drains Below

As with all models, getting good data to build and calibrate SEEP\W models is extremely important. P&P builds and calibrates SEEP\W models using data collected at the site then calibrates the model to match water level observations at the site without subsurface drains (or with open drains at sites that have them). The top portion of Figure 10 shows equipotential, groundwater flow lines, and water table line with an open drain the farmer had dug as a temporary solution. P&P modeled it to calibrate the model. The bottom portion of Figure 10 shows equipotential, groundwater flow lines, and the water table line with two interceptor drains at the same site.

Pipe Drains

J.M. Lord, Inc. and P&P have designed many of the pipe drains described in pages 203-243 with corrugated polyethylene drainage pipe and gravel envelope material meeting the specifications called for in The Drainage Manual and have had great success doing so.

Drainage Sumps and Pumping Plants

Many subsurface drainage systems have been designed with sumps and pumping plants using pages 243-245 of The Drainage Manual as a reference. An alternation in the formula on page 244 was found to be necessary to recognize that the flow condition requiring the maximum storage volume occurs when inflow is equal to half of the pump's design flow.

There are some cases where water stored in the mainlines entering the sump (when they are submerged) can and should be factored into the storage requirement, reducing the size of sump needed.

Special Drain Types

Drainage wells ("pumped wells" described in The Drainage Manual page 246) are commonly used successfully in many locations of the San Joaquin Valley to lower shallow groundwater levels for farming or for construction dewatering. The book "Groundwater and Wells" has been a very helpful reference for analyzing drainage wells.

CONCLUSION

Again, the Drainage Manual has been an incredibly useful guide for investigating and designing drainage systems throughout the author's career. The Author recommends that a new update be made to the Drainage Manual to include more current information and workarounds that are discussed in this paper. Furthermore, the author recommends new research be done related to crop tolerance for boron and leaching requirements for boron and other specific ions that crops are sensitive to.

APPLICATION OF GEOMEMBRANE BACKED GEOSYNTHETIC CEMENTITIOUS COMPOSITE MATS (GCCMS) TO MITIGATE WATER SEEPAGE OF EARTHEN IRRIGATION CANALS

Nathan Ivy[1]
Alejandro Paolini[2]
Simon Lester[3]

ABSTRACT

As water conservation becomes a higher priority for irrigation districts across the western states for environmental and financial reasons, this paper reviews the application of Geosynthetic Cementitious Composite Mats (GCCMs) as a low permeability liner of irrigation canals to mitigate water seepage. GCCMs are a well-established material technology within storm-water drainage but are relatively new in their use for lining irrigation canals. They are defined by ASTM D4439–20 'Standard Terminology for Geosynthetics' as factory-assembled geosynthetic composites consisting of a cementitious material contained within a layer or layers of geosynthetic materials that becomes hardened when hydrated. This paper explores key material characteristics of GCCMs pertinent to the lining of irrigation canals including the accommodation of differential ground movement, the importance of conformance to ASTM standards and the determination of permeability to liquids of three jointing techniques applicable to GCCMs. Specifically, this paper provides analysis of seepage data obtained from ponding tests before and following the installation of CCX© GCCM which was used to line a 1,440' reach of the Duni ditch operated by Henry Miller Reclamation District No. 2131 (HMRD) in Dos Palos, California. It also covers aspects of the general installation processes of the GCCMs versus traditional membrane and concrete solutions and an indication of the financial gains that irrigation districts can attract from the re-sale of saved irrigation water losses through seepage.

INTRODUCTION

As water usage rates continue to increase, and rainfall continues to drop – especially in populus arid regions such as California – the need to preserve water resources becomes increasingly important. Water is a vital natural resource required for growing crops, raising livestock and for human existence within any environment. Historically, irrigation canals have played an important role in maintaining and transporting water through arid regions. Largely, these canals have been unlined, earthen canals. Some have been lined with geomembrane or concrete or both in an effort to extend the life cycle and improve efficiency in both preserving and transporting water through the canal. Both products are effective – at least initially – in protecting water resources, but both are susceptible to damage and seepage losses – especially when used independently of each other. About 5 years ago, the USBR published the results of their 25-year durability

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report[1]. The study concludes that a geomembrane overlain by concrete provides the longest lasting protection. This paper discusses geomembrane backed GCCMs that impart both a geomembrane and a high strength concrete layer into a single product to provide an estimated lifespan in excess of 50 years when designed and installed properly. It will provide a brief history of the current ASTM standards that are available for specifying GCCM and will focus on a case study of a canal over ¼ mile long where it was successfully installed and greatly reduced water losses at a cost less than many competing technologies.

HISTORY OF GCCMs

The newest geosynthetics class, now known as GCCMs, were first developed in the UK in 2005. Their initial use was emergency shelters that could be rapidly installed for humanitarian aid projects. As the manufacturing process evolved, mass production began in 2009 for use in erosion control applications. Because they are a new class of geosynthetics, many existing ASTM test standards were not appropriate to test material that, as installed, is pliable, but ends up hardened after it is hydrated and cured. Much work has been done since those early days to develop test standards to support specifying this material. ASTM D8364 "Standard Specification for Geosynthetic Cementitious Composite Mat (GCCM) Materials" is the overarching test standard (Table 1). The standard defines 3 types of GCCM, Type I, II and III. They vary by thickness and required values for prescriptive test properties. The application (weed suppression, erosion control, water conveyance) and site-specific conditions (soil type, slope angle, water velocity) determine the best type of material to use for a specific project. Each type of GCCM is further defined by compressive strength, flexural strength and tensile strength among other important characteristics. Currently this is the only recognized test standard for specifying GCCM so it is important to ensure any GCCM used on a project meets or exceeds all of these requirements. Because it is new class of geosynthetics, ASTM D8173 "Standard Guide for Site Preparation, Layout, Installation and Hydration of GCCMs" is also available to guide first time specifiers in how to ensure a quality installation. Additionally, there are various training resources online from a variety of manufacturers.

TABLE 1. ASTM D8364 Requirements[2]

Property	Test Method	State of GCCM	Minimum Values		
			Type I	Type II	Type III
Thickness	D5199	uncured	4.5 mm	7.0 mm	
Mass per Area	D5993	uncured	6.5 kg/m^2	10.5 kg/m^2	
Density	D5993	uncured	1250 kg/m^3		
Flexural Strength (cured 24 hr)	D8058	initial load	625 N/m	1500 N/m	3450 N/m
		initial flex strength	3.5 MPa		
		final flex strength	4.0 MPa		
Compressive strength	D8329	cured 28 days	40 MPa	50 MPa	60 MPa

Pyramid Puncture	D5494	cured 28 days	2 kN	3.5 kN	4.5 kN
Abrasion	C1353	cured 28 days	0.3 mm		
Tensile Strength	D4885	uncured	8 kN/m		
		cured 28 days	3.5 kN/m	6.5 kN/m	9 kN/m
		cured 28 days	10 kN/m	19 kN/m	
Freeze-Thaw	C1185	cured 28 days	>80%		

JOINTING METHODS

There are 3 different ways to join panels of GCCM. The best method depends on the project application and expectations. Far and away, the most common method is using stainless steel screws at 4-8” centers to join the seams. This joint is not meant to be impermeable but is used for slope protection applications or for water conveyance applications where water is expected to be present only when flowing during storm events, for example. The water will be flowing over the seam and not back up into the seam – at least to any degree that would be meaningful for these applications. This method is also useful in areas of high hydrostatic uplift. In locations with high water tables, this approach allows seepage through the joints without exerting pressure on the joints which could cause damage to the joints or the material itself. This method also allows recharge by allowing water to seep from the channel back into the ground if that is desired.

There are two other methods available when a lower permeability seam is required. This is particularly important in applications such as irrigation, standing water or potentially contaminated water. One of these methods requires that an acceptable sealant first be applied to the seam and the screws installed through the bead of sealant. The downside is that the sealant becomes an additional consumable – driving up the installation cost – and can be messy. The anticipated design life may also be impacted by the design life of the sealant which is typically less than the GCCM. The other installation method to decrease permeability is to thermally bond the bottom of the top layer to the top of the bottom layer. This can be performed with standard thermal bonding equipment used for other types of geosynthetics. Although GCCMs are innovative, their installation and specification is similar to other conventional geosynthetics. The same stainless-steel screws are then used at 4” centers to account for any drying shrinkage and to provide the strongest, lowest permeability joint available.

HENRY MILLER RECLAMATION DISTRICT NO. 2131 (HMRD) CASE STUDY

Henry Miller Reclamation District No. 2131 was formed in FY2000. It works in conjunction with San Luis Canal Company (SLCC) to deliver the irrigation water and provide drainage to the company’s customers. The vast majority of the delivery facilities are now either owned by HMRD or have permanent easement. HMRD is in charge of operating and maintaining the canals and drains.

As a member of the San Joaquin River Exchange Contractors, SLCC has an annual right of 163,600 AF in a “normal” year, HMRD currently manages water services for 45,000 acres of farmland mostly in Merced County, CA. They are contractually required to deliver 163,000 acre-feet (53,000,000,000) gallons of water annually for irrigation of surrounding crops. Because this region is arid, agriculture would be very difficult without the water supplied by the irrigation district. Much of their existing canal infrastructure consists of earthen canals or concrete lined canals. The earthen canals demonstrate problems with seepage and erosion – as would be expected, but many of the concrete lined canals are decades old and in disrepair. For this particular project, the existing concrete was installed less than 20 years ago – in 2004. Much of the existing concrete was cracked, bulging or missing resulting in significant seepage losses (Figure 1). The objective of this project was to mitigate seepage losses in the irrigation canal such that water could be sold to farmers rather than lost. Prior to remediation efforts, this ¼ mile section of canal was losing 46 gallons per minute to seepage or more than 2,400,000 gallons of water per year based on 36 operation days per year.

