Select Techniques for Detecting and Quantifying Seepage from Unlined Canals

Science and Technology Program
Research and Development Office
Final Report No. ST-2020-19144-01

U.S. Department of the Interior

September 30, 2020

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188

1. REPORT DATE ***(DD-MM-YYYY)*** Date 09/30/2020	**2. REPORT TYPE** Research	**3. DATES COVERED** *(From - To)* FY17 to FY20

4. TITLE AND SUBTITLE Select Techniques for Detecting and Quantifying Seepage from Unlined Canals	**5a. CONTRACT NUMBER** XXXR4524KS-RR4888FARD1900801/FA987
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER 19144 (S&T)
6. AUTHOR(S) Evan J. Lindenbach, BOR, Civil Engineer Jong Beom Kang, BOR, Civil Engineer Justin B. Rittgers, BOR, Geophysicist Ramon C. Naranjo, USGS, Hydrologist	**5d. PROJECT NUMBER** Final Report ST-2020-19144-01
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER 86-68550

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Bureau of Reclamation Technical Service Center Denver, Colorado US Geological Survey Nevada Water Science Center Carson City, NV	**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Science and Technology Program Research and Development Office Bureau of Reclamation U.S. Department of the Interior Denver Federal Center PO Box 25007, Denver, CO 80225-0007	**10. SPONSOR/MONITOR'S ACRONYM(S)** Reclamation **11. SPONSOR/MONITOR'S REPORT NUMBER(S)** Final Report ST-2020-19144-01

12. DISTRIBUTION/AVAILABILITY STATEMENT
Final Report may be downloaded from https://www.usbr.gov/research/projects/index.html

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Canal seepage losses affect the ability of water conveyance structures to maximize efficiency and can be a precursor to canal failure. Identification and quantification of canal seepage out of unlined canals is a complex interaction affected by geology, canal stage, operations, embankment geometry, siltation, animal burrows, structures, and other physical characteristics. Seepage out of unlined canals can be coarsely estimated using a mass balance-type approach (water in minus water out with the difference assumed to be a combination of seepage and evapotranspiration). More sophisticated methods are used in some instances but are typically limited efforts aimed at quantifying seepage in a specific location. This paper presents a framework for identification and quantification of seepage from unlined canals disconnected from the groundwater table. Note that the focus of this report is on research funded by the Research and Development Office from about FY16 through FY21 and includes techniques still under development and refinement.

15. SUBJECT TERMS
Seepage, Canal, Water Losses

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**THIS PAGE**		**75**	Evan J. Lindenbach
U	U	U			**19b. TELEPHONE NUMBER** *(Include area code)* **303.445.2336**

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The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Disclaimer

Acknowledgements

The Science and Technology Program, Bureau of Reclamation, sponsored this research. The US Geological Survey provided extensive expertise and Reclamation's Lahonton Basin Area Office provided significant support for this project.

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prepared by

Bureau of Reclamation
Technical Service Center
Evan J. Lindenbach, Civil Engineer
Jong Beom Kang, Civil Engineer
Justin B. Rittgers, Geophysicist

US Geological Survey
Nevada Water Science Center
Ramon C. Naranjo, Research Hydrologist

Peer Review

Bureau of Reclamation
Research and Development Office
Science and Technology Program

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EVAN LINDENBACH Digitally signed by EVAN LINDENBACH Date: 2020.09.29 12:56:57 -06'00'

Prepared by: Evan J. Lindenbach, PE, PG
Civil Engineer, Geotechnical Laboratory and Field Support, 86-68550

JONG BEOM KANG Digitally signed by JONG BEOM KANG Date: 2020.09.29 14:36:42 -06'00'

Prepared by: Jong Beom Kang, PhD, PE
Civil Engineer, Geotechnical Laboratory and Field Support, 86-68550

JUSTIN RITTGERS Digitally signed by JUSTIN RITTGERS Date: 2020.09.29 14:50:57 -06'00'

Prepared by: Justin B. Rittgers, PhD
Geophysicist, Engineering Geology and Geophysics, 86-68320

RAMON NARANJO Digitally signed by RAMON NARANJO Date: 2020.09.29 12:14:56 -07'00'

Prepared by: Ramon C. Naranjo, PhD
Research Hydrologist, US Geological Survey

BOBBI JO MERTEN Digitally signed by BOBBI JO MERTEN Date: 2020.09.29 15:05:05 -06'00'

Peer Review by: Bobbi Jo Merten, PhD
Civil Engineer, Materials and Corrosion Laboratory, 86-68540

TODD CALDWELL Digitally signed by TODD CALDWELL Date: 2020.09.29 13:12:49 -07'00'

Peer Review by: Todd G. Caldwell, PhD
Hydrologist, US Geological Survey

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Contents

Executive Summary

Canal seepage losses affect the ability of water conveyance structures to maximize efficiency and can be a precursor to canal failure. Identification and quantification of canal seepage out of unlined canals is a complex interaction affected by geology, canal stage, operations, embankment geometry, siltation, animal burrows, structures, and other physical characteristics. Seepage out of unlined canals can be coarsely estimated using a mass balance-type approach (water in minus water out with the difference assumed to be a combination of seepage and evapotranspiration). More sophisticated methods are used in some instances but are typically limited efforts aimed at quantifying seepage in a specific location.

Seepage is generally broken out into two categories: diffuse and concentrated (or focused) seepage. Diffuse seepage is where the seepage discharges relatively constant over a given area, whereas concentrated (point discharge source) seepage discharges along preferentially focused areas. Diffuse seepage typically occurs in homogeneous conditions where the amount of water flowing into the subsurface is controlled by soil permeability and canal stage. Conversely, concentrated seepage occurs in areas of heterogeneous conditions where water flows into bedrock fractures, rodent burrows or other pre-existing discrete flow-paths. Concentrated seepage can also develop in the advent of sudden or excessive increases in hydraulic gradient which can lead to heaving, cracking, and development of backward erosion piping flow-paths. Concentrated and diffuse seepage can lead to seeps, in this case, a surface expression of water fed by irrigation water on canal embankment or at distal regions away from the canal.

