DISSERTATION

ASSESSING IRRIGATION CANAL SEEPAGE REDUCTION

USING POLYMER SEALANTS

Submitted by

Ahmad Abdur Rehman Lund

Department of Civil and Environmental Engineering

In partial fulfilment of the requirements

For the Degree of Doctor of Philosophy

Colorado State University

Fort Collins, Colorado

Fall 2024

Doctoral Committee:

Advisor: Joseph Scalia IV
Co-advisor: Timothy K Gates

S. Karan Venayagamoorthy
Allan A. Andales

ABSTRACT

ASSESSING IRRIGATION CANAL SEEPAGE REDUCTION

USING POLYMER SEALANTS

Irrigation canals around the world experience varying degrees of seepage losses, with several potential adverse consequences and influenced by numerous factors. A synthesis and interpretation of field seepage data from peer-reviewed literature (impact factor >1.5) on seepage measurement and control reveals several key insights: (i) seepage rates differ significantly due to diverse field conditions; (ii) the inflow-outflow method is the most reliable for measuring canal seepage in the field; and (iii) polymer sealants (PSs) offer a cost-effective alternative for reducing seepage in irrigation canals. Compared to conventional liners (CLs) such as concrete, geomembranes, or masonry, PSs are not only more affordable but also can be applied selectively, allowing for seepage when the surface water supply is sufficient and groundwater recharge is desirable. Studies show PSs can reduce seepage by 64% to 88%, while CLs achieve reductions of 53% to 95%, highlighting the potential of PSs for further research and application. However, best field application techniques for PSs, the uncertainty in evaluating effectiveness, and ambiguity in potential environmental impacts require more comprehensive investigation.

The most widely researched PS for reducing canal seepage is linear anionic polyacrylamide (LAPAM), a synthetic polymer sealant (SPS). When applied to canal water, LAPAM forms flocs through cation bridging with divalent cations (Mg^{2+} and Ca^{2+}) commonly found in canal water, which settle along the canal perimeter and reduce hydraulic conductivity. Observed seepage reduction from field trials of LAPAM that had been conducted prior to this study on three mid-sized canals (two in Colorado, USA and one in Sindh, Pakistan) using the recommended inflow-outflow method for seepage testing were analyzed. The average pre-LAPAM seepage rate was approximately 0.32 m/day, while the post-LAPAM rate dropped to 0.04 m/day, with results demonstrating seepage reductions between 69% and 100%. An uncertainty analysis of the pre- and post-LAPAM tests indicated an 85% probability that the seepage reductions were due to the LAPAM treatment. While LAPAM has proven effective, the long-term environmental impact of LAPAM treatment remains uncertain, underscoring the need to explore natural alternatives to synthetic polymer sealants.

Biopolymer sealants (BPSs) were identified and evaluated through both laboratory and field experiments, designed to mirror the approach used with LAPAM. These experiments were conducted in triplicate (lab) and duplicate (field) to enhance confidence. In the lab, constant head saturated hydraulic conductivity (K_{SAT}) tests simulated irrigation canal perimeter conditions. Five BPSs—pectin citrus (PC), cellulose hydroxyethyl ether (CHE), pullulan desalinated (PD), sodium alginate low viscosity

(SALV), and xanthan gum (XG)—were initially tested and compared against LAPAM. The pre-and post-polymer K_{SAT} values revealed that PC, PD, and XG achieved average reductions exceeding 40%, which was used as the threshold for further exploration. Subsequent testing under conditions more representative of irrigation canals identified XG as the most effective BPS. Alternative application rates were assessed, with 20 mg/L identified as the preferred concentration, as higher concentrations did not significantly enhance K_{SAT} reduction. Long-term performance tests in the lab showed that XG, at 40 mg/L, can reduce hydraulic conductivity by over 90% for 9–10 months and by 60–70% over 1.5 months at 20 mg/L. These findings were validated using seepage tests in the field, where XG applied to a 3-km earthen canal reach at 20 mg/L reduced seepage by up to 63% over a month (at which time the canal was taken out of service). While the use of SPSs may still be justified for controlling canal seepage, this research shows that BPSs such as XG, have the potential to replace SPSs for canal sealing. However, further work is needed to optimize application methods and dosage rates, to better understand working mechanisms, to demonstrate long-term effectiveness, and to assess scalability across diverse field conditions.

ACKNOWLEDGMENTS

I would like to express my deepest gratitude to my advisors, Professors Joseph Scalia IV and Timothy K. Gates. Their unwavering guidance, mentorship, and support throughout my time at Colorado State University have been instrumental in my academic journey. This dissertation, along with the many milestones I've achieved, would not have been possible without their encouragement and expertise.

I extend my heartfelt thanks to my fellow graduate students, whose collaboration and camaraderie were invaluable. Joseph Pugh, Samuel Jacobs, Parker Maddocks, and Ashar Ali, your assistance during fieldwork and your cheerful company during long, hot summer days made the challenges more bearable. To Aidan Allen, Angelita Chavez Cazarez, Celie Brockett, and Jillian Lukez, my dedicated undergraduate field and lab assistants, thank you for your contributions to the field and laboratory experiments.

My sincere thanks go to the Larimer and Weld Irrigation Company (LWIC), especially to Andy Pineda, for facilitating the field research and providing essential support. I am also grateful to Elise Cozzens for her help with field experiments. The in-kind support provided by the LWIC was vital to this research.

I acknowledge the generous funding and support from the United States Agency for International Development through the University of Utah, the Colorado Agricultural Experiment Station, and the Colorado Water Center. Their contributions enabled the progress and completion of this research.

Finally, I am profoundly thankful to my family, friends, teachers from CSU and beyond, and all those who have supported me in various ways throughout my PhD journey. Your encouragement, understanding, and kindness have made this achievement possible.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Executive Summary

INTRODUCTION

Irrigation canals are essential to convey water to irrigated agriculture. Most of the world's irrigation canals are dug into the earth and are not lined to prevent the water from seeping out through the canal perimeter, leading to seepage losses. Besides the economic loss resulting from the wastage of valuable water, canal seepage results in a variety of damages to the environment and to irrigated agriculture (Gates et al., 2012, 2016). Therefore, depending on the water availability in a canal command area, the channel properties, and the groundwater conditions along the canal, seepage losses can be substantial and often need to be controlled. Paramount to addressing the issue of canal seepage, are understanding the extent of its seriousness, analyzing the magnitude of seepage under varying field conditions, assessing methods to quantify canal seepage in the field, and evaluating treatment methods for seepage control.

Controlling canal seepage is not always economically feasible (Wichelns and Oster 2006), making exploring cost-effective alternatives essential. Prior studies have shown that Linear Anionic Polyacrylamide (LAPAM), a synthetic polymer, shows promise as an affordable sealant for mitigating seepage (Susfalk et al. 2008, Uribe et al. 2013). Field evaluations of LAPAM, along with assessment of the uncertainty in pre- and post-application seepage measurements, can help establish protocols for polymer-based seepage control methods. However, LAPAM may present environmental concerns, so the use of LAPAM for canal seepage control remains an open-ended question.

Advances in biopolymer research, which are generally environmentally benign, has led to the increased replacement of synthetic polymers with biopolymers in many applications (Macczak et al. 2020). The use of biopolymers in irrigation canals for seepage reduction can address the environmental concerns resulting from treating irrigation canals with LAPAM. Although the potential applications of biopolymers are broadly studied in environmental and agricultural applications (Sharma et al. 2006, Berninger et al. 2021), the effectiveness of biopolymers for canal seepage reduction has thus far remained unknown.

My research aimed to assess the use of polymer sealants to provide an environmentally friendly tool to address canal seepage and was accomplished by achieving three objectives: (1) synthesizing peer-reviewed canal seepage field data to characterize seepage by canal soil type, measurement methods, and control measures; (2) establishing the foundation of polymer-based seepage mitigation via evaluation of field studies of a synthetic polymer sealant and (3) identifying a preferred biopolymer alternative to the synthetic polymer LAPAM and performing field trials. Each objective is addressed in a separate chapter, published or submitted (at the time of writing) as individual journal articles.

METHODS

Methods used to meet Objective 1: Canal seepage field data from 44 peer-reviewed journal articles were identified, reviewed, summarized, and synthesized. Seepage values reported in different units across the studies were converted to units of m^3/day per m^2 and m^3/sec/ km to draw comparisons. The processed information was used to categorize seepage by major soil type in the canal perimeter (clayey, loamy, and all earthen), the common field seepage quantification methods (inflow-outflow, ponding, and point measurements), and any method of treatment to mitigate canal seepage (concrete, masonry, compacted earth, polymer sealants, and all others). The information was summarized to present the number of seepage tests, soil type, canal treatment (if applicable), test reach length, seepage rate, and seepage normalized by test reach area and length.

Methods used to meet Objective 2: Analyses were conducted on seepage estimates from canal test reaches along the Catlin and Rocky Ford Highline canals in Colorado, which were performed by a former CSU graduate student, as well as seepage data from the Tarah Canal in Sindh, Pakistan, collected by the author as part of his MS thesis work. The information revealed that the test reaches were selected based on input from canal companies, observed seepage, ease of conducting seepage measurements, and suitability for LAPAM treatment. Pre- and post-LAPAM seepage tests were conducted used the flowing water balance (inflow-outflow) method. The measured flow rates at the upstream (Q_{US}) and downstream (Q_{DS}) ends of the selected reaches were measured using acoustic Doppler current profiler (ADCP) devices. Most tests were "lagged," meaning the same equipment was used to measure Q_{US}, then transported downstream to measure Q_{DS}. Only a few tests were "simultaneous," where Q_{US} and Q_{DS} were measured concurrently with two ADCPs. The LAPAM applied in all canals had a molecular weight of 12 Mg/mol and contained less than 0.05% acrylamide. The application rate was determined based on the calculated wetted perimeter area of the canal, with LAPAM broadcast over the water surface from small boats. For the two Colorado canals, probability distributions and statistical analyses of pre- and post-treatment seepage values were calculated to estimate the uncertainty in LAPAM's effectiveness.

Methods used to meet Objective 3: Five biopolymers—pectin citrus (PC), cellulose hydroxyethyl ether (CHE), pullulan desalinated (PD), sodium alginate low viscosity (SALV), and xanthan gum (XG)—were evaluated and compared to synthetic LAPAM in laboratory experiments designed to simulate the perimeter of irrigation canals using constant head saturated hydraulic conductivity (K_{SAT}) tests. Steady-state K_{SAT} was measured on soil columns before and after the addition of each polymer, with each experiment performed in triplicate, and the average of the three results used as the representative K_{SAT} value. Initially, PC, PD, and XG were shortlisted based on their performance compared to LAPAM. Further tests identified XG as the most promising alternative; thus, XG was studied at varying concentrations to determine a preferred application rate and to estimate the long-term effectiveness. Laboratory findings were applied in the field, where a reach of the Larimer and Weld Canal (LWC) in northern Colorado was treated with XG in both dry and wet forms in 2021 and 2022, respectively, to reduce seepage. The seepage measurement protocols, refined from the work on Objective 2, ensured that all tests were conducted simultaneously and in duplicate to reduce systematic errors, instrument variability, and measurement bias.

MAJOR FINDINGS

Chapter 1, titled "Characterization and Control of Irrigation Canal Seepage Losses: A Field-Focused Review and Perspective," presents seepage data for untreated earthen and treated canals, as reported in peer-reviewed literature. Seepage rates measured in untreated earthen canals, using inflow-outflow, ponding, and point measurement methods, display skewed frequency distributions across the reviewed studies. Summary statistics reveal that seepage rates from earthen canals typically range on the order of 0.1 to 1 m^3/day per m^2 of canal perimeter, with variability reflecting differences in field conditions and measurement techniques. Point measurements generally yielded higher seepage values than reach-scale methods, with greater variability. The effectiveness of seepage control methods was found to depend on the age and condition of the liner at the time of assessment. Seepage measurements from treated canals indicate that seepage losses can sometimes be as significant as those from untreated canals, likely due to the deterioration of treatments over time. Hard-surface liners, such as concrete and masonry, reduced seepage by 53% to 96%, with an average reduction of 78%. Compacted earth treatments showed a wider range of effectiveness, from 16% to 85%, with an average of 73%. Polymer sealants were found to reduce seepage by 64% to 88%, with an average reduction of 82%. The chapter recommends the inflow-outflow method for field seepage quantification and suggests that polymer sealants, depending on field conditions, are effective for reducing canal seepage.

Chapter 2, titled "Field Evaluation of a Polymer Sealant for Canal Seepage Reduction," presents the results of 37 flowing water balance tests that had been conducted on three mid-sized canals. The findings demonstrate a 69-100% reduction in seepage following LAPAM treatment, with the effect lasting up to three months, highlighting LAPAM's potential to mitigate seepage losses throughout an irrigation season. For all post-treatment tests, seepage rates were consistently found to be lower than those measured pre-treatment. Earlier Monte Carlo simulations of seepage estimates confirmed that the mean post-LAPAM seepage values were always lower than pre-treatment values, indicating an 85% likelihood that some degree of seepage reduction was attributable to LAPAM treatment. The chapter concludes by recommending further exploration of more environmentally friendly alternatives to LAPAM and a systematic evaluation of factors such as soil type in the canal perimeter, total suspended solids in canal water, and the type and concentration of biopolymers to assess their efficacy in reducing seepage.

Chapter 3, titled "From Synthetic to Biopolymer Sealants: Using Xanthan Gum to Reduce Irrigation Canal Seepage," presents the results of laboratory testing and field applications of biopolymer alternatives to LAPAM. Initial experiments assessed four LAPAM variants and five biopolymers across two soil types, ultimately identifying pectin citrus (PC), pullulan desalinated (PD), and xanthan gum (XG) as promising candidates. These biopolymers showed average K_{SAT} reductions of 43%, 46.5%, and 72%, respectively, compared to the best LAPAM variant, which achieved a 95% reduction. The consistency of these results across both soil types reinforced XG as the top-performing biopolymer. Further testing of XG at three concentrations (20, 40, and 60 mg/L) indicated no significant improvement beyond 20 mg/L, establishing 20 mg/L as the preferred concentration. Findings demonstrated that at 40 mg/L, XG could reduce hydraulic conductivity by over 90% for 9-10 months and by 60-70% for 1.5 months at 20 mg/L. Additional testing revealed that the effectiveness of XG is influenced by the quantity of sediment available in the water. Subsequent field experiments, employing multiple inflow-outflow tests over two years, confirmed that applying XG at 20 mg/L to an irrigation canal reduced seepage by up to 63% over one month. The degree of seepage reduction due to XG treatment exhibited fluctuating trends in both laboratory and field settings. Initially, seepage markedly decreased following XG treatment, followed by a decline in effectiveness after one week, and then an increase in seepage reduction two to four weeks post-treatment. Possible causes of this fluctuating trend are hypothetically attributed to XG microbial degradation, XG viscosity effects, XG adsorption to clay particles in canal water, and the dropping of water level in the canal after every five days.

The key takeaways from this research include the systematic consideration of seepage measurement and control methods and materials, refining the inflow-outflow method to reduce measurement bias, and identifying xanthan gum (XG) as a potential environmentally friendly solution for seepage reduction. Future research opportunities and need are discussed in Chapter 4, titled "Future Research and Applications" Recommended future research directions identified include developing a comprehensive understanding of the mechanisms driving biopolymer effectiveness and modifying current experiments to ensure consistent, long-term performance. Additional identified areas for future research include study of the potential effectiveness of hybrid synthetic and biopolymers, designing experiments that better simulate real-world canal conditions in polymer testing, expanding research to other biopolymers, and conducting long-term field evaluations of XG or superior alternatives.

References

Berninger, T., Dietz, N. and González López, Ó., 2021. Water-soluble polymers in agriculture: xanthan gum as eco-friendly alternative to synthetics. *Microbial Biotechnology*, *14*(5), pp.1881-1896. DOI: 10.1111/1751-7915.13777.

Gates, T.K., Garcia, L.A., Hemphill, R.A., Morway, E.D. and Elhaddad, A., 2012. Irrigation Practices, Water Consumption, & Return Flows in Colorado's Lower Arkansas River Valley. *Color. Water Inst. Tech. Comp. Rep*, *221*, p.115. Technical report TR12-10.

Gates, T.K., Steed, G.H., Niemann, J.D. and Labadie, J.W., 2016. Data for improved water management in Colorado's Arkansas River Basin: hydrological and water quality studies. In *Colorado Water Institute Special Report No. 24*. State Univ., Fort Collins, Colorado.

Maćczak, P., Kaczmarek, H. and Ziegler-Borowska, M., 2020. Recent achievements in polymer bio-based flocculants for water treatment. *Materials*, *13*(18), p.3951. DOI: 10.3390/ma13183951.

Sharma, B.R., Dhuldhoya, N.C. and Merchant, U.C., 2006. Flocculants—an ecofriendly approach. *Journal of Polymers and the Environment*, *14*(2), pp.195-202. DOI: 10.1007/s10924-006-0011-9.

Susfalk, R., Sada, D., Martin, C., Young, M.H., Gates, T., Rosamond, C., Mihevc, T., Arrowood, T., Shanafield, M., Epstein, B. and Fitzgerald, B., 2008. *Evaluation of linear anionic polyacrylamide (LA-PAM) application to water delivery canals for seepage reduction* (Vol. 41245). Las Vegas: Desert Research Institute.

Uribe, H., Figueroa, R. and Llanos, L., 2013. Assessment of linear anionic polyacrylamide application to irrigation canals for seepage control. *Journal of Agricultural Engineering*, *44*(s2). https://doi.org/ 10.4081/jae.2013.s2.e156.

Wichelns, D. and Oster, J.D., 2006. Sustainable irrigation is necessary and achievable, but direct costs and environmental impacts can be substantial. *Agricultural water management*, *86*(1-2), pp.114-127. https://doi.org/10.1016/j.agwat.2006.07.014

Chapter 1

Characterization and control of irrigation canal seepage losses: A review and perspective focused on field data*[1]

SUMMARY

Canals compose the arterial structure of irrigated agriculture, transporting free-surface flows to the vast majority of the world's most productive farmland. Here we present a critical review and perspective of studies that describe the widespread and serious issue of seepage losses that occur as flows move through this critical network of watercourses. Such losses impact the hydrologic setting and pose challenges to water conservation, agricultural productivity, and water quality. With an aim to better understand the characterization and control of irrigation canal seepage in actual field settings, studies employing the most common field methods (inflow-outflow, ponding, and point measurements) in canals with different perimeter types (earthen, or treated with hard-surface, flexible membrane, compacted earth, and polymer sealants) are considered. Information from 44 peer-reviewed journal articles (impact factor ≥ 1.5) is summarized, synthesized, and evaluated. Statistics of measured seepage categorized by different units, methods of measurement, and type of canal treatment indicate significant

[1] This chapter was published as a review article in 2023 in *Agricultural Water Management*.
by A.A. Rehman Lund (the author of this dissertation), Timothy K. Gates (the co-adviser) and Joseph Scalia IV (the adviser)
https://doi.org/10.1016/j.agwat.2023.108516

variation within and across categories. Given the variation in site-specific conditions, reported seepage rates also vary markedly, with seepage from earthen canals ranging on the order of 0.1 to 1 m^3/day per m^2 of canal perimeter area. We find that much of the canal treatment literature lacks consistent and comparable reporting, with only a few studies providing both pre-and-post-treatment seepage values for a specific treatment method to assess effectiveness. Nevertheless, field data point to achievable levels of seepage reduction ranging from about 50 to 95% across treatment methods. Given the current state of knowledge and availability of refined measurement devices and protocols, we recommend the inflow-outflow method as the standard field technique for canal seepage characterization. Recognizing cost and the need for flexibility to allow groundwater recharge as key deciding factors for canal treatments, while acknowledging the need for further investigation, we recommend further consideration be given to the use of polymer sealants as a broadly promising means of canal seepage control.

1.1 Introduction

The principal way that water is conveyed and distributed for irrigating crops is by free-surface flow in earthen canals. That this simple technique remains dominant after millennia of use (Angelakis et al. 2020) is a testament to the comparative ease and low cost of this mode of water conveyance. Unfortunately, along the route to points of use, a substantial volume of water seeps downward and outward through the canal perimeter into the surrounding soil and rock. Even after canals have been lined or otherwise treated, seepage losses still occur, though ideally at much smaller rates. With water scarcity and diminishing water quality more acute than ever, canal seepage is drawing increased attention.

The primary concern about canal seepage is reduced flow conveyance efficiency (ratio of the flow delivered by the canal to the flow diverted into the canal) – water meant for equitable and timely irrigation to meet crop demands is diminished because of seepage. Seepage depends on several factors and induces several side effects, as illustrated in Fig. 1.1. Seepage causes unconfined groundwater tables to rise, with consequential upflux of groundwater to the soil surface via capillary forces driven by evapotranspiration. Under cropped fields, this upflux process often causes evaporative concentration of salts as well as waterlogging in the crop root zone. The result is often a decline in crop productivity (Singh 2015, Zorb et al. 2019). Under fallow and naturally vegetated areas, groundwater upflux from shallow water tables leads to non-beneficial consumption of water through evaporation and transpiration by weeds and phreatophytes. Additionally, seepage may cause negative impacts to subsurface return flows into streams and ponds. Higher groundwater tables and hydraulic gradients created by canal seepage can propel flows along or through unweathered and weathered strata to mobilize salts, trace elements, nutrients, and other pollutants toward environmental receptors in downgradient aquifers and streams.

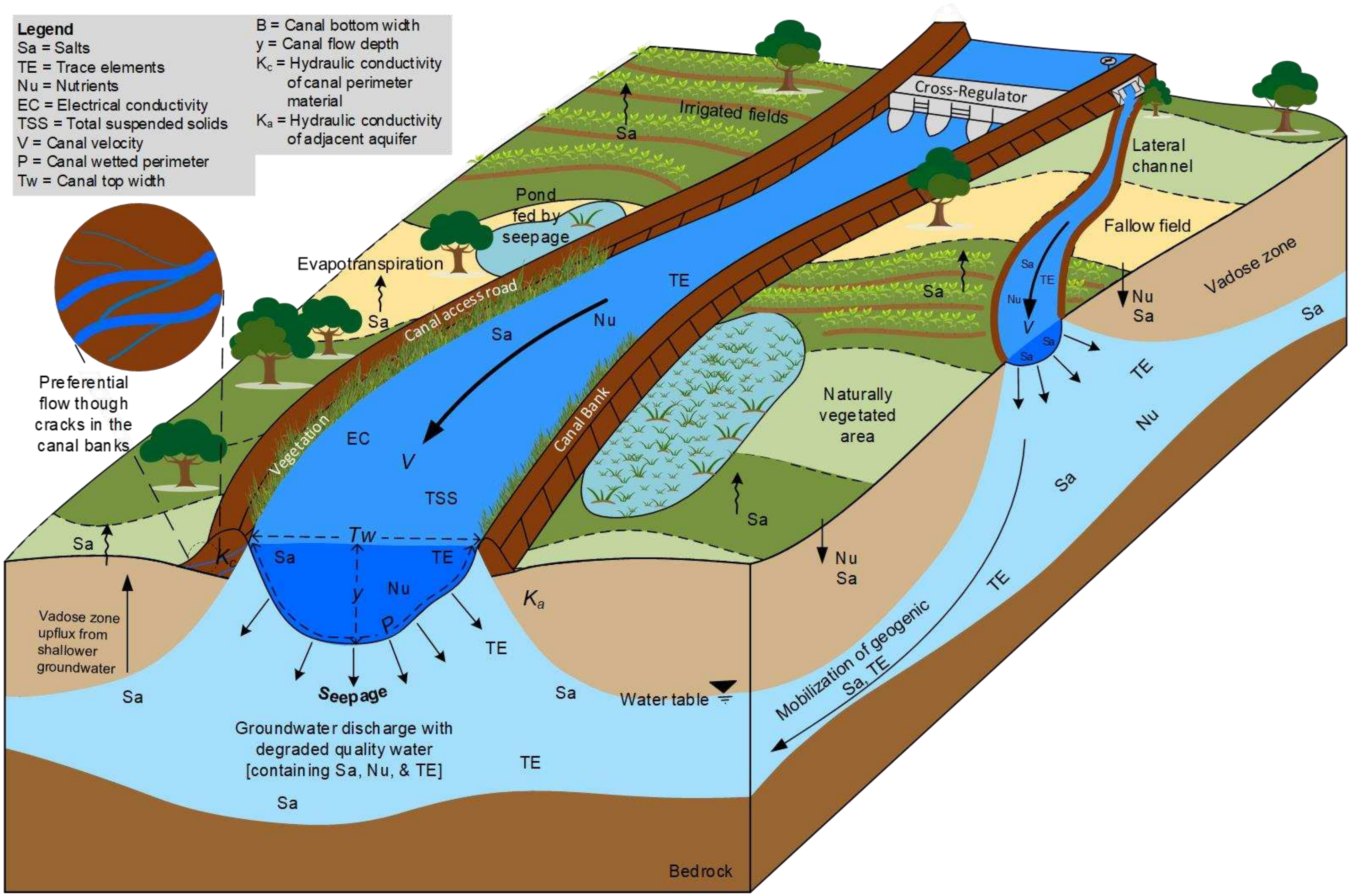

Figure 1.1: Conceptual sketch of processes deriving water loss and negative environmental impacts due to seepage.

Depending on the regional conditions, canal seepage also can produce some beneficial effects. A portion of canal seepage enhances groundwater recharge, increasing water stored for current or future use. In some settings, seepage can also dilute agricultural chemicals and can delay return flows in a manner that provides a supplement to in-stream flows at later times of shortage (Fernald and Guldan 2007).

Most irrigation canal networks experience significant seepage losses. Estimates of the magnitude of seepage losses in irrigation channels globally range from 10% to upwards of 70% of flows diverted from the source (Robinson and Rohwer 1957a, Brouwer et al. 1989, USGS 1990, Lentz 2003, Kahlown and Kemper 2005, Sahu et al. 2014, Sultan et al. 2014, Kulkarni and Nagarajan 2019, USDA 2020, Hrozencik et al. 2022). Since irrigated agriculture is responsible for an estimated 70% of all freshwater withdrawals worldwide (Siebert and Döll 2010, World Bank 2022), and water is delivered to farms primarily through canals, seepage comprises an immense loss of water. In addition, the sizeable ambiguity that is present in estimating seepage from canal systems contributes to uncertainty in our overall water budget (Puy et al 2022a).

Our aim in this paper is to provide a resource and perspective for water managers and modelers who need to evaluate and deal with canal seepage as a key component of agri-environmental water systems. Canal seepage is a major water resources management dilemma; but, just how sizable and disparate is seepage across different settings? What is known about the best ways to quantify seepage loss in a particular setting? What are the current and emerging prospects for controlling seepage? To help address these questions, we:

(1) Summarize the essential background needed for readers to understand the phenomenon of canal seepage;

(2) Gather the major findings from available refereed literature on field studies of seepage losses from both earthen canals and from canals that have been treated for seepage mitigation;

(3) Provide a review and critique of these findings, with data from reviewed studies processed, organized, and interpreted to offer information about typical seepage losses as influenced by a variety of factors and about prospects for controlling these losses; and

(4) Offer a summary of the current state of knowledge, knowledge gaps, constraints, and a perspective on the way to better understand and address the canal seepage problem.

Considering the scope of the paper, we provide the following outline to direct the reader to a specific section of interest:

2. Literature review methodology

3. Factors affecting canal seepage

3.1 Properties of canal perimeter soils

1.2 Literature review methodology

In addition to peer-reviewed journal articles that address canal seepage, a considerable amount of grey literature may be found, including academic theses, conference proceedings, and technical reports. Extracting information primarily from grey literature, while also including some of his own previously unpublished data, Worstell (1976) summarizes results of numerous ponding and seepage meter tests for measuring canal seepage. Mutema et al. (2022) discuss canal seepage and other conveyance losses in the context of their relation to canal shape, perimeter treatment, clay content of earthen canals, friction coefficient (not defined in the paper), width, longitudinal slope, flow depth, and the method of measurement or estimation. Their study synthesizes canal seepage rate data from predominantly grey literature and from papers published in low-impact (impact factor, IF < 1.5) journals. They present all seepage rate data in units of L/s per 100 m along the canal without considering the variation of canal sizes within each category of comparison.

Here we review articles reporting canal seepage data measured in the field. To enhance confidence in the reported data, and to avoid an arbitrary judgment, we include only peer-reviewed articles in journals with IF ≥ 1.5. We acknowledge the availability of technical reports and other grey literature by different organizations that present information on this subject; however, we rely only on studies vetted by an external peer-review process. Google Scholar and Web of Science search engines were primarily used for discovery of relevant studies. The literature search included keywords, alone and in combination, such as "canal seepage", "earthen canal seepage", "lined canal seepage", "canal seepage losses", "canal seepage measurement", "canal seepage measurement methods", "canal seepage quantification", "control of canal seepage", "canal sealing", "seepage from lined canals", "inflow-outflow method", "canal flowing water balance", "ponding method", "seepage meters", and similar. All journal articles were originally published in English. A few of the articles we found were excluded from review when we deemed them to be of dubious quality and reliability based upon our experience and discretion. Some grey literature has been referenced here for brief overview; however, these sources are not used in our synthesis and assessment of canal seepage data.

1.3 Factors affecting canal seepage

Numerous interacting factors influence canal seepage (Fig. 1.1). These include the properties of canal perimeter soils; characteristics of perimeter treatments; canal geometry; flow depth (y); flow velocity (V); the hydraulic gradient from the canal to the adjacent aquifer; the amount and type of canal vegetation; and the temperature, sediment load, and solute concentration of the canal water (Bouwer 1969, Worstell 1976). The singular and combined effects of these factors on seepage and infiltration in porous media have been investigated within a wide range of hydrologic and hydraulic settings, and the documenting literature is replete. Here we provide only a brief overview of key factors and how they may influence canal seepage.

1.3.1 Properties of canal perimeter soils

The texture and structure of soil in the canal perimeter (bottom and banks) can influence the soil hydraulic conductivity (K), specific yield, and degree of cracking, thereby directly affecting the seepage rate. Our review of the literature revealed that most papers on seepage measurement describe perimeter soils at test sites only in terms of texture, if at all. Soil texture provides a major predictor variable for canal seepage rates. Coarse-textured soils such as sand generally provide less resistance to seepage than finer textured soils such as silt and clay due to their higher *K* (Clapp and Hornberger 1978, Rawls et al. 1982, Rawls et al. 1998, Wesseling et al. 2009). However, clays, particularly plastic clays, have a higher propensity for the formation of cracks (preferential flow paths), which can also promote seepage.

1.3.2 Canal perimeter treatments

Treatments of the canal perimeter, such as lining, soil compaction, and sealing, are applied to remediate seepage. Generally, treatments reduce seepage; however, the effectiveness of treatments depends on the type, condition, and age of the treatment used. A brief description of canal treatment methods and their relative impact on seepage rates, along with supporting references, is reserved for Section 1.6.

1.3.3 Canal geometry

The shape (regular such as rectangular, triangular, semicircular; or irregular), size (dimensions such as bottom width, length of sides, etc.) and degree of variability of the canal cross section geometry affects flow depth and impacts the perimeter soil surface area through which seepage occurs (Bouwer 1969). Asl et al. (2020) employed a finite-element numerical simulation model, verified using seepage rates measured in seven canals in Iran and five canals in Turkey, to explore the effect of geometric parameters of trapezoidal, rectangular, and triangular canal cross sections. They report a strong linear dependence of computed seepage on the canal wetted perimeter (a larger wetted yields greater seepage) and a weak correlation with canal side slope.

1.3.4 Canal flow depth, velocity, and adjacent groundwater

There is contradictory evidence in the literature about the effect of canal flow depth on seepage. The depth of water in a canal, the proximity of the adjacent unconfined aquifer, and the direction of the flow impact the hydraulic gradient that drives seepage. A higher hydraulic gradient between the canal water surface and the water table, impacted by hydrologic and irrigation conditions on adjacent lands, should result in higher seepage flow in accordance with Darcy's law (Marino and Luthin 1982). Robinson and Rohwer (1957b) found that the seepage rate increases with an increase in flow depth; however, this effect was attributed to the observation that in some cases the upper part of the canal banks is more permeable than the lower part. In contract, using a statistical analysis of field data from canals of varying sizes, Mutema et al. (2022) found that the seepage rates did not significantly change with flow depth. The researchers did not offer a possible explanation. However, this finding may be associated with cases where saturated flow exists (hydraulic connection with the aquifer is established) and the canal seepage occurs essentially vertically at a steady state. In such cases, the hydraulic gradient is effectively one and the depth to the water table no longer matters. If the water table falls significantly below the canal bed, unlike the illustration in Fig 1.1, seepage flow may become unsaturated, with hydraulic connection to the adjacent aquifer lost. When unsaturated flow conditions exist unsaturated *K* and texture-dependent soil capillarity become important. A detailed account of groundwater-surface water scenarios may be found in Bouwer (1969).

The magnitude and variation of canal flow velocity determines the ability of water to entrain and transport sediment rather than depositing sediment on the canal perimeter and produces shearing stresses that develop on the canal perimeter. Each of these processes has the potential to affect seepage losses. Bouwer et al. (1963) studied the localized effect of flow velocity on seepage in a laboratory setting, revealing no direct impact of flow velocity on seepage through the bottom of the experimental channel. The findings support a contention for measuring canal seepage through still water bodies such as temporary ponds in canals or seepage meters. However, a short flume of only 10-m length with permeable sand and gravel bottom was used for the experiments and no information was provided about the suspended sediment concentration of the flow. We have found no publications that directly address the influence of canal flow velocity on measured seepage in a field setting.

1.3.5 Canal vegetation

Submerged vegetation and vegetation on canal banks have been found to increase seepage (Kahlown and Kemper 2004). The roots and shoots of canal perimeter vegetation provide a source of food for worms and insects, and attract foraging rodents, contributing to holes and deterioration of the banks. Values of flow velocity can be lowered in the vegetated zones, affecting shearing stress and sediment deposition which also may increase or decrease seepage (Devi and Kumar 2015). Plants also create a seepage-inducing pressure gradient in canal perimeter soils by extracting water to supply transpiration demands. Studies of the direct relation between vegetation characteristics (size and shape of leaves, dimensions of stems, depth of roots, etc.) and canal seepage rates were not discovered in our literature search.

1.3.6 Canal water properties

Properties of the canal water, including temperature, sediment load, and solute concentration, also influence seepage rates. Robinson and Rohwer (1957a) report that seepage increases with lower water temperature based on the results of tests with well permeameters. This behavior is the opposite of what might be expected from the increase of water viscosity with lower temperature. The researchers conjecture that this phenomenon was due to changes in soil K in response to changes in vapor pressure. For instance, increased vapor pressure can expand air bubbles within the soil as the temperature rises thereby lowering K. This effect may offset the effect of higher water viscosity. This example highlights the importance of accounting for the complex interaction between various factors in assessing the nature of canal seepage in actual field settings.

Salinity in the canal water can also influence the *K* and thus the seepage. A salinity exceeding an equivalent specific conductance of 0.2 dS/m can cause the clay in perimeter soil shrink and increase seepage (Ragusa et al. 1994). Sodicity, defined in terms of sodium adsorption ratio, also influences the *K* of soils (Adeyemo et al. 2022). This effect is more impactful for soils with greater percentages of plastic clay minerals. Levy et al. (2005) suggest that the effect of sodicity, salinity, and rate of wetting on the *K* should be considered as a whole, not individually. A higher exchangeable sodium percentage is associated with a lower *K* from clayey soils (Levy et al 2005). Thus, the concentration and composition of solutes in canal water will influence canal seepage.

The total suspended solids in the canal water has also been shown to substantially affect seepage. Cunningham et al. (1987) studied the impact of total suspended solids addition (200 to 1600 mg/L) on canal bed seepage and showed a 70-95% reduction. However, no significant difference in seepage was found with lower total suspended solids. Similarly, Ragusa et al. (1994) found that higher turbidity levels (1-10 g/L of clay) can reduce the seepage up to 100%. Previous studies on the effect of total suspended solids have allowed solids to deposit by a lack of flow velocity which may not represent the condition of a functioning canal.

Ranking the above discussed factors based on their importance needs detailed attention and is beyond the scope of this review. However, a study related to the uncertainty in seepage measurement by Martin and Gates (2014) provides some insight into the relative importance of some of these influencing factors.

1.4 Ways of quantifying canal seepage

Methods used to quantify canal seepage are summarized in Robinson and Rohwer (1959), Worstell (1976), Alam and Bhutta (2004), and Lindenbach et al. (2020) and may be broadly classified as methods of estimation (or indirect detection) and direct field measurement methods. References for published studies on methods of estimation are categorized and summarized in Table 1.1. These methods are especially useful for gaining insight into the sensitivity of canal seepage to a potential range of the influencing factors discussed in Section 1.3. Such parametric studies, nonetheless, must be verified by field measurements. Our attention here is placed on direct field measurements of canal seepage using inflow-outflow and ponding methods which are applied at the canal reach scale, and field point measurement techniques. Following a brief discussion of important considerations for conducting field investigations, past studies describing canal seepage quantification in untreated earthen canals are summarized categorically in Section 1.5. Field studies of seepage from treated canals are described in Section 1.6.

Table 1.1: References for published studies on different methods of estimation of canal seepage.

Method	Description	References
Laboratory testing	Measurement of seepage rates in a controlled setting using experiments with permeameters, flumes, and model channels	Ragusa et al. 1994, Moghazi and Ismail 1997, Korkmaz and Onder 2006, Lentz and Freeborn 2007, Phogat et al. 2008, Young et al. 2009, Zhu and Young 2009, Yao et al. 2012, Lentz 2015, Kang et al. 2015
Geophysical methods	Use of calibrated indirect measurements like electrical resistivity and electromagnetic induction to detect flow from canal perimeters.	Engelbert et al. 1997; Hotchkiss et al. 2001; Khan et al. 2008, 2009; Akbar et al. 2013; Pognant et al. 2013; Akbar et al. 2019
Remote sensing	Remote sensing techniques to detect seepage, including pattern classification of satellite images, the use of color infrared photography, and using thermal and multispectral images.	Engelbert et al. 1997, Huang et al. 2010, Chen et al. 2020, Traore et al. 2021
Analytical models	Analytical solutions to mathematical models of seepage, including conformal mapping and hodographs.	Hammad 1960; El Nimr 1963; Morel-Seytoux 1964; Bouwer 1965, 1969; Garg and Chawla 1970; Subramanya et al. 1973; Sharma and Chawla 1979; Remar et al. 1982; Goyal and Chawla 1997; Wolde-Kirkos and Chawla 1994; Yussuf et al. 1994; Swamee et al. 2000, 2001; Chahar 2001, 2006, 2007; Choudhary and Chahar 2014; Mahato and Dey 2020
Numerical models	Approximate numerical solutions to mathematical models of seepage, including finite element and finite difference methods.	Jeppson 1968, Jeppson and Nelson 1970, Bruch 1979, Mirnateghi and Bruch 1983, Fipps and Skaggs 1986, Wachyan and Rushton 1987, Rastogi and Prasad 1992, Demetracopoulos and Hadjitheodorou 1996, Katibeh 2004, Korkmaz and Onder 2006, Phogat et al. 2009, Yao et al. 2012, Zhang et al. 2017, Meredith and Blais 2019, Barkhordari et al. 2020, Salmasi and Abraham 2020, Elkamhawy et al. 2021, Han et al. 2021, Naranjo et al. 2023
Empirical models	Use of empirical data to develop and applying relationships between seepage and its governing factors such canal perimeter material, gradient between canal water level and adjacent groundwater, canal geometry, and canal hydraulic parameters.	Bakry and Awad 1997, Hotchkiss et al. 2001, Iqbal et al. 2002, Kinzli et al. 2010, Akkuzu 2012, Luo et al. 2016, Shaikh and Lee 2016, Zhang et al 2017, Asl et al. 2020, Shah et al. 2020, Singh et al. 2021

Selecting the right seepage quantification method for a given situation depends on factors that include cost; available equipment, supplies, and expertise; field conditions (ease of access, number of flow turnouts along the canal test reach); cooperation of landowners and canal managers; technical expertise of personnel; required and available duration for measurements; effect on normal canal operations; and the degree of accuracy needed. In addition to influencing the type of method used, these issues also shape the level of detail used within each study and how seepage results are reported. Listed below are several specific elements that are pertinent to address in carrying out and documenting a field campaign to measure canal seepage. Some of these elements are associated with factors known to affect seepage, as described in Section 1.3, while others concern logistical specifics of a field seepage test:

1. Canal name and location
2. Location of tests within the canal
3. Date of tests
4. Duration of tests
5. Canal perimeter material (untreated or treatment type)
6. Canal perimeter soil (texture, structure, permeability)
7. Canal geometry (shape, dimensions)
8. Canal vegetation
9. Length of canal test reach
10. Canal water total suspended sediments (TSS)
11. Canal water total dissolved solids (TDS)
12. Wetted perimeter

13. Wetted perimeter area
14. Method of velocity and flow rate measurements (devices, whether flow rates in inflow-outflow tests were simultaneous or lagged)
15. Number of measurement replications
16. Average canal flow velocity during the test
17. Average canal flow rate during the test
18. Canal flow depth or ponding depth
19. Ponding method (method of damming canal reach, source of ponded water)
20. Method used to measure stage and storage change
21. Channel storage change
22. Water surface evaporation method and results
23. Adjacent groundwater table
24. Seepage rate per unit canal length (if length of and wetted perimeter area are given, only total seepage rate need be reported)
25. Seepage rate per canal wetted perimeter area
26. Estimate of measurement uncertainty

Our search uncovered a total of 39 journal articles reporting results from inflow-outflow, ponding, and point measurement methods for seepage in both untreated earthen canals and treated canals. An overall sense of how thoroughly the collections of 16 inflow-outflow studies, 16 ponding studies, and 7 point measurement studies have documented testing and field conditions may be obtained from the radial bar plots in Fig. 1.2 – 1.4, respectively. These plots summarize the percentage of studies employing a given method that contain a description of relevant testing and field conditions pertinent to that method.