Many options were considered for remediation of the existing concrete lined canals. Among the options considered were replacement of concrete, a combination of geomembrane and shotcrete or GCCM. The District could not afford to shut down the canal for more than two to three weeks as they needed to supply water during the irrigation season. Ultimately, a Type II GCCM was chosen for the rehabilitation of the existing canal. The GCCM offered many advantages over the other options. The material was more cost effective than other alternatives, in part, because the district personnel could install the material themselves without the need for outside contractors. Using outside contractors would have added a level of complexity for scheduling, which meant the GCCM solution could be installed on a much tighter timeline and return the canal to operation more quickly. Unlike concrete, the GCCM that was chosen is able to withstand differential settlement of 12% or more without compromising the integrity of the containment solution – the 12 mil LLDPE geomembrane which provided the impermeability – would not be impacted by this level of settlement.

Figure 1. Typical condition of the existing concrete canal installed in 2004 prior to remediation efforts.

The graphs below (Figure 2) show tension versus strain for CCX-M. Immediately after the final crack, the top fabric ruptures exposing the underlying LLDPE geomembrane.

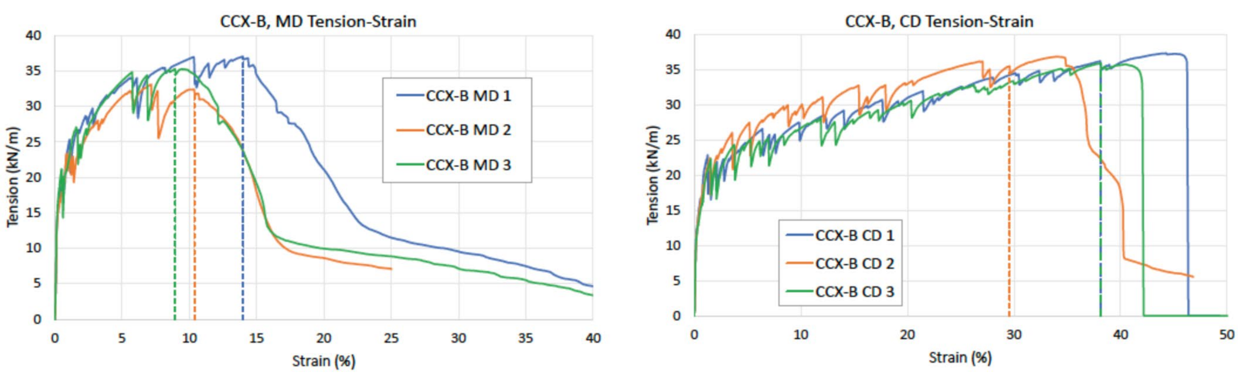

Figure 2. Tension Versus Strain for CCX-M

Table 2, is a summary of observed strain and tensile strength for CCX. When the layers above the LLDPE backing rupture, this indicates the point at which the LLDPE backing is compromised.

Product Type	Direction	Mean Geomembrane Failure Indicators	
		Final Failure Strain (%)	Ultimate Strength (lbf/in)
CCX-M™	MD	12.8	200
	CD	15	130

Table 2. Average strain and tensile strength for CCX-M.

As mentioned earlier, the USBR study indicated that a geomembrane overlain by concrete is the best solution for lining canals. This product offered a 2-in-1 solution – geomembrane and concrete. Another important consideration was the design life. While the existing concrete had failed in less than 20 years, the expected design life of the GCCM that was chosen is in excess of 50 years.

Because the existing concrete was in such disrepair the existing material was removed and the canal was reprofiled. The rolls were deployed across the invert of the canal with a spreader bar and cut to length. The canal structure involved gates, valves, and existing concrete all of which required mechanical attachments and sealant in order to minimize seepage at these connections (Figure 3).

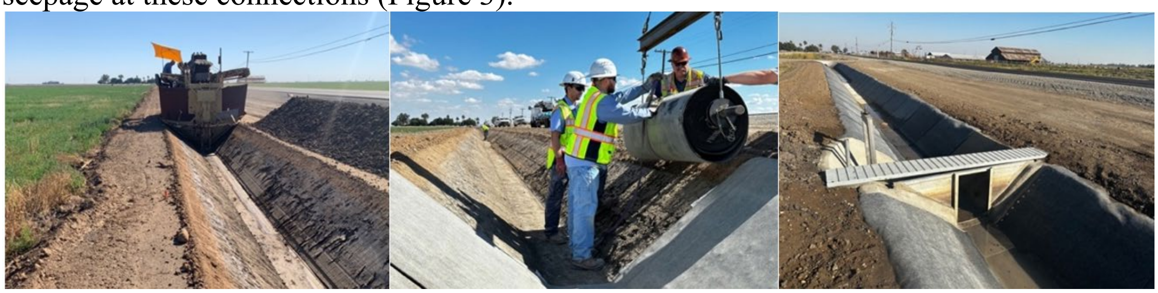

Figure 3. Reprofiling existing canal, deployment of GCCM and gates/valves.

The material was thermally bonded, and the seams screwed together with stainless steel screws. At the end of each day, the material that had been installed was fully hydrated. This is an important step in installing GCCM. It prevents partial pre-hydration resulting from unexpected rainfall or even heavy dew. If this were to occur, the upper most part of the concrete layer would cure, leaving concrete powder between the cured layer and the underlying geomembrane. While the entire layer would eventually cure, during that time, the GCCM would not exhibit the strength or durability of a fully hydrated and cured GCCM that was expected. The installation of 28,000 sf of GCCM on this ¼ mile section (1,440') of canal took 3.5 days (Figure 4).

SEEPAGE TESTING

After installation was complete, the District undertook seepage testing to measure water loss in the canal. As mentioned previously, the seepage before remediation was 46 gallons per minute (gpm). The test took place over a 4-day period shortly after installation was complete. To perform this testing, they first shut all of the vales within the section to isolate it. They estimated evaporative losses using the California Irrigation management Information System (CIMIS) summary of the hourly evapotranspiration (ETo) value for the duration of the test. Lastly, they factored in the addition of water due to rain events (Figure 5). During the test, they measured how much water had to be supplied to maintain a constant water level within the canal (Figure 6).

Figure 4. Completed canal section

Total Volume of Losses Due to Seepage

Total Seepage Losses = Total Volume added (ac-ft) + Net change in water level (ac-ft) - Volume Evaporated (ac-ft)

Total volume added (ac-ft)	0.019
Net change (ac-ft)	0.0252
Volume Evaporated (ac-ft)	0.0070
Rain (ft)	0.0058
Total Seepage Losses (ac-ft)	**0.0315**

1 AF = 325,851 gallons

Seepage Rate Calculation

Seepage Rate (gpm) = Total seepage volume (gal) / Total time elapsed (min)

Total Seepage Losses (ac-ft)	0.0315
Seepage Losses (ft^3)	1374
Seepage Losses (gal)	10276
Total Elapsed Time (min)	5880

Seepage Rate (gpm)	**1.75**
Seepage Rate (ac-ft/day)	**0.008**
Seepage Rate (ac-ft/Year)	**0.28**

Considering 36 days of operation

Figure 5. Volume losses due to seepage factoring in evaporation and rainfall.

Net Change in Water Level

Net change (ac-ft) = (average net change in water level) x (Total water surface area of test pool)
Difference in water level (ft) = FINAL Reading - INITIAL Reading

Initial Reading (ft)	ITRC 24439	2.2395	
Final Reading (ft)	ITRC 24439	2.1210	
	Difference in water level (ft)	**-0.1185**	(Drop in water level)

Initial Reading (ft)	ITRC 23824	2.6569	
Final Reading (ft)	ITRC 23824	2.5469	
	Difference in water level (ft)	**-0.1100**	(Drop in water level)

Average Δ in water level (ft) **-0.1143** (Drop in water level)

NOTE: Based on the average of the two pressure transducers, the net DROP in water level was **0.1143 feet** in 98 **hours.**

Net DROP in water level (ft)	0.1143
Net change (ac-ft)	**0.0252**

Total Volume of Water Added during Testing

Initial totalizer reading	5466517	gallons
Final totalizer reading	5472741	gallons
Total volume added	**6224**	**gallons**

Figure 6. Calculation of water needed to maintain constant water level.

RESULTS AND DISCUSSION

The test results indicate that seepage rate was reduced from 46 gpm to 1.75 gpm – a reduction of more than 96%. If these results were replicated widely throughout irrigation systems, millions of gallons of water – now lost to seepage – could be saved, sold and used to grown crops.

CONCLUSIONS

The District was faced with a problem of dilapidated concrete lined canals which were losing water due to seepage losses. This lost water represents lost revenue that could be gained from selling this water. They researched many available options to remediate the structure. They were constrained by cost, ease of installation and time required to return the canals to service. After exploring all options, they settled on the relatively new technology of a geomembrane backed GCCM. This solution provided both the durability of a concrete surface and the impermeability of a geomembrane backing. The USBR decided a long time ago that a combination of geomembrane and concrete is the best long-term solution for canal lining – one that provides the longest life, the lowest seepage and the best protection for water conveyance. Key wins to securing federal grants are solutions to address water scarcity and preventing saline waterlogging. The lining of canal assets maximizes the value of expenditure towards other irrigation systems such as pump and dosing stations.