This report focuses on work funded by the Research and Development Office from Fiscal Year 2016 through 2021 and the references provided pertain primarily to those efforts. This report also provides a generalized framework for how and when to investigate seepage out of an unlined canal based on the type of seepage, level of understanding about the seepage locations, geology, and knowledge of the subsurface conditions. The various methods used to locate seeps and quantify canal seepage are discussed in further detail, with references provided for the reader.

The following seepage investigation scenarios are discussed within the report:

1. Idealized workflow <u>insensitive to time</u> with highest quality data required
2. General workflow <u>sensitive to time</u> with highest quality data required
3. General workflow <u>insensitive to time</u> with <u>lowest cost</u> items preceding more costly techniques
4. <u>Newly developed concentrated seep</u>(s), concern about consequences (time sensitive)
5. <u>Newly developed or rapidly increasing diffuse seepage</u>, concern about consequences (time sensitive)
6. <u>Existing concentrated seep</u>(s), limited concern about consequences, <u>poor geologic</u> understanding
7. <u>Existing concentrated seep</u>(s), limited concern about consequences, <u>good geologic</u> understanding
8. <u>Existing diffuse seepage</u>, limited concern about consequences, <u>poor geologic</u> understanding
9. <u>Existing diffuse seepage</u>, limited concern about consequences, <u>good geologic</u> understanding

A workflow is given for each scenario which details recommended steps and the order in which those steps should be taken to maximize efficiency and data quality. The various seepage investigation techniques and estimated costs are discussed in more detail later in this report.

The next step is to take the data collected from the various methods and incorporate them into canal operations models to optimize deliveries. This step could also include the development of 3D seepage models to better understand the larger-scale groundwater-surface water interactions and how they are affected by the water delivery system.

Introduction

Canal seepage losses affect the ability of water conveyance structures to maximize efficiency, and seeps that develop on canal embankments can be a precursor to canal failure. Identification and quantification of canal seepage out of unlined canals can be complex as seepage is influenced by geology, canal stage, operations, embankment geometry, siltation, scour, animal burrows, structures, and other physical characteristics. Seepage out of unlined canals can be coarsely measured directly using a mass balance-type approach (water in minus water out with the difference assumed to be a combination of seepage and evapotranspiration). More sophisticated methods are used but are limited to estimating seepage in a specific location. A combination of methods is better suited for quantifying seepage over long reaches because of the inherent limitations of methods and suitability.

Seepage is generally broken out into two categories: diffuse and concentrated (focused) seepage. Diffuse seepage is where the water infiltrates through porous sediments, whereas concentrated (point source) seepage applies to water transported along preferentially focused small conduits. Diffuse seepage occurs in most conditions absent of bedrock, where the amount of water flowing into the subsurface is primarily controlled by sediment permeability and canal stage. Conversely, concentrated seepage occurs in areas of where openings in sediments are more porous, like surface desiccation cracks, bedrock fractures, rodent burrows, tree roots, or other discrete openings in the subsurface environment causing water to flow rapidly along discrete flow-paths. Concentrated seepage can also develop in the advent of sudden or excessive increases in hydraulic gradient which can lead to heaving, cracking, and development of backward erosion within embankment sediments causing piping of flow-paths.

In this report, a canal seepage detection, quantification, and modeling framework are developed with the goal of increasing the efficiency of water delivery systems and improving canal safety. Figure 1 presents a broad outline of the framework developed to evaluate the seepage out of an existing water delivery system.

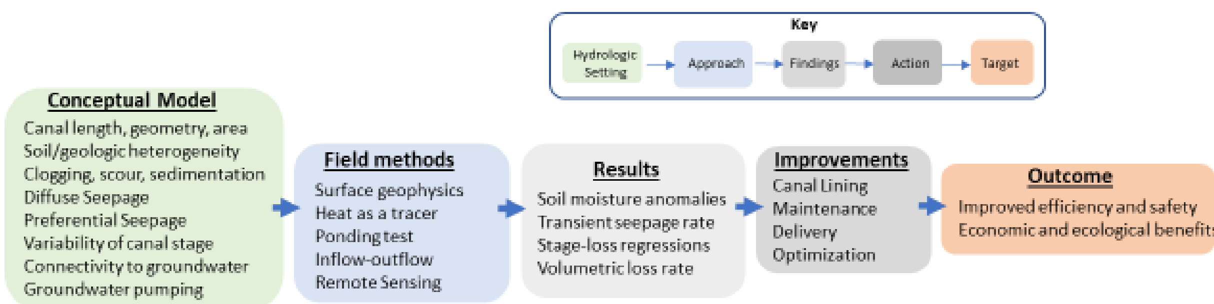


Figure 1 - Results chain for improved water resource management with knowledge of canal seepage losses.

The conceptual model development and seepage detection and quantification techniques are discussed in the next sections, with the general framework workflow presented in Figure 1 discussed in more detail at the end of the report. Note that the approaches or techniques detailed in this report may be impractical, not applicable or warranted for each investigation given budget constraints, the site conditions, and available data.

An improved understanding of the annual volumetric loss rate along sections of canal or at discrete locations can help prioritize canal maintenance, lining improvements, and optimization of canal operations. Ranking the sections of canal by loss rates could help prioritize funding resources for improvements. The results of a seepage analysis should be used to help guide irrigation districts and water management decisions on upgrades to conveyance systems to improve water usage, farm productivity, and restoration efforts to improve downstream water quality and ecosystems.

Seepage can be measured directly using methods described herein. However, many innovative approaches more widely used are grouped as indirect methods. In indirect methods, seepage rates or surface moisture is estimated through inversion algorithms (mathematical models) of ancillary data such as such as heat or electrical conductance to predict the rate of water movement or presence of soil moisture. The examples provided are not intended to be a comprehensive list of applicable approaches for detecting seepage. Rather, this report provides a concise synopsis of current methods along with references for more detailed descriptions.

Note that costs estimated within this report assume that Reclamation TSC staff are performing the work using available equipment. Work performed by a contractor may be more costly and/or take additional time.