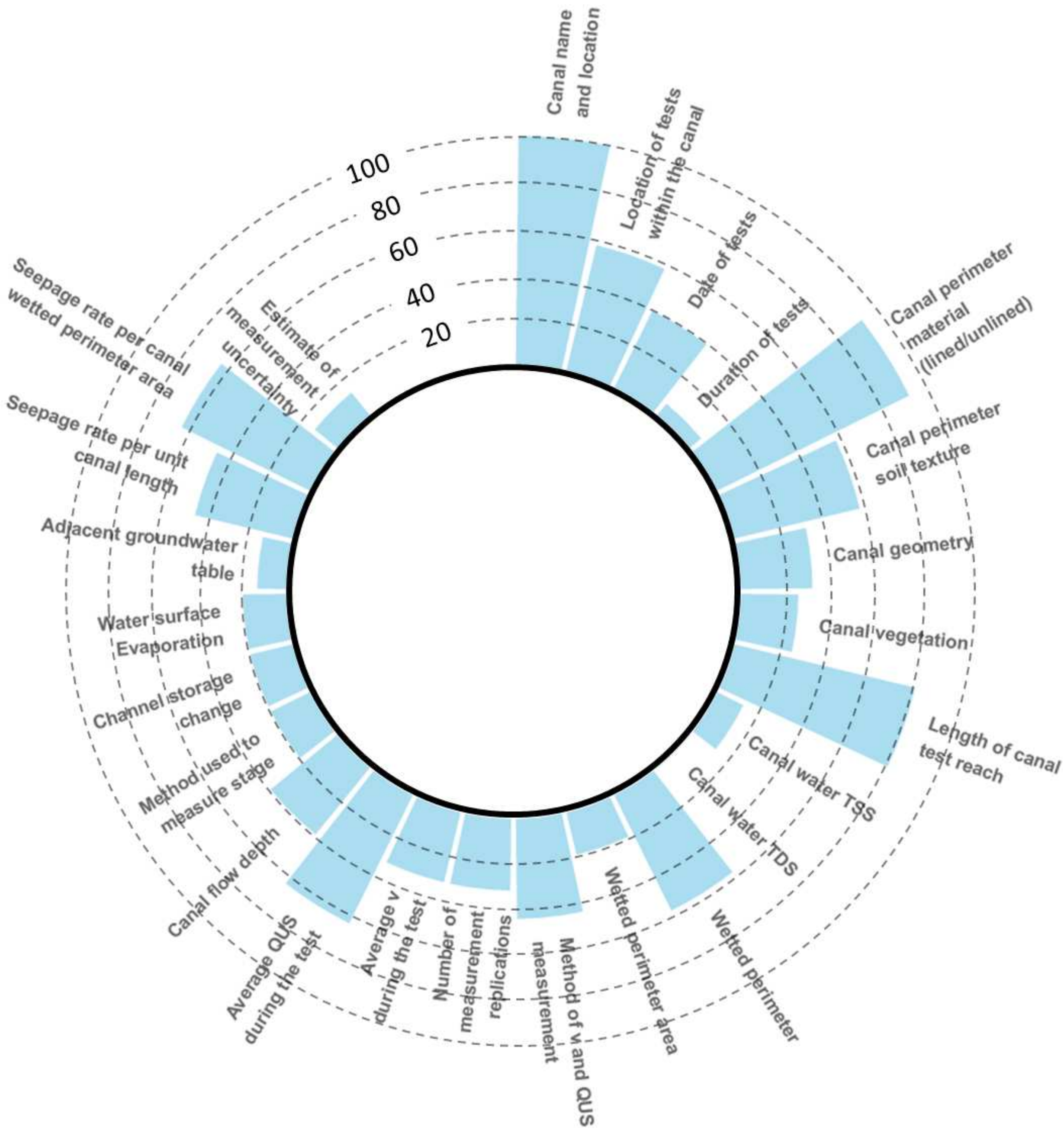

Figure 1.2: Radial bar plot depicting the percentage of reviewed studies that documented each pertinent element of field measurement of seepage from untreated earthen and treated canals using the inflow-outflow method

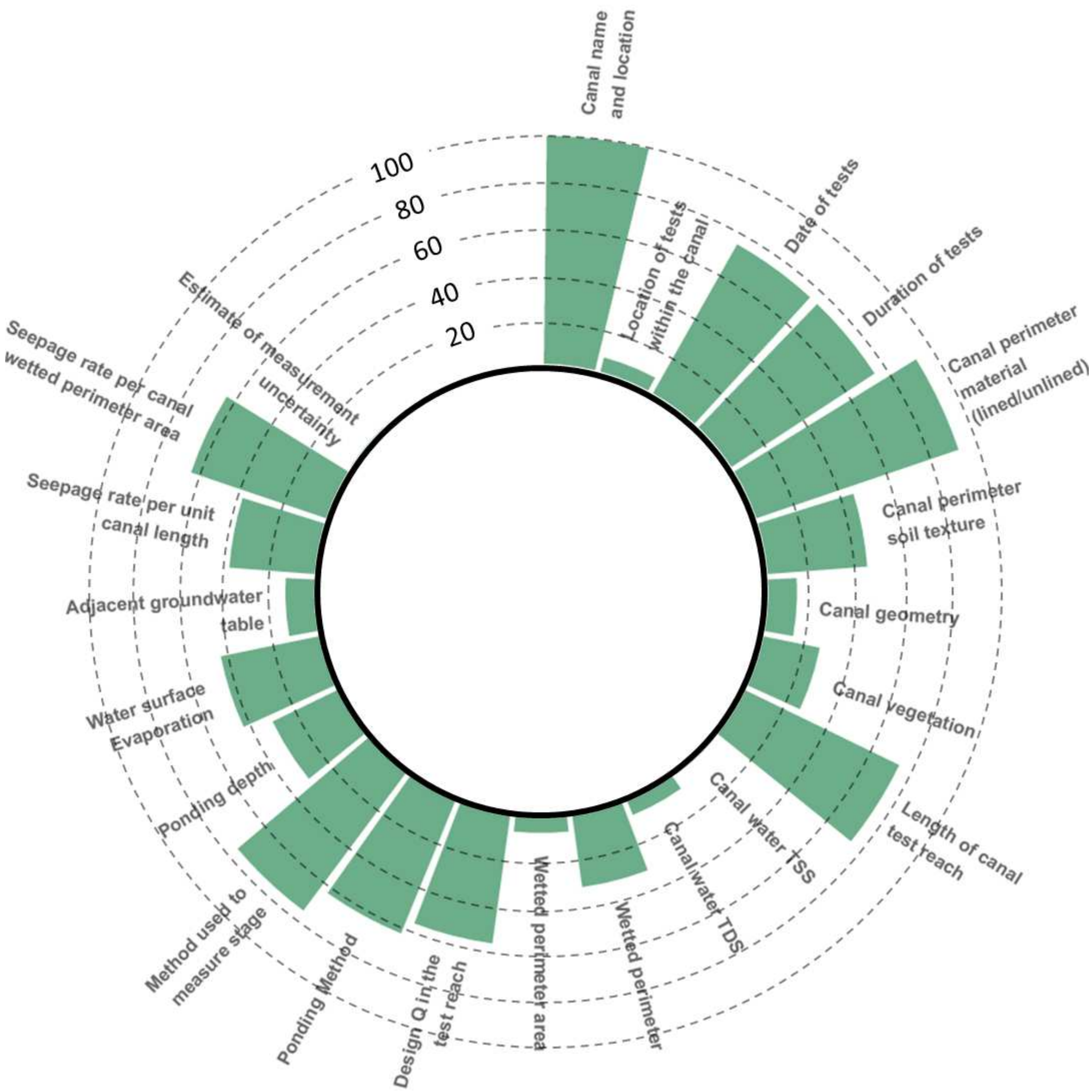

Figure 1.3: Radial bar plot depicting the percentage of reviewed studies that documented each pertinent element of field measurement of seepage from untreated earthen and treated canals using the ponding method.

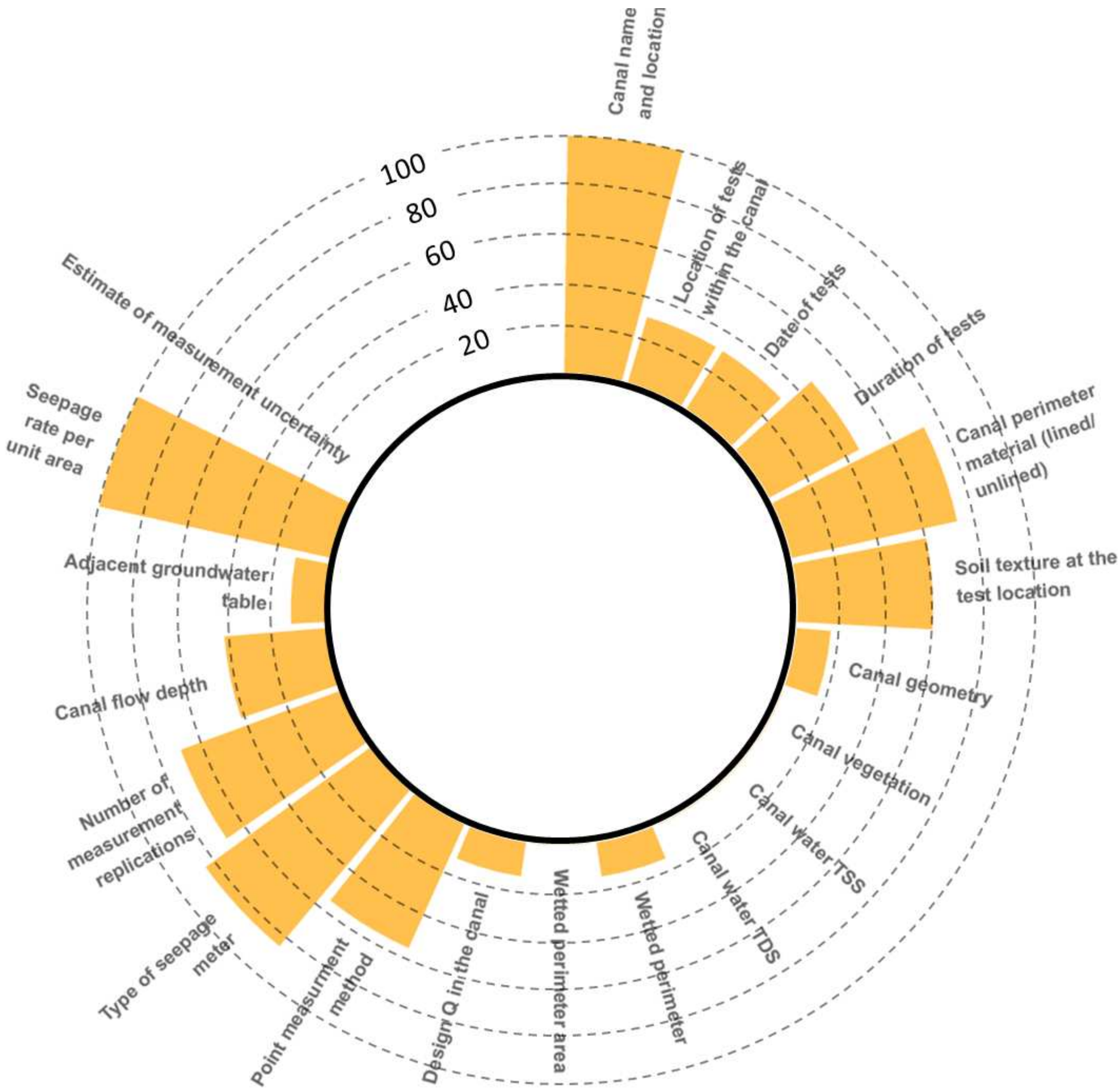

Figure 1.4: Radial bar plot depicting the percentage of reviewed studies that documented each pertinent element of field measurement of seepage from untreated earthen and treated canals using a point measurement method.

1.5 Measurement of seepage from untreated earthen canals

A synopsis of 31 field measurement studies in untreated earthen canals, along with a summary of their main results, are presented in the following subsections.

1.5.1 Inflow-outflow measurements in untreated earthen canals

The inflow-outflow method, also referred to as the flowing water balance method, entails conducting a water balance on a control volume (a reach or a segment) along a canal (shown schematically in Fig. 1.5) to determine seepage as an unknown outflow. All other outflows and inflows need to be measured, along with any change in stored volume, during a seepage test. The basic concept is to subtract the outflows from the inflows, while accounting for the storage change, over a canal reach with seepage loss being calculated as the unknown.

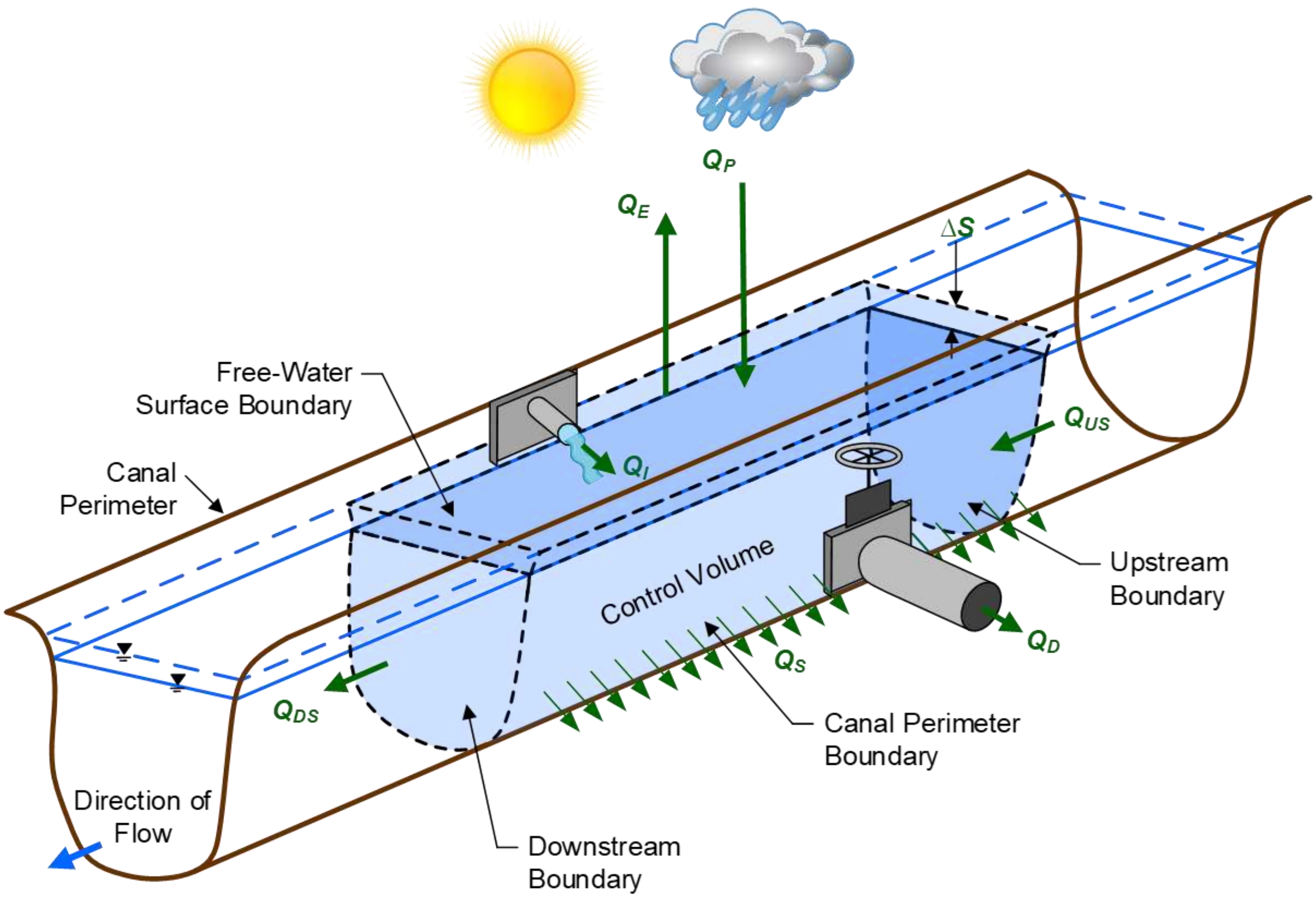

Figure 1.5: Illustration of the inflow-outflow method of measuring seepage along the reach of an irrigation canal.

As illustrated in Fig. 1.5 the inflows along a selected canal reach are the flow rate at the upstream cross section of the reach, Q_{US} [m^3/sec]; any inflows to the canal reach from adjacent irrigated lands, treatment facilities, etc., Q_I [m^3/sec]; and precipitation rate, if any, Q_P [m^3/sec]. Outflows are measured at the downstream cross section of the reach, Q_{DS} [m^3/sec]; as evaporation from the water surface along the reach, Q_E [m^3/sec]; and as any flow diversions (the turnouts) along the reach length, Q_D [m^3/sec]. Any changes in stored volume occurring throughout the seepage measurement, $\Delta S/\Delta t$ [m^3/sec], also must be measured. Seepage rate, Q_S [m^3/sec], can then be calculated as

$$Q_S = Q_{US} - Q_{DS} + Q_I - Q_D - Q_E + Q_P - \Delta S/\Delta t \qquad (1.1)$$

Details of the inflow-outflow method, along with a discussion of uncertainty in the measured components, can be found in Martin and Gates (2014).

The major advantage of the inflow-outflow method is that measurements are made under flowing water conditions with the canal remaining fully operational while seepage data are collected. This accounts for the effect of flow velocity on shearing stress along the canal perimeter, on the suspension of sediment within the canal water, and on flow depth variation along the test reach due to dynamic conditions. Disadvantages of the technique are (a) the hesitation of irrigators to close delivery turnouts during canal operation to avoid errors in measuring Q_D, (b) the need to measure $\Delta S/\Delta t$ in cases where the flow in the test reach is not steady, and (c) the need to conduct the test over a long-enough reach to insure that Q_S is sufficiently large compared to the collective errors that occur in measuring the component flows in Eq. (1) (Alam and Bhutta 2004, Martin and Gates 2014).

Values of Q_S measured in inflow-outflow studies are reported in the literature using a wide range of units. Reported units, expressed in SI, include L/s per 100 m along the canal, (L/s)/km, (m^3/s)/km, (m^3/day) per m^2 of canal perimeter area, and (m^3/sec)/hectare.

Wherever possible, we used data reported in studies on canal test reach length and perimeter area to convert reported seepage loss rates to $(m^3/s)/km$ and/or $(m^3/day)/m^2$ (simplified to m/day). The normalized units (m/day) provide a scaling by the size of the canal prism, facilitating comparison of results between canals of differing size.

Summaries of the 12 reviewed inflow-outflow studies in untreated earthen canals, including averages and ranges of reported Q_{US} values, are presented in Table 1.2. To aid in a comparison of the two reach-scale methods, summaries of the reviewed ponding studies (discussed in Section 1.5.2) are also included in Table 1.2. The reviewed papers include results from a total of 240 inflow-outflow tests. Reported test reach lengths range between 0.05 and 42.61 km and flow rates range between 0.022 and 24.62 m^3/sec. Table S1 in Supplemental Material summarizes additional details for each inflow-outflow test conducted as part of the studies of untreated earthen canals reviewed here: location, canal name, perimeter soil type, Q_{US}, average wetted perimeter, total wetted perimeter area, and Q_S reported as a percent of Q_{US}.

Of the 12 inflow-outflow studies summarized in Table 1.2, Kinzli et al. (2010), Martin and Gates (2014), and Lund et al (2021) report on the highest fraction of the pertinent study elements described in Section 1.4 (Fig. 1.2). All but one paper report Q_{US} values, revealing a wide range of test flow conditions from 0.04 to 60 m^3/s across the studies. Only three of the 12 studies provide details of how the inflow-outflow methodology was employed, such as the technique of flow measurement used and whether the flow was steady in the test reach or if storage change had to be measured. Characteristics of canal perimeter soils are described in about 60% of the papers and cross-section geometry in about 40%.

Table 1.2: Summary of reviewed papers on field measurement of seepage from untreated earthen canals using the inflow-outflow and ponding methods.

References	No. of tests performed	Test reach length average (range) *km*	Q_{US} average (range) *m³/sec*	Q_S average (range) *(m³/sec)/km*	*(m/day)*
			Inflow-Outflow		
Trout and Bowers (1981)	10	10.07 (0.98-25.12)	0.042 (0.024-0.071)	0.017 (0.0056-0.048)	--
Bakry and Awad (1997)	48	8.28 (5.55-12)	6.86 (2 - 12.10)	0.23 (0.01-0.43)	--
Alam and Bhutta (2004)	5	--	--	--	0.159 (0.098-0.204)
	12	12.98 (2.66-42.61)	1.71 (0.11-4.74)	0.0086 (-0.017-0.046)	0.148 (-0.050-0.55)
Kinzli et al. (2010)	25	5.15 (2.65-7.04)	2.14 (0.47-6.54)	0.02 (0.0085-0.051)	0.25 (0.06-0.5)
Raza et al. (2013)	20	(0.25-1.60)	0.041 (0.022-0.085)	0.015 (0.011-0.022)[1]	--
Uribe et al. (2013)	31	1.56 (0.51-3)	7.65 (0.12-24.62)	0.24 (-0.21-1.26)	--
Martin and Gates (2014)	31	4.65 (3.9-6)	3.92 (2.46-5.65)	0.033 (-0.019-0.085)	0.32 (-0.17-0.95)
Shaikh and Lee (2016)	25	1.064 (0.5-1.5)	0.069 (0.026-0.12)	0.0031 (0.0014-0.0045)	0.18 (0.089-0.29)
Mohammadi et al. (2019)	21	1.02 (0.25-2.15)	0.36 (0.04-1.48)	0.025 (0.0034-0.098)	0.87 (0.27-1.81)
Asl et al. (2020)	7	--	--	--	0.64 (0.35-1.102)
Lund et al. (2021)	1	5.3	5.09	0.025	0.362
Singh et al. (2021)	4	6.5 (2.7-9.8)	60.75 (11.60-107.40)	0.25 (0.19-0.40)	0.69 (0.31-1.15)
			Ponding		
Wilkinson (1985)	5	4.84 (0.9-24)			(0.01-1.74)
Iqbal et al. (2002)	24	0.15	--[2]	--	0.021 (0.0032-0.131)
Alam and Bhutta (2004)	6	--	--	--	0.06 (0.037-0.087)

Kahlown and Kemper (2004)	3	0.03	--	0.027 (0.002-0.0785)	--
Kahlown and Kemper (2005)	17	0.521 (0.081-3.01)	--	0.049 (0.0381-0.052)	2.86 (2.16-3.56)
Fernald and Guldan (2007)	1	0.06	--	--	0.12
Burt et al. (2010)	5	1.23 (0.30-3.12)	--	--	0.127 (0.02-0.28)
Kurse and Dutta (2013)	5	2.97 (0.4-8.75)	--	0.044 (0.0083-0.062)	--
Raza et al. (2013)	5	(0.05-0.055)	--	0.0032 (0.0016-0.0044)	--
Moavenshahidi et al. (2014)	778	--	--	--	0.0048[3] (0.0012-0.432)
Moavenshahidiet al. (2015)	1831 (778 old 1053 new)	--	--	--	0.0050[3] (0.0012-0.432)
Moavenshahidi et al. (2016)	21	--	--	--	0.0135[3] (0.0076-0.030)
Zhang et al. (2017)	2	0.03	--	--	(0.138 & 0.2)
Han et al. (2020)	1	0.03	--	0.004	0.2

Notes: 1 - These values are reported as averages over four canals within one of five groups
2 – Typical operating flow rates in canals with ponding tests are reported in Table S2
3 – Median values

In studies that include a description of canal perimeter soils, only Shaikh and Lee (2016) state results that allow direct comparison by categories of soil type. Tests on 25 earthen canals in the Indus River Valley of Pakistan, are grouped by perimeter soil types of clay, silty clay, clay loam, silty loam, and sandy loam, generally indicating greater seepage losses in canals with coarser textured soils. For the five canals with clay perimeter, having test reach length ranging from 0.8 to 1.4 km, average Q_S is 0.096 m/day. The average Q_S for the five silty clay canals, with test reach length ranging from 0.85 to 1.2, is 0.185 m/day. The average Q_S value for the five clay loam canals, with test reach ranging from 0.85 to 1.5 km, is 0.144 m/day. For the five silty loam canals, with test reach ranging from 1.1 to 1.4 km, the average Q_S is 0.200 m/day. The average Q_S for the five sandy loam canals, with test reach ranging from 0.7 to 0.8 km, is 0.294 m/day.

1.5.2 Ponding measurements in untreated earthen canals

In the ponding method, an impoundment is created between two temporary dams within a canal and a water balance is conducted on the depletion of the stored volume over time to determine Q_S (shown schematically in Fig. 1.6). This technique avoids the disadvantages of the inflow-outflow method described in Section 1.4.2.1. However, the method does not account for impacts on seepage that may be due to the influence of flow velocity on perimeter shearing stress and flow depth variation. Pondage also can result in deposition of otherwise flow-entrained sediments onto the canal perimeter thereby altering seepage.

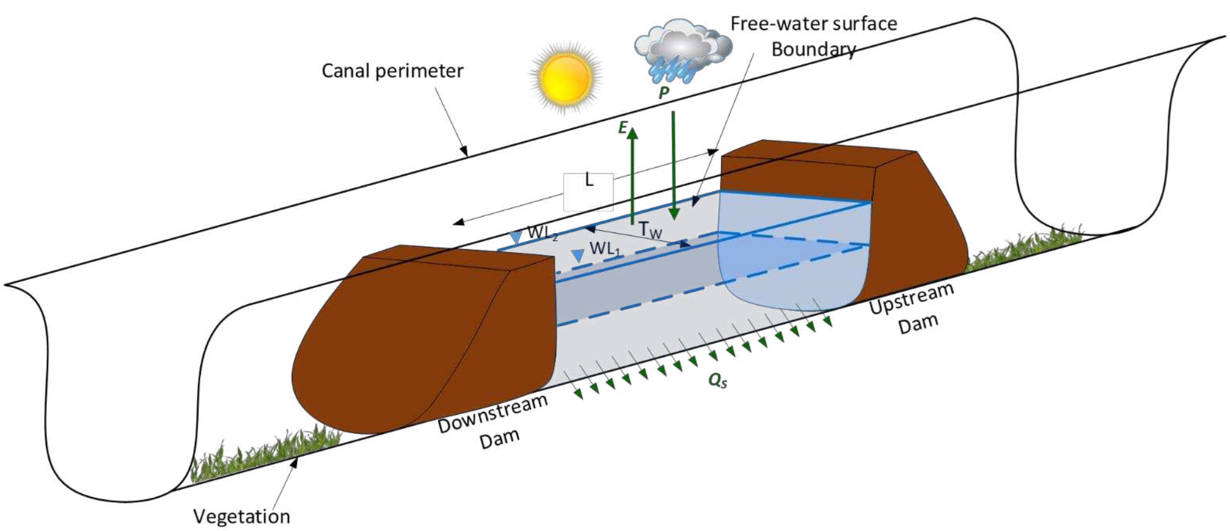

Figure 1.6: Illustration of the ponding method of measuring seepage along the reach of an irrigation canal.

The water level variation in the ponded reach over time can be either recorded manually or with water level loggers. Besides the dropping water level, other inflows and outflows such as the surface water evaporation, the precipitation, and any diversions or inflows returning from irrigated lands need to be accounted for. The value of Q_S [m^3/s] using the ponding method can be calculated as

$$Q_S = \frac{\overline{T}_w L\left[(WL_2 - WL_1) - E + P\right]}{(t_2 - t_1)} \tag{1.2}$$

where $\overline{T}_w$ is the average water surface top width [m] along the reach between times t_1 [s] and t_2 [s], L is the length of the ponded channel reach [m], WL_1 and WL_2 are the water levels [m] along the reach at t_1 and t_2, respectively, E is the water surface evaporation [m] between times t_1 and t_2, and P is the precipitation [m] between times t_1 and t_2. A detailed account of the ponding method can be found in ANCID (2003) and Alam and Bhutta (2004).

The 13 reviewed ponding studies in untreated earthen canals are summarized in Table 1.2. The reviewed papers include results from a total of 74 conventional ponding tests. Numerous other tests were conducted by Moavenshahidi et al. (2014, 2015, 2016) within a large irrigation canal network using an innovative channel control algorithm as described later in this section. Additional details for each ponding test on untreated earthen canals are summarized in Table S2 in Supplemental Material: location, canal name, perimeter soil type, typical canal flow rate, average wetted perimeter, and total wetted perimeter area.

Like the inflow-outflow studies, most reviewed studies using the ponding method lack a thorough documentation of the pertinent study elements (Fig. 1.3). The papers by Iqbal et al. (2002) and Burt et al (2010) contain the most comprehensive documentation. About 40% of the studies provide information about typical operating flow rates in the canals in which the ponding tests were conducted. These flow rates ranged from 0.013 to 2.1 m^3/s, indicating that ponding tests reported in the literature were generally performed on canal test reaches of considerably smaller flow capacity than those reported for inflow-outflow tests. The average length of the canal test reach for reported ponding studies was about 0.6 km, much shorter than the 5.2 km for the reported inflow-outflow studies.

In their study of 13 canals in southern Alberta, Canada, Iqbal et al. (2002) reported seepage rates Q_S for specific categories of canal perimeters soils. However, only a range of values for each category is provided, not individual values for each test.

Of the reviewed ponding studies, only Alam and Bhutta (2004) reported results for both ponding and inflow-outflow tests conducted in the same canals. The researchers found that values from ponding tests in six different canals were lower than values from inflow-outflow tests conducted in the same canals; however, data for the two methods were not gathered from the same canal reaches. The lack of such comparative data from the same canal test location constitutes a marked gap in the canal seepage literature.

A common question related to canal seepage losses concerns what proportion of the loss occurs through the canal banks versus through the canal bed. Burt et al. (2010) used the ponding method on five earthen canals in California, USA, to address this question. The study included a comparison of seepage loss reductions after (a) compaction of the canal sides and bed and (b) only compaction of the sides, revealing that most of the seepage occurs through the canal bed. The average Q_S reductions for the two cases were found to be 0.127 m/day and 0.027 m/day, respectively.

Conducting ponding tests of seepage by constructing temporary dams in a canal may not always be necessary. Moavenshahidi et al. (2014, 2015, 2016) applied a novel approach in Australia, using a technology called total channel control, which allows automatic control of all hydraulic structures and monitoring of flow rates and depths throughout the canal water delivery system. The researchers used the total channel control technology during the period of canal closure to analyze ponding conditions along canal reaches. Since the total channel control for the study was installed over an entire irrigation district with a 514-km total length of canals (including main, supply, and other canals), many ponding tests were essentially conducted over very long canal reaches. The papers provide a detailed description of the total channel control model, the study design, and the surface water evaporation; however, no information is provided about the size of the canals in the system, though the range of typical flow rates is reported. Reported results do not attribute Q_S values to specific canals but instead provide general analyses for the entire system. The median values of Q_S in m/day reported for these studies were calculated based on 778, 1838, and 21 ponding tests, respectively (results summarized in Table 1.2). Compared to values reported in studies using conventional ponding tests, these values are typically one to two orders of magnitude lower. This is likely since, in contrast to conventional ponding tests which routinely target canal reaches where seepage losses are suspected to be relatively high, this approach was applied over an entire canal delivery network.

1.5.3 Point measurements in untreated earthen canals

The earliest journal articles on irrigation canal seepage provide data from point measurements. In contrast to inflow-outflow and ponding tests that quantify Q_S over reach scales of 10 to1000 m within a canal, point measurements focus on localized seepage losses over scales of 0.01 to 1 m. The most common and traditional means of point measurement in canals is using a seepage meter. Seepage meters typically consist of a bell housing fabricated from metal connected to a measuring cup (small reservoir) via flexible tubing as shown schematically in Fig. 1.7. Sometimes a seepage bag containing a known volume or weight of water is used in connection to the seepage meter to measure the amount and direction of seepage flux. Rosenberry et al (2020) describes seepage meters and presents a detailed review of their history for measuring groundwater-surface water exchange in a variety of settings.

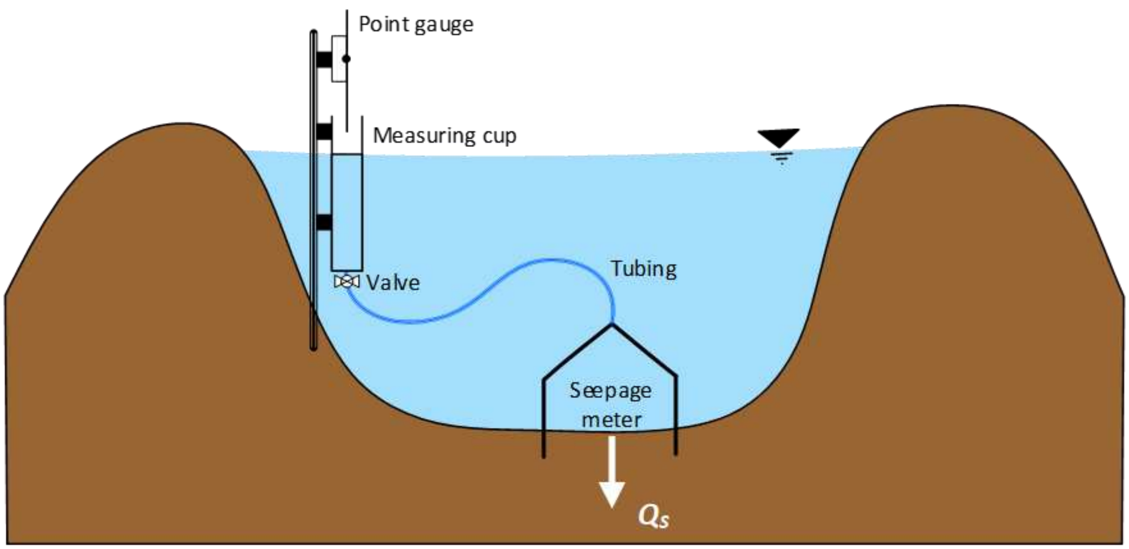

Figure 1.7: Conceptual drawing of a Bell-type seepage meter (modified from Hotchkiss et al 2001).

Here, we present results from seven published studies reporting on point measurements of canal seepage as summarized in Table 1.3. The reported Q_S values span a larger range than those reported in Table 1.2 for the inflow-outflow and ponding methods, reflecting the markedly smaller measurement scale compared to the reach scale and the fine scale variability in canal perimeter K. Similar to published inflow-outflow and ponding studies, very few published articles on point measurements report details on influencing factors such as canal perimeter soil characteristics, conditions of adjacent groundwater, canal geometry, vegetation, canal water properties, etc. (Fig. 1.4).

In the most intensive point measurement study we identified, Worstell (1976) presents seepage meter measurements taken every 30 m along a 4.8-km long reach of a canal in Idaho, USA (a total of 160 measurements). However, no details are presented about the type of seepage meter used or the measurement methodology. Khan et al (2008) report a total of 243 point measurements from 19 field channels in New South Wales, Australia using an Idaho seepage meter but do not provide the individual data points. Rather, basic statistics of the measured data are reported for each channel. Khan et al. (2009) used a portion of the data set reported in Khan et al. (2008) to test against seepage estimates made with geophysical and artificial intelligence techniques and included 75 of the individual point measurements. In an investigation using custom-built infiltrometers similar to seepage meters, Grismer (2021) described a majority of the pertinent elements listed in Section 1.4 in reporting 30 point measurements of seepage along a 13 to 15-km canal reach in California.

Table 1.3: Summary of reviewed papers on field measurement of seepage from untreated earthen canals using the point measurement method.

References	Type of seepage meter used	No. of tests performed	Q_S average (range) *(m/day)*
Bouwer and Rice (1963)	Bell	3	5.96 (0.45-12.19)
Worstell (1976)	--	160	0.79 (0.02-5.74)
Hotchkiss et al. (2001)	Bell	6	1.48[1] (0.37-2.52)
Khan et al. (2008)	Idaho	253	0.01 (0.0003-0.108)[2]

Khan et al. (2009)	Idaho	75	0.023 (0.01-0.073)
Akbar et al (2019)	Idaho	--	0.021 (0.007-0.057)[3]
Grismer (2021)	Customized infiltrometers	30	2.4 (0.00030 - 11)

Notes: 1 – Values are averages of two test replications
2 – Range of average seepage reported for 19 different canals
3 – Average of average seepage rates reported for different soil types

1.5.4 Evaluation of measured seepage data for untreated earthen canals

The respective distributions of Q_S measured in untreated earthen canals using inflow-outflow, ponding, and point measurement methods across all reviewed studies are plotted as frequency histograms in Fig. 1.8. Values reported for the reach-scale methods are provided in (m^3/s)/km. Also plotted for all methods are values of Q_S in m/day, normalized by available canal perimeter area data, and revealing shapes that are more typical of skewed probability distributions.

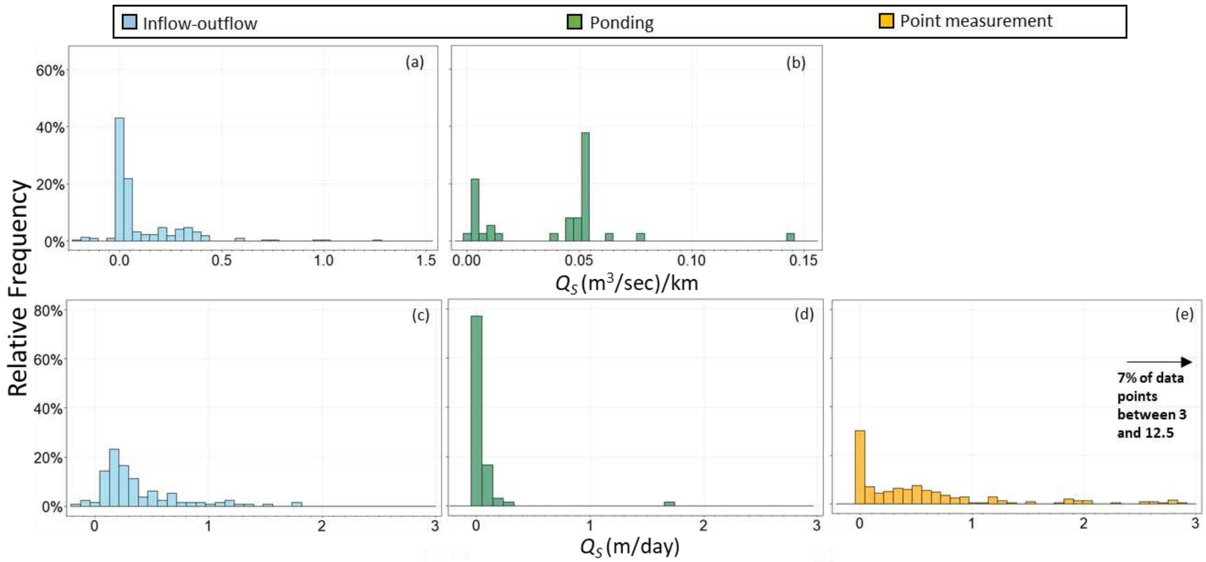

Figure 1.8: Frequency histograms of seepage in all untreated earthen canals reported in the peer-reviewed literature, (a) measured with the inflow-outflow method in units of $(m^3/s)/km$, (b) measured with the ponding method in units of $(m^3/s)/km$, (c) measured with the inflow-outflow method in normalized units of m/day, (d) measured with the ponding method in normalized units of m/day, and (e) measured with the point measurement method in normalized units of m/day.

The peer-reviewed literature is sufficient to allow untreated earthen canal data to be separated into clayey and loamy categories which are presented in Fig. 1.9 as box and whisker plots along with a category containing all untreated earthen canal perimeter data, in $(m^3/s)/km$ for the reach-scale methods and in the normalized units m/day for all methods in Fig. 1.10. Summary statistics for the three measurement methods are given in Table 1.4, providing a sense of the order of magnitude of Q_S observed in actual field settings. Variability in the data, as indicated by the standard deviation (SD) and the coefficient of variation (CV) across all tests in earthen canals, is relatively large, reflective of the differences in field conditions and methodologies across the different reported studies. The higher variability in the point measurement data indicates the much smaller scale at which the data are gathered compared to the reach scale.