ACKNOWLEDGEMENTS

We appreciate the support of Alejandro Paolini, Water Conservation Specialist for Henry Miller Reclamation District No 2121. He was instrumental in bringing this project to fruition and for performing the seepage testing to demonstrate the efficacy of a geomembrane backed GCCM for use in water conveyance applications.

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USING A PEER TO PEER ERROR SHARING CONTROL METHOD TO IMPROVE IRRIGATION CANCAL DELIVERY PERFORMANCE

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Blair Stringam[1]

ABSTRACT

The Elephant Butte Irrigation District (EBID) main canal has been modelled to evaluate water control methods for best water delivery performance. The goal of this work is to develop an irrigation canal control system that delivers the desired amount of water to irrigation farmers while reducing fluctuations. An additional requirement is to supply water diversions to the main canal from the Rio Grande at a near constant flow to reduce fluctuations for other water diversions downstream.

A ratio control method that was enhanced using a peer-to-peer error sharing technique provided the desired water deliveries. This was accomplished by passing control errors from lower canal reaches to reaches upstream. It was determined that the peer to peer technique reduced water level fluctuations throughout the main canal system. In addition, diversion flowrates were also kept at near constant levels.

The peer-to-peer technique was easy to implement and was successful at accomplishing the desired performance goals. As water diversions were simulated, diversion fluctuations were limited to less than 5%. When diversion changes occurred, the main canal system was returned to steady state conditions faster using peer to peer error sharing with Ratio Control rather than using just Ratio Control.

This control method was also tested on models of the Ferran Acequia and the ASCE steep canal. The data from these tests also indicate that peer-to-peer error sharing reduced fluctuations and returned the canal system back to steady state conditions at a quicker rate.

INTRODUCTION

Irrigation districts and water supply organizations in the United States as well as throughout the world strive to deliver water to the intended water users in the desired amount and at the required time. In addition, the water must be delivered with little loss in the process. In many instances, canals or river channels are the source for the required water supply. From the supply source to the farm fields, the delivery task is difficult because of open channel delay times between the water source and the delivery site. The delivery time is further complicated by weed growth and sediments that change delivery times.

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To deal with delay problems, water managers often satisfy water delivery requirements by sending more water than is required and water is wasted. In New Mexico and in many locations throughout the world, water is a dwindling resource.Technology that provides tools to water managers so that they can deliver water orders and limit waste is tremendously valuable.

Considering the difficulty to accurately deliver water orders from an open channel to an irrigated field, many water supply organizations have installed automation equipment. This equipment mainly consists of water level sensors, gate position sensors, motor-powered gates, computer monitoring and communication equipment. This equipment has helped reduce water losses, but the control system has limited intelligence and provides little more than remote control operations. Feedback control computer algorithms can continuously watch what is happening in the canal system and provide timely changes that limit water fluctuations and subsequently water losses.

Current research indicates that feedback control can operate a water delivery system optimally with little waste (Stringam and Libbin, 2019). Decreasing water losses will ensure that water is available for irrigation as well as other water obligations. In this work we focus on developing a Ratio feedback control routine in combination with a peer-to-peer error sharing feature to operate open channel water conveyance systems in an ideal manner. The control method was developed and tested on 3 canal models that were programed into an open channel canal model that was created using MATLAB (Stringam and Merkley, 2013).

This work focused on implementing a simple, robust and adaptable computer control routine for most open channel water conveyance systems. This control routine will operate multiple open channel reaches in an optimal manner. It is easy to design a controller that operates one or two reaches, but the majority of canal supply networks are made up of multiple reaches in series as well as branched systems.

Water diversions from a single reach can be compensated for using a simple proportional integral controller. If an additional reach is added in series, the controllers for each reach work against each other to an extent, but there is usually no problem. As reaches are added in series, the interaction between reaches becomes a problem. As water has to travel from reaches in the upstream end of the network down to the lower reaches, the system response time increases. This adds what is termed in control theory as system lag. Two methods of control have been proposed to handle these multi reach systems. One is centralized control (Montazar and Isapoor, 2012; Pison et al., 2020; Shahdany et al., 2019) and the other is distributed control (Alvarez et al., 2013; Negenborn et al. 2009; Sadowska et al. 2015; Zhu et al., 2023).

Researchers argue that centralized control is more desirable for operating irrigation canal systems because they consider the needs of the entire system and limit the shortages in critical areas. On the other hand, distributed control researchers make the argument that centralized control requires communication with a central computer controller. This requires that there is very good communication between the individual control sites and the central control computer. This is usually achievable but there are also instances when communication between the central control computer and the control site is impaired for some reason. This can disrupt communication for short periods of time or for a few days. If communication is interrupted, how do the canal control sites respond to water demand changes?

In order to try to adequately deal with the loss of communication issue, this research proposes using a local control scenario with a peer-to-peer communication feature or distributed control. Each control site on a canal system has sensors, actuators, control computers and communication with a central computer. It is argued that the site controllers have or can have the programing to control the individual site. The individual site controllers also have the capability of communication with each other so that individual site needs can be weighed against the needs of other control sites in the system. This allows for control decisions that meet the needs of the entire supply system. This feature helps to reduce the tendency of local controllers to interfere with each other because local site controllers strive to meet the needs of the individual site.

The distributed system allows for control when communication is down but since the controllers are communicating between each other, the communication distance is shorter and in most cases, more reliable.

In this work, Ratio controllers (Stringam and Wahl, 2015) are designed to maintain the downstream water level for a series of canal reaches. They are tuned using the Ziegler-Nichols tuning method (Ziegler and Nichols, 1942; Parr, 1989). However, the Ratio controllers are assisted with a peer to peer error sharing method.

Ratio Control Design

A ratio feedback control routine was designed based on the following ratio relationship:

$$\frac{ngp}{wlsp} = \frac{pgp}{pwl} \quad (1)$$

Where ngp = new gate position; wlsp = water level setpoint; pgp = present gate position; and pwl = present water level. This equation was altered for feedback control by adding an additional relationship:

$$\Delta\text{gp} = ngp - pgp \quad (2)$$

Where Δgp = change in gate position. The two equations were combined and rearranged, the following relationship is developed.

$$\Delta\text{gp} = (\frac{pgp}{pwl})(wlsp - pwl) \quad (3)$$

The term (wlsp – pwl) is normally defined as the error term which is normally defined as "e" for a feedback control routine. Normally if this term is used in the classic proportional control method, it would be multiplied by a constant term called the proportional gain. In this case the (pgp / pwl) term functions as a portion of the gain. It has an advantage because it can adjust throughout the operation of the feedback controller. This adjustment helps to make the control response more robust. As we have researched the capability of this control routine for operating a canal system, we have found that a more aggressive controller is needed for larger canal reaches. This equation is modified for larger canals by placing an additional gain on the equation.

$$\Delta \text{gp} = K_r(\frac{pgp}{pwl})e \quad (4)$$

In this equation, K_r is the ratio control gain that helps to speed canal system response. As this equation is used to design a canal feedback control system, the equation is not capable of returning the system all the way back to the setpoint. There is always an offset from the setpoint. The equation can get the system close, but there will be a slight offset. In order to completely return the water level to setpoint, an additional component called the integral gain is also needed (Cooper, 2006). This is accomplished by summing the control error over time and multiplying by the integral gain. This is added to the previous equation in the following manner.

$$\Delta \text{gp} = K_r\left(\frac{pgp}{pwl}\right)e + K_i \Sigma e \quad (5)$$

The K_i variable is the gain value that is used to return the downstream depth completely back to the desired depth. The previous equation works very well for 2 or 3 reaches in series, however controlling more than 3 reaches in series is more difficult. As additional reaches are added, the response time for the entire system of canal reaches is increased. It was discovered that when controlling the downstream depth on two reaches that are adjacent to each other, the control response can be shortened if the downstream error from the second reach is sent to next upstream reach (Figure 1). The full error cannot be sent but 50% of the error signal worked very well. This modified the control equation to the following form.

$$\Delta \text{gp} = K_r[\left(\frac{pgp}{pwl}\right)e_n + (K_{n+1}e_{n+1})] + K_i\ \Sigma[e_n + \ (K_{n+1}e_{n+1})] \quad (6)$$

In this equation, e_{n+1} is the error from the reach that is downstream from the present reach; and K_{n+1} is the gain factor that is applied to provide the correct amount of feedback to reduce response time and reduce water level fluctuations for multiple reaches in series.

METHODS

This control method was evaluated for 3 canal supply system models. One model was developed for the first 8 reaches of the EBID main canal system located north of the city of Las Cruces. The second model was for the Ferran acequia canal system located in the Rio Arriba County in the state of New Mexico. The third model was for the ASCE steep canal (Clemmens et al., 1998). Dimensions for the first 2 canal systems are indicated in tables 1 and 2. The dimensions for the ASCE steep canal system are specified by Clemmens et al. (1998). Local feedback controller gain values for the ratio and integral gains were determined using the Ziegler – Nichols tuning method (Ziegler and Nichols, 1942; Parr, 1989). The peer to peer gains were determined iteratively.