Conceptual Model

Overview

The information in the conceptual model will be based on a thorough literature review and desktop level reconnaissance. The desk-top level work should evaluate surface soils geologic maps, canal as-builts, known seepage locations, phreatophytes, and past and ongoing canal maintenance operations to identify suspect regions. The collected information should be coupled with a visual interpretation of aerial imagery to identify areas more likely to be susceptible to diffuse versus concentrated seepage. Using this information, the conceptual model is developed to represent the canal system incorporating soil types, geology, canal geometry, potential for scour or clogging, and type of seepage (diffuse vs concentrated). Seepage estimates may be necessary for systems that are hydraulically connected to the water table. In these environments, water table variations or declines caused by groundwater pumping can have influence on seepage rates seasonally. The conceptual model will help determine data gaps and where to focus data collection. Depending on the scope of problem, it may be necessary to monitor continuously throughout an irrigation season to capture seasonally important drivers. Refinement of the model may require field exploration to limit identified uncertainties.

Details

Topographic maps and aerial photos of the canal alignment should be obtained along with as-builts for the canal. Topographic maps at small scales and aerial photographs can be used to identify regions of surface water or steep topographic gradients, with larger scale maps used to further refine specific sites along the canal alignment for investigation. In areas where there is a topographic gradient between two surface water sources near the canal, there may be near-surface groundwater flow following topography and/or groundwater intersecting the canal prism. Groundwater recharge to the canal or flow directly out of the canal complicates the seepage estimating process. As-builts of the canal should be used to create cross-sections for conceptual model development.

Geologic maps should also be obtained prior to any field investigation. Geologic maps can be obtained from the United States Geological Survey (USGS) National Geologic Map Database (USGS, 2020). Geologic maps with the largest scale should be preferentially obtained, with small scale maps used to correlate features along the canal alignment. Both surficial and bedrock geologic maps should be used to guide the investigation. Canal segments underlain by igneous or metamorphic bedrock will likely have seepage governed by secondary permeability (fracture flow), while segments underlain by surficial geologic units (alluvium, loess, etc.) will likely be dominated by diffuse seepage. Sedimentary bedrock seepage may be dominated by fracture flow or diffuse seepage depending on the permeability of the intact rock, and the fracture characteristics (aperture, opening, density, connectivity, etc.).

Identifying areas where seepage daylights at the surface (herein defined as seeps) or zones where the seepage may recharge groundwater assists in conceptual model development and can help narrow investigation techniques. For this reason, it is important to identify areas of phreatophytes—plants with root systems intercepting the water table (e.g. cattails or willows)—which may indicate near-surface groundwater or seepage. Known seeps should be identified for later inspection.

The findings should be synthesized into an initial conceptual model. The canal length should be segmented out by the primary type of seepage (diffuse versus concentrated). Conceptual geologic cross-sections oriented perpendicular and parallel to the canal prism should be generated using the data collected previously. In the same canal system, it may be possible that multiple conceptual models apply given the variability in spatial and temporal scales.

The conceptual model should also focus on the addition of time and operational domains to the data set. Where surface water discharge measurements are available, volumetric differencing (inflow-outflow) can be used to provide preliminary estimates of losses along specific sections of the canal, with variability in losses quantified by other methods that account for canal stage and operations. Figure 2 presents a broad conceptual model of seepage.