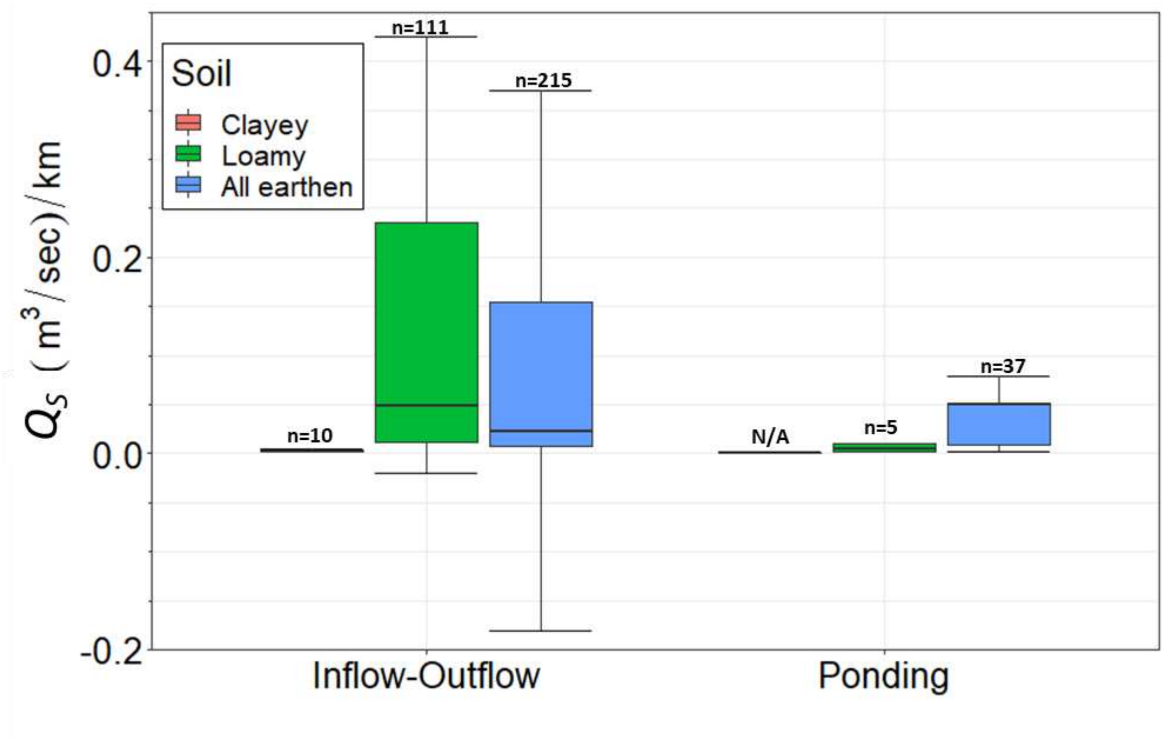

Figure 1.9: Box-and-whisker plots of seepage, Q_S, in clayey, loamy, and all earthen canal perimeter soils measured by the inflow-outflow and ponding methods in units of (m^3/s)/km. Bold line is the median value, upper and lower box limits are the 25th and 75th percentile values; and the whiskers are minimum and maximum values.

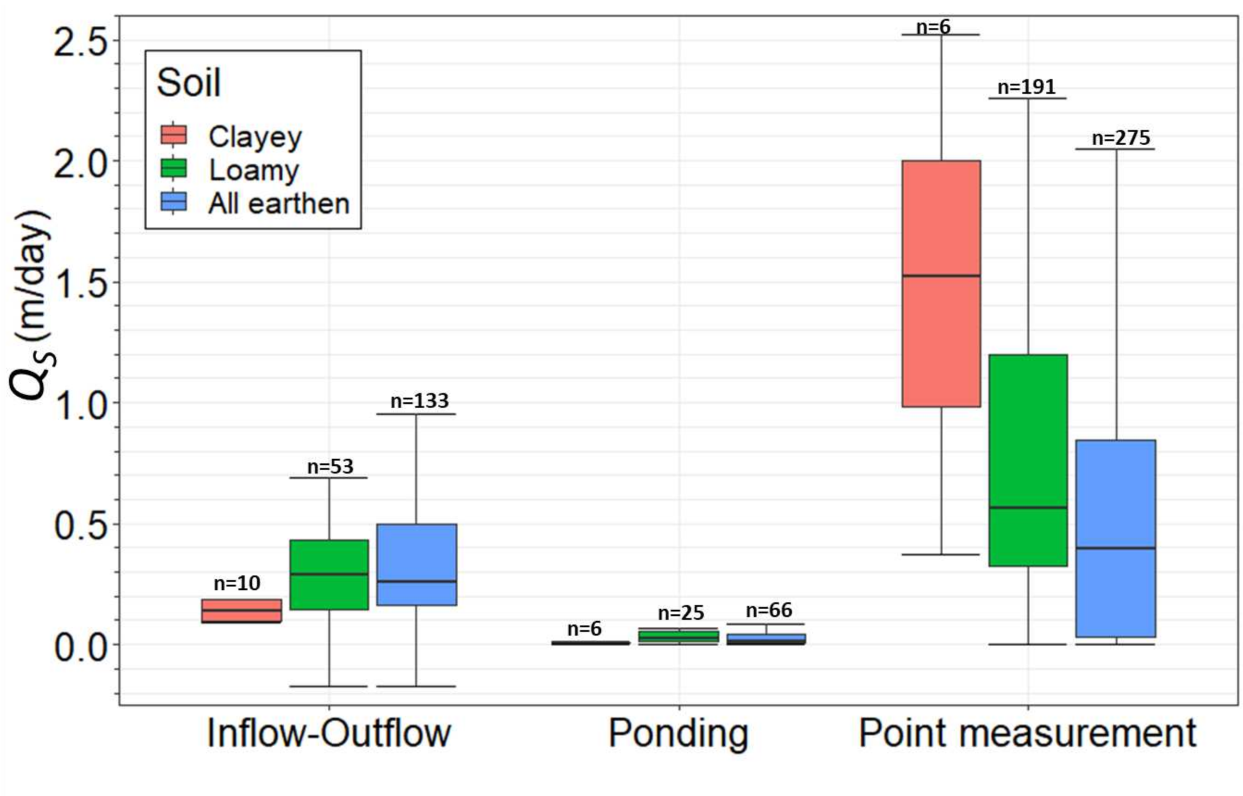

Figure 1.10: Box-and-whisker plots of seepage, Q_S, in clayey, loamy, and all earthen canal perimeter soils measured by the inflow-outflow, ponding, and point measurement methods in normalized units of m/day. Bold line is the median value, upper and lower box limits are the 25th and 75th percentile values; and the whiskers are minimum and maximum values.

Table 1.4: Summary statistics of seepage measured in untreated clayey, loamy, and all earthen canals using the inflow-outflow, ponding, and point measurement methods.

Material	Method	Unit	Count	Mean	SD	CV (%)	min	max	75th percentile
Clayey	Inflow-Outflow	*(m³/sec)/km*	10	0.0027	0.0011	41	0.0014	0.0043	0.0038
		m/day	10	0.14	0.047	34	0.090	0.19	0.19
	Ponding	*(m³/sec)/km*	--	--	--	--	--	--	--
		m/day	6	0.0082	0.0059	72	0.0035	0.020	0.0090
	Point measurement	*m/day*	6	1.48	0.80	54	0.37	2.52	2
Loamy	Inflow-Outflow	*(m³/sec)/km*	111	0.12	0.13	111	-0.020	0.43	0.24
		m/day	53	0.32	0.26	82	-0.17	1.15	0.43
	Ponding	*(m³/sec)/km*	5	0.014	0.020	147	0.002	0.05	0.01
		m/day	25	0.058	0.076	130	0.0032	0.28	0.056
	Point measurement	*m/day*	191	1.17	1.82	155	0	12.34	1.20
All earthen	Inflow-Outflow	*(m³/sec)/km*	215	0.10	0.19	180	-0.21	1.26	0.15
		m/day	133	0.37	0.36	97	-0.17	1.81	0.50
	Ponding	*(m³/sec)/km*	37	0.038	0.029	76	0.0016	0.14	0.052
		m/day	66	0.063	0.22	346	0.0032	1.74	0.045
	Point measurement	*m/day*	275	0.92	1.76	192	0	12.34	0.84

Reported data for the three methods are not directly comparable since the data are not derived from the same sites and conditions. However, evaluation of the normalized data for the two reach-scale methods in canals in the clayey, loamy, and all-earthen categories reveal reported Q_S for inflow-outflow studies to be one to two orders of magnitude higher than those for ponding studies. The difference in mean values of Q_S for all earthen canals measured using the inflow-outflow method and using the ponding method is statically significant at a significance level of 0.05 (pooled variance t-test). As discussed in Section 1.3, data from laboratory studies have indicated decreasing K with increasing total suspended solids in the ponded water of permeameters due to sediment deposition and clogging, suggesting that a similar mechanism may be at play within the immobile sediment-containing water of a canal ponding study. Additionally, in vegetated canals the drag imposed on the stems and foliage of vegetation by the flowing water in an inflow-outflow test might cause disruption of the adjacent perimeter soil, creating preferential flow pathways, hypothetically resulting in higher Q_S than in ponded conditions. This is akin to wind-induced movement of stems that longitudinally displaces stem-adjacent surface soils and creates flow-enhancing macropores (Martinez-Meza and Whitford 1996, Téchler and Berthier 2023). Values of Q_S reported for point measurements are on average larger than those reported for the reach-scale methods. This may reflect in part that locations selected for point measurement are often "hotspots" where Q_S along a canal is suspected by investigators to be high. Differences in the mean values of Q_S reported for point measurements and those reported for the inflow-outflow method and for the ponding method were both statically significant at a significance level of 0.05 (Welch-Satterthwaite t-test for unequal variances).

1.6 Control of canal seepage

1.6.1 Treatment methods for canal seepage control

Seepage from earthen canals can be reduced by installation of liners, soil compaction, or application of sealants. Common liners include concrete and geomembranes. Soil compaction involves homogenization and densification of canal perimeter soils to reduce soil *K*. Sealants reduce the *K* of canal perimeter soils and are typically linear anionic polymers. Herein we provide brief overview of these methods to reduce canal seepage. We then report and discuss the effectiveness of these methods based on peer-reviewed field studies.

1.6.1.1 Hard-surface liners

Hard-surface liners consist of concrete, bricks, asphalt, and stone (primarily used for bank stabilization not seepage mitigation; Ali et al. 2021). The most common form of hard-surface liners is concrete. Concrete liners that are constructed in the field are called in-situ concrete liners; pre-cast slabs of concrete can also be used. Concrete mix specifications, use of water-stop joints, and subgrade conditions impact concrete liner performance and stability (Rahimi and Abbasi 2007, Al-adili et al. 2016, Sarand and Hajialilue-Bonab 2017, Zia and Ali 2017). The effectiveness of concrete liners decreases with age due to concrete degradation (Raza et al. 2013) and is exacerbated by extreme weather (He et al. 2021). Concrete degradation can be limited by mix designs that limit cracking, such as fiber reinforcing (Zia and Ali 2017). Concrete liners can also be combined with other lining methods to lower the overall cost and improve effectiveness and longevity (Kahlown and Kemper 2005, Rahimi et al. 2011, Li et al. 2013, Bonaiti and Fipps 2021).

1.6.1.2 Flexible membrane liners

Flexible membrane liners, termed geomembranes, are increasingly used to reduce canal seepage. These waterproof polymer sheets are typically composed of polyolefins, such as high-density polyethylene (HDPE), although a variety of formulations are commercially available for different applications. An intact geomembrane is impermeable to water, but geomembranes are inevitably punctured during installation. Geomembranes can also be punctured in service and become less flexible and prone to stress cracking as they degrade with time. Burial of a geomembrane, either with soil or concrete decreases the rate at which these polymeric materials degrade (Comer et al. 1996). Of note, geomembrane technology has advanced significantly since initial use began in the 1950s.

Most studies of geomembrane liners present only a qualitative perspective on the efficacy of seepage reduction (e.g., Kraatz 1977, Wilkinson 1985, Snell 2001, Morgado et al. 2012, Elkamhawy et al. 2021). For example, Snell (2001) presents a thorough analysis of the construction of different configurations of geomembrane liners supported by qualitative evaluation of durability and water tightness, but no pre-and-post-liner seepage rates are provided. A general comparison of the merits and limitation of geomembranes versus other liner types is also provided in Ding and Gao (2020). At the time of writing, we were only able to find one peer reviewed journal article that provided a rigorous field-focused comparison of the effectiveness of geomembrane lining (viz., Han et al. 2020). Unfortunately, the liner at the time of evaluation was severely damaged; thus, it does not represent the typical outcomes of a geomembrane liner. The lack of rigorous field testing of geomembrane lining represents a surprising gap in the literature.

1.6.1.3 Compacted earth liners

The mechanical compaction of the soil in the perimeter of the canal has also shown potential in reducing seepage (Kahlown and Kemper 2004, Burt et al. 2010, Akbar et al. 2013). Compaction reduces perimeter soil *K* via a reduction in porosity. Macroscopic preferential flow paths, such as desiccation cracks, root casts, worm tubes, etc., are also reduced or eliminated via compaction, further reducing seepage.

1.6.1.4 Sealants

Water-soluble polymer sealants can be used to temporarily reduce canal seepage. Polyacrylamides (PAMs), typically in a linear anionic form (LAPAM), have been used most extensively as potential canal sealants (Young et al 2009, Lund et al 2021, Martin and Gates 2014). Due to concern for the eco-environmental friendliness of PAMs (Sojka et al. 2007, Woodrow et al. 2008, Acharya et al. 2010, Guezennec et al. 2015, and Buczek et al. 2017), plant-based polysaccharides such as xanthan gum have also been proposed for agricultural applications (Berninger et al. 2021) and currently are under investigation.

Waste materials such as rice hull ash and water treatment plant sludge have also been used as sealing agents along leakage-prevalent areas in canals (Akbar et al. 2013).

1.6.2 Measurement of seepage from treated canals

We considered 15 peer-reviewed articles that employed inflow-outflow and ponding methods to measure seepage in treated canals. A synopsis of these studies along with a summary of their main results are presented in the following subsections.

1.6.2.1 Inflow-outflow measurements in treated canals

Summaries of Q_S measured in the seven reviewed inflow-outflow studies in treated canals, including the treatment type along with averages and ranges of reported Q_{US} values, are presented in Table 1.5. For comparison, summaries of the reviewed ponding studies on treated canals (discussed in Section 1.6.2.2) are also included in Table 1.5. The reviewed papers include results from a total of 61 inflow-outflow tests in concrete-lined canals and 89 in polymer sealant treated canals. Reported test reach lengths range between 0.0047 and 9.09 km and flow rates range between 0.037 and 24.62 m^3/sec. Table S3 in Supplemental Material summarizes additional details for each inflow-outflow test.

Table 1.5: Summary of reviewed papers on field measurement of seepage from treated canals using the inflow-outflow and ponding methods.

References	No. of tests performed	Canal treatment	Test reach length average (range) *km*	Q_{US} average (range) *m³/sec*	Q_S average (range) *(m³/sec)/km*	Q_S average (range) *(m/day)*
			Inflow-Outflow			
Kilic and Tuylu (2010)	23	Concrete	0.46 (0.047-1.79)	3.47 (0.054-12.5)	0.36 (0.010-2.87)	--
Akkuzu (2012)	26	Concrete	2.24 (0.074-0.40)	2.35 (0.04-17.51)	0.17 (0.0010-0.95)	--
Raza et al. (2013)	5	Concrete	(0.05-0.055)	0.040 (0.037-0.051)	0.0096 (0.0076-0.013)	--
Shah et al. (2020)	7	Concrete	6.9 (5.04-9.09)	0.88 (0.44-1.27)	0.0017 (0.0014-0.0021)	0.03 (0.012-0.044)
Uribe et al. (2013)	31	Polymer sealant	1.56 (0.51-3)	7.65 (0.12-24.62)	0.086 (-0.36-0.84)	--

Martin and Gates (2014)	28	Polymer sealant	4.24 (3.9-4.8)	3.3 (1.83-4.40)	0.0049 (-0.031-0.041)	0.040 (-0.44-0.33)
Lund et al. (2021)	30	Polymer sealant	4.31 (3.9-5.3)	3.43 (1.83-5.36)	0.0024 (-0.073-0.041)	0.020 (-0.58-0.33)
			Ponding			
Kishel (1989)	9	Concrete	9.6	-- [2]	0.156 (0.091-0.289)	0.001 (0.0006-0.0017)
Kahlown and Kempe (2005)	44	Concrete and/or masonry	0.65 (0.081-3.51)	--	0.0068 (0.0009-0.026)	0.40 (0.044-1.782)
Raza et al. (2013)	5	Concrete	(0.05-0.055)	--	0.0013 (0.0008-0.0026)	--
Zhang et al. (2017)	2	Concrete	0.03	--	--	(0.068 & 0.104)
Han et al. (2020)	4	Concrete/ geomembrane or composite	0.03	--	0.0018 (0.0005-0.0036)	0.089 (0.027-0.18)
Fernald and Guldan (2007)	1	Stone bank	0.08	--	--	0.107
Wilkinson (1985)	2	Geomembrane	0.16 and 0.21	--		(1.1-2.5)
Kahlown and Kemper (2004)	8	Compacted earth and natural reinforcement	0.03	--	0.029 (0.0008-0.14)	--
Burt et al. (2010)	5	Compacted earth	1.23 (0.30-3.12)	--	--	0.027 (0.0056-0.057)

The inflow-outflow studies presented by Martin and Gates (2014), and Lund et al. (2021) report on the highest fraction of the pertinent study elements described in Section 1.4.1. All reviewed studies reported values of Q_{US}, spanning from 0.04 to 24.6 m^3/s across the studies.

1.6.2.2 Ponding measurements in treated canals

Nine ponding studies on treated canals are summarized in Table 1.5. Six of the reviewed studies reported typical operating flow rates for the canals tested, which ranged 0.03 to 40.6 m^3/s. The details of the ponding methodology employed were described by only two sources, and none provided details of the cross-section geometry. The average length of the treated canal test reach for reported ponding studies was about 1.5 km, compared to 2.8 km for the reported inflow-outflow studies. Table S4 in Supplemental Material summarizes additional details for each ponding test.

1.6.2.3 Evaluation of measured seepage data for treated canals

Frequency histograms of Q_S values measured in all treated canals using inflow-outflow and ponding methods across all reviewed studies are plotted in $(m^3/s)/km$ and in m/day in Fig. 1.11.

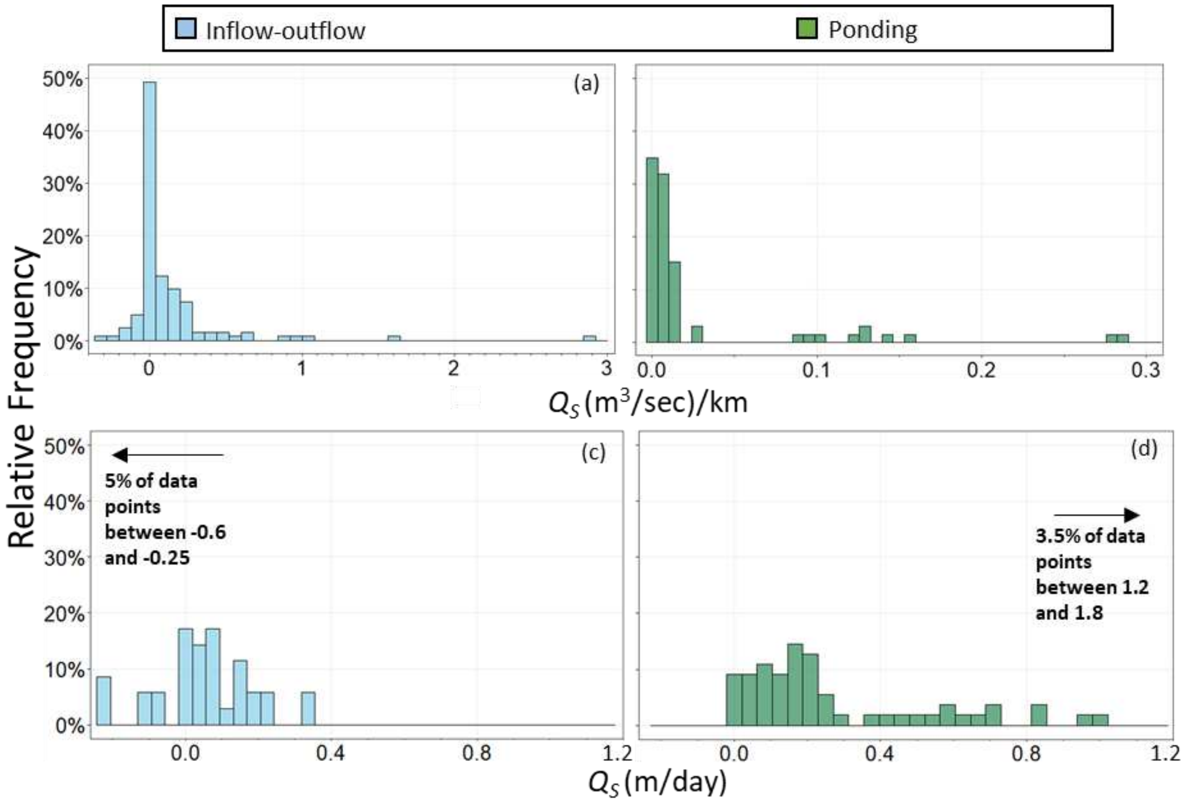

Figure 1.11: Frequency histograms of seepage, Q_S, in all treated canals reported in the peer-reviewed literature, (a) measured with the inflow-outflow method in units of $(m^3/s)/km$, (b) measured with the ponding method in units of $(m^3/s)/km$, (c) measured with the inflow-outflow method in normalized units of m/day, (d) measured with the ponding method in normalized units of m/day.

Box and whisker plots of Q_S for the major treatment categories along with all treated canal perimeter data for the two measurement methods, in $(m^3/s)/km$ and in the normalized units of m/day, respectively, are shown in Fig. 1.12 (a) and 1.12 (b). Summary statistics for the treatment categories and for the two measurement methods are given in Table 1.6. As in the case of the untreated earthen canals, reported values for the two methods are not directly comparable since they are not derived from the same sites and conditions.

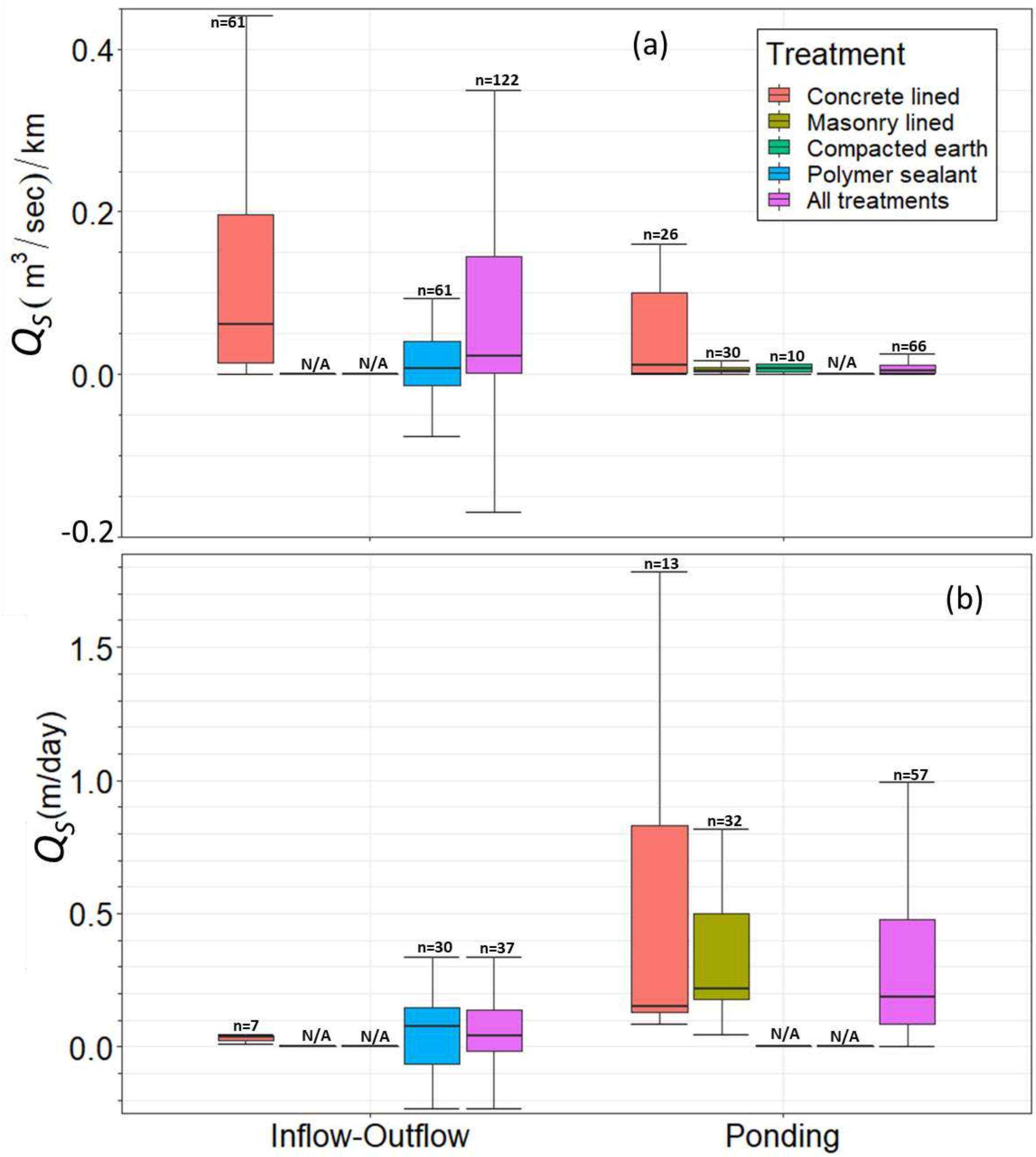

Figure 1.12: Box-and-whisker plots of seepage, Qs, in concrete lined, masonry lined, compacted earth, polymer treated, and all canal perimeter soils measured by the inflow-outflow and ponding methods in units of (a) (m^3/s)/km and (b) (m/day). Bold line is the median value, upper and lower box limits are the 25th and 75th percentile values; and the whiskers are minimum and maximum value

Table 1.6: Summary statistics of Q_s measured in treated canals using the inflow-outflow and ponding methods.

Treatment	Method	Unit	Count	Mean	CV (%)	min	max	75th percentile
Concrete	Inflow-Outflow	$(m^3/sec)/km$	61	0.21	213	0.001	2.87	0.20
		m/day	7	0.031	40	0.012	0.045	0.039
	Ponding	$(m^3/sec)/km$	26	0.058	145	0.0008	0.29	0.10
		m/day	13	0.54	111	0.084	1.78	0.83
Masonry	Inflow-Outflow	$(m^3/sec)/km$	--	--	--	--	--	--
		m/day	--	--	--	--	--	--
	Ponding	$(m^3/sec)/km$	30	0.0063	70	0.0009	0.017	0.0093
		m/day	32	0.34	72	0.045	1.00	0.50
Compacted earth	Inflow-Outflow	$(m^3/sec)/km$	--	--	--	--	--	--
		m/day	--	--	--	--	--	--
	Ponding	*(m3/sec)/km*	10	0.024	182	0.0008	0.14	0.013
		m/day	--	--	--	--	--	--
Polymer Sealant	Inflow-Outflow	$(m^3/sec)/km$	61	0.045	416	-0.37	0.84	0.040
		m/day	30	0.021	994	-0.59	0.34	0.15
	Ponding	$(m^3/sec)/km$	--	--	--	--	--	--
		m/day	--	--	--	--	--	--
All Treatments	Inflow-Outflow	$(m^3/sec)/km$	122	0.13	275	-0.37	2.87	0.14
		m/day	37	0.023	820	-0.59	0.34	0.14
	Ponding	$(m^3/sec)/km$	66	0.028	212	0.00054	0.29	0.012
		m/day	57	0.32	116	0.001	1.78	0.48

Comparing the results in Table 1.6 with those in Table 1.4 for untreated canals, we observe that treated canals can exhibit seepage losses that are as large as those measured in untreated earthen canals. This is due in part to treated canals in which most of the reported inflow-outflow and ponding tests were conducted, except for those treated with polymer sealants, being subject to some degree of deterioration.

Across all treated canals, Q_S in normalized units from ponding tests exceeds that from inflow-outflow tests by about an order of magnitude, opposite the results reported for untreated earthen canals. The difference in mean values of Q_S for all treated canals measured using the ponding method and using the inflow-outflow method is statically significant at a significance level of 0.05 (pooled variance t-test). This may be due to ponding tests being used more often when liners are more degraded and nearing replacement while inflow-outflow tests are used when canals are operational. We hypothesize that this outcome also may point to the influence that sediment deposition on the canal bed may play in lowering Q_S measured under ponding conditions in earthen canals compared to flowing conditions, an effect that is largely absent in treated canals.

1.6.2.4 Assessment of seepage reduction by treatment methods

Most studies on canal treatments to reduce seepage offer only a general or comparative description of the treatment methods, studies using numerical methods that simplify field conditions, or field studies not reporting data on the seepage rates before and after a specific treatment. Table 1.7 presents a summary and references to the reviewed papers on field evaluation of treatment methods discussed in the following paragraphs. While some field-focused studies did not report any information that could help in calculating the percent reduction in seepage, the average age and the condition of the lining at the time of evaluation are summarized for the majority of the studies.

Table 1.7: Summary of reviewed papers on canal seepage control technologies, their age, condition, and percent reduction in seepage.

Reference	Canal treatment	Age of treatment in years Avg(range)	Condition of treatment at the time of evaluation	Percent seepage reduction
Hard-surface liners				
Comer et al. (1996)	Concrete-covered geomembrane	3.7 (1-8)	Good (anecdotally lower seepage rates)	--
Comer et al. (1996)	Bituminous liner	1 and 3	Good (no serious damage)	--
Snell (2001)	Concrete	0-5	Fair (subject to the quality of joint sealant and its installation)	--
Snell (2001)	Concrete-covered geomembrane	0-5	Good	--
Kahlown and Kemper 2005	Brick masonry (plastered/unplastered)	1	New	94
Kahlown and Kemper 2005	Concrete	1	New	96
Kahlown and Kemper 2005	Concrete	1	New	94
Kahlown and Kemper 2005	Brick masonry (plastered/unplastered)	24	Good (no serious damage)	79
Kahlown and Kemper 2005	Concrete	24	Average to poor	57
Kahlown and Kemper 2005	Concrete	24	Good (no serious damage)	86
Zhang et al. (2017)	Concrete	< 1	--	53
Han et al. 2020	Concrete-covered geomembrane	0	New	86
Han et al. 2020	Concrete-covered geomembrane	3	Damaged with holes and cracks	68
Han et al. 2020	Concrete		Damaged with holes and cracks	57
Bonaiti and Fipps 2021	Concrete-covered geomembrane	10.7 (5-18)	Fair to excellent	--
Flexible membrane liners				
Wilkinson (1985)	Geomembrane	1	New	--

Comer et al. (1996)	Geomembrane	12	Satisfactory (continues to reduce seepage)	--
Comer et al. (1996)	Geomembrane	3	Satisfactory (no serious deterioration except for very few puncture holes)	--
Snell (2001)	Geomembrane	0-5	Poor to good (unlikely to reduce seepage by more than 60%)	--
Han et al. 2020	Geomembrane	3	Damaged with some large holes resulting from weed roots	11
Bonaiti and Fipps 2021	Geomembrane	10.7 (5-18)	Fair to serious damage except for a few projects	--
		Compacted earth		
Kahlown and Kemper 2004	Compacted earth	< 1	New	78
Burt et al. (2010)	Compacted earth (entire and partial canal average)	< 1	New	62
Burt et al. (2010)	Compacted earth	< 1	New	85
Burt et al. (2010)	Compacted earth (sides only)	< 1	New	31
Burt et al. (2010)	Compacted earth (sides only) adjusted	< 1	New	72
Burt et al. (2010)	Compacted earth (parts of sides only)	< 1	New	16
Burt et al. (2010)	Compacted earth (parts of sides only) adjusted	< 1	New	33
Akbar et al. (2013)	Compacted earth	< 1	New	55
		Sealants		
Uribe et al. (2013)	LAPAM	< 1	New	64
Marting and Gates (2014)	LAPAM	< 1	New	88
Lund et al. (2021)	LAPAM	< 1	New	94
		Other		
Akbar et al. (2013)	Waste material	< 1	New	58

The percent reduction for the hard-surface liners ranged between 53 and 96%. The average of the hard-surface liners that were not more than five years old was about a 78% reduction. Although the effectiveness of hard-surface liners is subject to the age and the condition of the lining, concrete liners have shown up to 86% reduction in seepage even after 24 years in some cases.

For geomembranes, unfortunately, we were unable to identify many studies reporting a percent reduction based on field measurements in any form. The sole study identified reported an (only) 11% seepage reduction for a very damaged geomembrane liner.

Compacted earth treatment results in a broad range of seepage reduction, ranging from 16 to 85%. Of note, only three of the reported values are from canals with entirely compacted sections; these cases showed an average seepage reduction of 73%. For most studies, only a portion of the studied reaches were compacted.

The percent reduction by polymer sealants ranged between 64 to 88% and averaged 82%. However, these results are for tests conducted within three months after application; sealants have not been demonstrated to be effective beyond the water year in which they are applied.

Given the small data set and the means of the percent reduction in different treatment methods being close, differences in the seepage reduction results for all categories except for the geomembrane appear to be statistically insignificant.

1.7 Summary, perspective, and the way forward

1.7.1 The canal seepage situation

Though estimation of accurate quantities is elusive, the volumes of water extracted globally from various sources to support the vital enterprise of irrigated agriculture are vast (Puy et al. 2022a, 2022b; Meier et al. 2018). Upon extraction, most of these waters are directed through canals, predominately earthen, to their points of use. The long-recognized and ubiquitous process of seepage losses along these watercourses is attracting heightened attention in this time of water scarcity and competition. Herein we have compiled, organized, and assessed peer-reviewed literature to focus on clarifying the current situation in the field.

We review the best available evidence of the magnitude of canal seepage losses, from both untreated earthen canals and treated canals, obtained from field measurements using the inflow-outflow, ponding, and point measurement methods. We uncover varying results that reflect the varying physical factors at measurement sites, as well as the differing procedures, tools, and scales of application. To our knowledge, no published studies have yet compared the three measurement methods on the same canal reaches at the same time to support a clear prioritization of one method over the others. Point measurements reveal that seepage rates fluctuate enormously along canals, even between proximate locations, suggesting the limitation of this method for efficiently quantifying seepage losses at the reach-scale. The ponding method, despite being a direct reach-scale field approach, is not designed to capture the dynamics of irrigation canal flow. Ponding tests necessarily use stagnant water that allows settling of suspended solids and does not impose stresses on vegetative elements that may disrupt the canal perimeter soil. These conditions are likely liable in part for the lower seepage rates reported in the literature for ponding studies compared to those for inflow-outflow tests in earthen canals. However, the inflow-outflow method encompasses two main challenges – error in the flow measurements and the need to maintain a control volume without flow diversions along the test reach – which can influence the measurement quality.

Irrespective of discrepancies between the measurement techniques, the best reckoning from published field measurements is that seepage losses from earthen canals range on the order of 0.1 to 1 m^3 daily through every square meter of wetted canal perimeter area. Given that the total worldwide extent of irrigation canals is estimated in the millions of kilometers, and that the perimeter of these canals ranges from one to hundreds of meters, seepage is an enormous issue.

Fortunately, the bulk of irrigation canal seepage returns via the subsurface to the hydrologic system. The importance of these returned flows to both downstream users and to instream benefits must be considered (Grafton et al 2018, Perez-Blanco et al 2020, Hoffmann and Villamayor-Tomas 2022). Nevertheless, the difficulties created by canal seepage, e.g. lessened hydraulic effectiveness in water distribution to farms, salinity and waterlogging, environmental pollution, and nonbeneficial water consumption, are deleterious. Jägermeyr et al. (2015), estimate that non-beneficial water consumption composes about 25% of global irrigation water withdrawals, a quantity that could be significantly reduced by irrigation improvements like seepage control. Also, recent studies by Jägermeyr et al (2016) and Siderius et al (2021) demonstrate the potential of irrigation improvements to boost agricultural productivity in an economically feasible manner.

Our own studies over the course of two decades in the intensively irrigated Arkansas River Valley of Colorado underscore how important reducing canal seepage losses is to agro-environmental enhancement. Using flow and solute transport models calibrated and tested with extensive field data, including canal inflow-outflow tests, Morway et al (2013) and Shultz et al (2018) examined the potential impact of several best management practices in two regions of the Arkansas River Valley. They predict that reducing canal seepage losses by 50 to 80%, alone and in combination with other best management practices, would result in significant lowering of saline shallow groundwater tables, mitigation of nonpoint source pollution of groundwater and streams, and substantial reduction in nonbeneficial water consumption.

The time has come to address the canal seepage issue aggressively and strategically. To accomplish this will require enhanced seepage characterization for purposes of system performance evaluation and decision-making along with better means of seepage control.

1.7.2 Advancing canal seepage characterization

Characterization of the distribution of canal seepage across the array of settings within the irrigated regions of the world remains limited. Accurate measurement in the field is difficult. Quantification of the spatial and temporal variability of seepage as influenced by a wide variety of factors, both natural and engineered, needs refinement. Especially needed are investigations that focus on reach-scale seepage losses that affect overall irrigation water delivery system performance. This will require improved technology and protocols.

As discussed herein, the ponding method is disruptive to the process of getting irrigation water to crops; thus, the likelihood that the method will be resisted by farmers and canal companies is substantial. Given this, and assuming that field quantification of seepage should be realized in a manner that is most representative of typical conditions, we recommend that the inflow-outflow method should be adopted as the standard technique for quantifying reach-scale seepage from irrigation canals. We contend that the disadvantages expressed in the literature about the inflow-outflow procedure, briefly discussed under section 1.5.1, often can be largely addressed using recent improvements to devices and procedures. The sources of uncertainty in the method must always be kept in mind (Martin and Gates 2014, Lund et al 2021), but the use of well-calibrated acoustic Doppler flow-measurement devices, guided by recent enhancements to protocol at a given canal location, can reduce errors and tighten confidence bands (Pugh et al. 2021). Other recommended procedural improvements include the use of multiple replications of simultaneous flow measurement and the interchange of two personnel-equipment teams, following the same procedures, on either end of the canal test reach. Canal storage changes due to transient flow can also now be quantified with greater confidence using data from accurate water-level loggers positioned along the test reach. Nonetheless, there can be field conditions where the inflow-outflow method may not yield reliable estimates. The disadvantage of the inflow-outflow method for short canal reaches has been mentioned in Section 1.5.1. Another example is a very wide canal with unsteady flow. In such a case where the time scale of the method of flow measurement, such as an acoustic Doppler velocity profiler (ADCP), may be too large to capture the flow fluctuations at the upstream and downstream ends of the study reach, significant error in calculating seepage may result.

1.7.3 Advancing canal seepage control

Studies of the treatment methods for canal seepage control yield a large range of findings. We review and discuss several field campaigns that document seepage rates from a variety of treated canals. There is a paucity of field studies that measure seepage along the same canal reach before and after treatment. Many of the seepage rates analyzed under the treated and untreated canal categories were taken from different canals with different field conditions and do not represent a "before-and-after" comparison.

The documented comparative "before-and-after" studies of the installation of new canal treatments indicate the general effectiveness of concrete liners, compacted earth liners, and sealants in reducing seepage rates by 50 to 95%. Surprisingly, the efficacy of well-placed geomembrane liners has not been quantitatively documented in the refereed literature, revealing an important gap in current knowledge; however, qualitative evaluation of geomembranes available in the literature does reveal fair to excellent success in reducing seepage. Geomembrane liners merit additional study.

The few studies that report comparative results for old and/or damaged canal lining materials point to the recognized problems of diminished effectiveness in seepage control due to poor construction and limited durability of liners (Ding and Gao 2020). Plusquellec et al. (2019) reports that the benefits of lining for seepage control are often overestimated, resulting in the cost of lining projects outweighing the benefits, although there are other objectives that may warrant the use of permanent liners, e.g. erosion control, efficient conveyance across unstable and highly porous sand and gravel. Permanent liners such as concrete and geomembranes also have the potential to produce unintended consequences by preventing the recharge of groundwater in cases when and where groundwater recharge may be desirable. This side effect of irrigation efficiency improvement can significantly impact groundwater reserves (Dench and Morgan 2021) and the magnitude and timing of downstream return flows. A recent survey by Hrozencik (2021) of hundreds of irrigation canal companies across the United States reveals that the restriction of groundwater recharge in the presence of permanent liners is a secondary reason that most canals remain unlined. The primary reason is high cost. This underscores the importance of an effective canal treatment option that is cost-friendly and has effects that diminish after an intended window of time to allow flexibility in groundwater recharge as needed.

Polymer sealant treatments need to be further investigated, especially under conditions of full-scale implementation. Available reports from the field indicate the promise of polymer sealants for playing a prominent role in controlling canal seepage. Studies document the ability of polymer sealants to reduce canal seepage by 80% or more (Martin and Gates 2014, Lund et al 2021). Moreover, polymer sealants address the impediments to canal treatment by being inexpensive and not having the same permanence as liners. A thorough economic analysis remains to be carried out; yet, based on our past and ongoing studies, a preliminary evaluation (briefly described in Supplemental Material) indicates the average cost of polymer sealants for an irrigation season to be only about \$0.08 per m^2 of canal perimeter area (accounting for supplies, equipment, and labor) which we estimate to be less than about 3% of the annualized cost of concrete and geomembrane linings (based on costs reported by Ding and Gao 2020, Giroud and Plusquellec 2022). The requirement that polymer sealants be reapplied seasonally might be deemed a disadvantage in terms of longevity but provides the flexibility of application at rates and locations that permit a degree of seepage in seasons where groundwater recharge is preferred. Because of uncertainty as to the potential environmental impact of some synthetic polymer sealants, such as linear-anionic polyacrylamide, we envision that the treatment of earthen canals with biopolymer or co-polymer sealants would be an important step toward effective and economical canal seepage mitigation for the future.