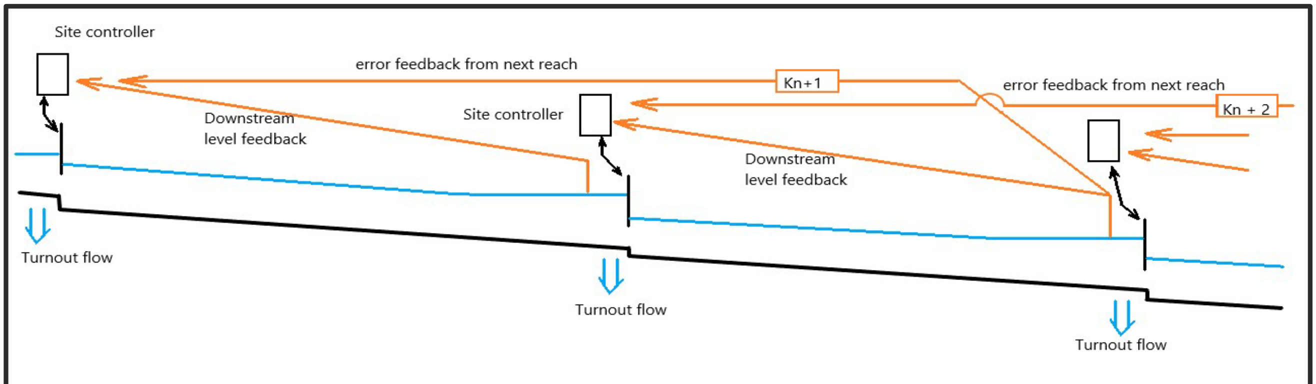

Figure 1: Diagram of the downstream feedback control scheme.

The EBID main canal, simulations were run for inflows of 10.19 m^3/s (high flow) and 4.53 m^3 / s (low flow). The flows into and out of the reaches are found in tables 3 and 4. The simulations were conducted for when peer to peer error sharing was turned off and for when peer to peer sharing was turned on.

Table 1. Dimensions for the first two Elephant Butte Irrigation supply canal reaches.

	Length (meters)	Roughness	Side slope	Bottom width (meters)	Slope
Reach 1	916	0.026	1.5	0.46	0.08
Reach 2	338	0.026	1.5	0.46	0.08
Reach 3	1150	0.026	1.5	0.46	0.2
Reach 4	279	0.026	1.5	0.46	0.2
Reach 5	449	0.026	1.5	0.46	0.2
Reach 6	363	0.026	1.5	0.46	0.2
Reach 7	339	0.026	1.5	0.46	0.2
Reach 8	388	0.026	1.5	0.46	0.2

In the EBID main canal, the controller for reach 1 has a slight different design. There are 8 inlet gates at the head of the diversion from the Rio Grande. These gates divert water into the first reach. The controller was designed to operate seven of these gates to maintain a constant flowrate into the reach despite changes in river and canal water levels. The eighth inlet gate controller was designed to maintain a downstream water level for the first reach. The goal of this arrangement was to try to maintain a diversion flowrate into the main canal that was as near constant as possible. This could be easily accomplished by simply programing the controller to maintain the constant flowrate.

However, the downstream depth of reach 1 needs to be maintained within a depth range that helps to maintain needed discharges into the second reach. By programming 7 gates to maintain a constant flowrate into reach 1 while programing the 8th gate to perform downstream control, the fluctuations in the river diversion were limited and the downstream level in reach 1 can help to provide compensating flowrates into reach 2.

Table 2. Ferran Acequia canal reaches.

	Length (meters)	Roughness	Side slope	Bottom width (meters)	Slope
Reach 1	1023	0.025	1.5	7.6	0.0005
Reach 2	1951	0.025	1.5	10.7	0.00026
Reach 3	1223	0.025	1.5	7.9	0.00026
Reach 4	1205	0.025	1.5	6.4	0.00026
Reach 5	1200	0.025	1.5	5.2	0.00026
Reach 6	3659	0.025	1.5	6.1	0.00026
Reach 7	1968	0.025	1.5	5.1	0.00026
Reach 8	1223	0.025	1.5	5.1	0.00026

The Ferran acequia inflows and outflows are specified in table 5. The inflows and outflows for the ASCE steep canal are found in Clemmens et al. (1998). The Ferran Acequia and ASCE steep canal local controllers were designed to maintain the downstream water levels in the canal reaches.

Table 3. Reach inflows and offtake discharges for the EBID main canal high flow test.

Reach	Reach Inlet Discharge	Offtake Discharge	Offtake Discharge 4 hours	Offtake Discharge 12 hours
1	10.19 m^3/s	0.0 m^3/s	0.0 m^3/s	0.0 m^3/s
2	10.19 m^3/s	0.57 m^3/s	0.57 m^3/s	0.28 m^3/s
3	9.63 m^3/s	0.57 m^3/s	0.28 m^3/s	0.28 m^3/s
4	9.06 m^3/s	0.57 m^3/s	0.28 m^3/s	0.57 m^3/s
5	8.5 m^3/s	0.57 m^3/s	0.0 m^3/s	0.28 m^3/s
6	7.93 m^3/s	0.0 m^3/s	0.85 m^3/s	0.28 m^3/s
7	7.93 m^3/s	0.28 m^3/s	0.28 m^3/s	0.57 m^3/s
8	7.65 m^3/s	0.57 m^3/s	0.85 m^3/s	0.85 m^3/s

Table 4. Reach inflows and offtake discharges for the EBID main canal low flowrate test.

Reach	Reach Inlet Discharge	Offtake Discharge	Offtake Discharge 4 hrs	Offtake Discharge 12 hrs
1	4.53 m^3/s	0.0 m^3/s	0.0 m^3/s	0.0 m^3/s
2	4.53 m^3/s	0.57 m^3/s	0.28 m^3/s	0.0 m^3/s
3	3.96 m^3/s	0.0 m^3/s	0.28 m^3/s	0.28 m^3/s

Reach	Reach Inlet Discharge	Offtake Discharge	Offtake Discharge 4 hrs	Offtake Discharge 8 hrs
1	0.127 m^3/s	0.0 m^3/s	0.0 m^3/s	0.0 m^3/s
2	0.127 m^3/s	0.014 m^3/s	0.028 m^3/s	0.042 m^3/s
3	0.113 m^3/s	0.028 m^3/s	0.014 m^3/s	0.028 m^3/s
4	0.085 m^3/s	0.028 m^3/s	0.014 m^3/s	0.0 m^3/s
5	0.057 m^3/s	0.028 m^3/s	0.042 m^3/s	0.028 m^3/s
6	0.028 m^3/s	0.014 m^3/s	0.014 m^3/s	0.007 m^3/s
7	0.014 m^3/s	0.014 m^3/s	0.014 m^3/s	0.021 m^3/s
4	3.96 m^3/s	0.28 m^3/s	0.28 m^3/s	0.28 m^3/s
5	3.68 m^3/s	0.28 m^3/s	0.0 m^3/s	0.28 m^3/s
6	3.40 m^3/s	0.0 m^3/s	0.28 m^3/s	0.57 m^3/s
7	3.40 m^3/s	0.28 m^3/s	0.57 m^3/s	0.28 m^3/s
8	3.11 m^3/s	0.57 m^3/s	0.28 m^3/s	0.28 m^3/s

Table 5. Reach inflows and offtake discharges for the Ferran Acequia.

RESULTS

Figure 2 shows the results for the EBID high flow test when error sharing was turned off as well as when it was turned on. The downstream level of reach 1 is not included in these graphs because it had a slightly different control strategy. This will be explained later. At the 4 hour flow change, the typical fluctuation in water depth can be observed for both tests. Considering the test with no peer to peer error sharing, the maximum fluctuation is observed for reach 5 downstream water depth where a drop of 4 cm is observed.

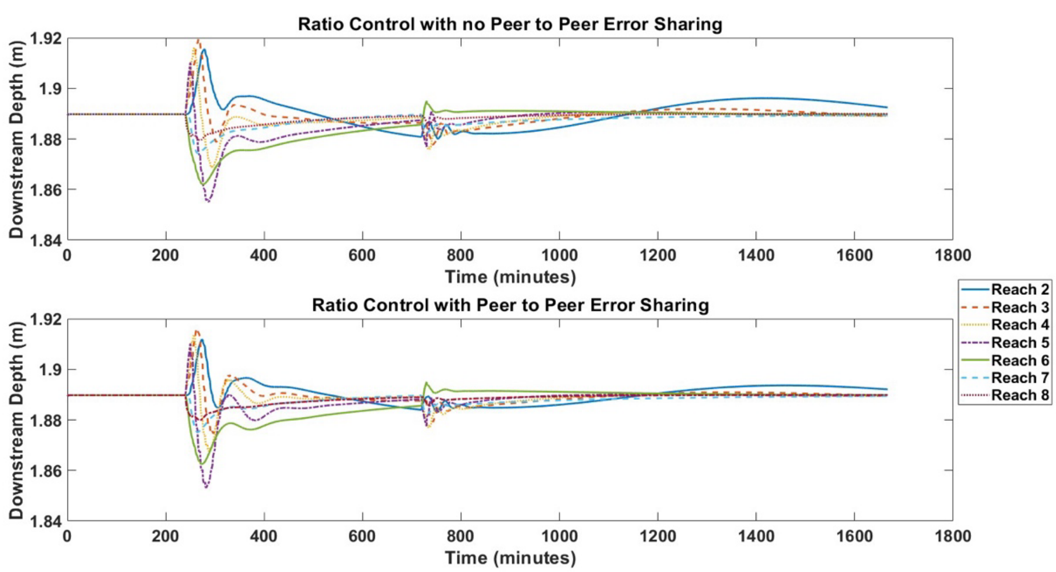

Figure 2: Downstream water depth for EBID main canal reaches 2 through 7. The discharge into the first reach is 10.19 m^3 / sec

The water fluctuations for the 4 hour (240 min) change are slightly less for the peer to peer error sharing controller than for the peer to peer delete error sharing controller. It happens that the offtake at the 4 hour time point for reach 5 is turned off so there is no error for offtake flow on reach 5. Reach 3 has the next maximum deviation at the 4 hour change point. The deviation has a maximum value of 3 cm which results in a brief diversion error of less than 2% for both control methods. As the site controllers respond to the offtake change, the reaches are being pulled back to their setpoint depths. In general there is a quicker return to steady state conditions using the peer to peer modification. The total flow change percentage between offtakes is 72.8%. It should be noted that there is still a large flowrate continuing down the main canal system and this helps to keep the system more stable.