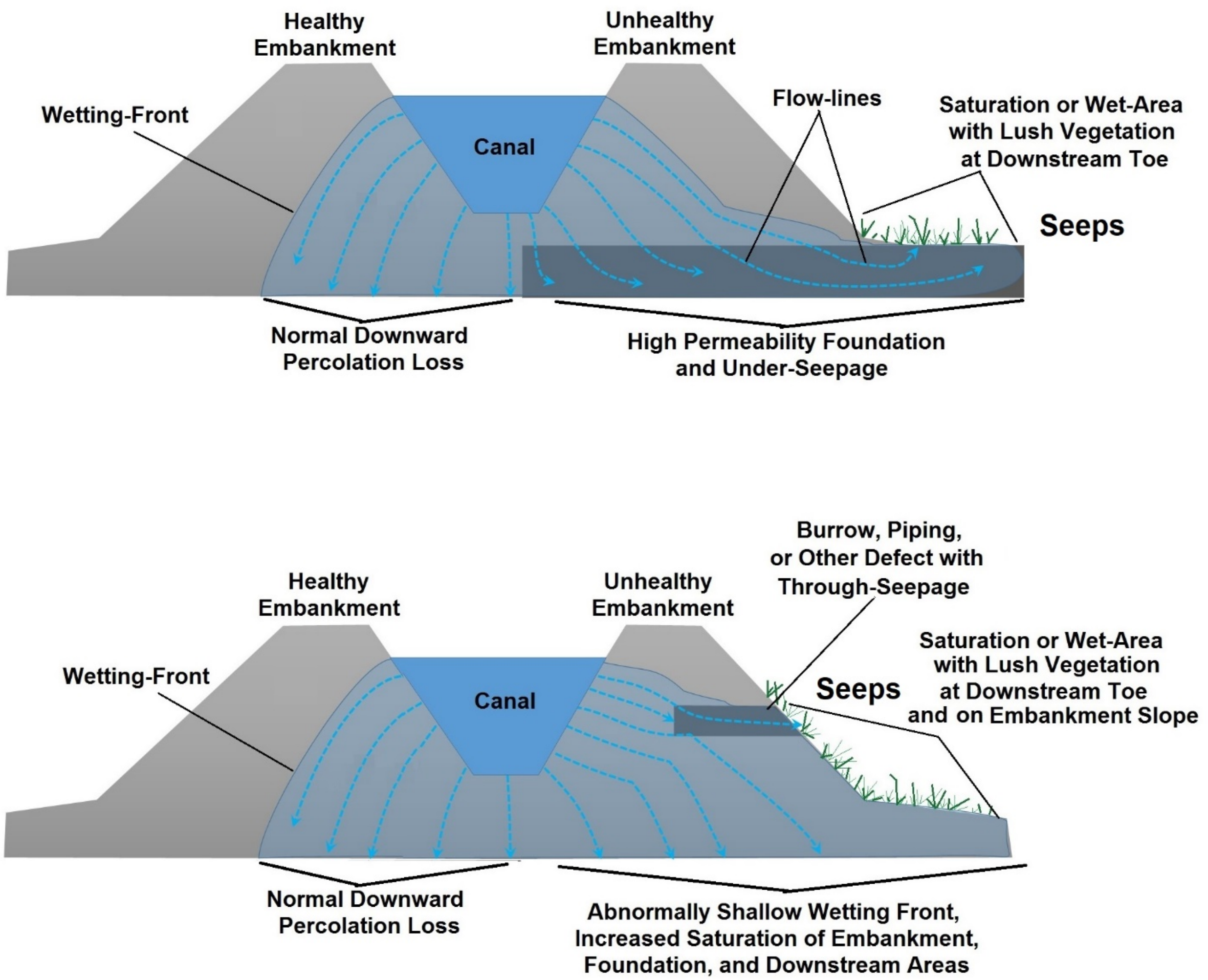


Figure 2 - Example of two conceptual models showing flow paths influenced by contrasts in permeability and the development of seeps on the toe of the embankment (upper panel) and within embankment material (lower panel).

Example questions to ask during refinement of the conceptual model should include:

1. How are identified seeps affected by changes in the water level within the canal?
2. Does nearby groundwater pumping seem to influence the canal losses?
3. Does the canal stage and operations model (ponding, etc.) influence losses?
4. What time of year does the canal experience the most/least losses?

Results

Results will include the development of a conceptual model that includes all available information about the structure. The model should be geospatially referenced (GIS) and readily updatable. Time spent on this step is invaluable for the rest of the project. Developing an accurate, realistic conceptual model forms the underpinning of the seepage investigation.

Schedule and Cost

Conceptual model development may require a significant effort or may be relatively simple depending on how much information is available about the canal. Generally, it could be assumed that two to three weeks of desk-top level effort would be required to develop a conceptual model. Additional effort may be required if the area of interest is large, geologically complex, or lacking in background documentation.

Geologic Investigations

For the purposes of this report, indirect refers to a method where characteristics are inferred based on a measured parameter (i.e., soil type from electrical conductivity contrasts) whereas direct measurements determine parameters from sampling (i.e., soil cores) or other tangible methods. Distributed refers to data collected over a large area or volume with the values being the average over the measured region; point data are discrete values collected at a single point. Non-invasive methods do not cause significant disturbance to the surface/subsurface (i.e., a truck-mounted system used in a roadway), whereas invasive methods involve disturbance (i.e., drilling). Geologic investigations typically rely on direct methods collecting point data with invasive or non-invasive techniques. Geophysical methods typically involve indirect methods collecting distributed data with non-invasive techniques.

Overview

The underlying and surrounding geology can control the type of seepage and where seeps daylights. Typical geologic investigation techniques include trenching, the Cone Penetration Test (CPT), and the Standard Penetration Test (SPT); see Design of Small Dams (USBR, 1987) for more details about field investigation techniques. The obtained sediments samples should be logged and interpreted by a qualified geologist. Field investigations should target known areas of interest such as near seepage locations, visual changes in geology and surface morphology.

Details

Geologic investigations help constrain uncertainties about the subsurface characteristics. This is performed by drilling and logging geologic material at discrete intervals. Trenching can provide a means to visually identify important lithological variations on a broader scale but may be impractical in some canal systems. Ideally, drilling operations should include characterizing the materials comprising a side of the canal prism, and the material below the canal prism. The field investigation should be used to iteratively update the conceptual model such that each step in the investigation further refines the data set. A geologist should be involved with this portion of the field investigation.

Laboratory testing of the obtained materials should include, at a minimum, wet density, water content, particle size distribution (gradation), Atterberg limits, and soil textural classification. Permeability testing of soils could be performed if representative, intact specimens can be obtained. Field scale testing of permeability could be performed in new or existing wells using slug-tests or other applicable techniques.

Where an excavation is performed, the excavation should be thoroughly mapped and photographed during trenching. Areas of anomalous seepage, dissimilar soil type, color, density, etc., should be noted and sampled where appropriate. Proper excavation safety measures should be followed per Occupational Safety and Health Administration (OSHA) requirements.

Soil from the canal walls or prism should be collected in 5-gallon buckets or heavy-duty sealable plastic bags (for corrosivity samples) with required quantities of material based on the maximum particle size encountered. Buckets should be sealed to preserve water content. Obtained soils should be representative of the existing material underlying the canal. Excavated soils should be replaced with similar soils based on the United Soil Classification System (USCS). To the best extent possible, the new backfill materials should be placed and compacted using the same methods used for initial construction, this is particularly important when excavating the side of canal that is elevated above the surrounding terrain (constructed from fill). Excavated soils should be transmitted to a laboratory for soil testing per appropriate methods.

CPT can be used to gather further geologic information by pushing an instrumented cone through the canal prism (if dewatered and of sufficient bearing capacity) or along the edges of the canal prism. The cone reads tip pressure and skin friction, which can then be used to estimate in-situ soil properties. No samples are obtained using this technique and the test is relatively rapid so many tests can be performed in a short amount of time. Dissipation testing can be used to estimate hydraulic conductivity in instances where the cone tip is below the groundwater table. CPT cannot be used in gravely or cobbly lenses as the system can be damaged. CPT is performed using a specialized rig (usually a truck) with an operator.

SPT uses a standard-sized sampler with a standardized impact energy to estimate the in-situ density of the soil. The SPT N-values (number of blows to drive the sampler 12 inches) can be correlated to a variety of engineering properties and the obtained sample can be tested in the lab for USCS testing. SPT is performed with a drill rig and can be performed in the canal prism or on the sides (Figure 3).

Figure 3 - Drilling on an embankment at the New York Canal.

Results

Trenching can provide a refined geologic understanding at the area of interest, and laboratory samples to determine USCS and other engineering properties (soil textural classification, permeability, shear strength, etc.). CPT provides a log of inferred soil properties with depth but does not provide samples for lab testing. SPT provides an estimate of density and other engineering properties with depth and provides samples for laboratory testing. All these investigation techniques are limited in spatial extent; a drill hole is a "needle in a haystack" for the entire length of the canal. Data collected should be interpreted by a qualified geologist and used in conjunction with other indirect methods (specifically surface-based geophysics) to update the conceptual model.