References

Abu-Sharar, T.M. and Salameh, A.S., 1995. Reductions in hydraulic conductivity and infiltration rate in relation to aggregate stability and irrigation water turbidity. Agric. Water Mgmt., *29*(1), pp.53-62. https://doi.org/10.1016/0378-3774(95)01184-6

Acharya, K., Schulman, C., and Young, M. H. 2010. Physiological response of *Daphnia magna* to linear anionic polyacrylamide: Ecological implications for receiving waters. Water Air Soil Poll., 212, 309 – 317. https://doi.org/10.1007/s11270-010-0344-x

Adeyemo, T., Kramer, I., Levy, G.J. and Mau, Y., 2022. Salinity and sodicity can cause hysteresis in soil hydraulic conductivity. Geoderma, *413*, p.115765. https://doi.org/10.1016/j.geoderma.2022.115765

Akbar, S., Abbas, A., Hanjira, M. A., and Khan, S. 2013. Structured analysis of seepage losses in irrigation supply channels for cost-effective investments: case studies from the southern Murray-Darling Basin of Australia. Irrig. Sci., 31, 11 – 25. https://doi.org/10.1007/s00271-011-0290-4

Akbar, S., Kathuria, A., and Maheshwari, B. 2019. Combining imaging techniques with nonparametric modelling to predict seepage hotspots in irrigation channels. Irrig. Sci., 37, 11 – 23. https://doi.org/10.1007/s00271-018-0596-6

Akkuzu, E. 2012. Usefulness of empirical equations in assessing canal losses through seepage in concrete-lined canal. J.Irrig. Drain. Engrg., 138(5), 455–460. https://doi.org/10.1061/(ASCE)IR.1943-4774.0000414

Alam, M. M. and Bhutta, M. N. 2004. Comparative evaluation of canal seepage investigation techniques. Agric. Water Mgmt., 66(1), 65 – 76. https://doi.org/10.1016/j.agwat.2003.08.002

Al-adili, A., Abd Al-ameer, O., and Al-sharbati, A. 2016. Experimental investigation of joint filing materials performance on preventing seepage in lined open concrete canal (laboratory and field model). KSCE J. Civil Engrg., 20(5), 1936 – 1947. https://doi.org/10.1007/s12205-015-0818-x

Ali, M. A. M., Kim, J-G., Awadallah, Z. H., Abdo, A. M., and Hassan, A. M. 2021. Multiple-criteria decision analysis using TOPSIS: Sustainable approach to technical and economic evaluation of rocks for lining canals. App. Sci., 11(20), 9692. https://doi.org/10.3390/app11209692

Angelakis, A. N., Zaccaria, D., Krasilnikoff, J., Salgot, M., Bazza, M., Roccaro, P., Jimenez, B., Kumar, A, Yinghua, W., Baba, A., Harrison, J. A., Garduno-Jimenez, A., and Fereres, E. 2020. Irrigation of world agricultural lands: evolution through the millennia. Water, 12. https://doi:10.3390/w12051285

ANCID (Australian National Committee on Irrigation and Drainage), 2003. Open channel seepage and control—Vol 1.4. Best practice guidelines for channel seepage identification and measurement.

Asl, R. H., Salmasi, F., and Arvanaghi, H. 2020. Numerical investigation on geometric configurations affecting seepage from unlined earthen channels and the comparison with field measurements. Engrg. App. Comput. Fluid Mech., 14(1), 236 – 253. https://doi.org/10.1080/19942060.2019.1706639

Bakry, M.F. *and* Awad, A.A.E.-M. 1997. Practical estimation of seepage losses along earthen canals in Egypt. Water Resour. Mgmt., 11*(3),* 197–206. https://doi.org/10.1023/A:1007921403857

Barkhordari, S., Shahadany, S.H., Taghvaeian, S., Firoozfar, A.R. and Maestre, J.M., 2020. Reducing losses in earthen agricultural water conveyance and distribution systems by employing automatic control systems. Computers and Electronics in Agriculture, 168, p.105122. https://doi.org/10.1016/j.compag.2019.105122

Berninger, T., Dietz, N., and Lopez, O. G. 2021. Water-soluble polymers in agriculture: xanthan gum as eco-friendly alternative to synthetics. Microb. Biotech., 14(5), 1881 – 1896. https://doi.org/10.1111/1751-7915.13867

Bonaiti, G., and Fipps, G. 2021. Evaluation of synthetic canal lining materials in South Texas over 18 years – Final results and conclusions. Irrig. Drain., Pre-pub. https://doi.org/10.1002/ird.2639

Bouwer, H. 1965. Theoretical aspects of seepage from open channels. J. Hydraul. Engrg., 91(3), 37 – 59. https://doi.org/10.1061/JYCEAJ.0001259

Bouwer, H. 1969. Theory of seepage from open channels. In Adv. Hydrosci., 5, 121-172.

Bouwer, H. and Rice, R.C., 1963. Seepage meters in seepage and recharge studies. *Journal of the Irrigation and Drainage Division*, *89*(1), pp.17-42. https://doi.org/10.1061/JRCEA4.0000252

Bouwer, H., Myers, L. E., & Rice, R. C. 1963. Effect of Velocity on Seepage and its Measurement. Trans. Amer. Soc. Civil Engineers, *128*(3), 279 https://doi.org/10.1061/JRCEA4.0000231

Brouwer, C., Prins, K., and Heibloem, M. 1989. "Irrigation water management: irrigation scheduling. " Training manual no. 4, Food and Agriculture Organization, United Nations, Rome.

Bruch, J. C., Jr. 1979. Seepage streams out of canals and ditches overlying shallow water tables. J. Hydrol., 41(1 – 2), 31 – 41. https://doi.org/10.1016/0022-1694(79)90102-1

Buczek, S. B., Cope, W. G., McLaughlin, R. A., and Kwak, T. J. 2017. Acute toxicity of polyacrylamide flocculants to early life stages of freshwater mussels. Environ. Toxic. Chem., 36(10), 2715 – 2721. https://doi.org/10.1002/etc.3821

Burt, C. M., Orvis, S., and Alexander, N. 2010. Canal seepage reduction by soil compaction. J. Irrig. Drain. Engrg., 136(7), 479 – 485. https://doi.org/10.1061/(ASCE)IR.1943-4774.0000205

Chahar, B. R. 2001. Extension of Vedernikov's graph for seepage from canals. Groundwater, 39(2), 272 – 275. https://doi.org/10.1111/j.1745-6584.2001.tb02308.x

Chahar, B. R. 2006. Analytical solution to seepage problem from a soil channel with a curvilinear bottom. Water Resour. Res., 42(1), W01403. https://doi.org/10.1029/2005WR004140

Chahar, B. R. 2007. Analysis of seepage from polygon canals. J. Hydraul. Engrg., 133 (4), 451-460. https://doi.org/10.1061/(ASCE)0733-9429(2007)133:4(451)

Chen, J., Tang, P., Rakstad, T., Patrick, M., and Zhou, X. 2020. Augmenting a deep-learning algorithm with canal inspection knowledge for reliable water leak detection from multispectral satellite images. Adv. Engrg. Inform., 46, 101161. https://doi.org/10.1016/j.aei.2020.101161

Choudhary, M., and Chahar, B. R. 2007. Recharge/seepage from an array of rectangular channels. J. Hydrol., 343, 71-79. https://doi.org/10.1016/j.jhydrol.2007.06.009

Choudhary, M., and Chahar, B. R. 2014. Recharge from an array of polygonal channels. J. Hydrol. Engrg., 19(5), 918 – 930. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000872

Clapp, R.B. and Hornberger, G.M., 1978. Empirical equations for some soil hydraulic properties. Water Resour. Res., 14(4), pp.601-604. https://doi.org/10.1029/WR014i004p00601

Comer, A., Kube, M., and Sayer, K. 1996. Remediation of existing canal linings. Geotex. Geomemb., 14(5 – 6), 313 – 325. https://doi.org/10.1016/0266-1144(96)00019-2

Cunningham, A.B., Anderson, C.J. and Bouwer, H., 1987. Effects of sediment-laden flow on channel bed clogging. J. Irrig. Drain. Engrg., *113*(1), pp.106-118. https://doi.org/10.1061/(ASCE)0733-9437(1987)113:1(106)

Demetracopoulos, A. C., and Hadjitheodorou, C. J. 1996. Seepage from surface canals by boundary element method. J. Irrig. Drain. Engrg., 122(1), 40 – 48. https://doi.org/10.1061/(ASCE)0733-9437(1996)122:1(40)

Dench, W. E., and Morgan, L. K. 2021. Unintended consequences to groundwater from improved irrigation efficiency: Lessons from the Hinds-Rangitata Plain, New Zealand. Agric. Water Mgmt., 145, 106530. https://doi.org/10.1016/j.agwat.2020.106530

Devi, T.B. and Kumar, B., 2015. Turbulent flow statistics of vegetative channel with seepage. J. Applied Geophysics, 123, pp.267-276. https://doi.org/10.1016/j.jappgeo.2015.11.002

Ding, K., and Gao, L. 2020. Development in canal lining technology in China. Irrig. Drain., 69(52), 36 – 40. https://doi.org/10.1002/ird.2438

El Nimr, A. 1963. Seepage from parallel trapezoidal channels. J. Engrg. Mech., 89(4), 1 – 11. https://doi.org/10.1061/JMCEA3.0000400

Elkamhawy, E., Zelenakova, M., and Abd-Elaty, I. 2021. Numerical canal seepage loss evaluation for different lining and crack techniques in arid and sem-arid regions: A case study of the River Nile, Egypt. Water, 13(21), 3135. https://doi.org/10.3390/w13213135

Engelbert, P. J., Hotchkiss, R. H., and Kelly, W. E. 1997. Integrated remote sensing and geophysical techniques for locating canal seepage in Nebraska. J. App. Geophys., 38(2), 143 – 154. https://doi.org/10.1016/S0926-9851(97)00022-0

Fernald, A. G., and Guldan, S. J. 2007. Surface water-groundwater interactions between irrigation ditches, alluvial aquifers, and streams. Rev. Fish. Sci., 14(1 – 2), 79 – 89. https://doi.org/10.1080/10641260500341320

Fipps, G., and Skaggs, R. W. 1986. Effect of canal seepage on drainage to parallel drains. Trans. ASABE, 29(5), 1278 – 1283. https://doi.org/10.13031/2013.30309

Garg, S. P., and Chawla, A. S. 1970. Seepage from trapezoidal channels. J. Irrig. Drain. Engrg., 96(6), 1261 – 1282. https://doi.org/10.1061/JYCEAJ.0002514

Giroud, J.P. and Plusquellec, H., 2022. Evaluation of concrete and geomembrane lining options for a canal in Egypt. Geosynthetics Inter., pp.1-5. https://doi.org/10.1680/jgein.22.00013

Goyal, R., and Chawla, A. S. 1997. Seepage from canals with infiltration from free surface zone. J. Irrig. Drain. Engrg., 123(4), 257 – 263. https://doi.org/10.1061/(ASCE)0733-9437(1997)123:4(257)

Grafton, R.Q., Williams, J., Perry, C.J., Molle, F., Ringler, C., Steduto, P., Udall, B., Wheeler, S.A., Wang, Y., Garrick, D. and Allen, R.G., 2018. The paradox of irrigation efficiency. Science, *361*(6404), pp.748-750. https://doi: 10.1126/science.aat9314

Grismer, M. E. 2021. Point- and reach-scale measurements are important for determining accurate seepage rates in controlled flow channels. Calif. Agric., 75(2), 74 – 82. https://doi.org/10.3733/ca2021a0013

Guezennec, A. G., Michel, C., Bru, K., Touze, S., Desroch, N., Mnif, I., and Motelica-Heino, M. 2015. Transfer and degradation of polyacrylamide-based flocculants in hydrosystems: a review. Environ. Sci. Pollut. Res., 22, 6390 – 6406. https://doi.org/10.1007/s11356-014-3556-6

Hammad, H. Y. 1960. Seepage loss from parallel channels. J. Engrg. Mech., 86(4), 42 – 50. https://doi.org/10.1061/JMCEA3.0000161

Han, X., Wang, X., Zhu, Y., Huang, J., Yang, L., Chang, Z., and Fu, F. 2020. An experimental study on concrete and geomembrane lining effects on canal seepage in arid agricultural areas. Water, 12, 2343. https://doi.org/10.3390/w12092343

Han, X., Wang, X., Zhu, Y., and Huang, J. 2021. A fully coupled three-dimensional numerical model for estimating canal seepage with cracks and holes in canal lining damage. J. Hydrol., 597, 126094. https://doi.org/10.1016/j.jhydrol.2021.126094

He, P., Dong, J., Ren, X., and Wu, X. 2021. Longitudinal deformation model and parameter analysis of canal lining under nonuniform frost heave. Adv. Mater. Sci. Engrg., 2021, 5519035. https://doi.org/10.1155/2021/5519035

Hoffmann, P. and Villamayor-Tomas, S., 2022. Irrigation modernization and the efficiency paradox: a meta-study through the lens of Networks of Action Situations. Sustainability Science, pp.1-19. https://doi.org/10.1007/s11625-022-01136-9

Hotchkiss, R. H., Wingert, C. B., and Kelly, W. E. 2001. Determining irrigation canal seepage with electrical resistivity. J. Irrig. Drain. Engrg., 127(1), 20-26. https://doi.org/10.1061/(ASCE)0733-9437(2001)127:1(20)

Hrozencik, R. A., Potter, N. A., and Wallander, S. 2022. A national estimate of irrigation canal lining and piping water conservation. Working Paper 30123, National Bureau of Economic Research, Cambridge, MA. https://www.nber.org/papers/w30123

Huang, Y. B., Fipps, G., Maas, S. J., and Fletcher, R. S. 2010. Airborne remote sensing for detection of irrigation canal leakage. Irrig. Drain., 59(5), 524 – 534. https://doi.org/10.1002/ird.511

Iqbal, Z., MacLean, R. T., Taylor, B. D., Hecker, F. J., and Bennett, D. R. 2002. Seepage losses from irrigation canals in southern Alberta. Canad. Biosys. Engrg., 44, 1.21 – 1.27.

Jägermeyr, J., Gerten, D., Heinke, J., Schaphoff, S., Kummu, M. and Lucht, W., 2015. Water savings potentials of irrigation systems: global simulation of processes and linkages. Hydrology and Earth System Sciences, 19(7), pp.3073-3091. https://doi.org/10.5194/hess-19-3073-2015

Jägermeyr, J., Gerten, D., Schaphoff, S., Heinke, J., Lucht, W. and Rockström, J., 2016. Integrated crop water management might sustainably halve the global food gap. Environmental Research Letters, 11(2), 025002. https://doi.org/10.1088/1748-9326/11/2/025002

Jeppson, R. W. 1968. Seepage from ditches – solution by finite differences. J. Hydraul. Engrg., 94(1), 259 – 283. https://doi.org/10.1061/JYCEAJ.0001749

Jeppson, R. W., and Nelson, R. W. 1970. Inverse formulation and finite difference solution to partially saturated seepage from canals. Soil Sci. Soc. Amer. J., 34(1), 9 – 14. https://doi.org/10.2136/sssaj1970.03615995003400010009x

Kahlown, M. A., and Kemper, W. D. 2004. Seepage losses as affected by condition and composition of channel banks. Agric. Water Mgmt., 65(2), 145 – 153. https://doi.org/10.1016/j.agwat.2003.07.006

Kahlown, M. A., and Kemper, W. D. 2005. Reducing water losses from channels using linings: costs and benefits in Pakistan. Agric. Water Mgmt., 74, 57 – 76. https://doi.org/10.1016/j.agwat.2004.09.016

Kang, J., McLaughlin, R.A., Amoozegar, A., Heitman, J.L. and Duckworth, O.W., 2015. Transport of dissolved polyacrylamide through a clay loam soil. *Geoderma*, *243*, pp.108-114. https://doi.org/10.1016/j.geoderma.2014.12.022

Katibeh, H. 2004. Seepage from lined canal using finite-element method. J. Irrig. Drain. Engrg., 130(5), 441-444. https://doi.org/10.1061/(ASCE)0733-9437(2004)130:5(441)

Khan, S., Abbas, A., Gabriel, H.F., Rana, T. and Robinson, D., 2008. Hydrologic and economic evaluation of water-saving options in irrigation systems. Irrig. Drain., *57*(1), pp.1-14. https://doi.org/10.1002/ird.336

Khan, S., Rana, T., Dassanayake, D., Abbas, A., Blackwell, J., Akbar, S., and Gabriel, H. F. 2009. Spatially distributed assessment of channel seepage using geophysics and artificial intelligence. Irrig. Drain., 58, 307 – 320. https://doi.org/10.1002/ird.415

Kilic, M., and Tuylu, G. I. 2010. Determination of water conveyance loss in the ahmetli regulator irrigation system in the lower Gediz Basin Turkey. Irrig. Drain., 60(5), 579-589. https://doi.org/10.1002/ird.602

Kinzli, K. D., Martinez, M., Oad, R., Prior, A., and Gensler, D. 2010. Using an ADCP to determine canal seepage loss in an irrigation district. Agric. Water Mgmt., 97(6), 801-810. https://doi.org/10.1016/j.agwat.2009.12.014

Kishel, J. 1989. Seepage and contraction joints in concrete canal linings. J. Irrig. Drain. Engrg., 115(3), 377-383. https://doi.org/10.1061/(ASCE)0733-9437(1989)115:3(377)

Korkmaz, S., and Onder, H. 2006. Seepage from a rectangular ditch to the groundwater table. J. Irrig. Drain. Engrg., 132(3), 263 – 271. https://doi.org/10.1061/(ASCE)0733-9437(2006)132:3(263)

Kraatz, D. B. 1977.Irrigation canal lining. FAO Land and Water Development Series. No. 1, Food and Agricultural Organization (FAO) of the United Nations, Rome.

Kulkarni, A.A. and Nagarajan, R., 2019. Hydrospatial modelling and simulations for assessing the irrigation canal conveyance losses. Model. Simul. Engrg., 2019. https://doi.org/10.1155/2019/1803748

Kusre, B. C., Patra, S. C., and Dutta, B. 2013. Ex post performance evaluation studies of Kaldiya medium irrigation project in Assam, India. Irrig. Drain., 62(5), 666 – 678. https://doi.org/10.1002/ird.1761

Lentz, R. D. 2003. Inhibiting water infiltration with polyacrylamide and surfactants: Applications for irrigated agriculture. J. Soil and Water Conservation, 58(5), 290-300.

Lentz, R. D., & Freeborn, L. L. 2007. Sediment and polyacrylamide effects on seepage from channeled flows. *Soil science*, *172*(10), 770-789. DOI: 10.1097/ss.0b013e3180de4a33

Lentz, R. D. 2015. Polyacrylamide and biopolymer effects on flocculation, aggregate stability, and water seepage in a silt loam. Geoderma, *241*, 289-294. https://doi.org/10.1016/j.geoderma.2014.11.019

Levy, G.J., Goldstein, D. and Mamedov, A.I., 2005. Saturated hydraulic conductivity of semiarid soils: Combined effects of salinity, sodicity, and rate of wetting. *Soil Science Society of America Journal*, *69*(3), pp.653-662. https://doi.org/10.2136/sssaj2004.0232

Li, Z., Liu, S., Feng, Y., Liu, K., and Zhang, C. 2013. Numerical study on the effect of frost heave prevention with different canal lining structures in seasonally frozen ground regions. Cold Reg. Sci. Tech., 85, 242 – 249. https://doi.org/10.1016/j.coldregions.2012.09.011

Lindenbach, E. J., Kang, J. B., Rittgers, J. B., and Naranjo, R. C. 2020. Select techniques for detecting and quantifying seepage from unlined canals. U. S. Bureau of Reclamation, Nevada Water Science Center, Final Report ST-2020-19144-01. https://pubs.er.usgs.gov/publication/70222937

Lund, A.R., Martin, C.A., Gates, T.K., Scalia IV, J. and Babar, M.M., 2021. Field evaluation of a polymer sealant for canal seepage reduction. *Agricultural Water Management*, *252*, p.106898. https://doi.org/10.1016/j.agwat.2021.106898

Luo, Y., Bai, K., Traore, S., Gu, H., Sun, Y., Xiong, Y., Jiao, X., and Fipps, G. 2016. Determining seasonal canal seepage using stage-seepage relationship. Irrig. Drain., 65(3), 334-340. https://doi.org/10.1002/ird.1960

Mahato, R. K., and Dey, S. 2020. Hydraulics of seepage from trapezoidal channels. J. Hydraul. Engrg., 146(12), 04020083. https://doi.org/10.1061/(ASCE)HY.1943-7900.0001825

Marino, M. A., & Luthin, J. N. (1982). Seepage and groundwater. Elsevier.

Martin, C.A., 2015. Uncertainty in measuring seepage from earthen irrigation canals using the inflow-outflow method and in evaluating the effectiveness of polyacrylamide applications for seepage reduction (Master's Thesis, Colorado State University).

Martin, C. A., and Gates, T. K. 2014. Uncertainty of canal seepage losses estimated using flowing water balance with acoustic Doppler devices. J. Hydrol., 517(19), 746-761. https://doi.org/10.1016/j.jhydrol.2014.05.074

Martinez-Meza, E., and Whitford, W. G. 1996. Stemflow, throughfall and channelization of stemflow by roots in three Chihuahuan desert shrubs. J. Arid Environ., 32, 271 – 287.

Meier, J., Zabel, F. and Mauser, W., 2018. A global approach to estimate irrigated areas–a comparison between different data and statistics. Hydrol. and Earth Sys. Sci., *22*(2), pp.1119-1133. https://doi.org/10.5194/hess-22-1119-2018

Meredith, E., and Blais, N. 2019. Quantifying irrigation recharge sources using groundwater modeling. Agric. Water Mgmt., 214, 9 – 16. https://doi.org/10.1016/j.agwat.2018.12.032

Mirnateghi, A., and Bruch, J. C. 1983. Seepage from canals having variable shape and partial lining. J. Hydrol., 64(1-4), 239-265. https://doi.org/10.1016/0022-1694(83)90071-9

Moavenshahidi, A., Smith, R., and Gillies, M. 2014. A computer model to estimate seepage rates from automated irrigation distribution channels during periods of shutdown. J. Hydroinform., 16(6), 1302 – 1317. https://doi.org/10.2166/hydro.2014.104

Moavenshahidi, A., Smith, R., and Gillies, M. 2015. Factors affecting the estimation of seepage rates from channel automation data. J. Irrig. Drain. Engrg., 141(6), 04014075. https://doi.org/10.1061/(ASCE)IR.1943-4774.0000842

Moavenshahidi, A., Smith, R., and Gillies, M. 2016. Seepage losses in the Coleambally irrigation area – loss estimates from channel automation data. Austral. J. Water Resour., 20(1), 78-88. https://doi.org/10.1080/13241583.2016.1227580

Moghazi, H. E. M., and Ismail, E.-S. 1997. A study of losses from field channels under arid region conditions. Irrig. Sci. 17, 105 – 110. https://doi.org/10.1007/s002710050028

Mohammadi, A., Rizi, A. P., and Abbasi, N. 2019. Field measurement and analysis of water losses at the main and tertiary levels of irrigation canals: Varamin irrigation scheme, Iran. Global Ecol. Conserv., 18, e00646. https://doi.org/10.1016/j.gecco.2019.e00646

Morel-Seytoux, H. J. 1964. Domain variations in channel seepage flow. J. Hydraul. Engrg., 2, 55 – 79. https://doi.org/10.1061/JYCEAJ.0001035

Morgado, F., Lopes, G. J., de Brito, J., and Feiteira, J. 2012. Portuguese irrigation canals: lining solutions, anomalies, and rehabilitation. J. Perf. Constr. Facil., 26(4), 507 – 515.https://doi.org/10.1061/(ASCE)CF.1943-5509.0000230

Morway, E.D., Gates, T.K. and Niswonger, R.G., 2013. Appraising options to reduce shallow groundwater tables and enhance flow conditions over regional scales in an irrigated alluvial aquifer system. Journal of Hydrology, *495*, pp.216-237. https://doi.org/10.1016/j.jhydrol.2013.04.047

Mutema, M., and Dhavu, K. 2022. Review of factors affecting canal water losses based on a meta-analysis of worldwide data. Irrig. Drain. 71, 559 – 573. https://doi.org/10.1002/ird.2689

Naranjo, R., Smith, D. and Lindenbach, E., 2023. Incorporating temperature into seepage loss estimates for a large unlined irrigation canal. Journal of Hydrology, 617, p.129117. https://doi.org/10.1016/j.jhydrol.2023.129117

Pérez-Blanco, C.D., Hrast-Essenfelder, A. and Perry, C., 2020. Irrigation technology and water conservation: A review of the theory and evidence. Rev. Environ. Economics and Policy. https://doi.org/10.1093/reep/reaa004

Phogat, V., Malik, R. S., and Kumar, S. 2009. Modelling the effect of canal bed elevation on seepage and water table rise in a sand box filled with loamy soil. Irrig. Sci., 27, 191 – 200. https://doi.org/10.1007/s00271-008-0132-1

Plusquellec, H. 2019. Overestimation of benefits of canal irrigation projects: Decline of performance over time caused by deterioration of concrete canal lining. Irrig. Drain., 68(3), 383-388. https://doi.org/10.1002/ird.2341 (serviceability/durability)

Pognant, D., Canone, D., Previati, M. *and* Ferraris, S. 2013. Using EM equipment to verify the presence of seepage losses in irrigation canals. Proced. Environ. Sci., 19, 836–845. https://doi.org/10.1016/j.proenv.2013.06.093

Pugh, J. E., Gates, T. K., and Venayagamoorthy, S. K. 2021. Refined protocols to mitigate user-induced uncertainty for ADCP moving-boat discharge measurement in irrigation canals. Flow Meas. Instrument., 102060. https://doi.org/10.1016/j.flowmeasinst.2021.102060

Puy, A., Sheikholeslami, Gupta, H. V., Hall, J. W., Lankford, B., Lo Piano, S., Meier, J., Pappenberger, F., Porporato, A., Vico, G., and Saltelli, A. 2022a. The delusive accuracy of global irrigation water withdrawal estimates. Nature Commun., 13, 3183 https://doi.org/10.1038/s41467-022-30731-8

Puy, A., Lankford, B., Meier, J., van der Kooij, S., and Saltelli, A. 2022b. Large variations in global irrigation withdrawals caused by uncertain irrigation efficiencies. Environ. Res. Letters, 17, 4, 044014. https://soi.org/10.1088/1748-9326/ac5768

Ragusa, S.R., De Zoysa, D.S. and Rengasamy, P., 1994. The effect of microorganisms, salinity and turbidity on hydraulic conductivity of irrigation channel soil. *Irrigation Science*, *15*(4), pp.159-166.

Rahimi, H., and Abbasi, N. 2007. Failure of concrete canal lining on fine sandy soils: a case study for the Saveh project. Irrg. Drain., 57(1), 83 – 92. https://doi.org/10.1002/ird.350

Rahimi, H., Abbasi, N., and Shantia, H. 2011. Application of geomembrane to control piping of sandy soil under concrete canal lining (Case study: Moghan Irrigation District, Iran). Irrig. Drain., 60(3), 330-337. https://doi.org/10.1002/ird.574f

Rastogi, A. K., and Prasad, B. 1992. FEM modelling to investigate seepage losses from the lined Nadiad branch canal, India. J. Hydrol., 138(1 – 2), 153 – 168. https://doi.org/10.1016/0022-1694(92)90162-O

Rawls, W.J., Brakensiek, D.L. and Saxtonn, K.E., 1982. Estimation of soil water properties. *Transactions of the ASAE*, *25*(5), pp.1316-1320. doi: 10.13031/2013.33720

Rawls, W.J., Gimenez, D. and Grossman, R., 1998. Use of soil texture, bulk density, and slope of the water retention curve to predict saturated hydraulic conductivity. Transactions of the ASAE, *41*(4), p.983. doi: 10.13031/2013.17270

Raza, A., Latif, M., and Shakir, A. S. 2013. Long-term effectiveness of lining tertiary canals in the Indus basin of Pakistan. Irrig. Drain., 62(1), 16 – 24. https://doi.org/10.1002/ird.1714

Remar, J., Burch, J. C., Jr., and Sloss, J. M. 1982. Free surface seepage from nonsymmetric channels. Inter. J. Num. Meth. Engrg., 18(1), 1547 – 1563. https://doi.org/10.1002/nme.1620181009

Robinson, A. R., and Rohwer, C. 1957a. Measurement of canal seepage. Trans. Amer. Soc. Civil Engrs., 122(1). https://doi.org/10.1061/TACEAT.0007491

Robinson, A. R., and Rohwer, C. 1957b. Closure to Robinson-Rohwer on canal seepage. Trans. Amer. Soc. Civil Engrs., 122(1). https://doi.org/10.1061/TACEAT.0007490

Robinson, A. R., and Rohwer, C. 1959. Measuring seepage from irrigation channels. Tech. Bull. No. 1203, U. S. Dept. Agric., Colo. Agric. Exper. Station, U.S. Bureau of Reclam.

Rosenberry, D. O., Duque, C., and Lee, D. R. 2020. History and evolution of seepage meters for quantifying flow between groundwater and surface water: Part 1–

Freshwater settings. Earth-science reviews, 204, 103167. https://doi.org/10.1016/j.earscirev.2020.103167

Sahu, P., Saxena, A.K. and Travadi, M.K., 2014. The use of canal lining available materials and its comparative study. IOSR J. Mechanical and Civil Engineering, *11*(3), pp.81-86.

Salmasi, F., and Abraham, J. 2020. Predicting seepage from unlined earthen channels using the finite element method and multivariable nonlinear regression. Agric. Water Mgmt., 234, 106148. https://doi.org/10.1016/j.agwat.2020.106148

Sarand, F. B., and Hajialilue-Bonab, M. 2017. Effect of unsaturated expansive soils on canal linings: a case study on the Tabriz Plain Canal, Iran. Irrig. Drain., 66(3), 396-410. https://doi.org/10.1002/ird.2113

Shah, Z., Gabriel, H., Haider, S., and Jafri, T. 2020. Analysis of seepage loss from concrete lined irrigation canals in Punjab, Pakistan. Irrig. Drain. 69(4), 668-681. https://doi.org/10.1002/ird.2474

Shainberg, I. and Letey, J., 1984. Response of soils to sodic and saline conditions. Hilgardia, *52*(2), pp.1-57.

Shaikh, I. A., and Lee, T. S. 2016. Estimating earthen tertiary water channel seepage losses as a function of soil texture. J. Irrig. Drain. Engrg., 21(2), 06015012. https://doi.org/10.1061/(ASCE)HE.1943-5584.0001292

Sharma, H. D., and Chawla, A. S. 1979. Canal seepage with boundary at finite depth. J. Irrig. Drain. Engrg., 105(7), 877 – 897. https://doi.org/10.1061/JYCEAJ.0005242

Shultz, C.D., Gates, T.K. and Bailey, R.T., 2018. Evaluating best management practices to lower selenium and nitrate in groundwater and streams in an irrigated river valley using a calibrated fate and reactive transport model. Journal of Hydrology, *566*, pp.299-312. https://doi.org/10.1016/j.jhydrol.2018.09.005

Siderius, C., Biemans, H., Conway, D., Immerzeel, W., Jaegermeyr, J., Ahmad, B. and Hellegers, P., 2021. Financial feasibility of water conservation in agriculture. Earth's Future, *9*(3), 2020EF001726. https://doi.org/10.1029/2020EF001726

Siebert, S. and Döll, P., 2010. Quantifying blue and green virtual water contents in global crop production as well as potential production losses without irrigation. J. Hydrol., *384*(3-4), pp.198-217. https://doi.org/10.1016/j.jhydrol.2009.07.031

Singh, A. 2015. Soil salinization and waterlogging: a threat to environment and agricultural sustainability. Ecolog. Indic., 57, 128 – 130. https://doi.org/10.1016/j.ecolind.2015.04.027

Singh, V., Raj, C., and Sandilya, S. S. 2021. Determination of canal seepage loss in Arrah Main Canal: A case study. Irrig. Drain., 70(5), 1107 – 1115. https://doi.org/10.1002/ird.2620

Snell, M. 2001. Lining old irrigation canals: thoughts and trials. Irrig. Drain., 50(2), 139 – 157. https://doi.org/10.1002/ird.13 (serviceability/durability)

Sojka, R. E., Bjorneberg, D. L., Entry, J. A., Lentz, R. D., and Orts, W. J. 2007. Polyacrylamide in agriculture and environmental management. Adv. Agron., 92, 75 – 162. https://doi.org/10.1016/S0065-2113(04)92002-0

Subramanya, K., Madhav, M. R., and Mishra, G. C. 1973. Studies on seepage from canals with partial linings. J. Hydraul. Engrg., 99(12), 2333-2351. https://doi.org/10.1061/JYCEAJ.0003835

Sultan, T., Latif, A., Shakir, A.S., Kheder, K. and Rashid, M.U., 2014. Comparison of water conveyance losses in unlined and lined watercourses in developing countries. Univ. Engineering and Technology Taxila. Technical Journal, 19(2), p.23.

Swamee, P. K., Mishra, G. C., and Chahar, B. R. 2000. Design of minimum seepage loss canal sections. J. Irrig. Drain. Engrg., 126(1), 28 – 32. https://doi.org/10.1061/(ASCE)0733-9437(2000)126:1(28)

Swamee, P. K., Mishra, G. C., and Chahar, B. R. 2001. Design of minimum seepage loss canal sections with drainage layer at shallow depth. J. Irrig. Drain. Engrg., 127(5), 287 – 294. https://doi.org/10.1061/(ASCE)0733-9437(2001)127:5(287)

Técher, D., and Berthier, E. 2023. Supporting evidences for vegetation-enhanced stormwater infiltration in bioretention systems: a comprehensive review. Environ. Sci. Pollut. Res., 30, 19705 – 19724. https://doi.org/10.1007/s11356-023-25333-w

Traore, S., Fipps, G., Swanson, C., Dufek, J., and Robin, M. 2021. Unmanned aerial vehicle system integrating high-resolution sensors for detecting leaks in irrigation canals – Proof of concept. Irrig. Drain., https://doi.org/10.1002/ird.2641

Trout, T. J., and Bowers, S. A. 1981. Operational evaluation of village level irrigation conveyance systems. Trans. ASABE, 24(3), 636 – 642. https://doi.org/10.13031/2013.34313

Uribe, H., Figueroa, R., and Llanos, L. 2013. Assessment of linear anionic polyacrylamide application to irrigation canals for seepage control. J. Agric. Engrg., 44, 773 – 778. https://doi.org/10.4081/jae.2013.398

U.S. Department of Agriculture (USDA). 2020. Irrigation organizations. National Agricultural Statistics Service, Washington, DC.

U. S. Geological Survey (USGS). 1990. National water supply summary, 1987: Hydrologic events and water supply and use. Paper 2350, Denver, CO.

Viviani, G., and Iovino, M. 2004. Wastewater reuse effects on soil hydraulic conductivity. J. Irrig. Drain. Engrg., 130(6), 451 – 540. https://doi.org/10.1061/(ASCE)0733-9437(2004)130:6(476)

Wachyan, E., and Rushton, K. R. 1987. Water losses from irrigation canals. J. Hydrol., 92(3-4), 275-288. https://doi.org/10.1016/0022-1694(87)90018-7

Wesseling, J.G., Stoof, C.R., Ritsema, C.J., Oostindie, K. and Dekker, L.W., 2009. The effect of soil texture and organic amendment on the hydrological behaviour of coarse-textured soils. Soil use and management, 25(3), pp.274-283. https://doi.org/10.1111/j.1475-2743.2009.00224.x

Wilkinson, R.W., 1985. Plastic lining on riverton unit, Wyoming. J. Irrig. Drain. Engrg., 111(3), pp.287-298. https://doi.org/10.1061/(ASCE)0733-9437(1985)111:3(287)

Wolde-Kirkos, A. T., and Chawla, A. S. 1994. Seepage from canals with asymmetric drainages. J. Irrig. Drain. Engrg., 120(5), 1- 8. https://doi.org/10.1061/(ASCE)0733-9437(1994)120:5(949)

Woodrow, J. E., Seiber, J. N., and Miller, G. C. 2008. Acrylamide release resulting from sunlight irradiation of aqueous polyacrylamide/iron mixtures. Agric. Food Chem., 56(8), 2773 – 2779. https://doi.org/10.1021/jf703677v

World Bank. 2022. Water in agriculture. https://www.worldbank.org/en/topic/water-in-agriculture Last accessed: 5 December 2022.

Worstell, R. V. 1976. Estimating seepage losses from canal systems. J. Irrig. Drain. Engrg., 102(1), 137 – 147. https://doi.org/10.1061/JRCEA4.0001080

Yao, L., Feng, S., Mao, X., Huo, Z., Kang, S., and Barry, D. A. 2012. Coupled effects of canal lining and multi-layered soil structure on canal seepage and soil water dynamics. J. Hydrol., 430-431, 91-102. https://doi.org/10.1016/j.jhydrol.2012.02.004 (outdoor ponding)

Young, M. H., Moran, E. A., Yu, Z., Zhu, J., and Smith, D. M. 2009. Reducing saturated hydraulic conductivity of sandy soils with polyacrylamide. Soil Sci. Soc. Amer. J., 73(1), 13 – 20. https://doi.org/10.2136/sssaj2007.037

Yussuff, S. M. H., Chauhan, H. S., Kumar, M., and Srivastava, V. K. 1994. Transient canal seepage to sloping aquifer. J. Irrig. Drain. Engrg., 120(1), 97 – 109. https://doi.org/10.1061/(ASCE)0733-9437(1994)120:1(97)

Zhang, Q., Chai, J., Xu, Z. and Qin, Y. 2017. Investigation of irrigation canal seepage losses through use of four different methods in Hetao Irrigation District, China. J. Hydrol. Engrg, 22(3), 05016035. https://doi.org/10.1061/(ASCE)HE.1943-5584.0001470

Zhu, J., and Young, M. H. 2009. Sensitivity of unlined canal seepage to hydraulic properties of polyacrylamide-treated soil. Soil Sci. Soc. Amer. J., 73(3), 695 – 703. https://doi.org/10.2136/sssaj2008.0261

Zia, H., and Ali, M. 2017. Behavior of fiber reinforced concrete for controlling the rate of cracking in canal lining. Const. Build. Mater., 155, 726 – 739. https://doi.org/10.1016/j.conbuildmat.2017.08.078

Zörb, C., Geilfus, C.M. and Dietz, K.J., 2019. Salinity and crop yield. Plant biology, *21*, pp.31-38. https://doi.org/10.1111/plb.12884

Chapter 2

Field evaluation of a polymer sealant for canal seepage reduction*[2]

SUMMARY

A large amount of the water diverted for irrigated agriculture seeps from earthen canals during its conveyance to fields. Besides a shortfall in water availability, a variety of environmental and economic damages are caused by canal seepage. Polymer sealants provide an economical alternative to permanent liners for reducing seepage from earthen canals temporarily. Field studies of the polymer sealant linear anionic polyacrylamide (LAPAM) conducted on two canals in Colorado, USA, and on a canal in Sindh, Pakistan, reveal the potential usefulness of LAPAM to substantially lower seepage losses. LAPAM application rates for the three experiments on the canals in Colorado were 14.2, 18.3, and 12.1 kg per ha of canal wetted perimeter area, and was 12.4 kg/ha for the canal in Pakistan. Flowing water balance tests show a decline of 69% to 100% in seepage rates for a period of up to three months after LAPAM application. Uncertainty analysis of the pre- and post-application tests on the Colorado canals indicates an 85% likelihood that seepage reduction of some magnitude occurred. Guidelines are presented for conducting further

[2] This chapter was published as a research article in 2021 in *Agricultural Water Management*.
by A.A. Rehman Lund (the author of this dissertation), Chad A Martin, Timothy K. Gates (the co-adviser), Joseph Scalia IV (the adviser), and M. Munir Babar
https://doi.org/10.1016/j.agwat.2021.106898

studies of LAPAM and other polymer sealants to systematically determine the impact of several factors that influence seepage control effectiveness.

2.1 Introduction

Irrigation is by far the largest human intervention in the hydrologic cycle, altering amounts, timing, and location of flows to provide the water needed to boost crop productivity to levels that can sustain an ever-growing world population. The vast social and economic benefits of irrigated agriculture are universally recognized, leading to the diversion of nearly 70 to 80% of the world's diverted freshwater resources (Ayars et al. 2006; Hotchkiss et al. 2001, and Kinzli et al. 2010). Given the current worldwide competition for limited water supplies, improving irrigation water management is paramount.

In most irrigation schemes, water is conveyed through earthen channels from the point of diversion out of the hydrologic system to the fields where the water is applied. Unfortunately, unless preventative measures are taken, earthen canals leak substantially, reducing the quantity and quality of water available for agriculture. Seepage losses worldwide have been estimated to be 17 to 70% of canal flows (Sharma 1975, USGS 1990, Lentz 2003, Fipps 2005, Kahlown and Kemper 2005, Kinzli et al. 2010, Kulkarni and Nagarjan 2019). In 1978 the United States Department of Interior estimated that about 17% of the total water lost due to irrigation inefficiencies in 61 study areas throughout the western United States was potentially preventable by controlling canal seepage

(USDOI 1978). Due to the aging of water infrastructure in the western United States and the lack of resources for expensive large-scale canal lining projects over recent decades, the loss prevention potential is likely even higher today.

Fig. 2.1 illustrates processes that generate water loss and agro-environmental degradation due to canal seepage. Causing inefficient flow conveyance, seepage directly diminishes water available for agricultural use. Also, because seepage contributes to shallower groundwater and capillary groundwater upflux, seepage results in non-beneficial water consumption by evapotranspiration from fallow and naturally vegetated areas. Canal seepage also degrades soil, groundwater, and surface water quality. Upflux from shallow groundwater brings salts into near-surface soils with resulting evaporative concentration and may also lead to waterlogging of cropped fields. These factors result in long-term declines in crop yields (Kahlown and Azam 2002, Zorb et al. 2019). Additionally, return flows from seepage mobilize salts, nutrients, and geogenic toxic trace elements to aquifers, streams, and eventually to environmental receptors (USGS 1990, Burkhalter and Gates 2005, Burt et al. 2010, Gates et al. 2012, 2016, and Bailey et al. 2015), further degrading water quality and environmental health. The economic losses or mitigation costs associated with this damage are substantial (Qadir et al. 2014, Sharp et al. 2016).