As the simulation progressed to the 12 hour point, the fluctuations are lower despite the fact that the total flow change percentage between offtakes is 82.1%. This is likely due to the fact that maximum flow change for an individual offtake was less than the changes that occurred at the 4 hour mark.

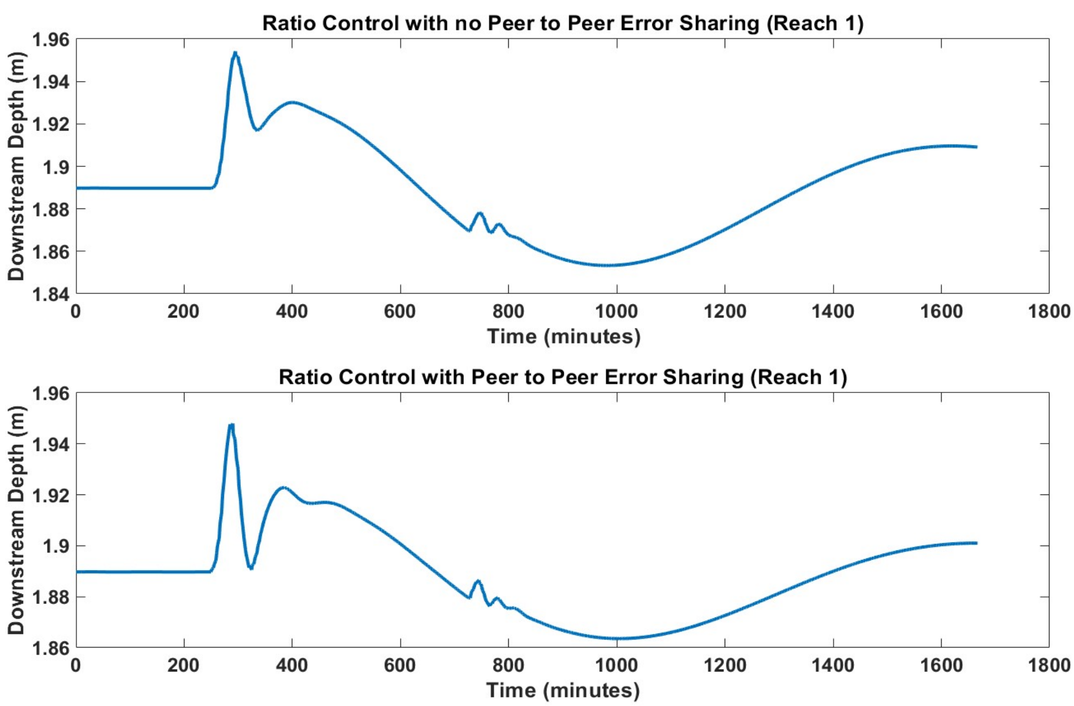

Figure 3: Downstream water level for reach 1. The discharge into the first reach is 10.19 m^3 / sec

Figure 3 shows the downstream depth from the first reach. The depth has a greater deviation because the first reach is treated like a reservoir. As long as this reach maintains a downstream depth that is within a band of plus or minus 15 cm, there is not a concern. In the peer to peer delete error sharing example the maximum deviation from setpoint water level is slightly more than 6 cm. When the peer to peer error sharing was turned on the water level fluctuations were less.

For the second test condition, the inflow from the river diversion was adjusted to 4.53 m^3 / sec. Fluctuations again occur with the changes in the offtake flowrates (Figure 4). When peer to peer error sharing is turned on, there are marked reductions in the fluctuations. There is also a quicker return to downstream water level setpoint.

Reach 3 has the maximum water level fluctuation which results in a brief diversion flowrate error of less than 1% for the peer to peer delete error sharing example. The peer to peer error sharing example produces a brief diversion flowrate error of less than 0.5%

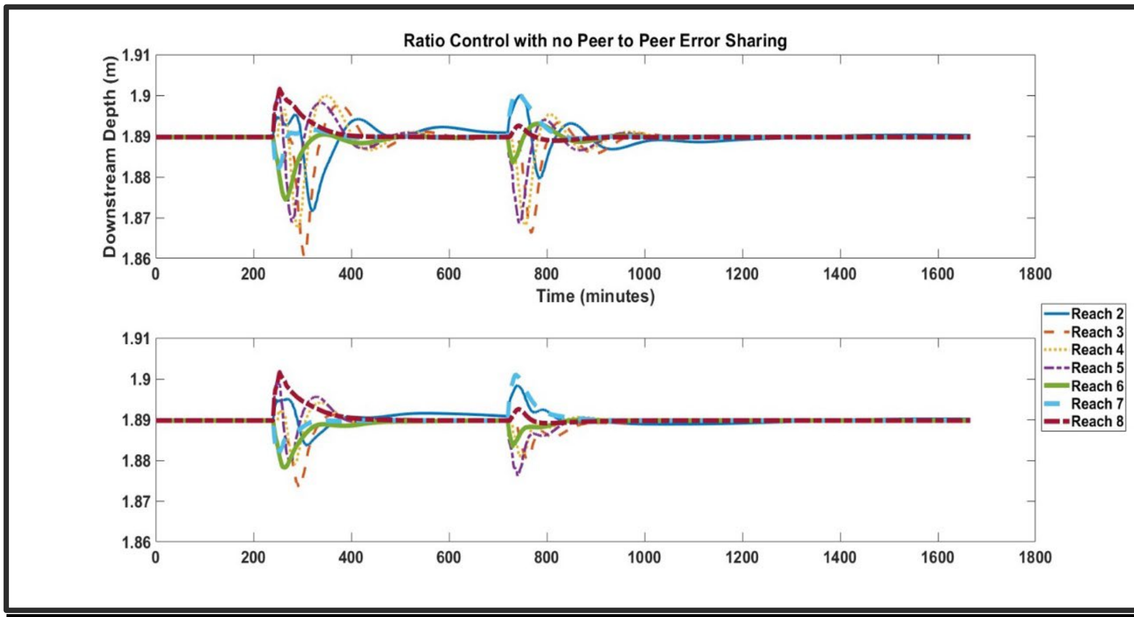

Figure 4: Downstream water depth for EBID main canal reaches 2 through 7. The discharge into the first reach is 4.53 m^3 / sec.

In figure 5 the EBID canal model was reconfigured with a larger roughness value. The original roughness was 0.025 and it was increased to 0.028. The ratio gains, integral gains and the peer-to-peer gains were the same as the previous tests. It can be observed from this test that the increase in roughness slowed the system response. The peer-to-peer error sharing improved response time and reduced fluctuations.

In this example the diversion errors are less than the first test that is shown in figure 2. However, it takes longer for the controller to bring the system back to setpoint which means that the total flowrate diversion will be over or under the intended value. An additional issue for this test is that reach 2 in the peer to peer delete error sharing example, continues to oscillate. The peer-to-peer error sharing example shows less oscillations.

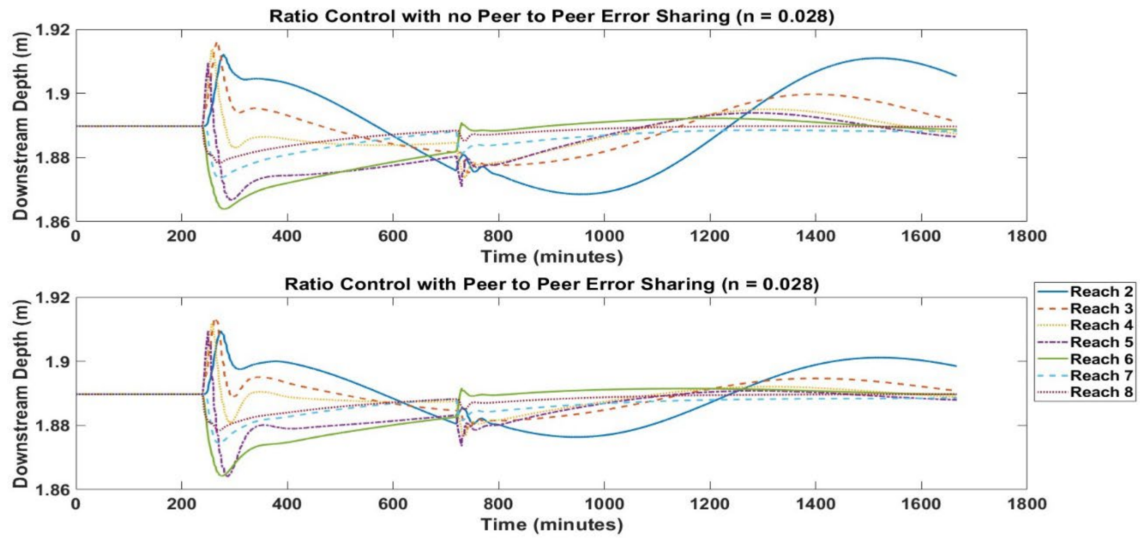

Figure 5: Downstream water depth for EBID main canal reaches 2 through 7. The channel roughness has been increased from 0.025 to 0.028. The discharge into the first reach is 10.19 m^3 / sec.