Schedule and Cost

Field explorations can range from a few holes or trenches to constrain identified uncertainty at a specific location, to an extensive exploration program if the underlying geology is poorly understood. In general, the field exploration program for most existing structures is likely to be relatively narrow and geared specifically towards a few areas of interest. Assuming a three to four CPT or SPT holes, and three to four trenches, the exploration program can be completed in a few weeks. Trenching can be ideal as it can generally be completed with simple to obtain equipment (i.e., a backhoe). Relative costs are summarized in Table 1, located at the end of this report.

Direct Field Methods: Inflow-Outflow, Direct Seepage Measurements, and Ponding Tests

Inflow-Outflow

Overview

Flow measurements are made along a reach of canal where flow differencing (inflow-outflow) can physically be made. Flow measurements may be needed at laterals, if present, to account for reductions in flow along the associated reach of the main canal.

Details

Flow measurements can be made using differential gaging from manual measurements potentially including existing gages, flumes, acoustic doppler current profilers (Kinzli et. al, 2010). The measurements could be large-scale for the entire length of the canal, or at smaller-scales (between laterals, structures, turn-outs, etc.) for more detailed estimates of losses by canal section. As the mass balance for the canal is also influenced by evaporation and/or evapotranspiration, the difference between inflow and outflow is not solely the result of seepage. Ideally these measurements are made multiple times during an irrigation season during corresponding steady flow conditions between measurements. To account for the influence of stage, multiple measurements can be made at low, normal and high stage conditions and during watering-up and watering-down. Return flows and diversions need to be measured to account for losses or gains in the canal system.

This method can be useful from a high-level perspective to identify sections of the canal with anomalously high losses, or as a method to compare losses from different canals that experience similar atmospheric conditions. Given the simplicity of the method and the fact that these data are collected as part of normal canal operations, using inflow-outflow measurements can be a quick method to monitor canal health. If losses are increasing, either gradually or rapidly, additional monitoring steps can be taken. These measurements also provide a way to check the data collected by more sophisticated methods, as the mass-balance provides an absolute upper-bound seepage estimate.

Results

Results are provided as a loss (seepage + evaporation) for a length of the canal. If done at multiple stage (flow) conditions, then a regression of stage-loss can be developed. The relationship provides the total loss between where the inflow/outflow measurements are taken and cannot differentiate between diffuse and concentrated seepage or identify whether losses change with distance along the section where streamflow was monitored.

Schedule and Cost

Inflow-outflow measurements for one discrete section of a canal will likely require about one day per month of field effort for the duration of the irrigation season, with additional office time to process the data. Table 1 provides a relative cost for this level of effort.

Seepage Meters

Overview

Seepage meters have been around for over 75 years and were first developed for measuring seepage from irrigation canals (Israelson and Reeve,1944). They are simple to use and can be made with simple materials such as the top of a 50-gallon metal drum, tubes and hoses, inflatable bags, and plastic containers (Rosenberry and Labaugh, 2008). Water infiltrating through the bottom of canals or along the embankment can be measured over the diameter of the drum as an instantaneous measurement or with additional sensors can be used to measure seepage over an irrigation season. For irrigation canals that are unwadable, seepage meters may be impractical. However, in irrigation canals that are wadable, repeat measurements can be taken across the channel or longitudinally along the entire length of canal to measure loss rates as a function of distance. Because of its simplicity, measurements can be taken from identified seeps directly or within the canal.

Details

Direct measurement of water exiting the embankment material can be done with the same methods as inflow-outflow, but in the case where flow is ponded, can be done with seepage meters. Seeps are surface expressions of exfiltration from the canal through the embankment cut and/or fill and are typically associated with focused discharge above low-permeability deposits. The focused discharge can result in ponded water or runoff at the land surface or within ephemeral drainages. The rate of seep discharge can be highly variable depending the hydraulic properties of the embankment material and the hydraulic connectivity with flow in the canal.

Flow from identified seeps should be measured directly at the discharge point multiple times during an irrigation season. Ideally, flow is measured at different canal stages and during watering up/down as well to add time and operational domains to the data. When seepage meters are installed within the channel, they can provide synoptic measurement of the loss rates. Along with heat-as-a-tracer transect locations, seepage-meter measurements can supplement continuous estimates (Rosenberry et. al., 2016).

Seeps discharging to ponds or to ephemeral channels can be determined from synoptic measurement on an appropriate (generally monthly) interval. The concept is relatively simple, movement of water into a bag shelter is timed until the bag is empty (Figure 4). This is done repeatedly to provide a range of values for repeatability and confidence in measurements. For seeps discharging at the surface, the elapsed time to fill the bag is measured. The areas of measurement are then scaled to the wetted areas of the canal or the wetted area of the seep. If necessary, temporary use of Parshall flume could be implemented for seeps with flowing water on the land surface for continuous discharge measurements.

Continuous hydraulic gradient data (either through a series of piezometers or a continuous change in stage) and synoptic seepage measurements at the seep locations within the canal can be used to better describe the relationship of seepage with canal stage. Obtaining continuous hydraulic gradient data during routine operations of the canal will aid in determining rates and level of hydraulic connectivity. Figure 4 illustrates a seepage meter collecting data in surface water.