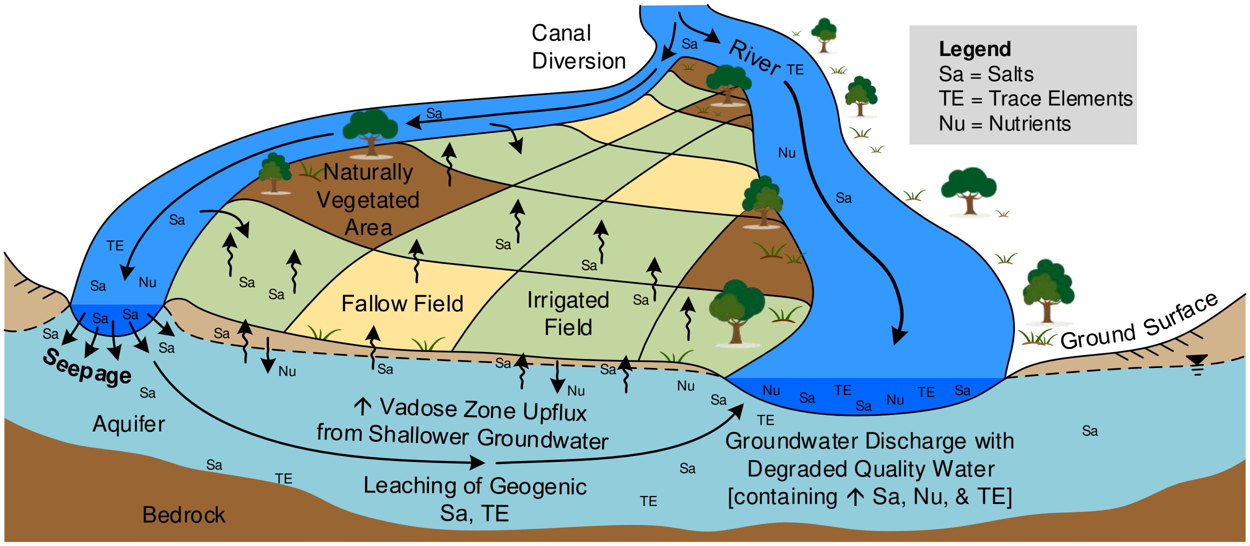

Figure 2.1: Conceptual schematic of water loss and negative environmental impacts from canal seepage.

Identifying and reducing canal seepage has been identified as a principal best management practice for preserving water quantity and quality in agriculture (Tavakoli Kivi 2018, Shultz et al. 2018, Aliyari et al., 2019). Numerous technologies are available, including permanent liners (e.g., concrete, asphalt, geomembranes) and less permanent sealants (e.g., bentonite clay, water-soluble polymers). Concrete liners have been shown to reduce seepage by 50 to 97% and can have a life span ranging from 20 to 60 years if constructed correctly (USDA 1997, Swihart and Haynes 2002, and Kahlown and Kemper 2005). Buried, concrete-covered, or exposed geomembranes reduced seepage from canals in the Western United States (Comer et al., 1996), resulting in up to 95 % conveyance efficiency (Swihart and Haynes 2002). However, the substantial up-front capital costs associated with permanent liners, along with on-going maintenance costs, can exceed benefits in many agricultural applications (Wichelns and Oster 2006). Besides, permanent liners are difficult to remove and cannot be implemented intermittently as water availability varies (e.g., allowing seepage for intentional groundwater recharge during periods of water surplus and preventing water loss from seepage during periods of water scarcity). Finally, liners can act as physical barriers that permanently prevent return flows derived from seepage possibly violating the water rights of downstream users who may be entitled to upstream return flows (Hayes 1991, Rohmat et al 2020).

Sealants provide a more palatable alternative for seepage mitigation in many circumstances, principally due to lower up-front costs and the ability to implement seepage mitigation on an as-needed basis. Anionic polyacrylamide (PAM) is most widely used for these reasons. There are different forms of anionic PAM, which include low-cost linear anionic polyacrylamide (LAPAM) and cross-linked PAM. Cross-linked PAM has a high molecular weight and includes molecular crosslinks such that the polymer does not dissolve in water but instead absorbs water to form a super-absorbent hydrogel. LAPAM, in particular, has shown significant promise as an effective sealant for temporary (e.g., one water season) seepage control from earthen canals and ditches in both lab and field. Similar water-soluble polymers are used to reduce leakage from energy and mine waste evaporation ponds and environmental containment facilities (Scalia et al. 2018).

The seepage reduction mechanism of LAPAM involves sediment-LAPAM floc formation, as described in detail by Sojka et al. (2007). When LAPAM, which is water-soluble, comes in contact with suspended sediments in the canal water, the sediments interact with the polymer chains to form flocs that grow large enough to settle to the canal perimeter. The deposition of flocs composed of fine-grained minerals around the canal perimeter reduces permeability and, thereby, the seepage rate. Additionally, LAPAM increases water viscosity, which restricts the penetration of water from the canal perimeter. Of note, for LAPAM to be effective, the canal water should carry a sufficient load of total suspended solids (TSS).

To date, only a few field studies have been reported on the use of various forms of polyacrylamide (PAM; not all linear) for mitigating seepage. Lentz and Kincaid (2008) treated the sides of an irrigation reservoir with a 1 g/L LAPAM solution or different combinations of cross-linked PAM granules and NaCl to achieve an average 50% reduction in seepage compared to pre-application rates. However, PAM in emulsion form is found to have adverse impacts on the aquatic environment as compared to its granular form (Weston et al., 2009). The field-scale experimental studies reported herein used PAM in the granular form. Uribe et al. (2013) reported the application of granular LAPAM using a motorboat on 11 different reaches of earthen irrigation canals in Chile and found some degree of seepage reduction in 80% of the cases. In 16 cases where an apparent decrease in seepage was reported, the average reduction was 58% for at least 27 days. However, Uribe et al (2013) did not provide the details of their LAPAM application methods, the field conditions at the time of application, the seepage measurement techniques, or an estimate of the uncertainty in their results. In a technical report published by the Desert Research Institute, Susfalk et al. (2008) report that within 24 hours of the application of LAPAM in granular form to earthen canals in Montana and Colorado, seepage was reduced by 28 to 87% in 8 of 11 experiments. Critically, if the correct procedure and rate of application of LAPAM are not followed, LAPAM will not reduce seepage (Story et al., 2013). Susfalk et al. (2007) present a set of guidelines for successful field application of LAPAM. Finally, Young et al. (2007) describe risks associated with the use of LAPAM to reduce seepage, including (1) the impacts on human and ecological health of residual acrylamide monomer from the LAPAM that is released in the environment and (2) physiological impacts of LAPAM, when released into streams, on benthic organisms. Young et al. (2007) conclude that, from an ecotoxicological perspective, a little effect is expected from the residual acrylamide within LAPAM.

Herein, we lay out the conditions, methods, and results of field campaigns to evaluate the effectiveness of the application of LAPAM. Tests were conducted on respective reaches of 4.8-km and 4-km length along two canals in Colorado, USA, and on a 5.3-km reach of a canal in Sindh, Pakistan. Quantification of seepage using the flowing water balance technique and LAPAM application methods are described. Moreover, in the case of the two Colorado canals, we follow the procedures described in Martin and Gates (2014), specifically developed for these canals, to add an estimate of the uncertainty in the calculations of seepage loss reduction. Finally, recommended guidelines are presented for an enhanced framework to systematically evaluate the effectiveness of LAPAM (or other linear anionic polymer sealants) to control canal seepage under a variety of field conditions.

2.2 Materials and methods

2.2.1 Study design

Our field studies to evaluate the effectiveness of LAPAM at reducing canal seepage consisted of the following components: (1) site selection, (2) measurement of baseline (pre-application of LAPAM) seepage conditions, (3) calculation of the required LAPAM application rate following the guidelines provided by Susfalk et al. (2007), (4) application of LAPAM, (4) measurement of post-application seepage conditions, and (5) evaluation of LAPAM effectiveness in canal seepage reduction. Materials, procedures, and considerations related to each of these components are described in this section.

2.2.2 Study sites

Reaches were selected along three mid-sized earthen irrigation canals for this investigation. Critical criteria for site selection included:

(1) Interest and agreement by canal managers and farmers to cooperate in a research study;

(2) Canal reaches which:

a. have few obstructions to hinder seepage measurements and polymer application;
b. are sufficiently long such that seepage losses exceed measurement errors associated with the flowing water balance method;
c. have few (or ideally zero) flow diversions and inflows, or the ability to close off these diversions and inflows during seepage measurements; and
d. have pathways along canal banks that facilitate equipment, material, and personnel access.

The Catlin and Rocky Ford Highline (RFH) canals in Colorado were measured and treated with LAPAM during 2006 and 2007. A similar study was conducted on the Tarah Canal in Sindh in 2018.

2.2.2.1 Catlin and Rocky Ford Highline Canals

The Catlin and RFH canals divert flow from the Arkansas River in the irrigated Lower Arkansas River Valley (LARV) in southeastern Colorado (Fig. 2.2). The maximum flow capacities of the Catlin and RFH canals are 9.7 m^3/s and 13.3 m^3/s, respectively. The Catlin Canal services about 7,550 ha, and the RFH services about 21,000 ha of irrigated farmland.

For both canals, input from canal managers and farmers regarding the presence of substantial seepage losses along the study reaches helped us select sites where seepage rates would suitably exceed measurement errors. The canals' cross-section geometry along the study reaches was relatively uniform with no substantial obstacles (Martin

2015). A 4.8-km reach of the Catlin Canal near Rocky Ford, CO was studied in 2006, but this study reach was shortened to 3.8 km in 2007 to avoid flow diversions along a portion of the reach. The reach cut through gravelly loam, silty loam, and clay loam soils. The main drawback of the Catlin Canal reach was its location 42 km downstream from the canal head gate on the Arkansas River, potentially making the reach susceptible to unsteady flow rates and storage changes due to fluctuating flow from 176 diversions along the upstream portion of the canal. A 4-km reach of the RFH Canal traversing through gravelly sandy loam, silty clay, and clay loam soils near Fowler, CO also was studied in 2006. It was located only about 7.4 km downstream of the canal head gate, presenting less concern about unsteady flow.

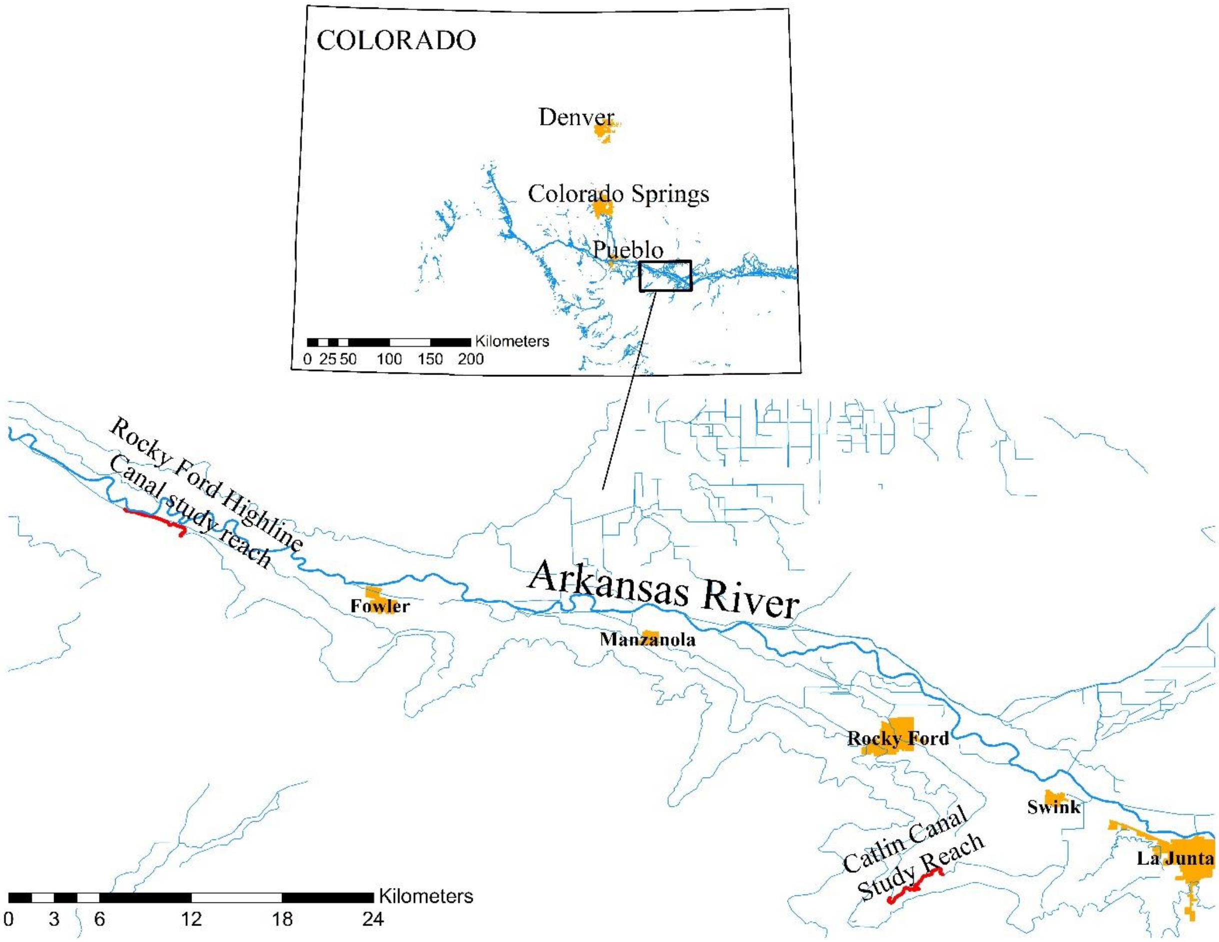

Figure 2.2: Locations of study reaches on the Catlin Canal and RFH Canal in the LARV in Colorado, USA. Study reaches are denoted with red lines.

2.2.2.2 Tarah Canal

The Tarah Canal is located about 25 km southeast of Sakrand in the Hala subdivision, Sindh, Pakistan, and offtakes from the Hala Branch Canal supplied from the Rohri Canal, which in-turn diverts from the Indus River (Fig. 2.3). The design capacity of the Tarah Canal is about 9.0 m^3/s, and the canal delivers water to approximately 13,600 ha of irrigated land.

A 5.3-km reach of the Tarah Canal, with anecdotal reports of high seepage loss, was selected for investigation. The reach is located about 3.5 km downstream of the headgate on the Hala Branch Canal, runs through predominantly sandy loam soil, and has a relatively uniform cross-section geometry with no significant obstacles. However, typical of distributary canals in this region, there are 18 outlets to farm channels along the reach. The need to ensure that these outlets remained closed during seepage studies posed a significant challenge requiring close cooperation with the Sindh Irrigation Department and local farmers.

‘’

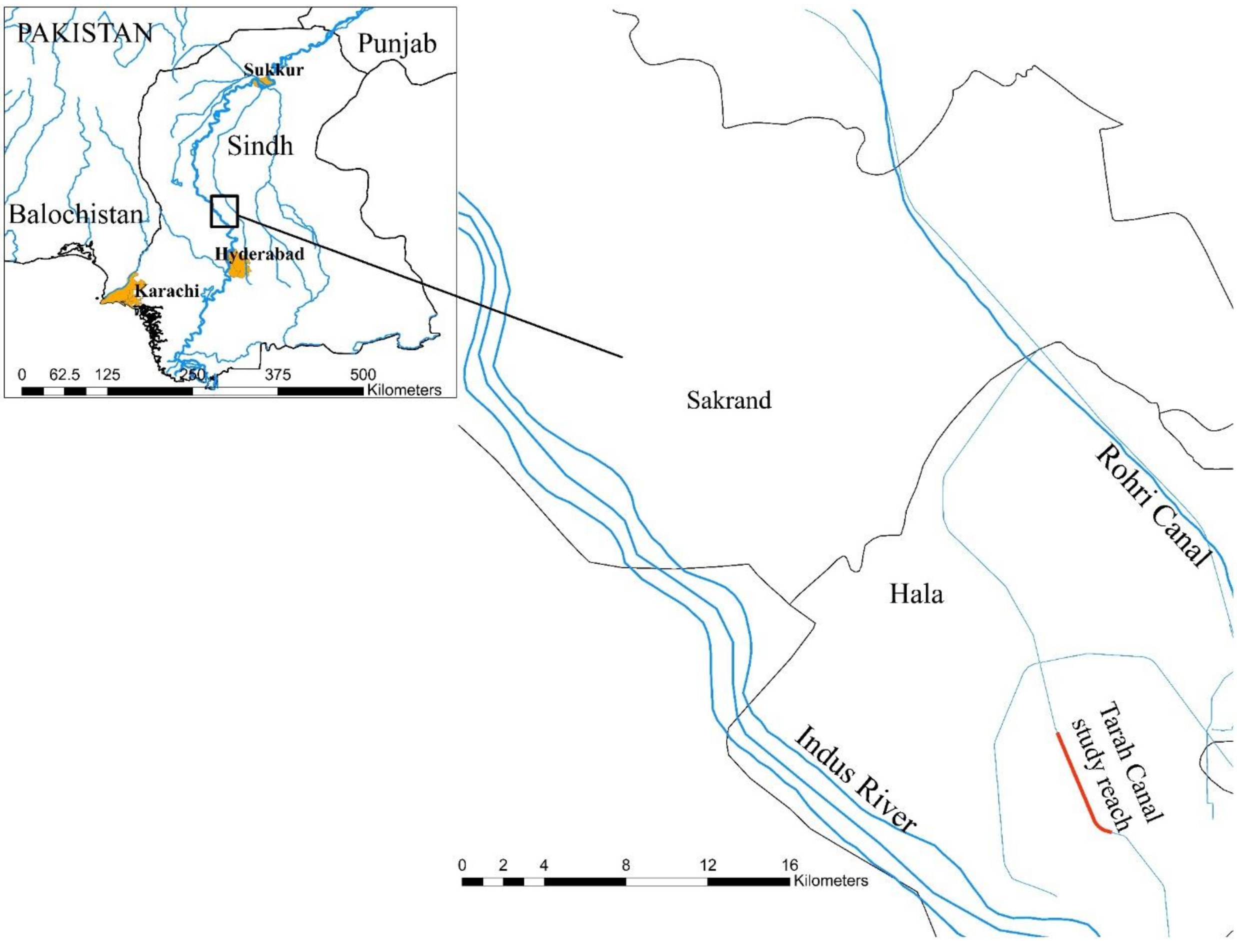

Figure 2.3: Location of study reach on the Tarah Canal in Sindh, Pakistan. Study reach is denoted with a red line.

2.2.3 Measurement of pre-treatment and post-treatment canal seepage

The flowing water balance method of seepage estimation was used in this study. The method requires measurement of discharge at the upstream end, Q_{US} (m^3/s), and downstream end, Q_{DS} (m^3/s), of a control volume defined along a canal reach during a test period Δt (s); estimation or measurement of any inflows, Q_I (m^3/s), or flow diversions, Q_D (m^3/s), along the reach; quantification of any storage change, $\frac{\Delta S}{\Delta t}$ (m^3/s), that may occur within the canal control volume over the duration of the seepage test; and estimation of outflow by water surface evaporation, Q_E (m^3/s), and inflow from precipitation, Q_P (m^3/s) (Fig. 2.4). Canal seepage along the measurement reach, Q_S (m^3/s), is calculated from the water balance equation:

$$Q_S = Q_{US} - Q_{DS} + Q_I - Q_D - Q_E + Q_P - \frac{\Delta S}{\Delta t} \tag{2.1}$$

Ideally, seepage tests are conducted during periods when Q_I, Q_D, and Q_P are zero or negligible.

Seepage tests on all canal study reaches were conducted both before and after treatment with LAPAM. Martin and Gates (2014) and Martin (2015) report the results of multiple tests conducted on the Catlin and RFH Canals within a period of up to 3.5 months before the LAPAM application. However, here only pre-application tests conducted within five days of application are reported, describing conditions in the canal just before the LAPAM application. After treatment, ten post-application tests over about five months were then performed on the Catlin Canal reach in 2006, and twelve post-application tests over about three months in 2007. On the RFH Canal, six post-application tests were conducted within 3.5 months of treatment. Finally, two post-application tests were performed on the Tarah Canal after polymer treatment.

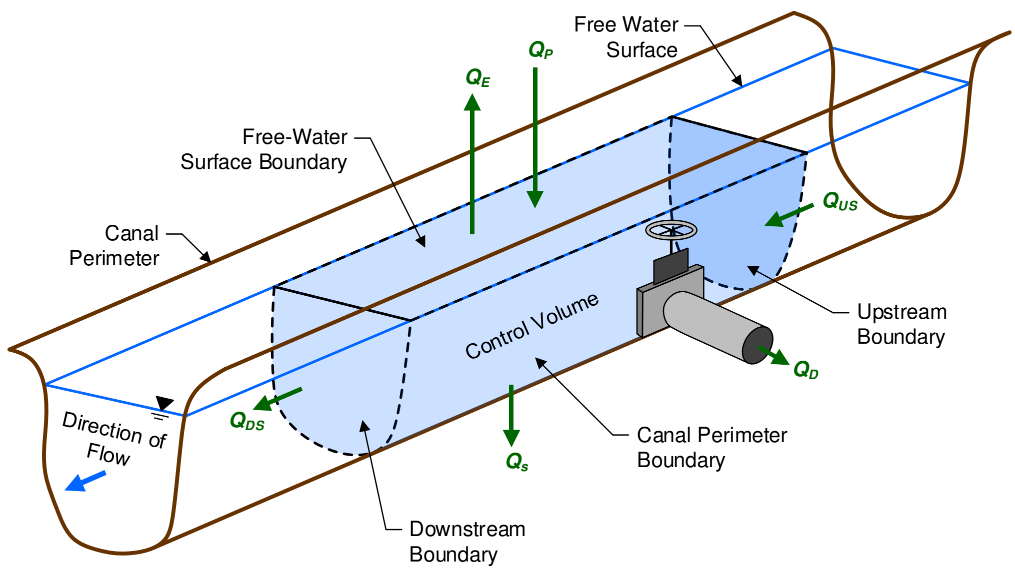

Figure 2.4: Control volume along a canal reach for a flowing water balance test of canal seepage.

Martin and Gates (2014) and Martin (2015) provide detailed accounts of the tools and methods to measure or estimate each of the terms in Eq (2.1). The canal flow rates Q_{US} and Q_{DS} were measured using either acoustic Doppler velocimeters (ADVs) or acoustic Doppler current profilers (ADCPs). On the Catlin and RFH Canals, a Sontek *Flowtracker* ADV and a Teledyne *Streampro* ADCP were used for flow measurement. On the Tarah Canal, a Sontek *RiverSurveyor M9* ADCP was used. In a small number of tests, flows were measured simultaneously at both ends of the canal reach, but in most cases, downstream measurements were lagged as the project team measured Q_{US} upstream at the beginning of the test and then moved immediately downstream to measure Q_{DS}. The advantages and disadvantages of the simultaneous versus lagged measurement approaches are discussed in Martin and Gates (2014).

In 2006, staff gauges were installed at the upstream and downstream ends of the test reaches in both the Catlin and RFH Canals. These staff gages were used, in conjunction with the Doppler flow measurement devices, to measure water surface fluctuations for use in calculating $\frac{\Delta S}{\Delta t}$. Staff gauge readings were recorded every 5 to 15 minutes while measuring Q_{US} and Q_{DS}. In 2007, calibrated Onset *Hobo* and In-Situ *LevelTroll 300* water level data loggers were installed for this purpose at three locations along the Catlin Canal study reach and recorded water level data at 15-minute intervals. In the Tarah Canal, three Global Water Instruments WL16U water level loggers were installed along the study reach and recorded water level data at 15-minute intervals. A total of 17, 20, and 19 cross-sections were surveyed to describe the hydraulic geometry along the reaches of the Catlin, RFH, and Tarah Canals, respectively. Finally, in nine out of 37 seepage tests conducted on the three canals, small amounts of Q_D occurred along the canal reach and were manually measured on a volumetric basis.

Values of Q_E were calculated by multiplying estimates of the rate of free-surface water evaporation during each test by the water surface area within the canal study reach. For the Catlin and RFH canals, the Penman Combination method (Jensen and Allen 2016) was used to estimate free-surface water evaporation using climatic data gathered from nearby Colorado State University CoAgMet weather stations during the seepage tests (Martin 2015). The CoAgMet station used for computing Q_E for the Catlin Canal was located about 8.5 km from the canal study reach, and that used for the RFH Canal was located approximately 22.1 km from the site. For the Tarah Canal, free-surface water evaporation values reported by the Central Cotton Research Institute in Sakrand, about 27 km from the canal study reach, were used to calculate Q_E. We intentionally avoided testing during periods of precipitation (i.e. Q_P was zero for all tests).

2.2.4 Treatment of canals with LAPAM

2.2.4.1 Chemical characteristics of the LAPAM used

The typical molecular weight for anionic PAM is between 10 and 20 Mg/mol (Green and Stott 2001, Lu et al. 2002, Sojka et al. 2007, Young et al. 2007). This polymer uses cation-bridging to bond to negatively-charged soil particles suspended in water (Seybold 1994, Sojka et al. 2007, Theng 1982). Cations form the bridge between the negatively-charged polymer and negatively-charged particulate that would otherwise repel each other. Divalent cations commonly found in surface water, such as Mg^{2+} and Ca^{2+}, are highly effective in forming the cation bridges required to develop these bonds, more so than monovalent cations such as Na^{+} and K^{+} (Gregory 1996, Lu et al. 2002, Susfalk et al. 2008). The divalent ion Ca^{2+} promotes flocculation process than the monovalent ion Na^{+} its smaller hydrated radius increases the proximity of soil particles and their binding by LAPAM (Sojka et al. 2007).

LAPAM is a synthetic polymer principally used to treat drinking water, conditioning potable water sludges, and sugar processing resulting in high-quality sugar and greater yield. However, inherent environmental and human health risks are still present when applying LAPAM due to unpolymerized acrylamide monomer, a neurotoxin suspected to be a human carcinogen (Seybold 1994, WHO 1985, Young et al. 2007). As such, the United States Environmental Protection Agency (EPA) and the Food and Drug Administration (FDA) have set the allowable concentrations for residual acrylamide in LAPAM (Young et al. 2007). Anionic PAM used for most applications contains less than 0.05% acrylamide by weight of the total mixture (Sojka et al. 2007). Guidelines for the safe use of LAPAM at a field scale are presented by Susfalk et al. (2007) and NRCS (2005).

The granular sodium LAPAM used on the Catlin and RFH canals was *Stokopam* manufactured by Evonik Industries in Essen, Germany, and obtained from JT Water Management, LLC of Parker, Colorado. This LAPAM has a minimum molecular weight of 12 Mg/mol, an anionic charge density of 30% ± 5%, and an assumed 92% active ingredient with a moisture content of 4%. On the Tarah Canal, granular *Magnafloc LT27 AG*, manufactured by BASF Corporation and obtained from BASF Pakistan in Karachi, was used. This polymer has an average molecular weight of 12 Mg/mol and is approximately 30% by weight sodium acrylate-acrylamide polymer, with an active content greater than 90% by weight and moisture content targeting around 5 to 7%. The methods and tools used to treat the canals with these LAPAM compounds are discussed in the following sub-sections.

2.2.4.2 LAPAM application using a motorboat

To apply LAPAM in granular form over the water surface in each canal, fertilizer spreaders loaded with LAPAM and small "Jon" boats with outboard motor were employed (Fig. 2.5). The application was started from the downstream end of the treatment reach and proceeded to the upstream end, with the turbulence created by the motor enhancing the mixing of the polymer in the canal water. The vigorous and relatively uniform dispersion of polymer granules over the water surface by broadcasting enhances robust sediment-LAPAM floc formation. An automatic fertilizer spreader mounted on the boat or a hand-held spreader (either hand-operated or automatic) was used to spread the polymer over the canal water surface. Before the polymer application, a pre-application trial was conducted in the field to synchronize the speed of the boat with the required speed and throw of the spreaders. A total of 3 to 5 personnel were engaged on the boat to apply the polymer, drive the boat, deflect floating debris, and refill the spreaders. Personnel operating the spreaders took safety measures to prevent direct exposure to the LAPAM by wearing protective coveralls, respiratory masks, and transparent goggles. During the application process, a vehicle traveled along the canal bank, carrying pre-weighed bags of granular LAPAM for transfer to personnel on the boat when the supplies on the boat were consumed. Care was taken in the boat during treatment to avoid slipping on polymer-coated surfaces. Product safety guidelines were followed for the clean-up of any LAPAM in the boat after application.

Figure 2.5: LAPAM application via motorized boat on (A) the RFH Canal using automated fertilizer spreader mounted on the boat and (B) the Tarah Canal using hand-operated fertilizer spreaders.

Another possible way of using LAPAM for seepage and erosion control in agricultural applications is to inject LAPAM stock solutions into the canal water (Weston et al 2009). However, LAPAM concentrations in stock solutions are limited by high viscosity, which increases the volumes required and makes it challenging to transport and distribute LAPAM. Additionally, because stock solutions are extremely sticky and gluey, a significant amount of polymer will adhere to the transport tanks and will ultimately clog the injectors.

2.2.4.3 Field conditions for LAPAM application

Susfalk et al. (2008) report that canal water ideally should contain turbidity levels of more than 80 to 100 nephelometric turbidity units (NTU) or TSS levels of 150-200 mg/L before being treated with LAPAM. Suspended sediment in the canal water was measured before each LAPAM application. For the Catlin and RFH canals, water samples were collected from the study reaches and a turbidity meter was used to measure the turbidity in NTU. Turbidity levels of about 270 NTU and 400 NTU were measured just before the

LAPAM application in 2006 to the RFH Canal and in 2007 to the Catlin Canal, respectively, exceeding the recommended minimum NTU. For the Tarah Canal, water samples were collected from four locations spread along the study reach just before the LAPAM application using a US DH-48 depth-integrating suspended-sediment sampler and were analyzed in the laboratory for TSS. Values range from 289 to 397 mg/L, exceeding the recommended minimum TSS level.

2.4.4 LAPAM applications to the canals in Colorado and Sindh

The conditions of the LAPAM application in kg per ha of wetted perimeter for the treatment reach of each canal are summarized in Table 2.1. The application varied with the wetted perimeter and ranged between 12.1 to 18.3 kg/ha for the four sets of experiments. Except for the LAPAM application on the RFH canal, where an automatic fertilizer spreader mounted at the front of a boat in 2006 (Fig. 2.5A) was used, hand-held fertilizer spreaders were used to spread LAPAM over the canal water surface.

Table 2.1: Summary of LAPAM application conditions on irrigation canals in Colorado and Sindh.

Canal	Application Date	Reach Length (km)	LAPAM Application Rate (kg/ha)	LAPAM Application Rate (kg/km)	Total Weight of Applied LAPAM (kg)
RFH	July 20, 2006	4	14.2	27.8	111.1
Catlin	June 3, 2006	4.8	18.3	13.9	66.7
Catlin	August 7, 2007	3.8	12.1	12.1	45.8
Tarah	August 9, 2018	5.3	12.4	14.3	75

2.2.5 Evaluation of LAPAM effectiveness

2.2.5.1 Calculation and comparison of pre-and post-application seepage

Using measured or estimated flow variables from flowing water balance seepage tests conducted before and after the LAPAM application, deterministic estimates of Q_S were computed using Eq. (2.1) for all three canals. To facilitate a comparison of results for canal reaches of different sizes, Q_S values were divided by the canal wetted perimeter area at the time of each test to obtain the seepage rate per unit area, $\hat{Q}_s$ [(m^3/s)/ ha]. The wetted perimeter area, A_P, was calculated using the surveyed cross-sections along each canal test reach and the flow depth at each surveyed cross-section during each seepage test.

Regardless of the method of seepage measurement (i.e. ADCP or ADV, lagged or simultaneous), all the pre-treatment $\hat{Q}_s$ measurements were averaged to obtain the values summarized in the Tables 2.3-2.6. The post-treatment $\hat{Q}_s$ values were individually compared to this pre-treatment average value of $\hat{Q}_s$. Additionally, results are summarized in Table 2.7 for post-treatment seepage tests performed after approximate intervals of 1-day, 1-week, 1-month, and 2-months. Post-treatment $\hat{Q}_s$ values measured at times close to these specified intervals or calculated as an average of two values measured near these intervals, were used to calculate corresponding percent reductions in seepage.

2.2.5.2 Estimation of uncertainty in seepage estimates

Each of the components involved in solving the flowing water balance model in Eq. (2.1) to estimate Q_S (i.e., discharge measurement, surface-water evaporation estimation, stage data, and the measurement of canal geometry) introduce a degree of uncertainty in the estimate due to random or systematic errors and spatial variability. Martin and Gates (2014) presented a method to account for these sources of uncertainty in estimating Q_S and $\hat{Q}_s$ in application to the Catlin and RFH canals. They considered a form of Type B uncertainty (ISO 2008) that assigns probability distributions and associated statistics, which are derived from available data and scientific judgment to describe probable errors over interpercentile ranges (IR) around measured or estimated quantities (Cox et al. 2003, Herschy 2004). In this approach, the true value of a variable is assumed to be equal to the measured or estimated value plus an error (which could be positive or negative); in other words, the value lies within what Harmel and Smith (2007) describe as a "probable error range." For example, if we expect to measure a flow rate in the canal within a probable error range of +/- 10% of the true value with a 90% probability, we would take the values at the upper and lower ends of the 90th IR range (i.e., at the 5th and 95th percentiles) for a given probability distribution function (PDF) to be equal to 90% and 110% of the measured flow rate, respectively.

Martin and Gates (2014) used Monte Carlo simulation to analyze the uncertainty in estimating canal seepage using measurements made in conjunction with the flowing water balance method. Uncertainty in each component of Eq. (2.1) was addressed by modeling the component as a random variable with an associated probable error range over an IR governed by a PDF. Each variable in Eq. (2.1) is a function of one or more variables or parameters directly measured or estimated from available data. Table 2.2 summarizes the probable error range, IR, and associated PDF assigned to variables or parameters used by Martin and Gates (2014), and subsequently applied in this study using Eq. (2.1) to compute Q_S for each pre-application and post-application test. In each case, the equation was solved using 5,000 joint Monte Carlo realizations of the random variables to obtain a distribution of possible values of Q_S, and associated values of $\hat{Q}_s$, for which related PDFs and statistics could be estimated. The rationale and methods used are presented in detail in Martin and Gates (2014) and are not repeated here.

Table 2.2: Summary of probable error range, IR, and PDF for use in Monte Carlo simulation of random variables and associated parameters in Eq. (1). Q_{US} is the discharge at the upstream end, Q_{DS} is the discharge at the downstream end, Q_D is the flow diversion, Q_I is the inflow to the canal, and Q_E is the outflow by water surface evaporation.

Measurement Type	**Variables and Parameters**	**Assumed PDF**	**Probable Error Range and IR**
Discharge Measurements	Q_{US}	normal	+/- 5% @ 90% IR
	Q_{DS}	normal	+/- 5% @ 90% IR
	Q_D	normal	+/- 5% @ 90% IR
	Q_I	normal	+/- 5% @ 90% IR
Predicting Q_{US} and Q_{DS} for unsteady-lagged tests	Random errors in estimating flow rates during lag period	normal	+/- 5% @ 90% IR
		normal	+/- 15% @ 90% IR
		normal	+/- 15% @ 90% IR
Free-water Evaporation	Q_E	normal	+/- 20% @ 90% IR
Canal Stage			
Staff Gage Reading		normal	+/- 0.04 feet @ 90% IR
Absolute Water Pressure		normal	+/- 0.04 feet @ 90% IR
Atmospheric Pressure		normal	+/- 0.04 feet @ 90% IR
Hydraulic Geometry			
At-a-Station Cross-Section Geometry	Random errors in estimating canal wetter perimeter and top width	logistic	unique to each canal cross-section
Along-the-Canal Trendline Coefficients	Random parameters for estimating trend coefficient for wetted parameter variation along the canal	logistic	unique to each coefficient
	Random parameters for estimating trend coefficient for top width variation along the canal	logistic	unique to each coefficient
Thalweg Elevation	Random error in thalweg elevation	normal	unique to each canal reach

In the present study, the work of Martin and Gates (2014) was extended by computing probability distributions and statistics of the difference between pre-application and post-application values of $\hat{Q}_s$ for the Catlin and RFH canals to approximate the uncertainty in estimations of LAPAM effectiveness. An uncertainty analysis was not performed for the Tarah Canal because of the comparatively limited field data. Also, given the similar seepage data collection and polymer application methodology followed in both locations, we assumed the uncertainty calculated for the Colorado tests provides an initial estimate of the general uncertainty associated with tests performed by similar methods.

2.3 Results and discussion

2.3.1 Calculated seepage from measurements pre- and post-application with LAPAM

Measured and estimated components of the flowing water balance, along with calculated values of Q_S and $\hat{Q}_s$, are summarized in Tables 2.3 through 2.6 for tests conducted pre-and post-application with LAPAM on the Catlin Canal in 2006 and 2007, the RFH Canal in 2006, and the Tarah Canal in 2018, respectively. Seepage reductions, in percentages, for Catlin Canal in 2006 and 2007, RFH Canal in 2006, and Tarah Canal in 2018, respectively, are summarized in Table 2.7. The results of the seepage tests show 69 to 100 % reductions in seepage because of polymer application. For all cases, flow conditions at the upstream end of the canal reach for pre-and post-application tests were similar (stable geometry and fairly steady flow rates of similar magnitude), with differences between pre-and post-application average measured Q_{US} values ranging between only 1 and 15%. The $\hat{Q}_s$ estimated from post-application tests were, in all cases, lower than those estimated from pre-application tests. Similar to the findings by Uribe et al. (2013), negative values of $\hat{Q}_s$ were calculated in the present study for 10 out of the 30 reported post-application flowing water balance tests. We hypothesize that these negative values are the result of return flow from canal bank storage, causing net flow accumulation to the canal reach for the test. However, for simplicity, we assigned negative values of $\hat{Q}_s$ to be zero for use in calculating the seepage reduction between pre-and post-application conditions.

Table 2.3: Measurements for seepage loss in Catlin Canal in 2006 for pre- and post-application with LAPAM. A_P is the wetted perimeter area of the canal, Q_{US} is the discharge at the upstream end, Q_{DS} is the discharge at the downstream end, Q_D is the flow diversion, Q_I is the inflow to the canal, $\frac{\Delta S}{\Delta t}$ is the rate of storage change in the canal, Q_E is the outflow by water surface evaporation, Q_S is the canal seepage rate along the measurement reach, and $\hat{Q}_s$ is the seepage rate per unit wetted perimeter area of the canal.

Days before (-)/after (+)application	Measurement Equipment and method	A_P (ha)	Q_{US} (m³/s)	Q_{DS} (m³/s)	Q_D (m³/s)	Q_I (m³/s)	$\Delta S/\Delta t$ (m³/s)	Q_E (m³/s)	Q_S (m³/s)	$\hat{Q}_S$ [(m³/s)/ha]
0	ADCP, Lagged	2.87	3.17	2.89	0	0	0	0.006	0.278	0.097
0	ADV, Simultaneous	2.91	3	2.86	0	0	0	0.006	0.130	0.045
LAPAM APPLICATION- June 03, 2006										
+1	ADV, Simultaneous	2.95	3.22	3.21	0	0	-0.023	0.008	0.028	0.010
+1	ADCP, Lagged	2.95	3.71	3.65	0	0	0	0.008	0.048	0.016
+1	ADCP, Lagged	2.95	3.62	3.77	0	0	0	0.008	-0.150	-0.051
+22	ADV, Simultaneous	2.87	2.83	2.87	0	0	0.028	0.006	-0.068	-0.024
+22	ADV, Simultaneous	2.87	2.84	2.87	0	0	-0.014	0.006	-0.023	-0.008
+26	ADV, Lagged	2.87	2.92	2.81	0.02	0	0	0.006	0.076	0.027
+34	ADCP, Lagged	2.87	2.92	2.93	0	0	0	0.006	-0.020	-0.007
+67	ADCP, Lagged	2.87	3.03	2.92	0	0	0	0.003	0.110	0.038
+115	ADCP, Lagged	2.67	2.02	2	0.01	0	0	0.003	0	0
+150	ADCP, Lagged	2.67	1.83	1.80	0	0	0	0.003	0.025	0.010

Table 2.4: Measurements for seepage loss in Catlin Canal in 2007 for pre- and post-application with LAPAM. A_P is the wetted perimeter area of the canal, Q_{US} is the discharge at the upstream end, Q_{DS} is the discharge at the downstream end, Q_D is the flow diversion, Q_I is the inflow to the canal, $\frac{\Delta S}{\Delta t}$ is the rate of storage change in the canal, Q_E is the outflow by water surface evaporation, Q_S is the canal seepage rate along the measurement reach, and $\hat{Q}_s$ is the seepage rate per unit wetted perimeter area of the canal.