The Farren acequia model demonstrated similar results to the EBID model (Figure 6). This canal system is much smaller than the EBID model and the reach flowrates and setpoint water levels are lower as well. The inflow into the first reach was 0.127 m^3/sec. The offtake flowrates were also much smaller than the EBID model. For this model the water level fluctuations were generally larger for the peer to peer delete error sharing controller. The return to the water level setpoint was faster for the peer to peer controller example. It should be noted that the first reach in this example did not have any downstream offtake diversions and functioned as a small reservoir.

The maximum level error is observed for reach 4 for the error sharing delete test, but in this situation the offtake is shut off so there is no flowrate error. Reach 5 has the next largest error with a deviation of about 3 cm. This results in a brief error in the offtake flowrate of just under 4%. The peer to peer error sharing example had an offtake flowrate error of just over 3% for reach 5. No additional tests were conducted on this model.

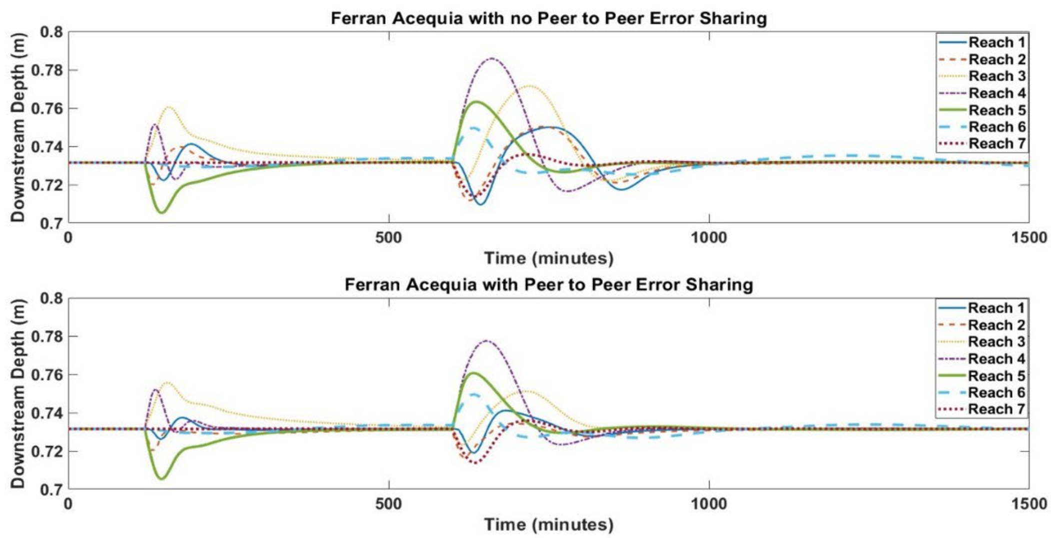

Figure 6: Downstream water depth for Ferran Acequia reaches 1 through 7. The discharge into the first reach is 0.127 m^3/sec.

A final test was performed on the ASCE steep canal model. The test was conducted on the large flow example where the flowrate into the first reach was 2.0 m^3 / sec. This is a difficult canal system to control. The difficulty is demonstrated by the oscillatory response that is exhibited by the reaches in the peer to peer delete as well as the peer to peer error sharing examples in figure 7. In addition, the peer to peer delete controller is having more difficulty pulling the downstream water levels back to setpoint. It should be noted that the Ratio controller that was developed for this model was designed for a wide variety of operating conditions that are specified in Clemmens et al. (1998).

CONCLUSION

The 3 canal examples demonstrate the benefit of peer-to-peer error sharing. In all three examples, the oscillatory behavior is reduced and downstream levels return to setpoint faster. Reducing the level fluctuations also reduced the offtake flowrate error. The controller with peer to peer sharing also responds faster when there are changes to main canal flowrate in the system or when the canal roughness is changed. These changes usually require major modifications to the controller gains. However, peer to peer error sharing appears to provide more tranquil responses and widens the control span of a simple ratio controller.

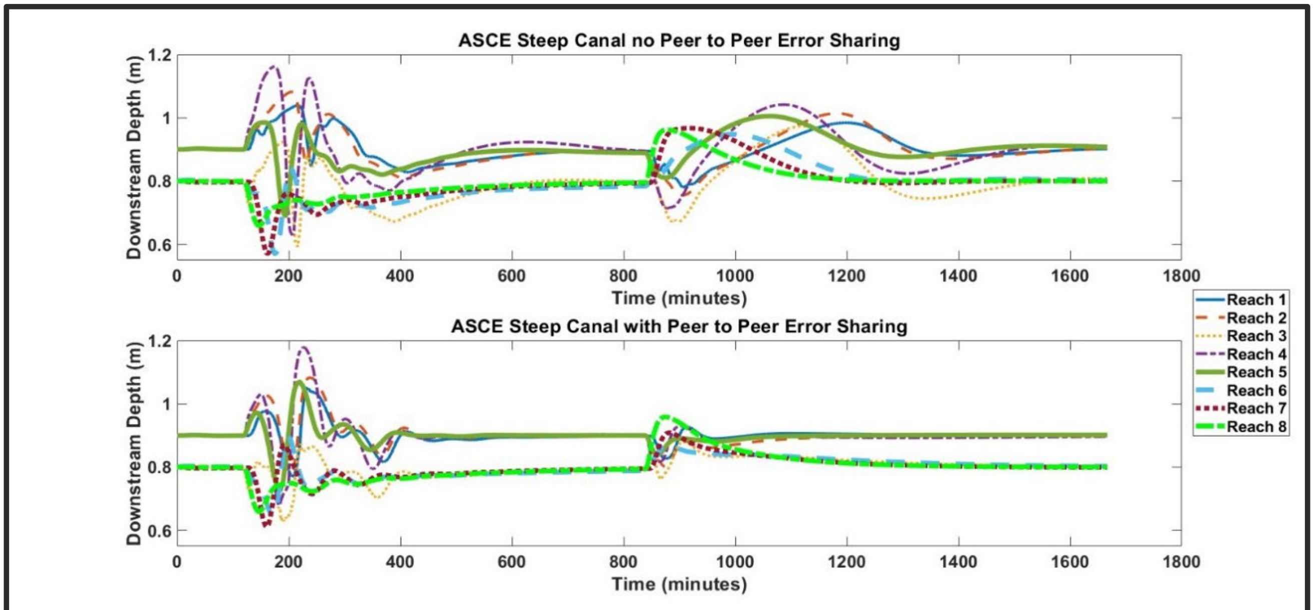

Figure 7: Downstream water depth for Ferran Acequia reaches 1 through 7. The discharge into the first reach is 2.0 m^3 / sec

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RISING WATERS, RISING CONCERNS: THE SLOW DECLINE OF IRRIGATION SYSTEMS
A CASE STUDY OF SINDH'S IRRIGATION CRISIS

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Pakistan recently endured one of its worst floods in history, with a third of the country submerged, resulting in loss of life, homes, and livelihoods. Over the past 18 months, my team of experts at the Sindh Flood Emergency Rehabilitation Project (Irrigation Component) Data Center have dedicated considerable efforts to recovery. Immediate priorities were clear, rebuild damaged infrastructure, drain flooded fields, and get farmers on the field as soon as possible to start the next growing season. It is imperative to prevent further loss, not only in terms of crop production but also for the financial and subsistence needs of farmers.

Figure 1: Kotri Barrage, one of the major infrastructures of the Sindh Irrigation System

We initiated a thorough analysis of the root causes of the disaster, and we came up with a combination of choking points in the natural system, the built infrastructure, the governance and administration of the system, and an overall failure of the of the irrigation system itself (figure 2).

Although all identified choking points are worth a thorough discussion, this essay focuses on the latter issue: the slow, but undeniable collapse of the entire irrigation system. It is important to recognize that the Indus irrigation system, established in the 1930s during

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the British colonial era, is part of a set of large-scale irrigation systems that are all showing signs of aging. These systems, including those in the Mekong Delta, India, and the Nile, were pivotal for the green revolution in arid regions, transforming underproductive lands into thriving agricultural zones. Initially successful, these systems increased crop yields, advanced development, and filled British and French coffers with taxes to fuel imperial ambitions.

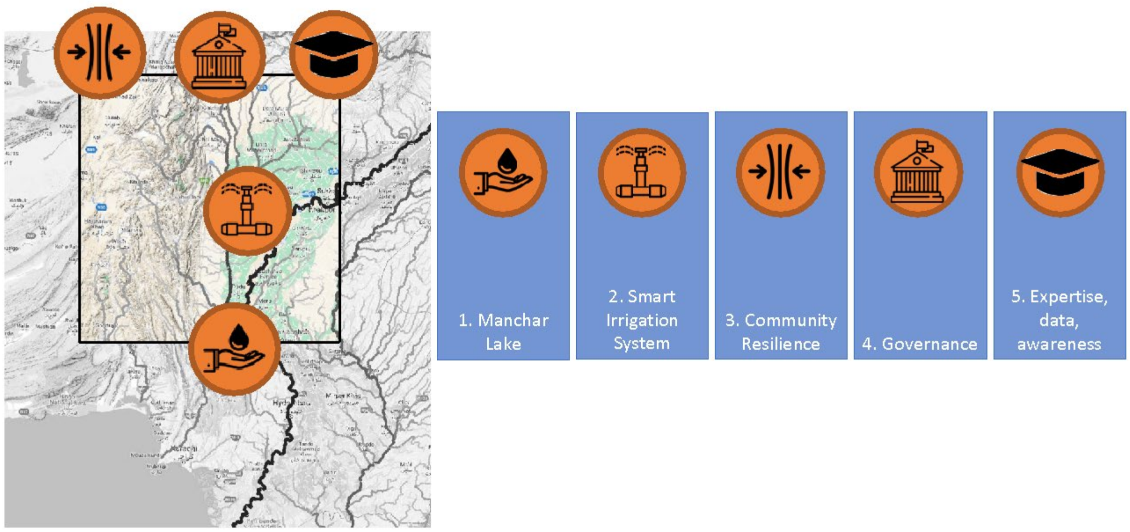

Figure 2: Inventory of the choking points resulting in the 2020 flood disasters in the Sindh

Initially, these irrigation systems were a resounding success. Crop yields were huge, and development flourished (see Figure 3). Embankments protected crops and property from seasonal floods, while a strictly controlled water allocation system supplanted the region's natural water dynamics, ensuring optimal agricultural production.