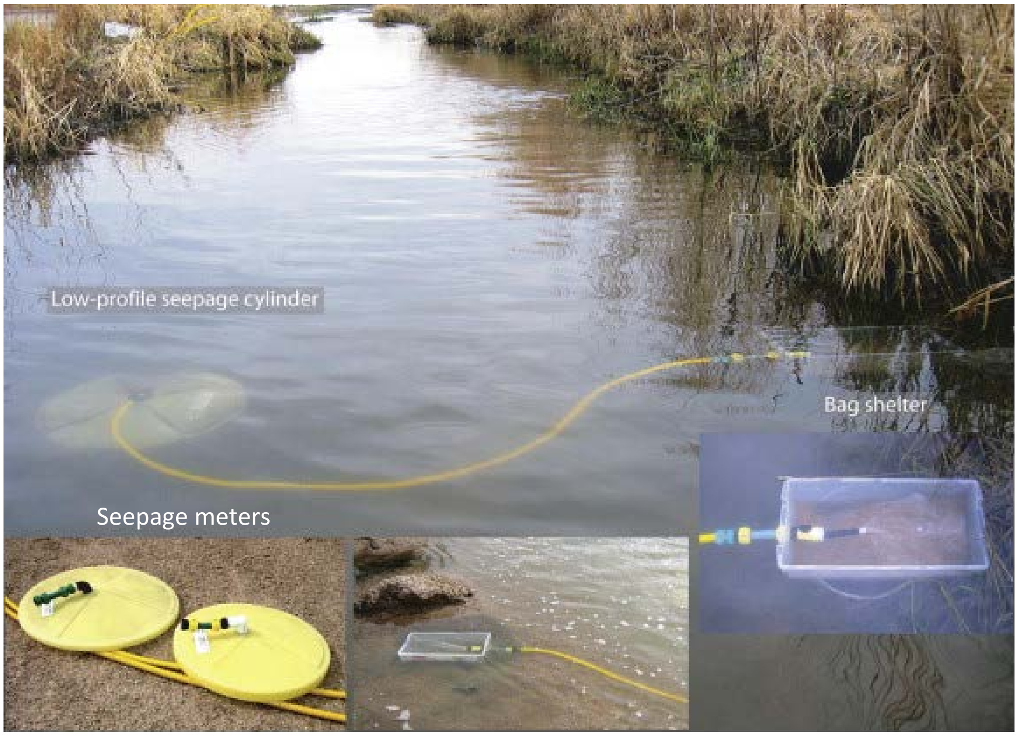


Figure 4 - Seepage meter deployed in surface water (Rosenberry et al., 2020). Bag shelter is where the seepage collection/discharge bag is housed to ensure the bag is protected and isn't influenced by head fluctuations. Water entering or exiting the sediment-water interface is measured by noting the volume change over time. Volume is determined weighing the water from the bag shelter.

Results

Results include seepage measurements made within the canal or at the individual seeps and can be coupled with canal operations. Scaling the results from a point measurement to an entire reach requires an accurate conceptual model and good engineering/scientific judgement. These data represent direct measurements of seepage and are therefore invaluable in further refining the regional scale operations models and can be used as observations to constrain numerical groundwater flow models.

Schedule and Cost

A single seepage measurement will require an hour to set up and about an hour to complete measurements needed to average the rates. This is also dependent on seepage rates, with low seepage rates taking more time to empty or fill the bag. Because of the relatively low costs of equipment (less than $100) more than one seepage meter measurement can be set up and monitored at a time. Thus, within a day, about 5-7 site measurements can be completed. To account for temporal variability, repeat site visits on a monthly basis can easily be done for the duration of the irrigation season. Table 1 provides a relative cost for this type of effort.

Ponding Tests

Overview

Ponding tests, where practical, can be used to directly measure loss rates over a length of canal in a controlled infiltration experiment. This involves filling and stemming flow in a section of canal and monitoring the decline in stage over time, as shown in Figure 5.

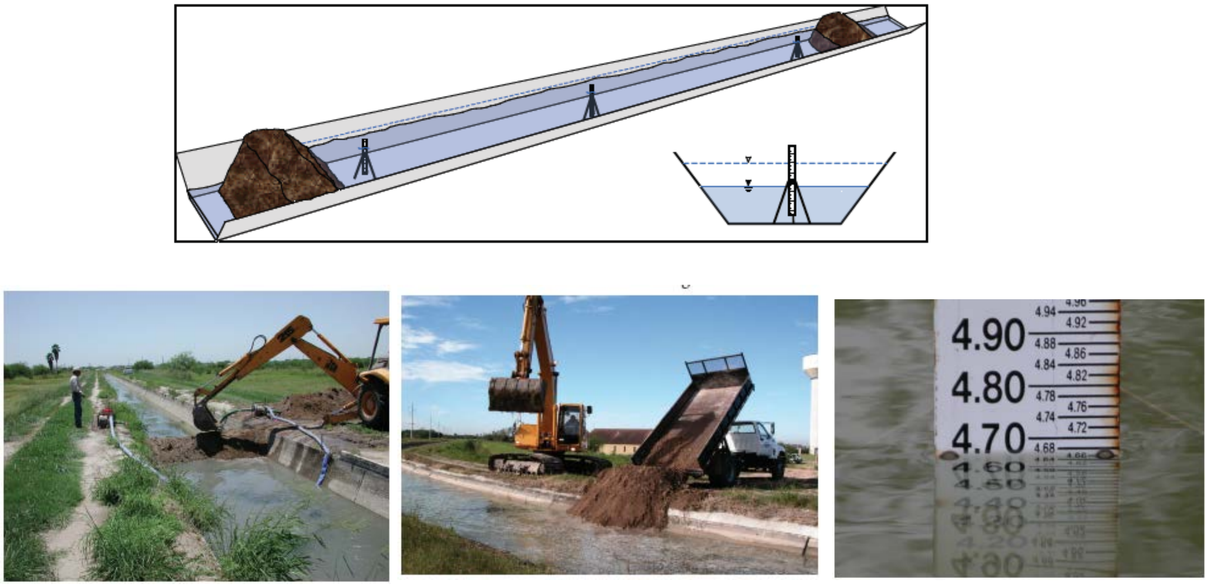


Figure 5 – Diagram and photos showing the design and construction of ponding test in an irrigation canal (from Leigh and Fipps, 2016).

Details

Ponding tests involve filling a section of the canal to a predetermined static water level and measuring the water loss over time (Leigh and Fipps, 2016). Filling material is typically done with native material and efforts to limits failure must be completed to engineering standards. Lining of the material may also be necessary to avoid losses through the infill material. The measured losses by a pond test are a combination of seepage and evapotranspiration; an accurate assessment of local climactic conditions at the time is required to estimate evapotranspiration losses. This test has the benefit of being simple to implement and understand but will result in disruption of water deliveries.