Days before (-)/after(+) application	Measurement Equipment and method	A_P (ha)	Q_{US} (m³/s)	Q_{DS} (m³/s)	Q_D (m³/s)	Q_I (m³/s)	$\Delta S/\Delta t$ (m³/s)	Q_E (m³/s)	Q_S (m³/s)	$\hat{Q}_S$ [(m³/s)/ha]
-5	ADCP, Lagged	3.04	3.87	3.68	0.042	0	-0.031	0	0.181	0.060
-1	ADCP, Lagged	3.20	4.25	4.02	0	0	0	0.003	0.224	0.070
0	ADCP, Lagged	3.20	4.30	4.05	0	0	0	0.003	0.252	0.079
LAPAM APPLICATION- August 07, 2007										
0	ADCP, Lagged	3.20	4.33	4.30	0	0	0	0.006	0.023	0.007
0	ADCP, Lagged	3.20	4.24	4.34	0	0	-0.014	0	-0.082	-0.026
+1	ADCP, Lagged	3.20	4.08	4.07	0	0	0.082	0.008	-0.085	-0.027
+2	ADCP, Lagged	3.08	3.82	3.77	0	0	0	0.006	0.037	0.012
+2	ADCP, Simult.	3.12	3.82	3.85	0	0	0	0.006	-0.040	-0.013
+8	ADCP, Lagged	3.04	3.77	3.76	0	0	0	0.006	0.003	0.001
+10	ADCP, Lagged	3.20	4.40	4.32	0.042	0	0	0.008	0.031	0.010
+15	ADCP, Lagged	2.99	3.47	3.40	0.028	0	-0.017	0	0.057	0.019
+39	ADCP, Lagged	2.99	3.58	3.57	0.028	0	-0.054	0.006	0.031	0.010
+59	ADCP, Lagged	2.79	2.59	2.59	0.028	0	0	0.003	-0.034	-0.012
+78	ADCP, Lagged	2.83	2.88	2.85	0.028	0	0	0.003	-0.006	-0.002
+92	ADCP, Lagged	2.75	2.41	2.38	0.028	0	0	0	0.006	0.002

Table 2.5: Measurements for seepage loss in RFH Canal in 2006 for pre- and post-application with LAPAM. A_P is the wetted perimeter area of the canal, Q_{US} is the discharge at the upstream end, Q_{DS} is the discharge at the downstream end, Q_D is the flow diversion, Q_I is the inflow to the canal, $\frac{\Delta S}{\Delta t}$ is the rate of storage change in the canal, Q_E is the outflow by water surface evaporation, Q_S is the canal seepage rate along the measurement reach, and $\hat{Q}_s$ is the seepage rate per unit wetted perimeter area of the canal.

Days before (-)/after (+)application	Measurement Equipment and method	A_P (ha)	Q_{US} (m³/s)	Q_{DS} (m³/s)	Q_D (m³/s)	Q_I (m³/s)	$\Delta S/\Delta t$ (m³/s)	Q_E (m³/s)	Q_S (m³/s)	$\hat{Q}_S$ [(m³/s)/ha]
-1	ADCP. Lagged	4.29	4.11	3.77	0	0	0	0.0113	0.328	0.077
			LAPAM APPLICATION - July 20, 2006							
+1	ADCP. Lagged	4.21	3.34	3.26	0	0	0	0.0028	0.082	0.020
+6	ADCP. Lagged	4.17	3.34	3.23	0	0	0	0.0113	0.096	0.023
+6	ADCP. Lagged	4.17	3.32	3.24	0	0	0	0.0085	0.071	0.017
+15	ADCP. Lagged	4.17	3.26	3.09	0	0	0	0.0057	0.164	0.039
+21	ADCP. Lagged	4.33	4.11	3.99	0	0	0	0.0113	0.102	0.024
+73	ADCP. Lagged	4.21	2.72	2.65	0	0	0	0	0.074	0.017

Table 2.6: Measurements for seepage loss in Tarah Canal in 2018 for pre- and post-application with LAPAM. A_P is the wetted perimeter area of the canal, Q_{US} is the discharge at the upstream end, Q_{DS} is the discharge at the downstream end, Q_D is the flow diversion, Q_I is the inflow to the canal, $\frac{\Delta S}{\Delta t}$ is the rate of storage change in the canal, Q_E is the outflow by water surface evaporation, Q_S is the canal seepage rate along the measurement reach, and $\hat{Q}_s$ is the seepage rate per unit wetted perimeter area of the canal.

Days before (-)/after (+)application	Measurement Equipment and method	A_P (ha)	Q_{US} (m³/s)	Q_{DS} (m³/s)	Q_D (m³/s)	Q_I (m³/s)	$\Delta S/\Delta t$ (m³/s)	Q_E (m³/s)	Q_S (m³/s)	$\hat{Q}_S$ [(m³/s)/h]
-2	RiverSurveyor M9, Lagged	5.30	5.09	4.01	0	0	0.86	0.01	0.22	0.042
			LAPAM APPLICATION- August 09, 2018							
+1	RiverSurveyor M9, Lagged	5.67	5.36	4.67	0	0	1.08	0.01	-0.39	-0.068
+32	RiverSurveyor M9, Lagged	5.42	5.19	4.43	0	0	0.71	0.005	0.04	0.008

Table 2.7: Percent reduction in seepage after LAPAM application as a function of time.

Canal and Treatment year	Time after LAPAM Application				
	~1 day	~1 week	~1 month	~2 months	~3 months
Catlin 2006	88%	100%	81%	73%	73%
Catlin 2007	97%	88%	81%	100%	97%
RFH 2006	74%	74%	69%	N/A	78%
Tarah 2018	100%	N/A	81%	N/A	N/A

2.3.2 Uncertainty in the estimation of seepage reduction

Relative frequency histograms and box-and-whisker plots of the distributions of the estimates of $\hat{Q}s$ generated via Monte Carlo simulation are presented side-by-side in Fig. 2.6 for tests conducted pre-and post-application of LAPAM on the Catlin Canal in 2006 and 2007, and in the RFH Canal in 2006. While the generated frequency histograms of pre and post-LAPAM estimates of $\hat{Q}s$ overlap, indicative of the test uncertainty, the means of the post-LAPAM $\hat{Q}s$ values are always less than those of the pre-LAPAM values. Moreover, taking into account all significant sources of error, computed differences in the realizations of $\hat{Q}s$ estimates from tests conducted just before and just after LAPAM treatment reveals that 85%, 86%, and 88% of these differences were positive for the Catlin Canal in 2006, the Catlin Canal in 2007, and the RFH Canal in 2006, respectively. In other words, there are likelihoods of about 85%, 86%, and 88% that some magnitude of seepage reduction due to LAPAM application did occur along these canal reaches.

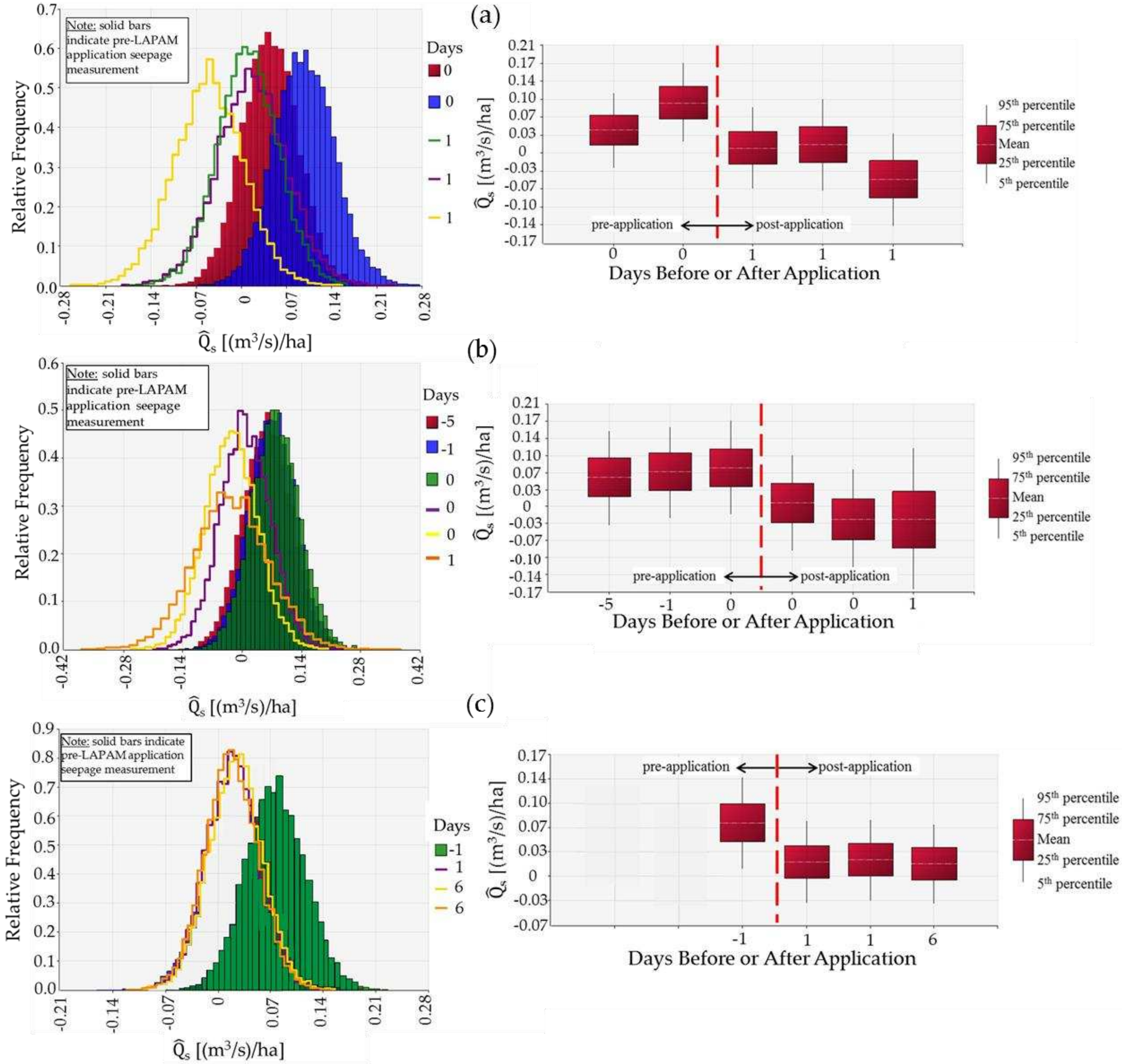

Figure 2.6: Relative frequency histograms and box-and-whisker plots of the distribution of seepage rates per unit wetted perimeter area of the canals, $\hat{Q}$s, for pre-and post-application of LAPAM for (a) Catlin Canal in 2006, (b) Catlin Canal in 2007, and (c) RFH Canal in 2006.

2.4 Future investigation of polymers for canal seepage control

The results reported in this study illustrate the potential effectiveness of canal sealing via LAPAM to reduce seepage. We hope that this study can stimulate future research on linear anionic polymers to reduce canal seepage. However, our study did not systematically address the relative influence of numerous factors associated with the effectiveness of LAPAM. These factors are outlined in the following section. Finally, based on lessons learned from the studies outlined herein, recommended guidelines for improving future systematic field investigation of polymers for canal seepage reduction are presented.

2.4.1 Influencing factors for future study

Numerous factors are known or anticipated to influence the effectiveness of LAPAM at reducing canal seepage. To optimize the use of LAPAM, further investigation of the following parameters is recommended. Parameters are grouped based on hypothesized influence on seepage reduction within a range of reasonable natural conditions for water conveyance canals.

Parameters of major hypothesized significance include:

- Polymer dosage rate. A dosage rate of approximately 11 kg/ha of the wetted perimeter is recommended by Susfalk et al. (2008); however, specific guidance is needed to better determine how polymer dosage rate affects the magnitude of seepage reduction and should be modified based on other factors listed subsequently.

- TSS. A TSS of ≥ 150 mg/L is recommended by Susfalk et al. (2008); however, the interplay between polymer dosage and TSS is poorly understood. TSS can be readily controlled in the field by timing (e.g., the early season during spring runoff sediments) or by bed raking, etc.
- Canal bed soil texture. Our studies evaluated a limited set of canal bed soil textures. Additional work is needed to understand the effectiveness and limitations of LAPAM-based seepage reduction in canals with banks and bed composed of a range of sediment textures.
- Polymer type. Although two specific commercially available LAPAMs are demonstrated to be viable canal sealants, additional work is needed to identify the attributes of LAPAM that maximize seepage reduction. Also, the synthetic nature of LAPAM, and the possible presence of residual acrylamide monomer, may limit the social acceptance of this technology. Additional research is needed to identify alternative greener polymers that are effective and economically viable for use in canal sealing.

Factors of moderate hypothesized significance include TDS [≥ 200 mg/L is recommended by Susfalk et al. (2008)], the ratio of monovalent to divalent cations, sediment mineralogy, flow velocity (and bed shear stress), and gradient to groundwater.

Factors of minor hypothesized significance include water temperature (although small variability in temperature is commonly expected during irrigation seasons), canal geometry, bank vegetation, and polymer application method.

2.4.2 Recommendations for improved field studies

Accurate seepage calculations using Eq. (2.1) depends on accurate data. The best use of the mass balance equation to solve for the seepage rates is only possible for a time where all water level loggers collect data and all outlets from and inlets to the canal have been shut off. All outlets and inlets should be closed at least one hour before each test to allow flow stabilization. In addition, outlets and inlets along the watercourse should be monitored during the test to ensure that closure is maintained for the duration of treatment or seepage measurements.

Often, as was the case in the present study, a single team and single flow measurement device (e.g., ADCP, ADV) is used to measure both Q_{US} and Q_{DS}. In such cases, it is desirable in the weeks preceding the test to make several flow measurements at each of the upstream and downstream ends of the canal study reach to develop rating equations for describing the flow rate as a function of the water level (stage). Stage-discharge rating equations may then be developed to estimate the flow rate at a cross-section if the water level changes during the portion of the test when flow measurements are not being made at that cross-section. Water level loggers (or staff gauge readings every 15 minutes) can be used to create a large dataset for analysis.

2.5 Summary and conclusions

As an alternative to costly conventional lining, the polymer sealant LAPAM was investigated to assess its effectiveness for reducing seepage losses from earthen canals. Results from 37 flowing water balance tests conducted in the field on three different mid-sized canals reveal the potential for LAPAM to substantially lower seepage losses over an extended portion of the irrigation season. Tests on two canals in Colorado, USA, showed estimated seepage reduction ranging from about 69% to 100%, sustained for up to three months after LAPAM application. Tests on a canal in Sindh, Pakistan, showed a drop in seepage rate of about 81% to 100% for up to one month following the LAPAM application. Consideration of measurement and estimation error in the tests conducted on the Colorado canals reveals significant uncertainty in test results. Nevertheless, accounting for this uncertainty in results, the likelihood that seepage losses from these canals in fact were reduced by LAPAM was estimated to exceed about 85%. Although the study presented here shows the potential of LAPAM to control seepage losses on typical irrigation canals, it does not systematically assess the relative influence of the several factors that influence the degree of LAPAM efficacy. These factors include type and application rate of polymer, TSS, canal bed texture, and multiple other factors; these factors require further study to optimize the safe use of LAPAM for canal seepage mitigation. Also, alternative polymer sealants that are more environmentally acceptable need to be similarly investigated. Guidelines for conducting more refined research efforts, including addressing a variety of practical concerns, are presented.

References

Aliyari, F., Bailey, R. T., Tasdighi, A., Dozier, A., Arabi, M., and Zeiler, K. (2019). Coupled SWAT-MODFLOW model for large-scale mixed agro-urban river basins. Environmental Modelling & Software, *115*, 200-210.

Ayars, J. E., Christen, E. W., Soppe, R. W., and Meyer, W. S. (2006). The resource potential of in-situ shallow ground water use in irrigated agriculture: a review. Irrigation Science, 24(3), 147-160.

Bailey, R. T., Romero, E. C., and Gates, T. K. (2015). Assessing best management practices for remediation of selenium loading in groundwater to streams in an irrigated region. J. Hydrology, 521, 341-359.

Burkhalter, J. P., and Gates, T. K. (2005). Agroecological impacts from salinization and waterlogging in an irrigated river valley. J. Irrigation and Drainage Engineering, 131(2), 197-209.

Burt, C. M., Orvis, S., and Alexander, N. (2010). Canal seepage reduction by soil compaction. J. Irrigation and Drainage Engineering, 136(7), 479-485.

Comer, A., Kube, M., and Sayer, K. (1996). Remediation of existing canal linings. Geotextiles and Geomembranes, 14(5-6), 313-325.

Cox, M., Harris, P., and Siebert, B. L. (2003). Evaluation of measurement uncertainty based on the propagation of distributions using Monte Carlo simulation. Measurement Techniques, 46(9), 824-833.

Fipps, G. (2005). Potential water savings in irrigated agriculture for the Rio Grande Planning Region (Region M), 2005 Update. Texas Water Resour. Inst., Texas A&M University, College Station, Tex.

Gates, T. K., Garcia, L. A., Hemphill, R. A., Morway, E. D., and Elhaddad, A. (2012). Irrigation practices, water consumption, and return flows in Colorado's lower Arkansas River Valley: field and model investigations. Technical report TR12-10, Colorado Agricultural Experiment Station, Colorado State Univ., Fort Collins.

Gates, T. K., Steed, G. H., Niemann, J. D., and Labadie, J. W. (2016). Data for improved water management in Colorado's Arkansas River Basin: hydrological and water quality studies. In Colorado Water Institute Special Report No. 24. State Univ., Fort Collins, Colorado.

Green, V. S., and Stott, D. E. (1999). Polyacrylamide: A review of the use, effectiveness, and cost of a soil erosion control amendment. In The 10th International Soil Conservation Organization Meeting. Purdue University and the USDA-ARS National Soil Erosion Research Laboratory, pp. 384-389.

Gregory, J. (1996). Polymer adsorption and flocculation. In C. A. Finch, ed., Industrial water soluble polymers, Pentafin Associates, Aylesbury, UK, 62–75.

Harmel, R.D. and Smith, P. K. (2007). Consideration of measurement uncertainty in the evaluation of goodness-of-fit in hydrologic and water quality modeling. J. Hydrology, 337 (3–4), 326-36.

Herschy, R. W. (2004). Estimation of uncertainties in hydrometric measurements. In Sehlke, G., Hayes, D. F., and Stevens, D. K. (eds.), Proc. 2004 World Water and Environmental Resources Congress, Salt Lake City, UT.

Hotchkiss, R. H., Wingert, C. B., and Kelly, W. E. (2001). Determining irrigation canal seepage with electrical resistivity. J. Irrigation and Drainage Engineering, 127(1), 20-26.

Hayes, D. L. (1991). The All-American Canal Lining Project: A Catalyst Rational and Comprehensive Groundwater Management on the United States-Mexico Border. Nat. Resources J., 31, 803.

International Organization for Standardization (ISO). (2008). Guide to expression of uncertainty in measurement (GUM). Guide 98-3:2008, Geneva, Switzerland.

Jensen, M. E., and Allen, R. G., eds. (2016). Evaporation, evapotranspiration, and irrigation water requirements. 2nd ed. ASCE Manuals and Reports in Engineering Practice No. 70, American Society of Civil Engineers, Reston, Virginia.

Kahlown, M. A., and Azam, M. (2002). Individual and combined effect of waterlogging and salinity on crop yields in the Indus basin. Irrigation and Drainage, 51(4), 329-338.

Kahlown, M. A., and Kemper, W. D. (2005). Reducing water losses from channels using linings: Costs and benefits in Pakistan. Agricultural Water Management, 74(1), 57-76.

Kinzli, K. D., Martinez, M., Oad, R., Prior, A., and Gensler, D. (2010). Using an ADCP to determine canal seepage loss in an irrigation district. Agricultural Water Management, 97(6), 801-810.

Kulkarni, A. A., and Nagarajan, R. (2019). Hydrospatial modelling and simulations for assessing the irrigation canal conveyance losses. Modelling and Simulation in Engineering, 2019.

Lentz, R. D. (2003). Inhibiting water infiltration with polyacrylamide and surfactants: applications for irrigated agriculture. J. Soil and Water Conservation, 290-300.

Lentz, R. D., and Kincaid, D. C. (2008). Polyacrylamide treatments for reducing seepage in soil-lined reservoirs: A field evaluation. Transactions of the ASABE, 51(2), 535-544.

Lu, J., Wu, L., and Letey, J. (2002). Effects of soil and water properties on anionic polyacrylamide sorption. Soil Science Society of America J., 66(2), 578-584.

Martin, C. A. (2015). Uncertainty in measuring seepage from earthen irrigation canals using the inflow-outflow method and in evaluating the effectiveness of polyacrylamide applications for seepage reduction. MS thesis, Colorado State University, Fort Collins, CO.

Martin, C. A., and Gates, T. K. (2014). Uncertainty of canal seepage losses estimated using flowing water balance with acoustic Doppler devices. J. Hydrology, 517, 746-761.

Natural Resources Conservation Service (NRCS). (2005). Irrigation water conveyance anionic polyacrylamide ditch and canal treatment. Code 754 (Interim Conservation Practice Standard), US Dept. Agriculture.

Qadir, M., Quillérou, E., Nangia, V., Murtaza, G., Singh, M., Thomas, R. J., ... and Noble, A. D. (2014). Economics of salt-induced land degradation and restoration. Natural Resources Forum, 38(4), 282-295.

Rohmat, F., Gates, T. K., and Labadie, J. W. (2020). Enabling improved water and environmental management in an irrigated river basin using agent-based optimization of reservoir operations. Environ. Model. Software, 104909.

Scalia IV, J., Bohnhoff, G. L., Shackelford, C. D., Benson, C. H., Sample-Lord, K. M., Malusis, M. A., and Likos, W. J. (2018). Enhanced bentonites for containment of inorganic waste leachates by GCLs. Geosynthetics International, 25(4), 392-411.

Seybold, C. A. (1994). Polyacrylamide review: Soil conditioning and environmental fate. Communications in Soil Science and Plant Analysis, 25(11-12), 2171-2185.

Sharma, H.D. (1975). Manual of canal lining. Technical Report No. 14, Central Board of Irrigation and Power, New Delhi, India.

Sharp, M., Hoag, D., Bailey, R. T., Romero, E. C., and Gates, T. K. (2016). Institutional constraints on cost-effective water management: Selenium contamination in Colorado's Lower Arkansas River Valley. J. Amer. Water Resour. Assoc., 52(6), 1420 – 1432.

Shultz, C. D., Gates, T. K., and Bailey, R. T. (2018). Evaluating best management practices to lower selenium and nitrate in groundwater and streams in an irrigated river valley using a calibrated fate and reactive transport model. J. Hydrology, 566, 299-312.

Sojka, R. E., Bjorneberg, D. L., Entry, J. A., Lentz, R. D., and Orts, W. J. (2007). Polyacrylamide in agriculture and environmental land management. Advances in Agronomy, 92, 75-162.

Story, B. T., Urynowicz, M. A., and Vance, G. F. (2013). Field demonstration of polyacrylamide in an unlined irrigation canal. J. Irrigation and Drainage Engineering, 139(5), 399-404.

Susfalk, R., Sada, D., Martin, C., Young, M. H., Gates, T., Rosamond, C., ... and Fitzgerald, B. (2008). Evaluation of linear anionic polyacrylamide (LA-PAM) application to water delivery canals for seepage reduction. Desert Research Institute, Reno, Nevada.

Susfalk, R. B., Young, M. H., and Smith, D. M. (2007). Application guidelines: Use of granular, linear anionic polyacrylamide (LA-PAM) in water delivery canals for seepage control. Desert Research Institute, Reno, Nevada.

Swihart, J., and Haynes, J. (2002). Canal-lining demonstration project year 10 final report. US Bureau of Reclamation, Denver.

Tavakoli Kivi, S. (2018). Simulating the fate and transport of salinity species in a semi-arid agricultural groundwater system: model development and application. PhD dissertation, Dept. Civil and Environ. Engrg., Colorado State Univ., Fort Collins.

Theng, B. K. G. (1982). Clay-polymer interactions: summary and perspectives. Clays and Clay Minerals, 30(1), 1-10.

Uribe, H., Figueroa, R., and Llanos, L. (2013). Assessment of linear anionic polyacrylamide application to irrigation canals for seepage control. J. Agricultural Engineering, 44. https://doi.org/10.4081/jae.2013.s2.e156.

United States Department of Agriculture (USDA). (1997). Irrigation guide. Natural Resources Conservation Service. 210-vi-NEH, September 1997.

United States Department of Interior (USDOI). (1978). Report on the water conservation opportunities study. Bureau of Reclamation and Bureau of Indian Affairs.

United States Geological Survey (USGS). (1990). National water supply summary, 1987: Hydrologic events and water supply and use. Paper 2350, Denver, CO.

Weston, D. P., Lentz, R. D., Cahn, M. D., Ogle, R. S., Rothert, A. K., & Lydy, M. J. (2009). Toxicity of anionic polyacrylamide formulations when used for erosion control in agriculture. Journal of Environmental Quality, 38(1), 238-247.

World Health Organization (WHO). (1985). Acrylamide. Environmental Health Criteria No. 49, Geneva, Switzerland.

Wichelns, D., and Oster, J. D. (2006). Sustainable irrigation is necessary and achievable, but direct costs and environmental impacts can be substantial. Agricultural Water Management, 86(1-2), 114-127.

Young, M. H., Tappen, J. J., Miller, G. C., Carroll, S., and Susfalk, R. B. (2007). Risk characterization: Using linear anionic polyacrylamide (LA-PAM) to reduce water seepage from unlined water delivery canal systems. Desert Research Institute, Reno, Nevada.

Zörb, C., Geilfus, C. M., and Dietz, K. J. (2019). Salinity and crop yield. Plant Biology, 21, 31-38.

Chapter 3

From synthetic to biopolymer sealants: using xanthan gum to reduce irrigation canal seepage*[3]

SUMMARY

Synthetic polymers have been explored as a cost-effective alternative to traditional liners for mitigating irrigation canal seepage losses. This study compares the efficacy of various synthetic polymers with natural biopolymers. Through laboratory experiments designed to mimic conditions in irrigation canals, we identify xanthan gum, a natural polymer derived from corn starch, as an effective alternative to synthetic linear-anionic polyacrylamide. Findings show that xanthan gum, at a concentration of 40 mg/L, can reduce the hydraulic conductivity of turbid water through soils by more than 90% over 9-10 months and by 60 to 70% over 1.5 months at 20 mg/L. These results were backed up by subsequent field experiments, demonstrating that xanthan gum, applied to an irrigation canal at 20 mg/L, reduced seepage by up to 63% over one month. Both lab and field tests were conducted in triplicate and duplicate, respectively, to enhance confidence. Results point to biopolymers meriting further study for the economical and environmentally benign control of canal seepage losses.

---

[3] This chapter was submitted for possible publication as a research article on September 14, 2024. by A.A. Rehman Lund (the author of this dissertation), Joseph Scalia IV (the adviser), and Timothy K. Gates (the co-adviser).

3.1 Introduction

During the transport of irrigation water to irrigated fields via earthen canals, a significant portion of water exits the canal perimeter, contributing to groundwater without serving direct beneficial use—this phenomenon is termed canal seepage. The scope, causative factors, methodologies for quantification, and the imperative of comprehending canal seepage have been summarized in detail by Mutema et al. (2022) and Lund et al. (2023). Seepage yields diminished conveyance efficiencies, reducing availability of water for agricultural purposes, along with other associated issues including elevated groundwater tables, non-beneficial water consumption, discharge of polluted return flows into freshwater bodies (Morway et al., 2013), and soil salinization and waterlogging of cultivated fields contribute to diminished crop yields (Kahlown and Azam 2002, Ghazaw 2011, Zorb et al., 2019). Depending on various contributing factors, seepage losses from irrigation canals can be substantial, encompassing a range from 10 to 70% of the total diverted water (Ashour et al. 2023, Gad et al. 2023, Kalybekova et al. 2023, Mao et al. 2024, Selim et al. 2024) necessitating effective control measures. Predominant strategies for controlling canal seepage are the use of permanent liners such as concrete, geomembranes and asphalt, or their combination, which have demonstrated reductions in seepage ranging from 50 to 97% (Comer et al. 1996, USDA 1997, Swihart and Haynes 2002, USDOI 2002, Kahlown and Kemper, 2005). However, these liners may pose cost constraints (Wichelns and Oster 2006), impede groundwater recharge during periods of water surplus, and potentially conflict with specific water laws concerning the return flows from seepage into the hydrologic environment (Hayes 1991; Rohmat et al. 2021).

Less permanent liners such as water-soluble polymer sealants, specifically linear anionic polyacrylamide (LAPAM) have also been under investigation over the last decades. Unlike permanent liners, sealants have lower up-front costs and can be implemented on an as-needed basis to mitigate canal seepage, which makes them a good alternative to permanent liners in many applications. The seepage reduction mechanisms and the field application of LAPAM are discussed in detail by Sojka et al. (2007) and Lund et al. (2021). LAPAM has shown great potential, reducing seepage within a wide range of 28 – 100%, in field trials in different parts of the world under varying canal conditions (Susfalk et al. 2008, Uribe et al. 2013, and Lund et al. 2021). However, the direct application of synthetic polymers can cause environmental concerns (Tepe and Cebi 2019). Susfalk et al. (2008) found that when LAPAM was excessively applied, or applied under unfavorable conditions, residual acrylamide monomer (a human carcinogen), though in low concentrations (typically below US EPA regulatory thresholds), was detected in downstream waters.

Given the limitations of permanent liners and the unlikely yet possible environmental impacts from LAPAM, there is a basic need for a seepage control technology that is (i) cost-effective, (ii) easy to be applied, (iii) can allow groundwater recharge when water is plentiful, (iv) does not interrupt the normal canal flow operations, and (v) does not result in agro-environmental damages. Recent advances in the biopolymer industry (Berninger et. al 2021) portend the use of biopolymers for numerous agricultural purposes.

In this study, we evaluate polysaccharide biopolymers identified through our review of literature (Arai and Shikata 2020, Macczak et al. 2020, Berninger et al. 2021, Liu et al. 2022, Muthusamy et al., 2022) against different configurations of the widely used synthetic polymer LAPAM in the lab and apply the findings in the field. Previous experiments assessing polymer efficacy in reducing canal seepage through mixed-head columns (Ragusa et al. 1994, Lentz 2015) were not replicated at a field scale. As a result, the extrapolation of simplified 1D column experiment polymer concentrations to a field-scale scenario has remained unrealized. This highlights the need to bridge the gap between laboratory findings and field applications.

Findings of a lab-based biopolymer identification are presented which pinpoint xanthan gum (XG) as the most suitable candidate for field application. Confirmatory field experiments on an operating irrigation canal are described which reveal similar seepage loss reductions and suggest the need for more detailed study to refine understanding of XG effectiveness under varying field conditions.

3.2 Laboratory tests of biopolymers for seepage control

3.2.1 Laboratory materials

Conditions near the bed of irrigation canals were replicated in the laboratory to perform controlled experiments. Analyses were conducted using canal water, fine sand and bed soils from a nearby irrigation canal. Moreover, the selection of the range of polymers used in this study is presented.

3.2.1.1 Soil and water

Fine sand was used in initial laboratory experiments because fine sand in the field is characteristic of a canal with high seepage. In addition to fine sand, soil from a typical canal in northern Colorado near Fort Collins was used. As per the USDA SSURGO soil classification, the field canal soil predominantly consisted of loam, with traces of clay, sand, and gravel. The standard Proctor maximum dry density of the field soil, assessed following ASTM D698 (ASTM, 2012), was 1.9 g/cm^3 at 11% water gravimetric content.

3.2.1.2 Synthetic polymers

The selection of synthetic polymers for our experiments was guided by prior field-scale studies (Lund et al. 2021) and consultations with an expert from a polymer flocculant manufacturer (R. Yap, Solenis™, personal communication, 17 November 2020) . We tested four configurations of linear anionic polyacrylamide (LAPAM). Anionic PAM is a negatively-charged polymer composed of repeating acrylamide units (-CH2-CH(CONH2)-). LAPAM acts as a flocculant by bridging total suspended solids (TSS) in canal water, forming flocs that settle and are hypothesized to clog the canal perimeter (Gregory and Barany 2011). The LAPAM samples used in our study varied in charge density and relative molecular weight (MW). Higher charge density increases ionic strength, enhancing particle bridging (Gregory and Barany 2011). As MW increases, so do the length (increased number of repeating units) and viscosity of the LAPAM solution, making higher MW PAMs more effective for seepage reduction (Green and Stott 1999).

The commercial names of the LAPAM were Magnafloc™ LT25, Magnafloc™ LT27 AG, Magnafloc™ LT30, and Stockopam™. Solenis supplied the Magnafloc products, while Stockopam, now discontinued, was sourced from an old stock purchased from Evonik Corporation. To better reflect their scientific attributes, we renamed the polymers based on their charge density and MW. Although the exact charge data is proprietary, personal communications (R. Yap, Solenis™, personal communication, 4 November 2020) allowed us to categorize them as non-ionic (0%), low (< 20%), medium (20-35%), and high (> 40%). Similarly, because the polymer industry's quantitative descriptions of MW are often contentious, we used qualitative relative descriptions. Table 3.1 details the chemical attributes and naming scheme for the polymers used in this study.

Table 3.1: Chemical properties and naming scheme of synthetic polymers used in the laboratory experiments.

Polymer	Charge density	Relative molecular weight	Assigned name
Magnafloc LT25	Low	Low	LAPAM-1
Magnafloc LT27 AG	Medium	Medium	LAPAM-2
Magnafloc LT30	High	High	LAPAM-3
Stockopam	Medium	Very high	LAPAM-4

3.2.1.3 Biopolymers

Polysaccharides, essentially bio-based flocculants or biopolymers are gaining increasing attention due to their environmentally friendly nature and biodegradability (Sharma et al. 2006). Our selection of biopolymers was informed by a review by Macczak et al. (2020), which provides an overview of various biopolymers that could serve as potential alternatives to synthetic polymers. We examined five biopolymers—pectin citrus (PC), cellulose hydroxyethyl ether (CHE), pullulan desalinated (PD), sodium alginate low viscosity (SALV), and XG—as potential replacements for synthetic LAPAM. CHE and SALV were excluded after initial experiments, while the remaining three underwent further study, ultimately leading to the selection of XG for detailed examination.

XG is an extracellular polymeric substance primarily produced by various Xanthomonas spp. bacteria (Berninger et al. 2021). The molecular structure of XG comprises 4-linked β-1 subunits of glucose connected by a trisaccharide chain. XG exhibits a high MW, ranging from 10^6 to 10^7 g/mol (Casas et al. 2000), making it ideal for canal seepage reduction applications. The XG used in this study was manufactured by the Fefung Group and distributed by Level 7 Chemical and Supply. According to the manufacturer, XG was produced from corn starch through processes of fermentation with Xanthomonas campestris, followed by extraction, drying, and grinding. The biopolymer passed 100% through a 60-mesh (250 μm) sieve, at least 95% through an 80-mesh (180 μm) sieve, and had an MW greater than 10^6.

3.2.2 Laboratory Methods

3.2.2.1 Biopolymer identification

Candidate biopolymers that could replace synthetic polymers previously used for canal seepage control in the field (Susfalk et al. 2008, Uribe et al. 2013, and Lund et al. 2021) were identified in the lab using fine sand and a field canal soil. The experimental setup and procedure for selecting a candidate biopolymer for field testing are outlined in this section.

3.2.2.2 Laboratory experimental setup

Constant head saturated hydraulic conductivity (K_{SAT}) tests were used as shown in Fig. 3.1. Variables tested included polymer type, polymer concentration, and soil type. Steady-state K_{SAT} was determined on soil columns before and after the addition of candidate polymers (described subsequently) in the column headwater. Each experiment was performed in three simultaneous replicates. The K_{SAT}, obtained from the three columns, was used to determine average K_{SAT} values.

Rigid-wall constant head permeameters, referred to as columns herein, were used. As shown in Fig. 3.1, columns had a 10 cm inside diameter and were ~40 cm tall. Three valves were installed in each column: at the base of the column; just above the soil surface in the column to drain the water after the experiments were complete, and at approximately 4 cm below the top of the column to maintain a constant head at the inflow boundary.

Columns were assembled from the bottom up with the following layers: a non-woven filter geotextile at the base of the column followed by an ~40-mm layer of clean gravel, a non-woven filter geotextile at the top of the gravel layer, and finally a 90-100-mm layer of soil. All polymers were evaluated using the fine sand with higher permeability and/or the field canal soil. The fine sand was poured into the columns in a loose state and leveled manually at a dry density of ~1.5 g/cm^3. For the more-plastic field canal soil, soil was compacted in the column to 80% of standard Proctor maximum dry density to approximate field conditions.

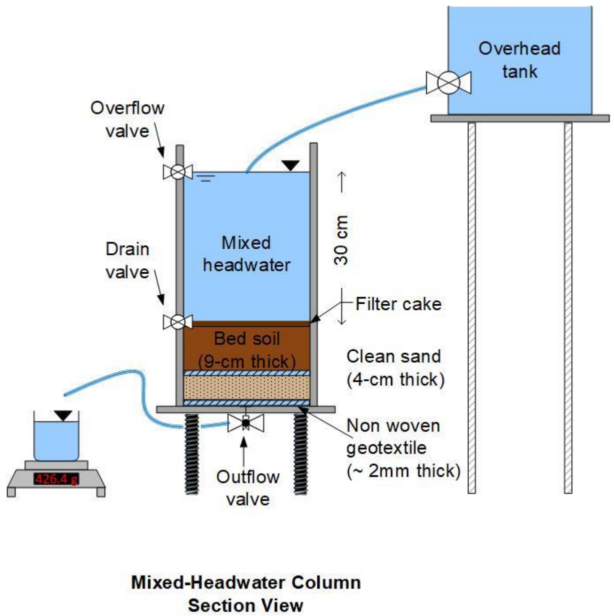

Figure 3.1: Schematic of the mixed headwater column showing the dimensions and arrangement of soil layers and fittings

Soil columns were gradually (to prevent liquefaction) saturated from the bottom valve with the water supplied from the overhead tank. Once the columns were saturated, water was supplied to the columns from the top to create a pond on the soil.

The K_{SAT} was calculated using Darcy's equation for flow through porous media.

The outflow from the columns was weighed at varying time intervals. The weight of outflow was divided by the density of water to determine the volumetric flow rate through the column. The hydraulic gradient in each experiment was established at unity in most of the experiments by controlling the apex of the outflow tube (i.e., the elevation of the outflow air-water interface). The K_{SAT} readings were not continuous. After readings were taken on a specific day, the outflow valves were closed until the next reading day. Experiments were terminated once four readings within twenty-five percent of the mean were recorded with no obvious upward or downward trend per ASTM D5856 (ASTM 2007).

3.2.2.3 Down-selecting promising synthetic and biopolymers

i. Testing numerous polymers: The first step toward down selecting a potential biopolymer was to test numerous polymers at a high concentration and simplified test conditions. Eighteen tests were performed with the two different soil types and with nine polymers added to the column headwater at 70 mg/L. Of note, the maximum recommended polymer treatment level (for LAPAM) suggested by NRCS (2005) is 35 mg/L. Since this task was aimed at only down-selecting promising polymers, the recommended concentrations were doubled to ensure reductions in K_{SAT} were apparent. The experiments were first run at baseline conditions (no polymer) until the average pre-polymer steady state K_{SAT} was determined, termed the control readings. Since the results of these experiments guide the ranking of the biopolymers, follow-up experiments on fine sand were not performed; instead, only the field canal soil was used for subsequent tests.

ii. Determining the preferred application rates of down-selected polymers: Based on the information obtained from preliminary column experiments, the synthetic polymer exhibiting the greatest reductions in K_{SAT} (LAPAM-4) was examined through a second round of column experiments run to better simulate field conditions. The two experimental variables believed to be most influential to treatment effectiveness, i.e., the TSS and the soil type (Clapp and Hornberger 1978, Ragusa et al. 1994, Kinzli et al. 2009, Wesseling et al. 2009, Young et al. 2009) were replicated. Three experiments with different polymer concentrations viz. 10, 20, and 30 mg/L were performed to determine the influence of reduced concentration on treatment effectiveness. The preferred concentration of LAPAM-4 was then used to short list a biopolymer from PD, XG, and PC. Since XG showed the most promising results, XG was further tested at 20, 40 and 60 mg/L. The highest TSS observed in the later test of XG in the field (Table 3.3) was 69 mg/L. Fig. 3.3 shows the reductions in K_{SAT} resulting from the varying concentrations of LAPAM-4 and the three biopolymers at the identified preferred concentration. This experiment guides the selection of the rate for field application.

3.2.2.4 Biopolymer longevity

The biopolymer identified in Section 3.2.2.3 was further examined for potential long-term effectiveness within a water year. Like previous experiments, typical field canal soil and TSS were used. The rationale behind these experiments was to assess the longevity of the best biopolymer treatments in a laboratory setting given the difficulty in assessing the longevity at a field scale. The K_{SAT} values were recorded before the polymer addition; immediately after the polymer addition; and at 1, 4, 7, 12, 32, and 42 days of the polymer addition. The experiment at 40 mg/L concentration, was additionally continued until 9.6

months and K_{SAT} readings were also recorded at 63, 104, 122, 123, 182, 244, 251, 275, 278, 280, 281, 282, and 288 days.

3.2.2.5 Additional tests

Two additional experiments with the down-selected biopolymer added at 20 mg/L were performed to determine if the percent reduction in K_{SAT} changed with a) the thickness of the soil specimen and b) the height of the water column above the specimen. Tests were performed to determine if field application rates should be based on the canal wetted perimeter, or on the total amount of sediment in the water available for interaction with the polymer. The role of variation in the thickness of the specimen provides knowledge about the transport of the polymer through the soil layer and if the sediment filter cake formation only occurs in the topmost soil (e.g., top 10 to 20 mm).

3.2.3 Laboratory Results and discussion

3.2.3.1 Biopolymer identification

3.2.3.1.1 Preliminary experiments to shortlist polymers

Pre- and post-polymer addition K_{SAT} values and the percent reduction due to the polymer addition are presented in Table 3.2. All polymers were evaluated on fine sand and field canal soil. Polymers with prominent average K_{SAT} reductions (LAPAMs > 90% and biopolymers > 40%) in both type of soils were selected for subsequent experiments. LAPAM-4 was selected for further testing by virtue of demonstrating the largest percentage deductions in K_{SAT}. This is the same polymer that was used previously in field trials by Lund et al. (2021). For biopolymers, PC, PD, and XG showed an average K_{SAT} reduction of 43%, 46.5%, and 72% reductions, respectively, for both soil types. CHE and SALV had percent reductions less than 40% and were not further evaluated.