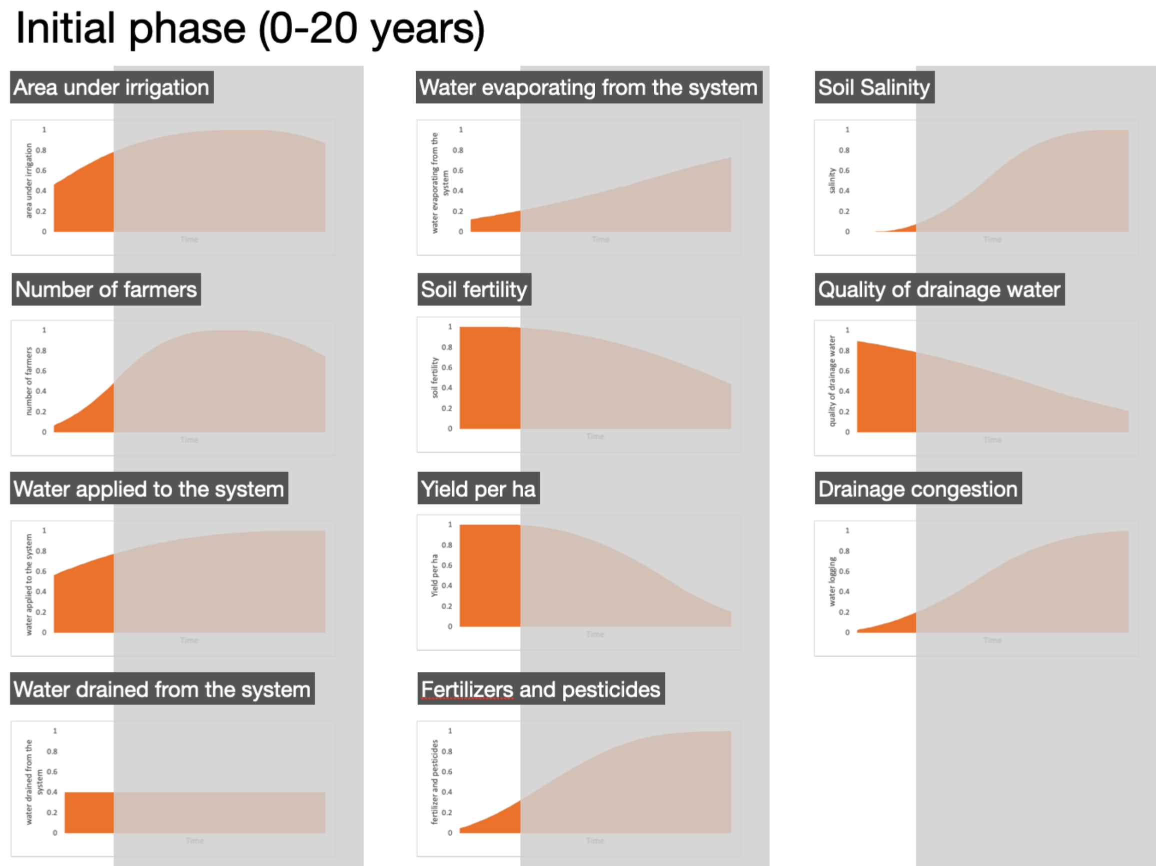

Figure 3: The initial phase of the large-scale irrigation systems

We slowly enter the second phase, the maturing and consolidation phase. The successes are still there, but they seem to come with a price. At first not visible, at first not worrying, but a slow decline in environmental conditions. Barely visible at first and overshadowed by the early successes (figure 4). The high initial success-rate attracted more settlers to the area, expanding cultivation and increasing water demand. But the initial design was not modified to adapt for this increase in scale. While the primary aim of any irrigation system is to deliver water on the land, inadequate drainage poses a significant challenge, allowing water, salt, and agro-chemicals to accumulate. The omission or reluctance to modify the drainage system exacerbated this issue, as it became ill-equipped to handle the increasing water demand and allocation.

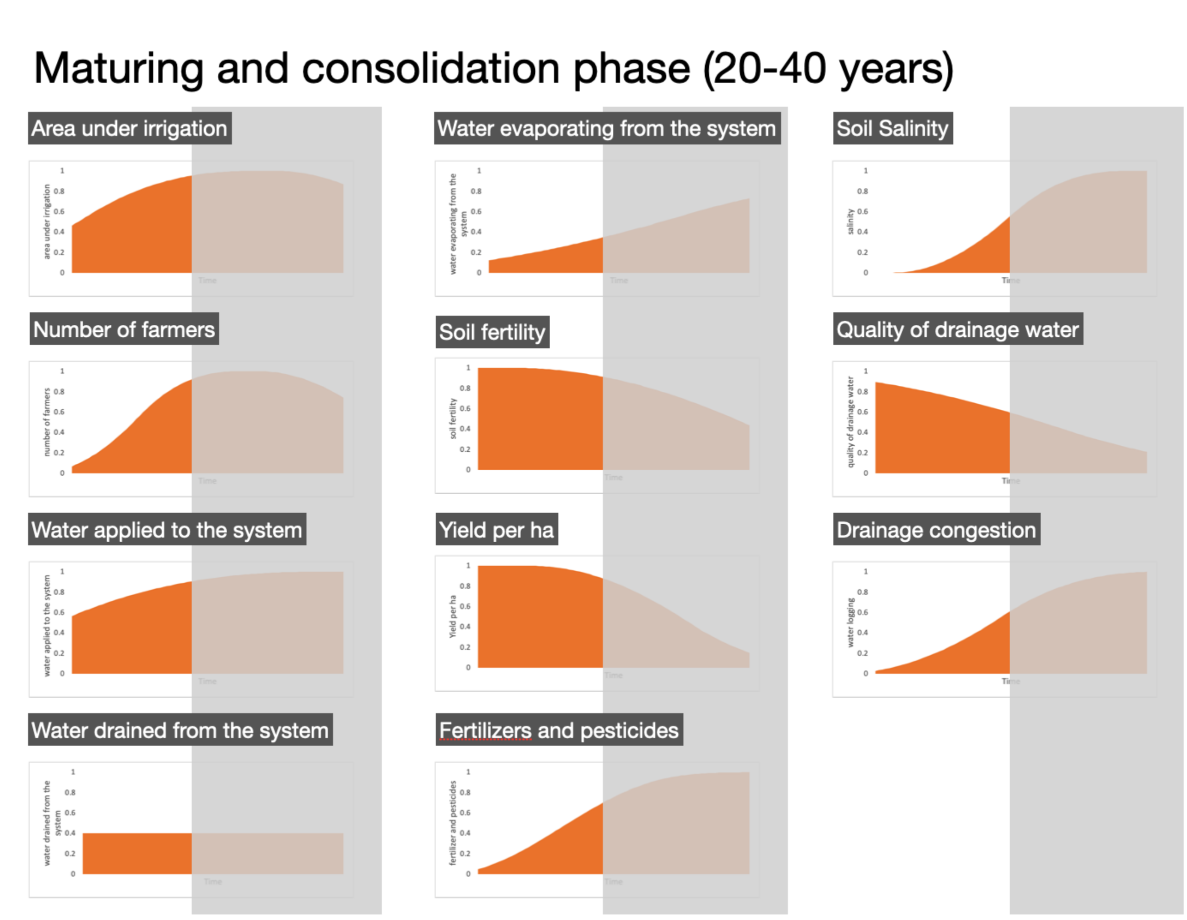

Figure 4: the maturing phase and consolidation of initial success

As we transition into the third phase, the degradation phase, managing the system becomes increasingly challenging. Declining crop yields serve as a strong indicator of soil fertility loss, as the absence of monsoon floods fails to replenish soil nutrients. Farmers resort to chemical inputs to compensate for the lack of natural fertilizers and to combat pests affecting their increasingly vulnerable crops. The system's inadequate drainage exacerbates these issues, allowing chemicals and salt to accumulate in the root zone and soil. Moreover, excess water not properly drained begins to accumulate, causing groundwater levels to rise and exacerbating salinity issues through evapotranspiration from shallow groundwater. This situation mirrors a bathroom with an inadequate sewer system, leading to water and dirt accumulation in the sink. Over time, these symptoms become undeniable, signaling our entry into the degradation phase of the irrigation system—where the system resembles an aging man struggling to cope with its challenges.