Results

Data obtained would include stage versus loss as a function of time for the isolated section. Because the stage is fundamentally in decline as water infiltrates, multiple ponding experiments may be needed to capture seepage-stage relationships. While a constant head test is possible, the control of the water level in the ponding area may be difficult. It should be noted that heterogeneity in the canal prism walls will have a significant influence on the calculated losses; different starting head levels will be required to characterize the seepage loss zones in this instance. Excavated canals can be expected to have a more heterogeneous characteristics than ones build with fill.

Additional losses from evapotranspiration also may influence results. Note that the influence of the groundwater could affect the data depending on depth to water and if a hydraulic connection to the groundwater system changes during the test.

Schedule and Cost

A ponding test would require a few days of field effort and a disruption to canal operations. Table 1 provides a relative cost for this type of effort. The disruption to canal operations may preclude this type of test.

Indirect Field Methods: Heat-as-a-Tracer

Heat-as-a-Tracer

Overview

The application of heat as tracer has been used in many hydrological investigations spanning many decades. In recent years, methodology and instrumentation improvements have resulted in a significant increase in the number of applications of the heat-as-a-tracer method (see review papers by Stonestrom and Constantz, 2003; Anderson, 2005; and Rau et al., 2014). Sediment temperatures can be used to estimate rates of losing and gaining segments of surface water systems. Advances in sensor technology has resulted in improved capabilities for investigating gaining conditions using fiber optic cable systems (Selker et al., 2006) or thermal infrared cameras mounted on small unmanned aircraft systems (Pai et al., 2017). The application of large-scale methods provide insight into local or site scale thermal anomalies where site-scale approaches can be used in a more targeted manner. Site-scale approaches often have the advantage of utilizing established sites with long-term measurements where losses are influenced by changing hydrological conditions. In canal systems, site-scale approaches, such as heat-as-a-tracer, can be used during normal canal operations without disruption because data are retrieved from the canal embankment (Naranjo and Turcotte, 2015). Long-term data collection also can lead to improved understanding of regional scale influences such as groundwater pumping, scour or siltation on seepage rates (Naranjo and Smith, 2016). Moreover, long-term monitoring provides opportunities to gain valuable insight on process understanding to support management decisions (Tetzlaff et. al., 2017; Naranjo, 2017).

Details

Sediment temperature profiles measured continuously have been used in groundwater flow models to estimate seepage rates under dynamically changing surface flow conditions (Constantz, 2008). The usefulness of temperature data for canal seepage investigations has been recently demonstrated in irrigation canals (Naranjo and Smith, 2016). Part of the success of this approach was the ability to estimate losses for multiple irrigation seasons, while incorporating the dynamic behavior of canal operations and groundwater pumping on seepage rates (Figure 6 and Figure 7). Seepage investigations have benefited from the use of a newly developed temperature probe designed specifically for heat-as-a-tracer approach (Naranjo and Turcotte, 2015). The main advantages of this device are the simple low-profile design, open-source software, and accuracy of measurements (Figure 8).

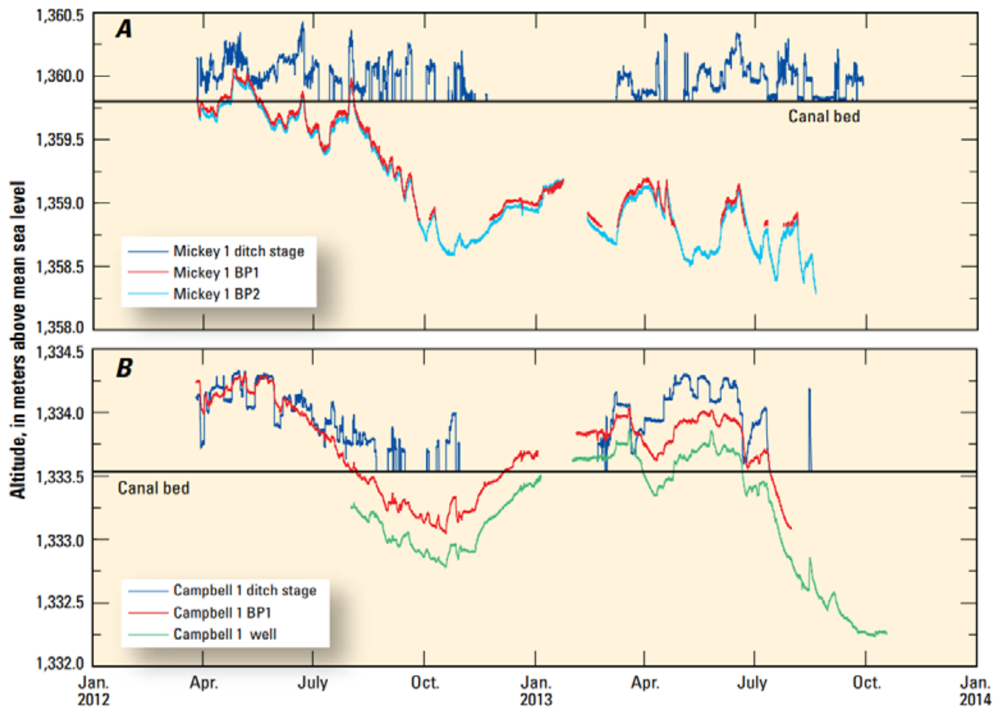


Figure 6 - Canal stage (blue line) and water levels measured in bank piezometers and wells located within transects sites in A) Mikey and B) Campbell ditches located in Nevada during the 2012-13 irrigation season (from Naranjo and Smith, 2016). During periods where water levels drop below the canal bed, the channel becomes hydraulically disconnected from groundwater and seepage rates subsequently increase. Groundwater levels decline due to regional groundwater pumping used for irrigation.