Table 3.2: Summary of the 70 mg/L experiments on both types of soils

Exp #	Polymer name	Soil type in the permeameter	Average pre-polymer K_{SAT} (cm/sec)	Average post-polymer K_{SAT} (cm/sec)	Reduction in K_{SAT} (%)	Average reduction (%)
1	LAPAM-2	Fine sand	7.9×10^{-3}	2.5×10^{-3}	68	42
2		Field canal soil	1.2×10^{-3}	1.0×10^{-3}	16	
3	LAPAM-3	Fine sand	7.4×10^{-3}	1.3×10^{-3}	82	60.5
4		Field canal soil	6.0×10^{-3}	3.6×10^{-3}	39	
5	LAPAM-1	Fine sand	6.4×10^{-3}	1.5×10^{-3}	77	78
6		Field canal soil	8.7×10^{-4}	1.9×10^{-4}	78	
7	LAPAM-4	Fine sand	8.3×10^{-3}	4.7×10^{-4}	94	95
8		Field canal soil	9.3×10^{-3}	3.8×10^{-4}	96	
9	CHE*	Fine sand	3.4×10^{-2}	2.7×10^{-2}	20	31
10		Field canal soil	2.2×10^{-3}	1.3×10^{-3}	42	
11	SALV*	Fine sand	2.3×10^{-2}	2.1×10^{-2}	5	25
12		Field canal soil	2.3×10^{-3}	7.2×10^{-4}	46	
13	PC*	Fine sand	2.9×10^{-2}	1.8×10^{-2}	37	43
14		Field canal soil	2.8×10^{-3}	1.4×10^{-3}	49	
15	PD*	Fine sand	4.9×10^{-2}	2.2×10^{-2}	54	47
16		Field canal soil	1.4×10^{-3}	8.8×10^{-4}	39	
17	XG*	Fine sand	3.0×10^{-2}	3.7×10^{-3}	88	72
18		Field canal soil	2.5×10^{-3}	$1.\times10^{-3}$	56	

*Biopolymers

Overall, the results of polymer effectiveness showed similarity for both soils. XG was the best performing biopolymer. Each experiment in Table 3.2 was run for 1-2 hours after running the experiments at baseline conditions (without polymer). The polymer selection was narrowed down to one synthetic and three biopolymers based on their average K_{SAT} reduction in both types of soils. Plots of percent reduction of K_{SAT} versus time are shown for the synthetic (only >90%) and biopolymers in Fig. 3.2. LAPAM-4 showed significant reductions in the K_{SAT} after addition. The replicate columns showed some variability but the overall reduction in the case of fine sand and field canal soil was around 94% and 96%, respectively. Almost equally effective results were achieved when XG was added in the fine sand columns, although the average range in K_{SAT} reduction among replicates was slightly higher (49% vs 36% with LAPAM-4). When added to the columns with field canal soil, XG results were not comparable to LAPAM-4, showing a 56% reduction in K_{SAT} compared to 96% with LAPAM-4. However, this result was superior to other biopolymers tested. Despite the relatively lower effectiveness of PD and PC, namely 39% and 49% in field canal soil and 54% and 39% in fine sand, respectively, these polymers were further examined in the next phase under field TSS. We attribute the variability across the columns to the heterogeneity in the soil specimens due to sample preparation as well as measurement errors. SALV and CHE, although ineffective in fine sand, showed up to 46% reduction in seepage in the field soil. However, the readings were highly variable, and these biopolymers were therefore not explored further.

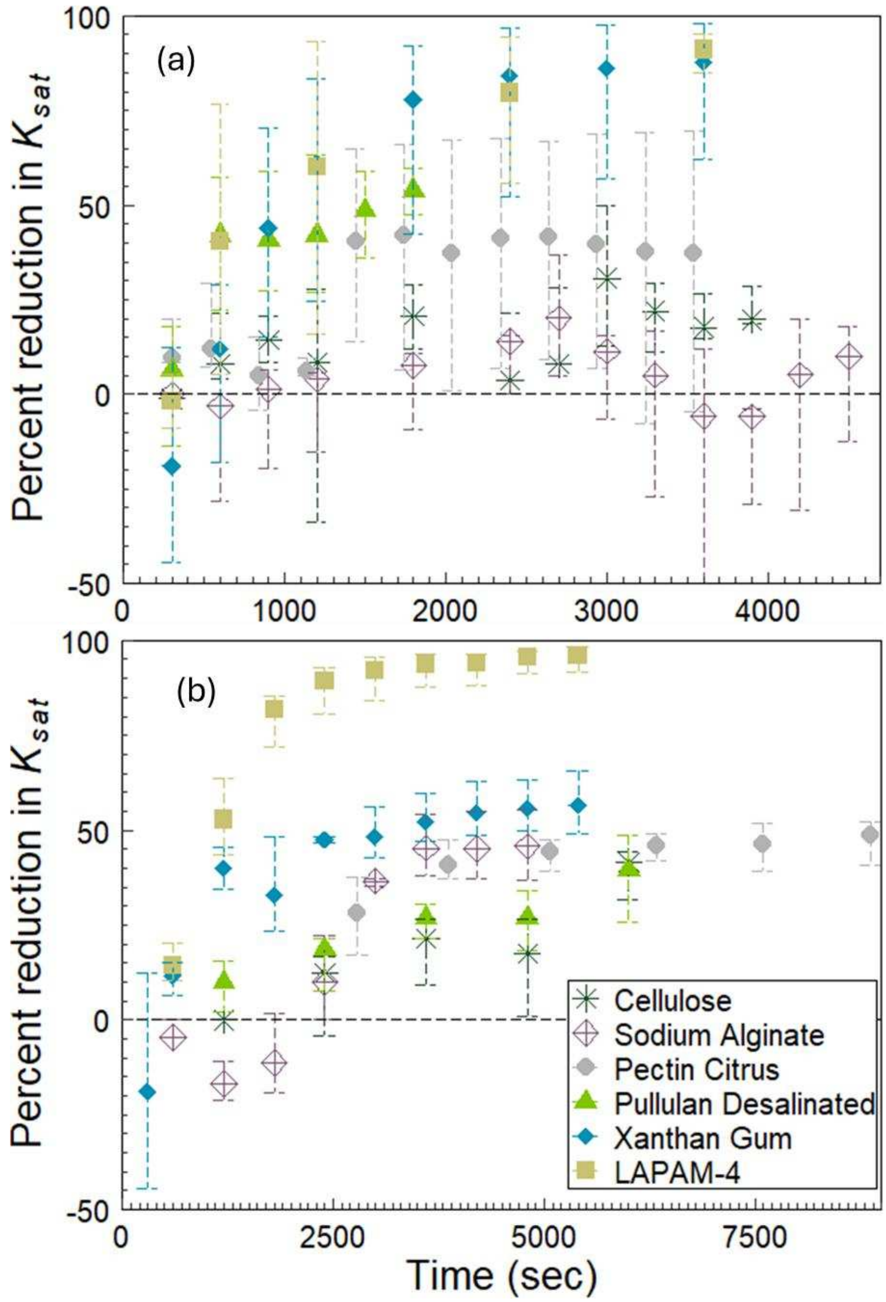

Figure 3.2: The plots of transient K_{SAT} of (a) fine sand and (b) the field canal soil with 70 mg/L Cellulose hydroxyethyl ether, sodium alginate, pectin citrus, pullulan desalinated, XG, and LAPAM-4. The markers in the plots show the average of the three data points and whiskers denote the minimum and maximum of three replicate tests.

3.2.3.1.2 Determining the preferred application rate

The preferred application rates of LAPAM-4 were determined by testing at three different concentrations (10, 20, and 30 mg/L) with field canal soil and typical TSS. The average reduction in K_{SAT} because of LAPAM-4 addition were 63%, 85%, and 79% for 10, 20, and 30 mg/L, respectively as illustrated in Fig. 3.3(a). The results suggest that LAPAM-4 concentrations greater than 20 mg/L may not result in further reductions in K_{SAT}. Thus, 20 mg/L was considered the preferred application rate for LAPAM-4 under conditions tested in this study. To compare the effectiveness of the shortlisted biopolymers at a similar rate, all biopolymers were tested at 20 mg/L, except for XG which was tested at 20, 40, and 60 mg/L, as illustrated in Fig. 3.3(b).

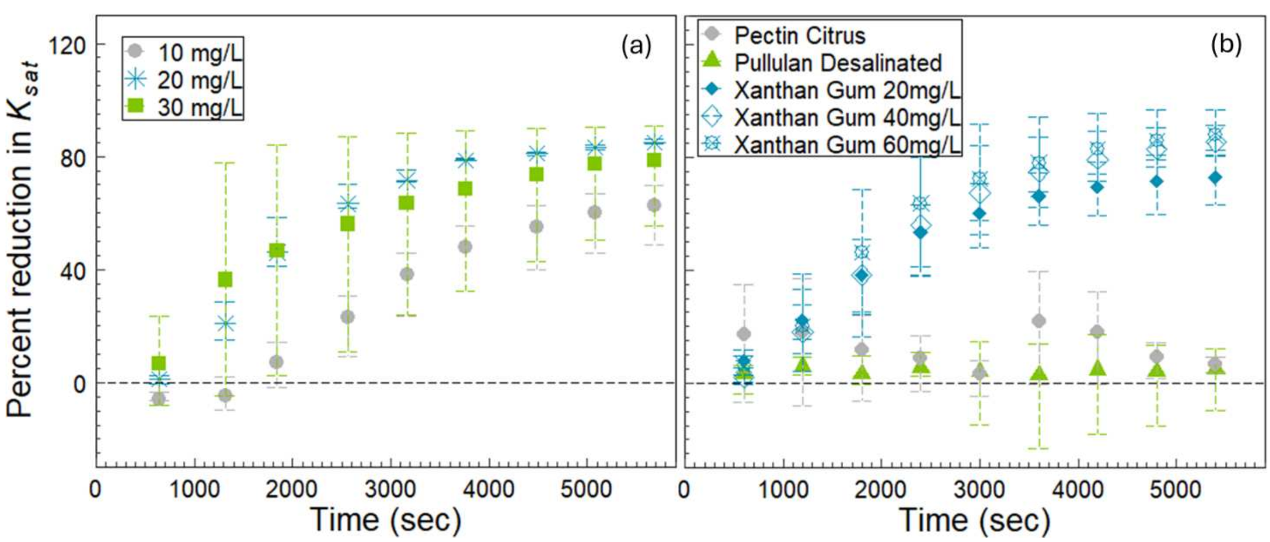

Figure 3.3: Percent reduction in K_{SAT} of the field canal soil after treating the soil column with a 10, 20, and 30mg/L concentration of LAPAM-4, and with (b) biopolymers pectin citrus, pullulan desalinated, and XG at 20, 40 and 60 mg/L while replicating typical TSS. The markers in the plots show the average of the three data points and whiskers denote the minimum and maximum of three replicate tests.

The results of the biopolymer evaluation experiments suggest that XG could be a potential replacement for synthetic polymers previously tested in the field. Regarding the average reduction in K_{SAT} due to XG addition, only slightly better performance was observed at 40 and 60 mg/L concentrations. Therefore, from a feasibility perspective, the

20 mg/L concentration was considered the optimal XG field application rate. The long-term performance of different XG concentrations, prior to field trials, is further discussed in Section 3.2.3.2. Overall, the percent reductions in K_{SAT} recorded before terminating the experiments were 5%, 73%, and 7% for PD, XG (20 mg/L), and PC, respectively. Although the higher variability in individual columns in the PD and PC experiments induced some bias in the results, no column in either of the experiments exceeded a 37% reduction in the K_{SAT}. In contrast, the minimum reduction in individual columns for XG experiments was 63%.

The effects of LAPAM-4 and the biopolymers on the surface of the specimen were visually distinct; the columns treated with LAPAM-4 had a noticeable fine cake formed over the specimen surface. No such film was observed in the case of biopolymers, although the specimen surface had become firmer when compared to the untreated specimen.

3.2.3.2 Biopolymer longevity

XG provided the greatest K_{SAT} reduction of the biopolymers tested in this study and was thus selected for evaluation at three different concentrations (20, 40, and 60 mg/L) with field canal soil and typical TSS over a longer duration. Results of long-term testing are shown in Fig. 3.4. Temporal results show an unanticipated decline in XG effectiveness after one week followed by an increase in effectiveness after one month. The mechanisms behind this fall and rise are unknown. We hypothesize that this behavior may result from a combination of mechanisms described in the literature by Norris et al. (2022) and Arabani et al. (2024) albeit not in the context of canal sealing. These mechanisms include increases in hydraulic conductivity due to biopolymer microbial degradation and reductions in hydraulic conductivity due to viscosity (hydrogel) effects, polymer adsorption to clay mineral surfaces, polymer crosslinking, and pore clogging. Future study is needed to evaluate the dominant mechanisms underlying the observed behavior for the specific canal-sealing XG use case.

For the experiment performed with 20 mg/L concentration, on average the K_{SAT} was 72% lower post-XG addition on the same day. The reduction decreased from 72% to 43% in one week; however, reduction transitioned to rising again and was close to approximately 64% reduction at the end of the experiment i.e., day 42.

The 40 mg/L concentration of XG was continued for 9.6 months (288 days). The K_{SAT} percent reduction was approximately 84% post-XG addition on the same day and plateaued at the same level for approximately one week. The K_{SAT} started increasing until approximately one month (day 32) and was followed by another cycle of K_{SAT} reduction. The K_{SAT} reduction before termination (day 288) was 94%. The experiment with 60 mg/L revealed higher reductions in K_{SAT} as an immediate effect of XG addition, 87 % immediately after the polymer addition. The percent reduction recorded on day 7 was approximately 93%. However, the K_{SAT} started increasing after one week, and a 54% reduction in the K_{SAT} was recorded on day 42.

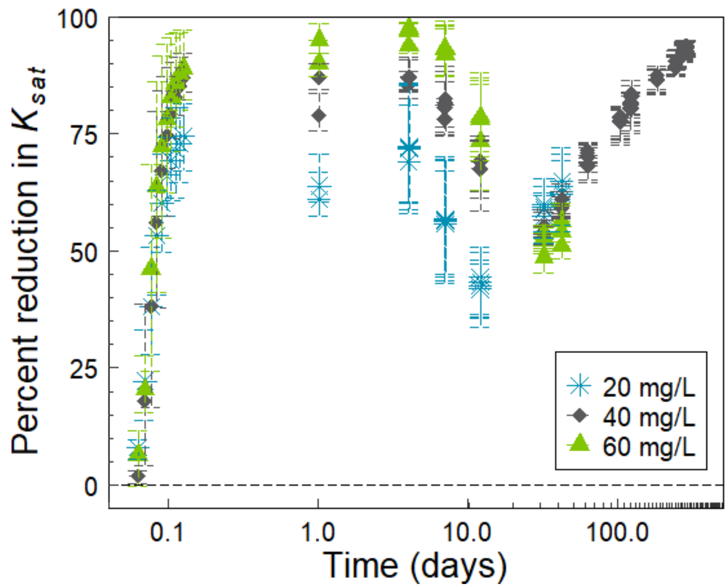

Figure 3.4: Percent reduction in K_{SAT} of the field canal soil due to XG application over 42 days (at 20 and 60 mg/L) and 288 days (at 40 mg/L) in the lab. The markers in the plots show the average of the three data points and whiskers denote the minimum and maximum of three replicate tests.

The results show that higher concentrations of XG tend to perform better immediately after addition, but this trend diminishes with time; all concentrations yield close to the same results at the end of the experiment. The results suggest choosing lower concentrations, 20mg/L, for the field experiments from a cost-effective perspective.

3.2.3.3 Effects of soil column thickness and inflow headwater

The effects of the thickness of the soil specimen and the water head (h_w) in the column were further examined via a supplemental column test. The XG effectiveness increased a minimal 3 percentage points (76% vs 73% reduction) with a thinner specimen (50 mm vs 100 mm) (Fig. 3.5). Though there may be other reasons such as increased effective stress from the higher hydraulic gradient (higher seepage induced stress), the slight increase in effectiveness points toward the likelihood that pore-clogging and filter cake formation occur only in the topmost portion of the soil specimen.

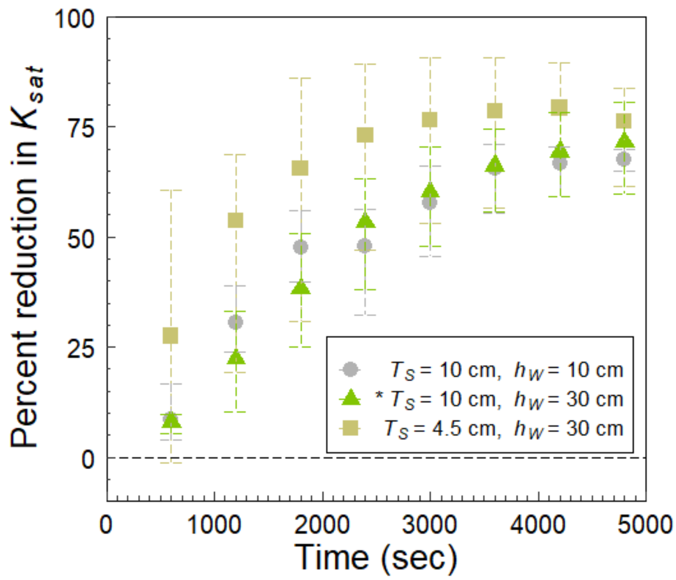

Figure 3.5: The impact of soil layer thickness and water column head on the transient K_{SAT} of the typical field canal soil with 20 mg/L XG. T_s is the soil thickness and h_w is the water column head. *shows the baseline condition. The markers in the plots show the average of the three data points and whiskers denote the minimum and maximum of three replicate tests.

A lower hydraulic gradient results in higher K_{SAT} when compared to the gradient associated with the 250 mm head used in most of the experiments. In terms of the K_{SAT} reductions, the 100 mm head experiment resulted in 67% reduction at termination compared to 76 % for 300 mm head. Fig. 3.5 shows the results of K_{SAT} for the reduced water head experiment. The findings of this experiment indicate that the quantity of available sediment impacts the XG effectiveness.

3.3 Field tests of most effective laboratory biopolymer

A reach along the Larimer and Weld Canal (LWC), an earthen irrigation canal located in the South Platte River Basin of Colorado was used for field verification of laboratory findings. The selection of the study reachabout 30 km east of Fort Collins (Fig. 3.6) for seepage quantification was based on the criteria described by Lund et al. (2021). The reach extends 2.9 km in length and contains two flow offtake structures, both of which were closed during seepage experiments. Wetlands were present adjacent to the southern bank of the lower portion of the LWC reach.

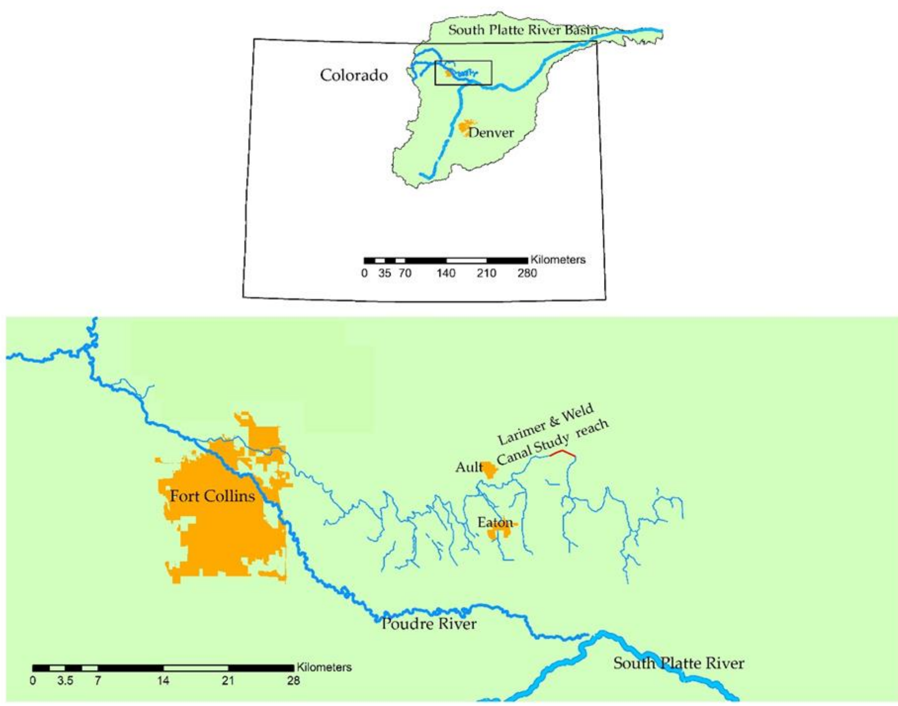

Figure 3.6: The location of the study reach along the Larimer and Weld Canal in the South Platte River Basin in Colorado, USA. The study reach is denoted with a red line.

3.3.1 Field materials

According to the USDA classification system, the LWC soil surrounding the study reach was not substantially different from the field canal soil used earlier in the laboratory tests. In both soils, more than half of the coarse fraction was finer than 4.76 mm (U.S. sieve #4), broadly classifying them as sandy. Field density tests conducted at six different locations along the reach ranged from 1.3 to 1.8 g/cm^3 at an average 23% moisture content. The TSS concentration measured in the canal water was as high as about 70 mg/L (see Table 3.3). XG was the only biopolymer used in the field and is described, along with the particle size, in section 3.2.1.3.

3.3.2 Field methods

The steps in the field evaluation of XG involved a) quantifying the baseline seepage rates from the canal study reach b) treating the canal at the biopolymer dosage determined in the lab and, c) quantifying the canal seepage post-treatment. The seepage quantification methodology (same for the pre- and post-treatment tests) and the field methods of treating the canal with the XG are discussed in subsequent sections.

3.3.2.1 Field seepage quantification

The flowing water balance technique, commonly referred to as the inflow-outflow method, was used to measure seepage in the field before and after treating the canal reach with the lab-identified XG. The underlying concept in the inflow-outflow method is to subtract the outflows and the storage change from the inflows over a canal reach with seepage loss being the unknown; thus, the difference (the balance) yields the loss or gain in the water due to seepage. The inflows along a selected canal reach are the inflow into the reach or the upstream section Q_{US} (m^3/sec); any inflows to the canal reach from the adjacent irrigated lands, treatment facilities, etc. Q_I (m^3/sec); and precipitation rate, if any, Q_P (m^3/sec). The outflows include the flow measured at the downstream section of the reach, Q_{DS} (m^3/sec); evaporation from the water surface along the reach, Q_E (m^3/sec); any flow diversions (the turnouts) along the reach length, Q_D (m^3/sec); and any change in stored volume throughout the seepage measurement expressed as a rate, $\frac{\Delta S}{\Delta t}$ (m^3/sec).

Based on knowledge of these terms, the seepage rate, Q_S (m^3/sec), is calculated as

$$Q_S = Q_{US} - Q_{DS} + Q_I - Q_D - Q_E + Q_P - \frac{\Delta S}{\Delta t} \quad (3.1)$$

A detailed account on the estimation of terms in Eq. 3.1 is given by Martin and Gates (2014) and Lund et al. (2021). The Q_E term in the water balance was assumed negligible in this study given the short duration of the seepage tests and the insignificant sensitivity of results to the Q_E term (Martin and Gates 2014).

3.3.2.2 Advanced seepage measurement methodology

Modifications based upon Lund et al. (2023) were made to the field seepage data collection methodology presented in Martin and Gates (2014) and Lund et al. (2021), as described subsequently. Measurement errors related to canal cross section geometry and the protocols of flow measurement (Q_{US} and Q_{DS} terms of Eq. 2.1) with advanced Doppler devices were addressed.

3.3.2.2.1 Canal cross-section survey

Canal seepage is often normalized by dividing by the wetted perimeter area, A_P, calculated from the canal geometry obtained through a cross-section survey. This facilitates a better understanding of the amount of seepage in relation to canals of varying size. Previous methods involved surveying canal cross section geometry using traditional leveling instrument with attendant error, and with relatively few survey points within each cross-section. In this study a Teledyne StreamPro acoustic Doppler current profiler (ADCP) device was used to survey six cross-sections along the selected canal reach. The reach was divided into five sub reaches ranging from 0.15 to 0.5 km depending on the observed frequency of changes in the canal prism. The ADCP allowed measuring the geometry during normal canal operation, and the processed ensemble data from the ADCP were extracted to determine the cross section wetted perimeter (*P*). The distance traveled by the ADCP was plotted against the beam average depth in AutoCAD and the length of the plot line was measured to calculate *P*. The length of each canal sub-reach was multiplied by the average of the *P* values at each end to determine the sub-reach value of A_P. Finally, the A_P values computed for the five sub-reaches were summed to obtain the total study reach value.

3.3.2.2.2 *Refined flow measurement protocols and data analysis*

Like previous studies, Q_{US} and Q_{DS} were measured with ADCP devices. The ADCP employs an area-velocity approach for calculating the flow rates. At a given cross-section, incremental areas with point velocities perpendicular to those areas are measured and the resulting incremental discharges are then aggregated to derive a cumulative discharge. A complete traverse of the ADCP across the canal, from one bank to the other, constitutes a flow transect, providing a cumulative discharge value for the cross-section. Following the guidelines of Pugh et al. (2021), each measurement of Q_{US} and Q_{DS} involved the execution of at least four flow transects, each lasting four minutes, with a reciprocal number of transects performed in both directions (commencing from the left bank, traversing to the right bank, and vice versa). Previous studies relied solely on the default WinriverII™ software for processing ADCP discharge data. In contrast, the current study processed all Q_{US} and Q_{DS} measurements using both WinriverII and the USGS-recommended Qrev software (Mueller 2016). The flow rates provided by both software packages were then averaged to enhance confidence in the calculated values.

The largest source of uncertainty in the inflow-outflow method of canal seepage measurement is derived from the flow measurements (Q_{US} and Q_{DS}) at the selected reach boundaries (Martin and Gates 2014). Following guidelines in Lund et al (2023), the uncertainty in flow measurement was addressed by realizing two replications. Previous studies included lagged seepage tests, wherein flow measurements were sequentially conducted at each end of the study reach. In the current methodology simultaneous measurements were taken at each end using two ADCPs. Subsequently, the ADCP operating teams interchanged locations, leading to another set of congruent measurements at both canal ends. This process yields two flow measurements for each end, each conducted by different teams and ADCP devices. The averaged values of the two measurements were computed and used.

3.3.2.3 Biopolymer field application

Our field-scale application of XG evolved iteratively, with the methodologies refined based on insights gained over the field campaign. Below are the methodologies employed during the trials with XG in both dry and wet forms.

3.3.2.3.1 Xanthan Gum application in dry form

The first round of XG application was performed in early September 2021. Approximately 46 kg of XG in powdered form were dispersed across the LWC test reach. To ensure uniform application, the total calculated mass of XG was pre-weighed and divided into 4-L plastic bags, each designated for a 0.08 km increment along the study reach. This facilitated tracking of the XG application.

The application process involved walking along the selected reach and evenly distributing XG onto the water surface. This method was feasible due to the relatively shallow water depth of ~1 meter. Initially, an on-bank application commenced from the downstream end of the canal study reach and progressed upstream. The XG dispenser was positioned approximately 0.9 m above the water surface and was attached to a truck. However, at around 1.2 km upstream, the designated backup application tool used for the on-bank application failed. Consequently, application transitioned to manual dispersion with individuals wading in the canal and broadcasting the XG using a fertilizer spreader for the remaining 1.7 kilometers. When broadcast, some polymer was carried away by air currents. Additionally, applying XG by walking through the canal proved labor-intensive and impractical for relatively deep flow. Natural turbulence of canal water was insufficient for instant hydration, causing some XG to float out of the intended application area. However, after our study the manufacturer started producing a finer grade (mesh size 200) of XG that is designed to hydrate more rapidly and may be more functional for future field trials.

The field XG application rate, defined as the mass of polymer per unit wetted perimeter area, was determined based on the average rates observed in previous field experiments documented by Lund et al. (2021) – approximately 15 kg/ha. Initially, this rate was adjusted by the ratio of the preferred laboratory concentration for XG to that for LAPAM-4, as outlined in Section 3.3.2. This adjustment factor was calculated from the comparative analysis presented in Section 3.2.3. The application rates used in Lund et al. (2021) were initially informed by consultations with polymer distributors and previous experimental studies discussed in Susfalk et al. (2005), NRCS (2005), and Susfalk et al. (2006). While NRCS (2005) suggested an application rate of 44 kg/ha, lower rates reported in Lund et al. (2021) were selected to minimize environmental impact of the synthetic polymer. However, the environmentally benign nature of biopolymers at low concentrations suggests that higher application rates could potentially be employed safely. Logistical constraints, particularly the cost of procuring biopolymers, especially in small quantities, led to the application of only the preferred amount.

Following the XG application, two seepage tests were conducted to quantify the reduction in seepage resulting from the treatment. Flowing water balance tests, as detailed in Sections 3.2.4 and 3.2.5, were carried out both before and after the XG application (refer to Tables 3.3 and 3.4 for timing) to assess the magnitude of seepage reduction attributable to XG.

3.3.2.3.2 Xanthan Gum application in wet form

Given the challenges associated with the dry application of XG, a wet form of application was employed. Pre-mixed XG with water, resulting in an XG-water solution was used for the tests conducted in 2022. The dosage remained consistent with the powdered application at 15 kg/ha. Based on the calculated wetted perimeter area (2.42 ha), approximately 36 kilograms of XG were required for application to the canal reach. Since there are no known guidelines on how to use XG in solution form for agricultural applications, the main question revolved around determining the concentration of the XG-water solution. Although our laboratory findings reveal that the effectiveness of XG is a function of the amount of sediment accessible for XG (Section 3.2.3.3), the application rate was adjusted as per the wetted perimeter area because of the relatively low amount of sediment (presented in Table 3.3) in the canal water at the time of field testing.

Our examination of differing rheology among the XG-water solutions revealed that concentrations higher than 6 g/L need intense mechanical mixing to achieve a uniform solution and formed lightweight globules that floated along the canal out of the study area without hydrating. A concentration of 6 g/L was optimal for the field preparation and application of a XG. This equated to a total requirement of 6000 L of the XG solution to treat the selected canal reach.

A 700-L truck-mounted tank was used for preparation and transport of the XG solution. We used a Makita 8.5 Amp Corded Spade Handle Drill with a 100-mm steel eggbeater cement mixing paddle to prepare the viscous solution. The mixer was powered by a generator. We used a Honda WDP30XK1AT pump, a fuel-operated 76-mm positive displacement diaphragm pump with a capacity of 5 L/s to transfer the XG solution from the tank to the canal.

We prepared nine 700-L batches of XG solution in the field, depositing the solution at the upstream sections of nine sub-reaches, each spanning 0.36 km. The concentration of the XG solution was slightly less than 6 g/L in the field. Water was drawn from the canal into the tank using a small (2-3 L/s) centrifugal pump. Pre-weighed XG, packaged in 2-kg bags, was then added, thoroughly mixed, and subsequently applied to the canal via the positive displacement pump. Each batch of the XG solution required around 25-30 minutes to complete, including the time needed to fill the tank with canal water, mix the XG, pump out the prepared solution, and set up and dismantle equipment at each location. The pre- and post-XG treatment seepage rates are presented in Table 3.3 and 3.4, respectively.

3.3.3.1 Field seepage baseline tests

A total of ten seepage tests pre- and post-XG application were performed on the LWC study reach in 2021 and 2022. The canal flow parameters, geometry, and water quality parameters recorded during the seepage tests in 2021 and 2022 are summarized in Table 3.3.

The baseline seepage results from four pre-tests are presented in Table 3.4. The average seepage normalized by canal wetted perimeter area was 0.63 $(m^3/day)/m^2$ [m/day]. The water level at the flow measurement sections remained generally stable over the course of the flow measurements resulting in only minimal storage changes throughout the baseline tests. On average, the baseline seepage in 2022 (5.1% of the reach inflow) was slightly higher than in 2021 (4.5% of the reach inflow). We attribute this to the lower amount of TSS measured in the LWC in 2022. The measured seepage compares well with earthen canal seepage rates reported for the Lower Arkansas River Valley in Colorado, which ranged between -0.17 and 0.95 $(m^3/day)/ m^2$ in untreated canals (Martin and Gates 2014).

Table 3.3: Canal characteristics observed during the field tests on the LWC study reach, where y is canal flow depth at the thalweg, v is the average flow velocity, L is the length of the test reach, T_w is the top width of the canal, P is the average wetted perimeter along the canal test reach, A_P is the wetted perimeter area of the canal reach, T is the water temperature and TSS is the total suspended solids.

Test no and date	Average flow variables and geometry						Average water quality		
	y (m)	*v* (m/s)	*L* (km)	*Tw* (m)	*P* (m)	*Ap* (m²)	T (C°)	EC (µS/cm)	TSS (mg/L)
2021 Pre-XG Seepage tests									
T1-Aug 31	0.96	0.607	2.89	8.34	8.51	24271	20.7	531.6	69.6
T2-Aug 31	0.98	0.61	2.89	8.34	8.51	24271	22.35	531.6	69.6
2021 Post-XG Seepage tests									
T1-Sep 01	0.92	0.59	2.89	8.12	8.49	24227	21.76	475.8	--
T2-Sep 01	0.92	0.59	2.89	8.06	8.49	24227	21.52	511.3	--
2022 Pre-XG Seepage tests									
T1-Aug 09	0.97	0.605	2.89	7.99	8.51	24271	24.36	321.3	36.05
T2-Aug 09	0.97	0.605	2.89	7.99	8.49	24227	24.46	331.9	36.05
2022 Post-XG Seepage tests									
T1-Aug 11	1.01	0.615	2.89	8.21	8.6	24536	25.41	528.6	25
T2-Aug 12	1.03	0.615	2.89	8.12	8.66	24731	22.89	516.43	69.3
T3-Aug 18	0.96	0.585	2.89	7.81	8.49	24220	21.55	488.11	64.75
T4-Aug 18	0.96	0.59	2.89	7.81	8.5	24229	22.54	492	64.75
T5-Aug 25	1.07	0.62	2.89	8.06	8.72	24872	21.78	384.6	18.3
T6-Aug 25	1.07	0.62	2.89	8.06	8.71	24859	21.63	--	18.3
T7-Sep 09	0.84	0.53	2.89	7.77	8.29	23629	19.23	305.21	--
T8-Sep 09	0.84	0.525	2.89	7.77	8.29	23613	18.61	302.58	--

Table 3.4: Summary of baseline (pre-XG application) seepage tests in 2021 and 2022 along the LWC study reach, where Q_{US} is the flow rate measured at the upstream boundary of the selected reach, Q_{DS} is the flow rate measured at the downstream boundary of the selected reach, CV is the coefficient of variation of the US and DS flow measurements, $\Delta S/\Delta T$ is the storage change, Q_S is the seepage rate, Q_S/L is the seepage rate per unit canal length, and Q_S/A_P is the seepage rate per unit wetted perimeter area.

Test no and date	Avg Q_{US} (m^3/s)	Avg Q_{DS} (m^3/s)	*CV Avg* (min-max) of measurements (%)	Avg $\Delta S/\Delta t$ (m^3/s)	Q_S (m^3/s)	Q_S/L ($(m^3/sec)/km$)	Q_S/Ap ($(m^3/day)/m^2$)	Q_S as a % of Q_{US}
Tests performed in 2021								
T1-Aug 31	3.72	3.51	1.7 (0.39-2.9)	0.017	0.198	0.07	0.70	5.3
T2-Aug 31	3.80	3.68	2.4 (1.5-3.1)	-0.011	0.139	0.05	0.49	3.6
Tests performed in 2022								
T1-Aug 09	3.64	3.52	2.8 (2.2-3.9)	-0.005	0.120	0.04	0.43	3.3
T2-Aug 09	3.65	3.37	2.5 (1.1-5.2)	0.007	0.250	0.09	0.91	6.9

3.3.3.2 Field seepage measurement after xanthan gum treatment

The results of the 2021 and 2022 post-XG application field seepage tests are summarized in Table 3.5. The flow rates at the upstream section ranged from 2.51 to 4.56 m^3/s during the tests. The flow measurements had a low CV, indicating a high level of confidence.

Although the CV generally appears to be within the recommended range (5 %) (Teledyne RDI 2007) for all flow rates reported in Tables 3.3 and 3.4, the maximum CV values estimated during test 2 (T2) on Aug 09, 2022, and during T2 on Aug 31, 2021, were slightly higher. This may have been due to windy conditions associated with thunderstorms that occurred during these measurements. The ADCP movement speed and total number of transects were adjusted until measurements were achieved within or close to a CV of 5%.

The calculated storage changes along the canal study reach had an insignificant effect on the calculated overall seepage rate. The storage changes during the tests ranged between -0.009 and 0.011 m^3/s. The terms for flow diversions, evaporation, inflows, and precipitation were not included in the summary table because they were deemed negligible. The seepage per unit area of the canal test reach following the XG treatment ranged between 0.01 to 0.7 $(m^3/day)/m^2$, being higher than the range reported for canals treated with synthetic polymers (Lund et al. 2023). However, the canal seepage rates per unit length of the test reach- were 0.001 to 0.07 (m^3/sec)/km, lying in the reported range of seepage rates after synthetic polymer treatments.

Except for one seepage test performed on August 18, 2022, seepage as a percentage of the incoming flow was lower than the average baseline seepage for all post-XG treatment tests. The average of the two seepage tests performed a few hours after the XG application in 2021 revealed a 58% reduction in seepage. In 2022, seepage tests were performed a few hours after XG application, and one, seven, fourteen and twenty-nine days after the XG. Like the percent reduction in K_{SAT} in the XG longevity experiments discussed in Section 3.2.3.2, the canal seepage was noticeably reduced following the XG treatment, increasing to more than 95% after one day, as seen in Fig. 3.7 where percent reduction in field-measured canal seepage has been plotted upon the percent reduction in K_{SAT} in the laboratory shown in Fig. 3.4. However, the degree of seepage reduction dropped to about 14% after a week, then rebounded to about 75% reduction after two weeks. The average of the two seepage tests performed on day twenty-nine after the XG treatment showed a 63% reduction in seepage (Fig. 3.7).

Besides the likely microbial degradation and other mechanisms discussed under section 3.2.3.2, canal seepage in the field is influenced by various factors, as described by Lund et al. (2023), which may have partially or fully contributed to the observed fluctuations in the seepage reduction rate. One possible explanation is that the water supply to the canal was shut off on weekends, leaving about 0.3 m of standing water, perhaps playing a role in the observed pattern. During 2022 post-XG tests (Table 3.5), this occurred between tests 2 and 3, 4 and 5 and twice between test 6 and 7, totaling four weekends. Overall, XG showed potential in reducing canal seepage during the 2021 and 2022 field tests.

Table 3.5: Summary of post-XG application seepage tests in 2021 and 2022 along the LWC study reach, where Q_{US} is the flow rate measured at the upstream boundary of the selected reach, Q_{DS} is the flow rate measured at the downstream boundary of the selected reach, CV is the coefficient of variation of the US and DS flow measurements, ΔS/ΔT is the storage change, Q_S is the seepage rate, Q_S/L is the seepage rate per unit canal length, and Q_S/A_P is the seepage rate per unit wetted perimeter area.

Test no and date	Avg Q_{US} (m^3/s)	Avg Q_{DS} (m^3/s)	*CV* Avg (min-max) of measurements (%)	Avg $\Delta S/\Delta t$ (m^3/s)	Q_S (m^3/s)	Q_S/L (m^3/sec)/km	Q_S/A_P (m^3/day)/m^2	Q_S as a % of Q_{US}
Tests performed in 2021 (XG treatment on Sep 01)								
T1-Sep 01	3.28	3.25	2.4 (1.0-3.8)	-0.009	0.042	0.01	0.15	1.3
T2-Sep 01	3.36	3.27	3.3 (1.7-5.5)	0.014	0.084	0.03	0.30	2.5
Tests performed in 2022 (XG treatment on Aug 11)								
T1-Aug 11	4.08	3.97	1.8 (0.56-3.1)	0.001	0.12	0.042	0.43	3.31
T2-Aug 12	4.07	4.05	2.0 (0.37-3.9)	0.011	0.004	0.00	0.01	0.10
T3-Aug 18	3.60	3.40	2.1 (1.6-2.5)	0.004	0.196	0.07	0.70	5.44
T4-Aug 18	3.56	3.45	2.4 (0.7-3.6)	-0.007	0.12	0.042	0.43	3.31
T5-Aug 25	4.54	4.50	2.5 (1.7-3.7)	-0.007	0.047	0.02	0.17	1.04
T6-Aug 25	4.56	4.49	2.6 (3.8-1.5)	0.005	0.065	0.02	0.23	1.43
T7-Sep 09	2.55	2.57	1.6 (1.4-2.01)	-0.017	0.12	0.042	0.43	3.31
T8-Sep 09	2.52	2.51	1.6 (0.86-2.5)	-0.001	0.011	0.00	0.04	0.44

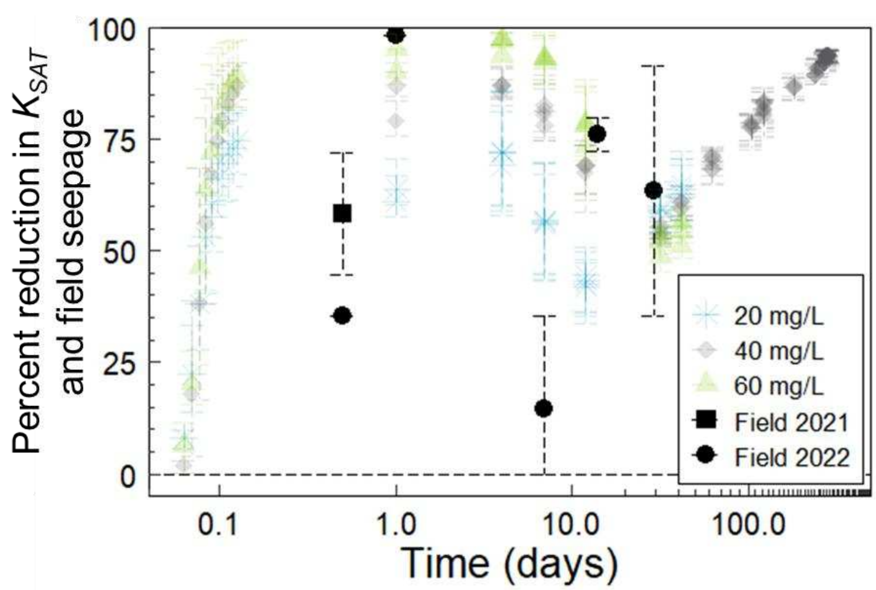

Figure 3.7: Percent reduction in canal seepage measured in the field (LWC) due to XG application in 2021 and 2022 superimposed on percent reduction in K_{SAT} of the field canal soil due to XG application over 42 days (at 20 and 60 mg/L) and 288 days (at 40 mg/L) in the lab. The markers in the plots show the average of the three data points and whiskers denote the minimum and maximum of three replicate tests.