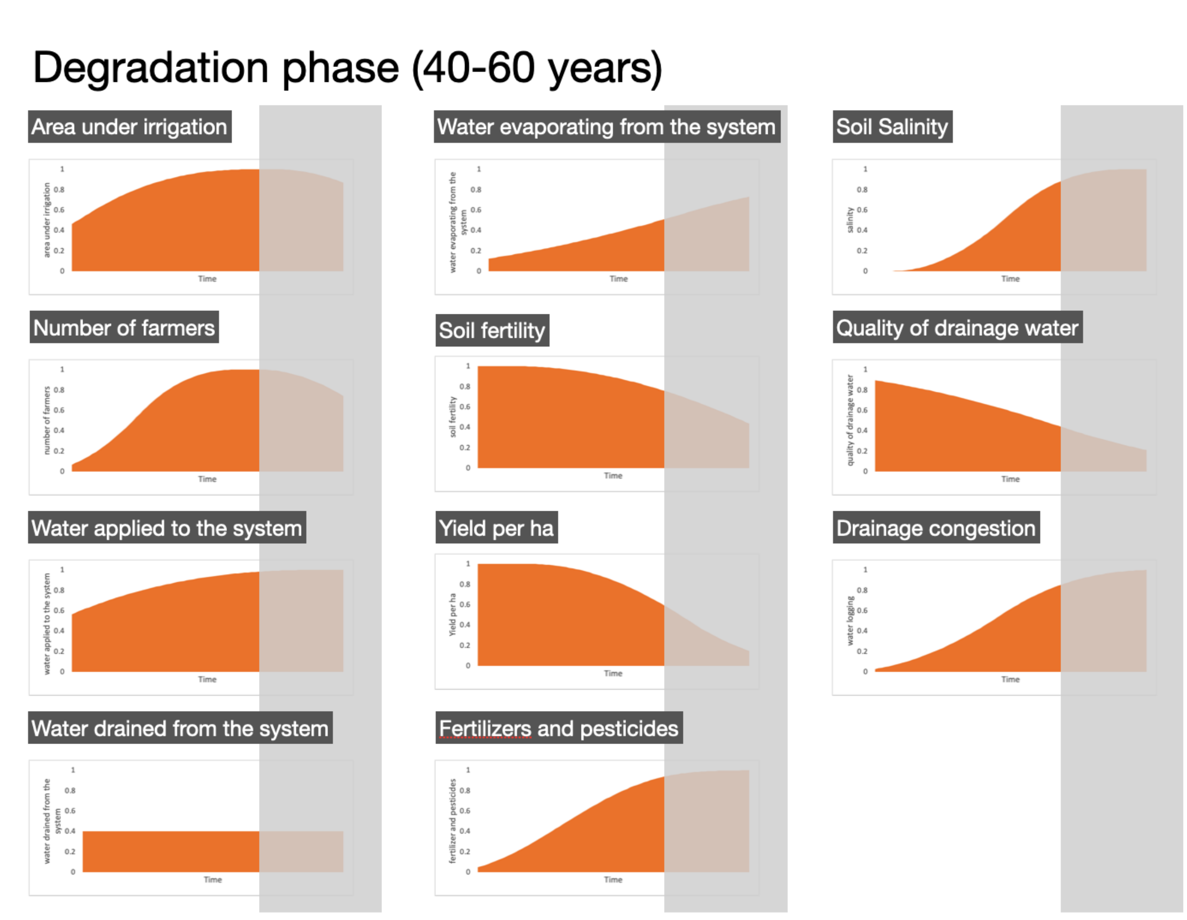

Figure 5: The degrading phase in the life cycle of large-scale irrigation systems

In the final phase, the irrigation system enters a state of collapse. What was once a beacon of progress now stands as a dark reminder of its challenges. Managing the system becomes insurmountable, and the optimism of earlier stages fades. Despite well-intentioned interventions, issues such as saline soils and waterlogging persist. The implementation of large drainage structures, such as the Right Bank Outfall Drain, proves inadequate and exacerbates the problem by serving as a highway for highly polluted water.

The well-documented issues of waterlogging, salinity, and rising groundwater tables now manifest alongside flooding and inundation, all symptomatic of insufficient drainage. This period is characterized by a collective loss of understanding and memory regarding the earlier optimism.

Additionally, climate change has brought about unpredictable weather patterns, leading to irregular rainfall and prolonged droughts, exacerbating water scarcity issues. These interconnected issues underscore the urgent need for comprehensive strategies and sustainable solutions to address the water and environmental challenges facing Sindh province.

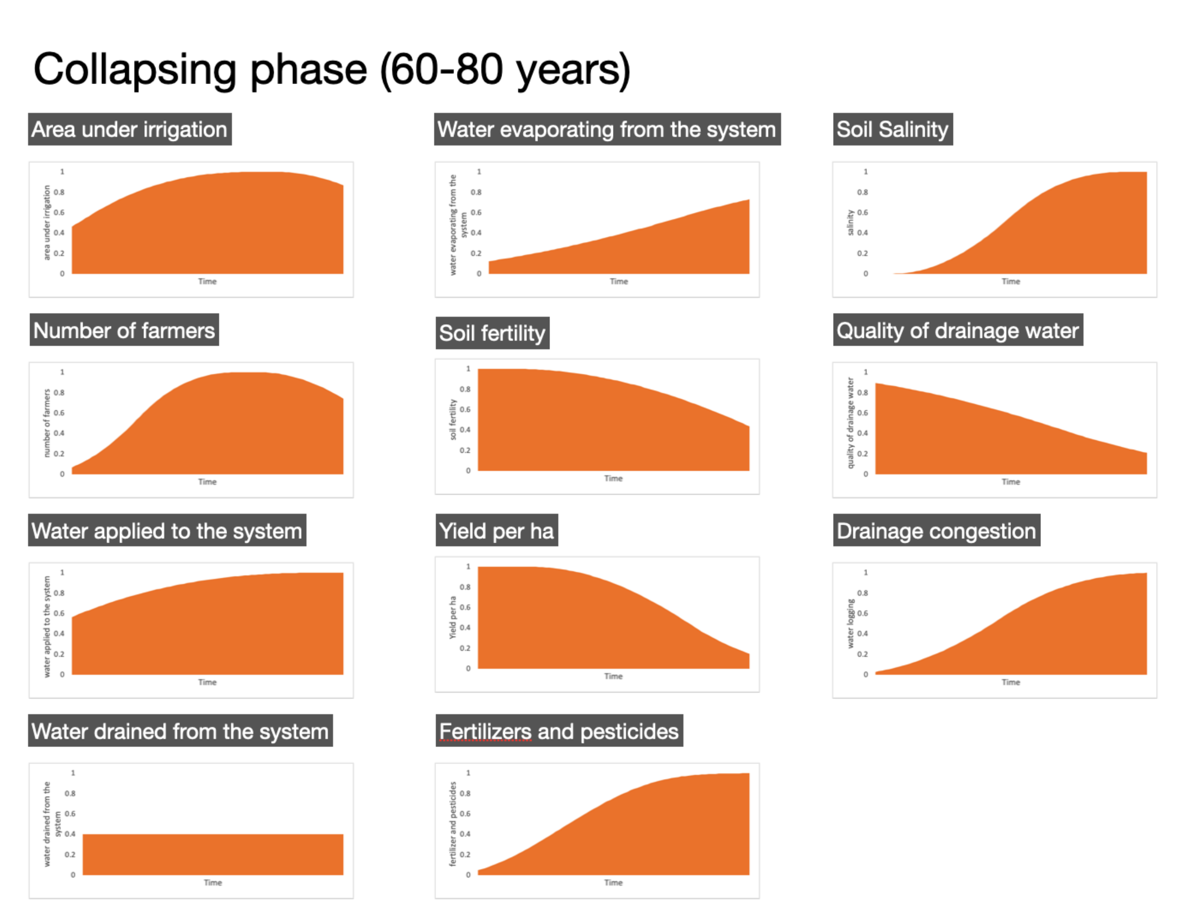

Figure 6: the collapsing phase of the irrigation system

In summary, it's evident that continuously increasing water and chemical inputs without sufficient flushing mechanisms results in salt and water accumulation within the system. The demand-driven nature of the system exacerbates salinity and chemical inputs, while inadequate drainage leads to system exhaustion.

Mbine

I think this is the stage that we reached in the Sindh irrigation system. I think this is the stage that we reached in the Nile. I think this is the stage we reached in Mekong. All of them are clear-cut cases of overreach and of human-induced exhaustion of natural ecosystems, with a huge loss in fertility, soil health and crop production. The very unnerving realization that our great food baskets of the past, the food producing powerhouses of the past has become old men.

Moreover, as we confront the challenges of climate change, regions like Sindh are experiencing heightened uncertainties in water availability and agricultural productivity. Changes in precipitation patterns, increased temperatures, and extreme weather events further compound the vulnerabilities of irrigation systems, exacerbating soil degradation and water scarcity issues. Adapting to these climate impacts is imperative to safeguarding agricultural livelihoods and ensuring food security in the face of evolving climatic conditions.

The unnerving realization that we must start rethinking and redesigning the large irrigation systems. While revival is possible, it requires moving beyond traditional approaches of patchwork fixes. Our focus should be on reimagining objectives, utilization, functionality, and management of these systems to ensure their long-term viability and sustainability. In addressing these challenges, there is an opportunity to enhance the resilience of Sindh's agricultural/irrigation sector and improve the livelihoods of its people. By adopting a holistic approach that integrates ecological, social, economic, physical and governance considerations, we can effectively address the complexities of natural resources management and climate change adaptation. Additionally, promoting true integrated resources management practices can help optimize the use of our natural resources (soil, water, ecosystems), minimize conflicts, and ensure sustainable development. By integrating these principles into our irrigation systems, we can build resilience, foster adaptation, and safeguard the well-being of communities in Sindh for generations to come.