3.4 Conclusions and recommendations

Through systematic laboratory tests of K_{SAT}, xanthan gum (XG) was identified as a potential alternative to synthetic polymers for canal seepage reduction. XG was applied to a reach of the LWC in Colorado in dry and wet forms in 2021 and 2022, respectively, with both resulting in a significant drop in measured seepage immediately following the application. The addition of wet XG produced an average seepage reduction of 63% over a month, being within the range of percent reduction in K_{SAT} measured in the lab. Unfortunately, due to time constraints, extended post-XG treatment field seepage tests were not possible. However, the longevity XG treatment effectiveness was evaluated over nine months in the lab showed a maintenance of performance. Measurement errors in both settings were mitigated by performing lab experiments in triplicate and field seepage tests in duplicate. While results indicate XG's effectiveness, an identical unexpected rise and fall, followed by a recovery in effectiveness was observed both in the lab and field, warranting further study. In addition, testing was limited in scope and should not be generalized to assume similar seepage reduction will occur prior to canal-specific testing.

Enhancing the application procedure of XG also requires additional trials. The dry application method used in 2021 highlighted significant areas for improvement in ease of application and XG use. The wet application method used in 2022 allowed efficient mixing and hydration of the biopolymer with canal water. However, the system required significant resources, including various tools, machinery, and personnel, making this application method labor- and time-intensive. An efficient system integrating all components for mixing and applying XG in wet form is recommended.

The concept of polymer-based control measures to reduce irrigation canal seepage is not new. However, the abundant availability of biopolymers together with advances in irrigation water management engineering offer excellent potential for sustainably and economically sealing canals without posing harm to the environment. Though several aspects require further study, including the process by which XG biodegrades and interacts with the canal perimeter in a field setting under influences such as canal bed shear and cyclic fluctuations in flow rate and depth, our research suggests that biopolymers like XG can replace or coordinate with synthetic polymers for canal seepage control. Given the vast scope of irrigated agriculture, biopolymer sealing of irrigation canals could lead to major enhancement in managing quantity and quality in the world's largest water demand sector.

References

Arabani, M., Shalchian, M., and Baghbani, A. 2024. A state-of-the-art review of interactive mechanisms and multi-scale application of biopolymers (BPs) in geo-improvement and vegetation growth. *Journal of Environmental Management*. DOI: 10.1016/j.jenvman.2024.120905.

Arai, K. and Shikata, T., 2020. Hydration/dehydration behavior of hydroxyethyl cellulose ether in aqueous solution. *Molecules*, 25(20), p.4726. DOI: 10.3390/molecules25204726.

Ashour, M.A., Aly, T.E., Abu-Zaid, T.S. and Abdou, A.A., 2023. A comparative technical study for estimating seeped water from irrigation canals in the Middle Egypt (Case study: El-Sont branch canal network). *Ain Shams Engineering Journal*, 14(3), p.101875. DOI: 10.1016/j.asej.2022.101875.

ASTM, D., 2012. Standard test methods for laboratory compaction characteristics of soil using standard effort (12,400 ft-lbf/ft3 (600 kN-m/m3)). D698-12.

ASTM, 2010. Standard test methods for filterable matter (total dissolved solids) and nonfilterable matter (total suspended solids) in water.

ASTM, 2007. Standard test method for measurement of hydraulic conductivity of porous material using a rigid-wall, compaction-mold permeameter.

Berninger, T., Dietz, N. and González López, Ó., 2021. Water-soluble polymers in agriculture: xanthan gum as eco-friendly alternative to synthetics. *Microbial Biotechnology*, 14(5), pp.1881-1896. DOI: 10.1111/1751-7915.13777.

Casas, J.A., Santos, V.E. and Garcıa-Ochoa, F., 2000. Xanthan gum production under several operational conditions: molecular structure and rheological properties. *Enzyme and Microbial Technology*, 26(2-4), pp.282-291. DOI: 10.1016/S0141-0229(99)00156-4.

Clapp, R.B. and Hornberger, G.M., 1978. Empirical equations for some soil hydraulic properties. *Water Resources Research*, 14(4), pp.601-604. DOI: 10.1029/WR014i004p00601.

Comer, A., Kube, M. and Sayer, K., 1996. Remediation of existing canal linings. *Geotextiles and Geomembranes*, 14(5-6), pp.313-325. DOI: 10.1016/S0266-1144(96)00018-4.

Gad, M., Abdelhaleem, H.M. and OAS, W., 2023. Forecasting the seepage loss for lined and un-lined canals using artificial neural network and gene expression programming. *Geomatics, Natural Hazards and Risk*, 14(1), p.2221775. DOI: 10.1080/19475705.2023.2221775.

Ghazaw, Y.M., 2011. Design and analysis of a canal section for minimum water loss. *Alexandria Engineering Journal*, 50(4), pp.337-344. DOI: 10.1016/j.aej.2012.01.006.

Gregory, J. and Barany, S., 2011. Adsorption and flocculation by polymers and polymer mixtures. *Advances in Colloid and Interface Science*, 169(1), pp.1-12. DOI: 10.1016/j.cis.2011.06.004.

Green, V.S. and Stott, D.E., 1999, May. Polyacrylamide: A review of the use, effectiveness, and cost of a soil erosion control amendment. In *Sustaining the Global Farm: the 10th International Soil Conservation Organization Meeting held May* (pp. 24-29).

Hayes, D.L., 1991. The All-American Canal Lining Project: A Catalyst Rational and Comprehensive Groundwater Management on the United States-Mexico Border. *Nat. Resources J.*, 31, p.803.

Kahlown, M.A. and Azam, M., 2002. Individual and combined effect of waterlogging and salinity on crop yields in the Indus basin. *Irrigation and Drainage: The Journal of the International Commission on Irrigation and Drainage*, 51(4), pp.329-338. DOI: 10.1002/ird.55.

Kahlown, M.A. and Kemper, W.D., 2005. Reducing water losses from channels using linings: Costs and benefits in Pakistan. *Agricultural Water Management*, 74(1), pp.57-76. DOI: 10.1016/j.agwat.2004.09.016.

Kalybekova, Y., Zhu, K., Nurlan, B., Seytassanov, I., Ishangaliyev, T., Yermek, A., Ismailova, G., Kurmanbek, Z., Issakov, Y. and Dávid, L.D., 2023. Minimizing seepage in irrigation canals in land reclamation systems via an innovative technology. *Frontiers in Sustainable Food Systems*, 7, p.1223645. DOI: 10.3389/fsufs.2023.1223645.

Kinzli, K.D., Martinez, M., Oad, R., Prior, A. and Gensler, D., 2010. Using an ADCP to determine canal seepage loss in an irrigation district. *Agricultural Water Management*, 97(6), pp.801-810. DOI: 10.1016/j.agwat.2010.01.002.

Lentz, R.D., 2015. Polyacrylamide and biopolymer effects on flocculation, aggregate stability, and water seepage in a silt loam. *Geoderma*, 241, pp.289-294. DOI: 10.1016/j.geoderma.2014.11.018.

Liu, Y., Weng, P., Liu, Y., Wu, Z., Wang, L. and Liu, L., 2022. Citrus pectin research advances: Derived as a biomaterial in the construction and applications of micro/nano-delivery systems. *Food Hydrocolloids*, 133, p.107910. DOI: 10.1016/j.foodhyd.2022.107910.

Lund, A.R., Gates, T.K. and Scalia IV, J., 2023. Characterization and control of irrigation canal seepage losses: A review and perspective focused on field data. *Agricultural Water Management*, 289, p.108516. DOI: 10.1016/j.agwat.2023.108516.

Lund, A.R., Martin, C.A., Gates, T.K., Scalia IV, J. and Babar, M.M., 2021. Field evaluation of a polymer sealant for canal seepage reduction. *Agricultural Water Management*, 252, p.106898. DOI: 10.1016/j.agwat.2021.106898.

Maćczak, P., Kaczmarek, H. and Ziegler-Borowska, M., 2020. Recent achievements in polymer bio-based flocculants for water treatment. *Materials*, 13(18), p.3951. DOI: 10.3390/ma13183951.

Mao, W., Zhu, Y., Huang, S., Han, X., Sun, G., Ye, M. and Yang, J., 2024. Assessment of spatial and temporal seepage losses in large canal systems under current and future water-saving conditions: A case study in the Hetao Irrigation District, China. *Agricultural Water Management*, 291, p.108615. DOI: 10.1016/j.agwat.2023.108615.

Martin, C.A. and Gates, T.K., 2014. Uncertainty of canal seepage losses estimated using flowing water balance with acoustic Doppler devices. *Journal of Hydrology*, 517, pp.746-761. DOI: 10.1016/j.jhydrol.2014.06.022.

Morway, E.D., Gates, T.K. and Niswonger, R.G., 2013. Appraising options to reduce shallow groundwater tables and enhance flow conditions over regional scales in an irrigated alluvial aquifer system. *Journal of Hydrology*, 495, pp.216-237. DOI: 10.1016/j.jhydrol.2013.04.047.

Mueller, D.S., 2016, QRev—Software for computation and quality assurance of acoustic Doppler current profiler moving-boat streamflow measurements—Technical manual for version 2.8: U.S. Geological Survey Open-File Report, 2016–1068, 79 p., http://dx.doi.org/10.3133/ofr20161068

Muthusamy, S., Anandharaj, S.J., Kumar, P.S., Meganathan, Y., Vo, D.V.N., Vaidyanathan, V.K. and Muthusamy, S., 2022. Microbial pullulan for food, biomedicine, cosmetic, and water treatment: a review. *Environmental Chemistry Letters*, 20(5), pp.3199-3234. DOI: 10.1007/s10311-022-01404-4.

Mutema, M. and Dhavu, K., 2022. Review of factors affecting canal water losses based on a meta-analysis of worldwide data. *Irrigation and Drainage*, 71(3), pp.559-573. DOI: 10.1002/ird.2632.

Natural Resources Conservation Service (NRCS), 2005. Interim Conservation Practice Standard: Irrigation Water Conveyance Anionic Polyacrylamide Ditch and Canal Treatment. Code 754. NRCS, CO.

Norris, A., Scalia, J., and Shackelford, C. 2022. Mechanisms controlling the hydraulic conductivity of anionic polymer-enhanced geosynthetic clay liners. *Geosynthetics International*. DOI: 10.1680/JGEIN.21.00051.

Pugh, J. E., Gates, T. K., and Venayagamoorthy, S. K. 2021. Refined protocols to mitigate user-induced uncertainty for ADCP moving-boat discharge measurement in irrigation canals. *Flow Meas. Instrument.*, 102060.

Ragusa, S.R., De Zoysa, D.S. and Rengasamy, P., 1994. The effect of microorganisms, salinity and turbidity on hydraulic conductivity of irrigation channel soil. *Irrigation Science*, 15(4), pp.159-166. DOI: 10.1007/BF00191967.

Rohmat, F.I., Gates, T.K. and Labadie, J.W., 2021. Enabling improved water and environmental management in an irrigated river basin using multi-agent optimization of reservoir operations. *Environmental Modelling & Software*, 135, p.104909. DOI: 10.1016/j.envsoft.2020.104909.

Selim, T., Elshaarawy, M.K., Elkiki, M. and Eltarabily, M.G., 2024. Estimating seepage losses from lined irrigation canals using nonlinear regression and artificial neural network models. *Applied Water Science*, 14(5), p.90. DOI: 10.1007/s13201-023-02025-y.

Sharma, B.R., Dhuldhoya, N.C. and Merchant, U.C., 2006. Flocculants—an ecofriendly approach. *Journal of Polymers and the Environment*, 14(2), pp.195-202. DOI: 10.1007/s10924-006-0011-9.

Sojka, R.E., Bjorneberg, D.L., Entry, J.A., Lentz, R.D. and Orts, W.J., 2007. Polyacrylamide in agriculture and environmental land management. *Advances in Agronomy*, 92, pp.75-162. DOI: 10.1016/S0065-2113(04)92002-0.

Susfalk, R.B., Young, M.H. and Smith, D.M., 2007. Application guidelines: Use of granular, linear anionic polyacrylamide (LA-PAM) in water delivery canals for seepage control. Reno, NV: Desert Research Institute.

Susfalk, R.B., Sada, D., Martin, C., Young, M.H., Gates, T., Rosamond, C., and Fitzgerald, B., 2008. Evaluation of linear anionic polyacrylamide (LA-PAM) application to water delivery canals for seepage reduction. Desert Research Institute.

Susfalk, R.B., Young, M., Schmidt, M., Epstein, B., Goreham, J., Swihart, J. and Smith, D., 2006, July. Use of Polyacrylamide to Reduce Seepage from Unlined Irrigation Canals: Small Scale Tests. In *The 18th World Congress of Soil Science*.

Susfalk, R.B., Young, M.H., Schmidt, M., Epstein, B.J., Goreham, J., Swhihart, J. and Smith, D., 2005, December. Use of Polyacrylamide to Reduce Seepage from Unlined Irrigation Canals: Initial Results from Small Scale Test Troughs. In *AGU Fall Meeting Abstracts* (Vol. 2005, pp. H21E-1399).

Swihart, J. and Haynes, J., 2002. Canal-lining demonstration project year 10 final report. US Department of the Interior, Bureau of Reclamation, Denver Technical Service Center, Civil Engineering Services, Materials Engineering Research Laboratory.

Teledyne, R.D.I, 2007. WinRiver user's guide. *RD Instruments Poway, CA, USA*.

Tepe, Y. and Çebi, A., 2019. Acrylamide in environmental water: a review on sources, exposure, and public health risks. *Exposure and Health*, 11, pp.3-12. DOI: 10.1007/s12403-018-0283-1.

United States Department of Agriculture (USDA), 1997. Irrigation guide, Natural Resources Conservation Service, USDA. 210-vi-NEH, Sept. 1997.

Uribe, H., Figueroa, R. and Llanos, L., 2013. Assessment of linear anionic polyacrylamide application to irrigation canals for seepage control. *Journal of Agricultural Engineering*, 44(s2). DOI: 10.4081/jae.2013.519.

Wesseling, J.G., Stoof, C.R., Ritsema, C.J., Oostindie, K. and Dekker, L.W., 2009. The effect of soil texture and organic amendment on the hydrological behaviour of coarse-textured soils. *Soil Use and Management*, 25(3), pp.274-283. DOI: 10.1111/j.1475-2743.2009.00220.x.

Wichelns, D. and Oster, J., 2006. Sustainable irrigation is necessary and achievable, but direct costs and environmental impacts can be substantial. *Agricultural Water Management*, 86(1-2), pp.114-127. DOI: 10.1016/j.agwat.2006.07.004.

Young, M.H., Moran, E.A., Yu, Z., Zhu, J. and Smith, D.M., 2009. Reducing saturated hydraulic conductivity of sandy soils with polyacrylamide. *Soil Science Society of America Journal*, 73(1), pp.13-20. DOI: 10.2136/sssaj2007.0312.

Chapter 4

Future Research and Applications

The hypothesized complex and interwoven mechanisms influencing the efficacy of XG observed in the lab and field experiements are not well understood. Flocculation and filter cake formation are thought to underlie the effectivness of flocculant-based seepage mitigation (Lund et al. 2021). However, floc stability in the presence of perturbations from flowing water is likely impacted by XG biodegredation – an independently complex topic. In analog, research focusing on XG degradation in activated sludge indicates XG starts to degrade as quickly as 7 days (Muchova et al. 2009) and degrades by about 80% within 28 days (Berninger et al. 2021) while research by Hovland (2015) indicates XG resistance to degradation for several months. In addition, polymer viscosity effects and pore clogging (Norris et al. 2022, Arabani et al. 2024) may impact or underlie seepage reduction (and may further be impacted by biodegredation). Given the greater effectiveness of synthetic polymers (Lund et al. 2021) to control seepage, along with their reletively lower degradability (Hennecke et al. 2018), along with the greater environmental friendliness of biopolymers, combinations of the two polymer types should be explored.

Our laboratory tests, performed with tap water containing TSS levels observed in canals showed XG had some degree of reduction in hydraulic conductivity; however, these test conditions are not representative of a real-world canal bed. To help address questions on the timing and impact of XG biodegredation on canal seepage reduction, laboratory tests should be performed using canal water and bed soil (to capture a more representative microbial profile) at field-relevant temperatures over a longer period of time. More accurate comparisons may also be drawn if the laboratory explorations are conducted with both soil and water samples taken from the same canal selected for field testing. Experiments to address this element will be started soon at Colorado State University in a continuation of this research. Soil and canal water samples will be collected from the LWC in Colorado and column experiments, using the same methodology discussed under section 3.2.2.2., will be performed over a duration of six to seven months (typical of an irrigation season). The findings may reveal whether the rate and magnitude of microbial degradation, influenced in part by using canal water instead of tap water, changes significantly. This could have important implications for the long-term viability (long-term defined here as an irrigation season) of XG as a solution for seepage control in the field.

The current laboratory setup using column permeamters, while allowing assessment of the effectiveness of biopolymers, does not fully replicate an irrigation canal where larger water surface area would be exposed to the environment resulting in different microbial activities. A refined laboratory setup simulating an irrigation canal would better capture the XG seepage reduction mechanisms. This could be a flume that allows overlying water to continously move across the soil surface so that the experiment replicates important mechanisms like bed shear stress and the movement of XG-TSS flocs due to shearing forces, and allows simultaneous seepage measurements (continued until steady-state conditions are reached). The principal advantage of this type of flume relative to a column or conventional (linear) flume would be the ability to better replicate the floc-formation deposition and pore-clogging and/or filter-cake formation processes that occur in the field over tens to hundreds of meters of flow. Also, the K_{SAT} permeameter experiments could be altered to allow continous flow through the permeameters, unlike the current setup where flow through the columns was stopped between K_{SAT} readings taken on different days. The soils studied in this research were relatively permeable, making continuous experiments challenging due to the need to store and measure large outflows over periods exceeding twenty hours. Implementing mechanical automation to measure and discard outflow at predetermined intervals over extended durations could help address the challenge of maintaining continuous flow through the columns over long periods. This would allow a closer replication of seepage occuring in a field canal and will rule out attributing the fluctuating trends in K_{SAT} reductions to the stopping of tests between readings, which may enable a greater degree of pore clogging and potentially cause changes in soil stress thus impacting porosity.

The methods of dry and wet application of XG explored in the field seem promising but need further study and refinement. The dry application of XG may prove to be effective when performed on canals with some degree of natural turbulence to allow mixing and proper hydration of XG. An example of this could be locations just downstream of weirs (e.g., Fig. B3-1 in Appendix B). Otherwise, the wet application of XG is recommended. Devising an integrated system that automatically hydrates dry XG and pumps the hydrated solution in wet form for more uniform dispersion over the canal would allow canal managers to more carefully control the degree of treatment for selected canal segments.

Irrespective of the application method, study of the settling rate of the XG flocs along the canal perimeter in relation to the flow within the canal is essential. This sutdy is necessary to determine how far downstream the biopolymer travels from the intended application area. Additionally, focused study on the balance of settling rate and canal flow would clarify whether the calculated dose of XG could be effectively applied from a series of fixed structures, such as bridges or in-channel hydraulic structures (with excellent mixing conditions), upstream of the target area. Investigating this in the field would require considerable effort. One potential approach could involve designing a large-scale model, spanning around a kilometer, in a laboratory setting. The canal bed and sides could be sectioned to measure seepage from different zones, allowing an evaluation of the XG floc settling rate under varying flow conditions. An alternative approach might be to use a isotopically labeled XG to track biopolymer migration downstream of an application point in a real-world canal. Samples would collected isotopic analysis used to identify the downstream distribution of XG from the application point.

While a brief cost overview of polymer sealant applications, based on the experiments discussed in Chapters 2 and 3, is provided in Supplemental Materials (Appendix A), large-scale demonstrations are needed for a thorough economic analysis of biopolymer sealants. This analysis should include in-depth economic analysis of the agro-environmental costs of canal seepage to fully understand costs.

Finally, after refining lab tests and small-scale field applications, applying XG on a larger scale (tens of kilometers) to a field canal would offer more comprehensive insights into the effectiveness of XG compared to other seepage control methods. Larger scale testing is necessary to cleanly demonstrate the effectiveness of biopolymer canal seepage mitigation at a level that is robustly outside of water balance measurement errors.

References

Arabani, M., Shalchian, M.M. and Baghbani, A., 2024. A state-of-the-art review on interactive mechanisms and multi-scale application of biopolymers (BPs) in geo-improvement and vegetation growth. *Journal of Environmental Management*, *358*, p.120905.

Berninger, T., Dietz, N. and González López, Ó., 2021. Water-soluble polymers in agriculture: xanthan gum as eco-friendly alternative to synthetics. *Microbial Biotechnology*, 14(5), pp.1881-1896. DOI: 10.1111/1751-7915.13777.

Hennecke, D., Bauer, A., Herrchen, M., Wischerhoff, E., and Gores, F. (2018) Cationic polyacrylamide copolymers (PAMs): environmental half life determination in sludgetreated soil. Environ Sci Eur 30: 16.

Hovland, B. (2015) Assessment of the biodegradability of xanthan in offshore injection water. Master's Thesis, The University of Bergen.

Lund, A.R., Martin, C.A., Gates, T.K., Scalia IV, J. and Babar, M.M., 2021. Field evaluation of a polymer sealant for canal seepage reduction. *Agricultural Water Management*, 252, p.106898. DOI: 10.1016/j.agwat.2021.106898.

Muchová, M., Růžička, J., Julinová, M., Doležalová, M., Houser, J., Koutný, M. and Buňková, L., 2009. Xanthan and gellan degradation by bacteria of activated sludge. *Water Science and Technology*, *60*(4), pp.965-973.

Norris, A., Scalia IV, J. and Shackelford, C.D., 2022. Mechanisms controlling the hydraulic conductivity of anionic polymer-enhanced GCLs. *Geosynthetics International*, *30*(6), pp.628-650.

Appendix A: Supplemental Materials

Supplementary data associated with Chapter 1 of this dissertation can be found in online version at doi:10.1016/j.agwat.2023.108516.

Appendix B: Photo Library

B1 Field seepage measurement

Figure B1-1: ADCP flow measurement in progress at the upstream section of the Larimer and Weld Canal (LWC) in 2021.

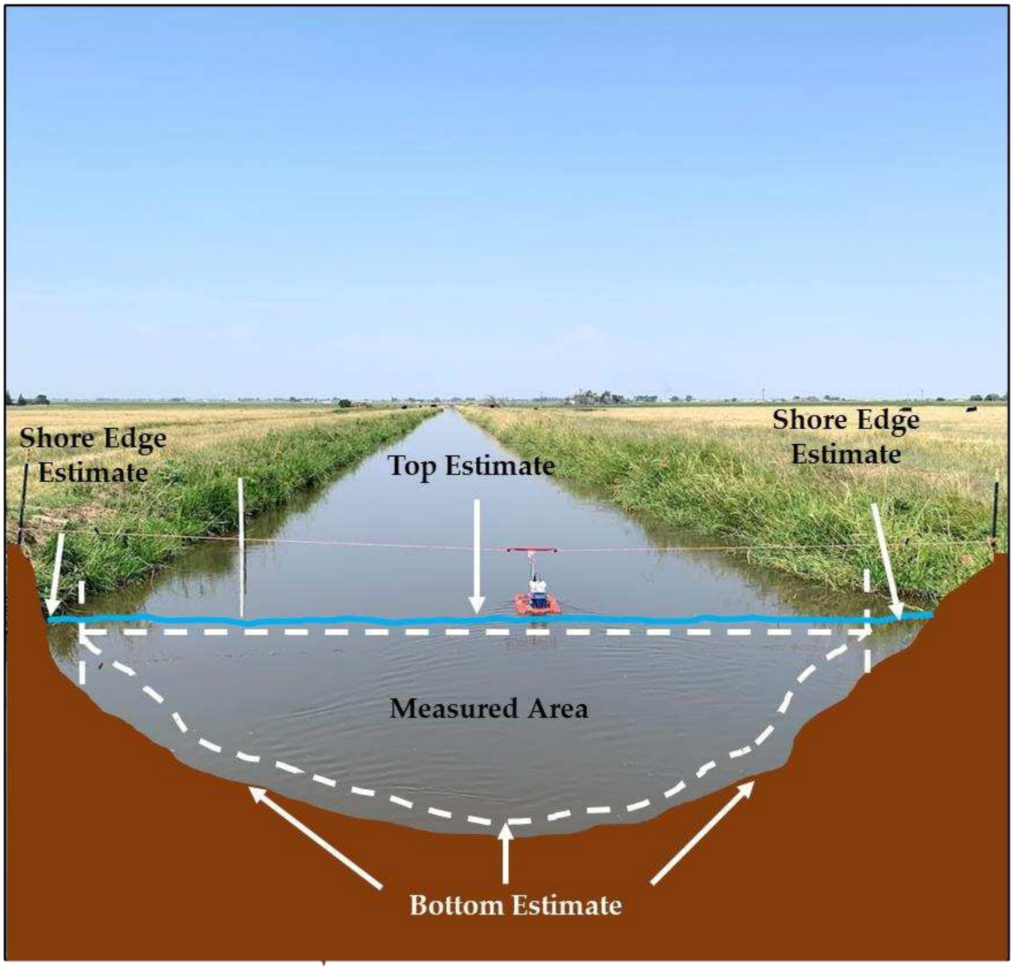

Figure B1-2: Schematic of flow areas measured and estimated during ADCP flow measurement. The illustration shows the downstream section (looking upstream) of the LWC test reach in 2021.

Figure B1-3: Perforated PVC pipe installed to hold the HOBO water level logger, used for recording water level fluctuations for storage change calculations.

Figure B1-4: Technician collecting canal water samples near the upstream section of LWC reach for TSS analysis, replicated in laboratory experiments.

Figure B1-5: A view of the LWC reach from the downstream section looking in the upstream direction in 2022.

Figure B1-6: A view of a weri at the downstream end of the LWC canal in 2022. The downstream section of the LWC reach was located ~ 6-8 m upstream of this weir.

B2 Identification of biopolymers

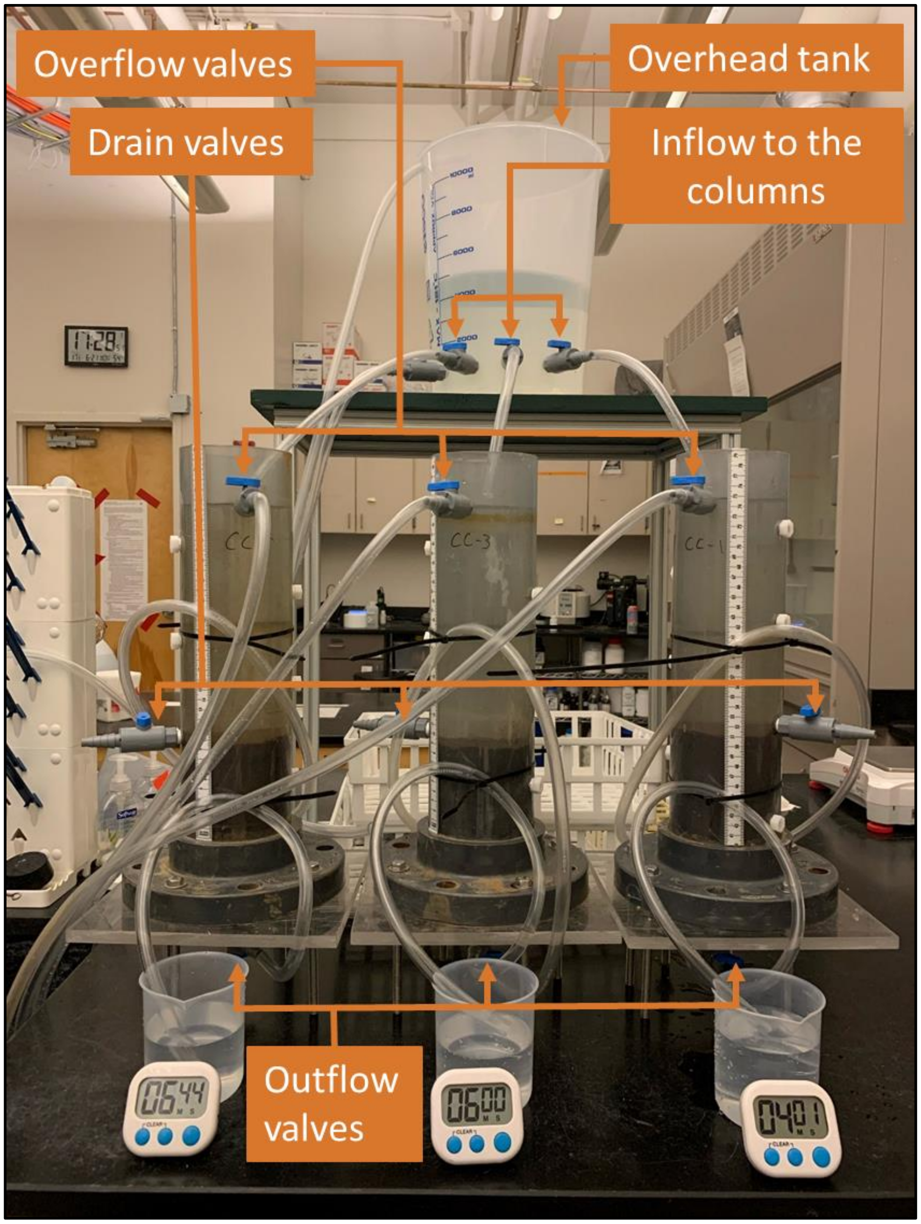

Figure B2-1: One of three experimental stations used for column experiments in the laboratory, each equipped identically.

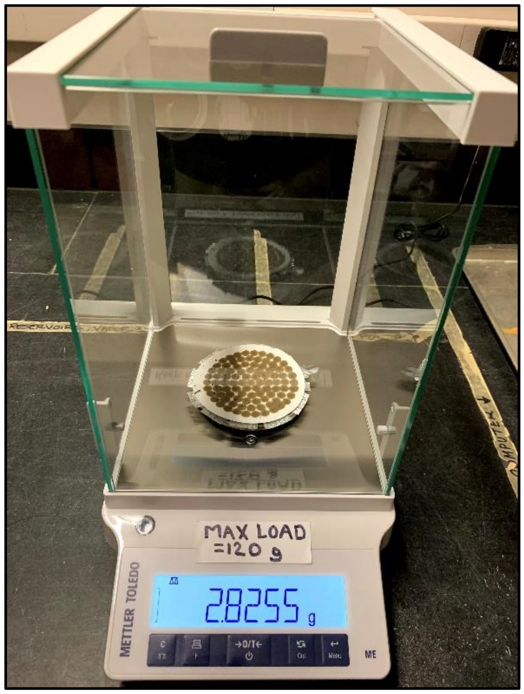

Figure B2-2: TSS (Total Suspended Solids) measurement after filtration from the canal water samples using an analytical scale in the laboratory.

Figure B2-3: Pre-weighed TSS and polymer prepared in the laboratory for column experiments.

Figure B2-4: Top view of a column after pre-weighed Xanthan Gum (XG) was added, showing a slimy texture on the water surface.

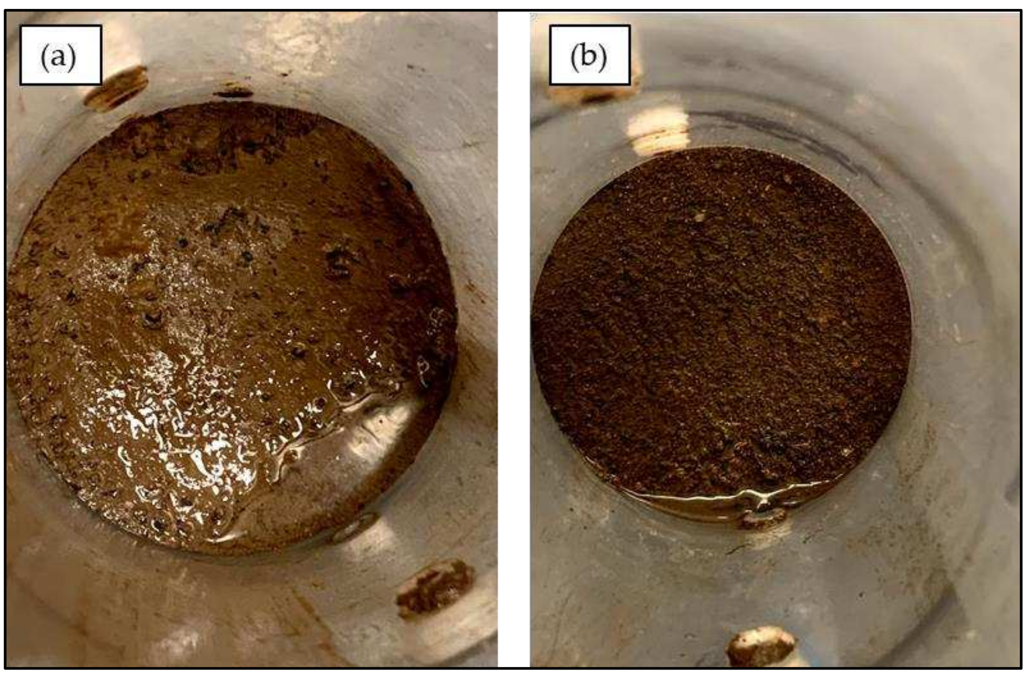

Figure B2-5: Soil specimen 90 minutes after applying (a) LAPAM-4 at 20 mg/L and (b) Xanthan Gum at 20 mg/L in the permeameter.

Figure B2-6: Pre-weighed Xanthan Gum in ziplock bags, ready for field application

B3 XG application in dry form

Figure B3-1: Dry XG applied at a flow-regulating structure (a tilting weir) during the 2022 XG application, approximately 300 meters upstream from the test reach on the LWC

Figure B3-2: Dry XG application tool designed for use from the canal bank in 2021. An automated fertilizer spreader, loaded with XG, was mounted on a rod that was securely fixed to the bed of a truck carrying the supplies, including the XG.

Figure B3-3: Another trial of dry XG application tool designed for use from the canal bank in 2021. One technician operated an automated fertilizer spreader, loaded with XG, while the other used a leaf blower to direct the XG onto the canal water surface.

Figure B3-4: Technician applying dry Xanthan Gum in the LWC in 2021 using a handheld fertilizer spreader while walking in the canal.

Figure B3-5: Spread of dry Xanthan Gum on the canal water surface approximately 5 minutes after application.

B4 XG application in wet form

Figure B4-1: Wet Xanthan Gum application tools assembly. One truck carried the tank, while the other transported the generators and pumps.

Figure B4-2: Technicians applying wet Xanthan Gum to the Larimer and Weld Canal from the bank, with the pump's throw covering the canal's width.

Figure B4-3: Honda WDP30XK1AT pump used to pump the viscous Xanthan Gum solution from the tank to the canal.

Figure B4-4 Centrifugal pump drawing water from the canal to the tank for Xanthan Gum preparation.

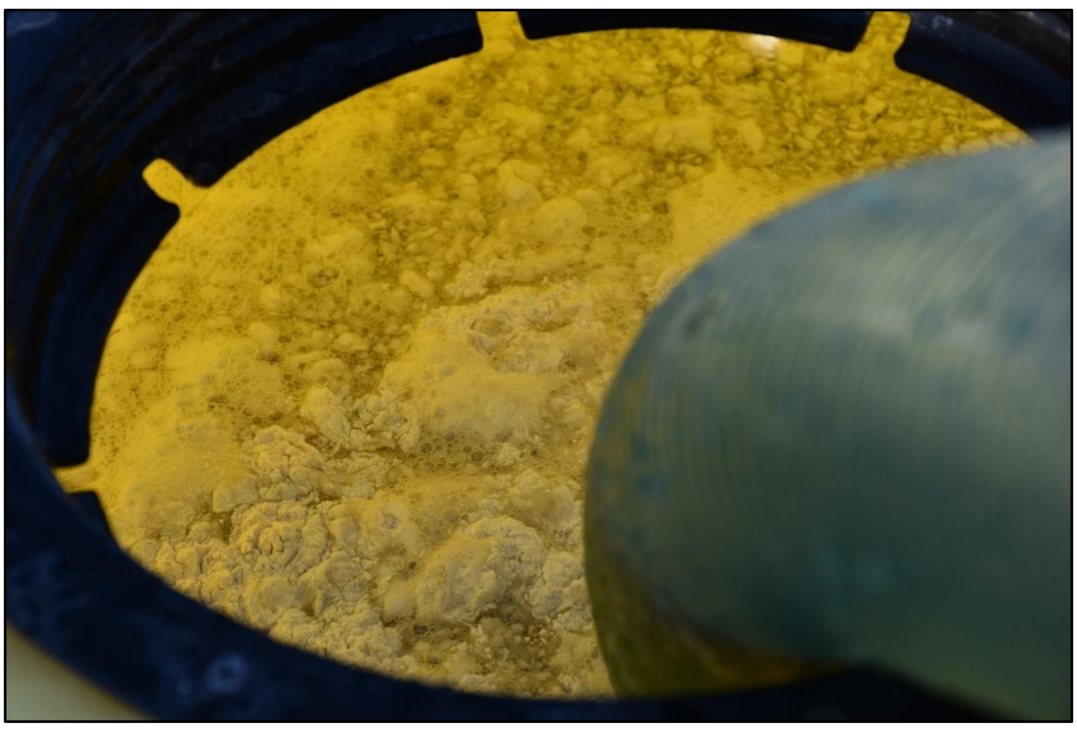

Figure B4-5: Dry Xanthan Gum poured into the spray rig tank, where it formed clumps and required mechanical mixing for proper hydration.

Figure B4-6: Technician using a Makita 8.5 Amp Corded Spade Handle Drill to mix and prepare the viscous Xanthan Gum solution.

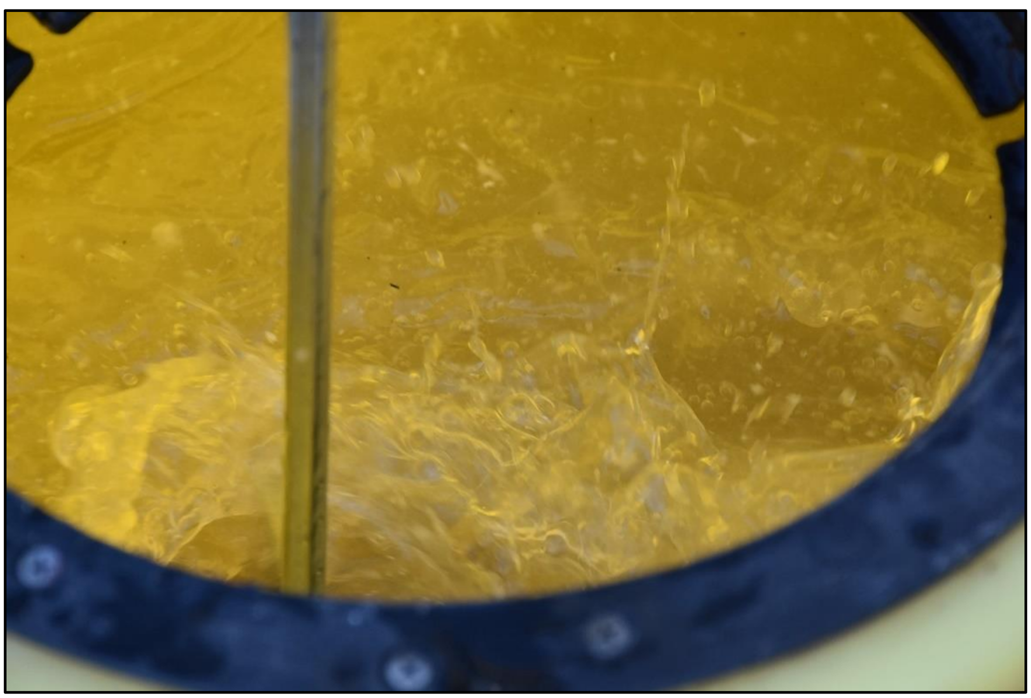

Figure B4-7: Inside view of the Xanthan Gum solution tank, showing the homogenized slimy mixture after mixing.

Figure B4-8: Viscous Xanthan Gum solution being poured into the canal via pump.