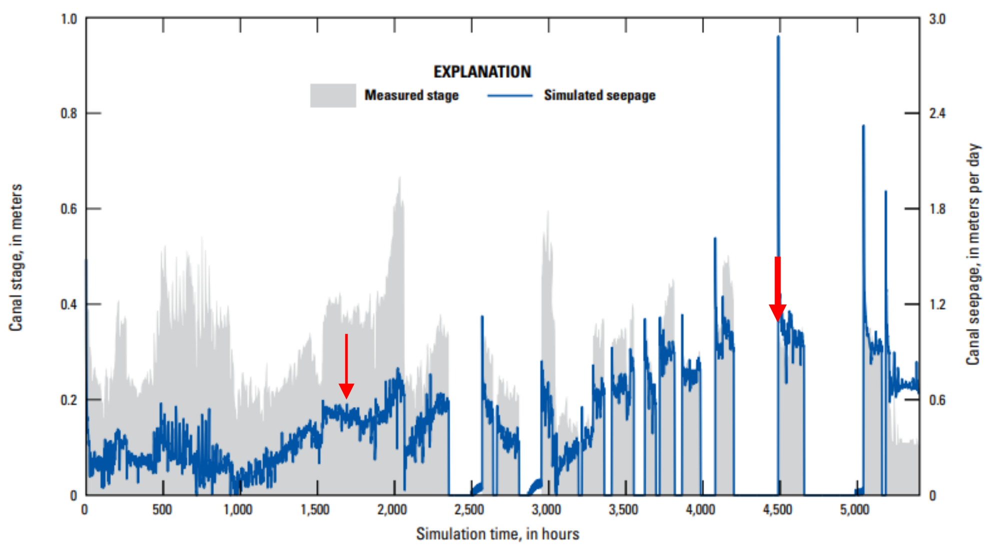


Figure 7 - Measured stage and estimated seepage losses from Mikey ditch (from Naranjo and Smith, 2016) using heat-as-a-tracer applied to variably saturated two-dimensional heat (VS2DH model simulations. Note the increase in seepage loss denoted by red arrow at time 1,700 hrs (0.4 m/d) compared to 4,510 hrs (1.1 m/d) for approximately the same stage conditions (0.38 m). Seepage rates

increase during the simulation period as the aquifer becomes hydraulically disconnected from the canal due to regional groundwater pumping.

Figure 8 - Temperature probe being installed into a A) pilot hole and B) sealed with bentonite-filled pilot hole (Naranjo, 2019). Data from the temperature probe can be easily downloaded using a laptop connected to the 25 ft communication cable.

The use of heat-as-a-tracer for estimating canal seepage loss involves monitoring sediment temperatures at multiple depths below the canal and variations in canal stage. This monitoring approach was implemented to estimate seepage losses at 20 transects during two irrigation seasons (2018-19) at 30-minute intervals on the Truckee Canal, Nevada. Seepage models were developed from site specific information, such as depth to bedrock and layered sedimentary deposits characterized by boreholes drilled vertically through embankment material. At each transect, two temperature probes were installed in the bottom of the channel along with a single piezometer instrumented with temperature sensors (Figure 9). A simple conceptual model was defined for each transect with soil zones delineating the shallow sediments beneath the sediment water interface. Additionally, piezometers were installed and instrumented with temperature sensors in the canal bank. The spatial variability of seepage rates was assessed by monitoring temperature at 15 to 20 locations within each of the 20 transects.

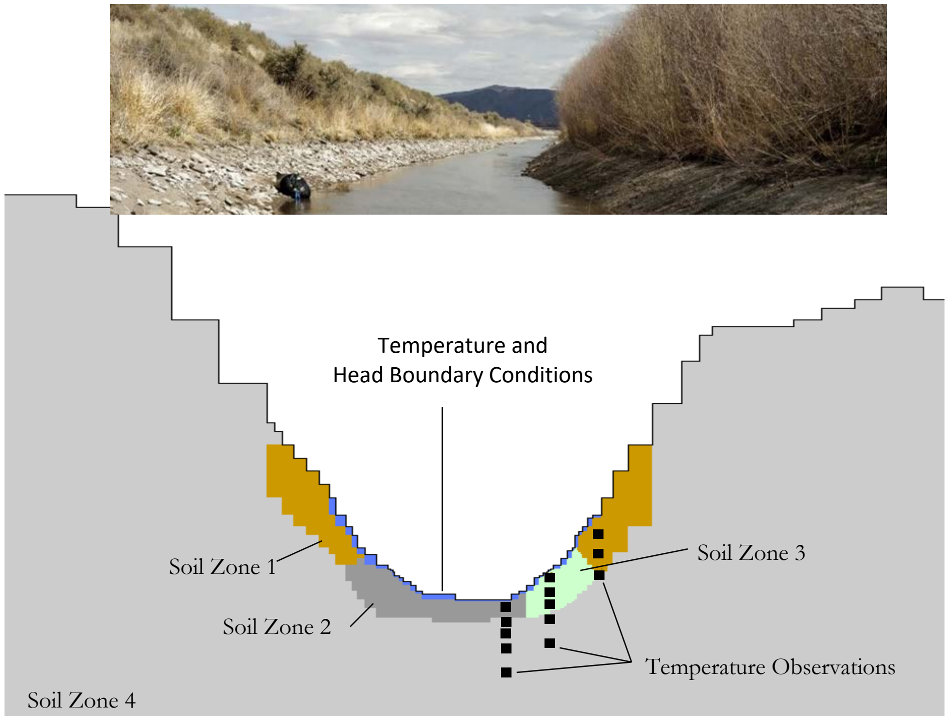


Figure 9 - Conceptual model showing soil zones, observations, and boundary conditions (In blue) used for two-dimensional (2D) seepage models on the Truckee Canal, NV. In this example, layered subsurface deposits were absent and not included in the model. Zones were specified as broad areas defined by hand texturing, soil cores and variations visually observed. Refinement of hydraulic and thermal properties for each zone is constrained by temperature observations within each zone.

Geological information available from boreholes along the canal were beneficial in identifying subsurface features that impede vertical flow paths (USBR, 2015a, 2015b, 2015c). Bedrock and lake lacustrine sediment deposits identified by drilling through embankment material to a depths 10-20 ft below the bottom of the canal were used to simulate flow paths to embankment seeps. These deposits can act as an impediment to vertical seepage and create pathways for groundwater flow laterally. Seeps created by these lateral flow paths can establish habitat for aquatic and terrestrial ecosystems as wells dynamically vary in flow rate depending on canal stage and hydraulic gradients (Figure 10). Where subsurface sediment information was available from nearby boreholes, additional soil zones were added to the simplified conceptual models to represent sediment layers or bedrock boundaries.

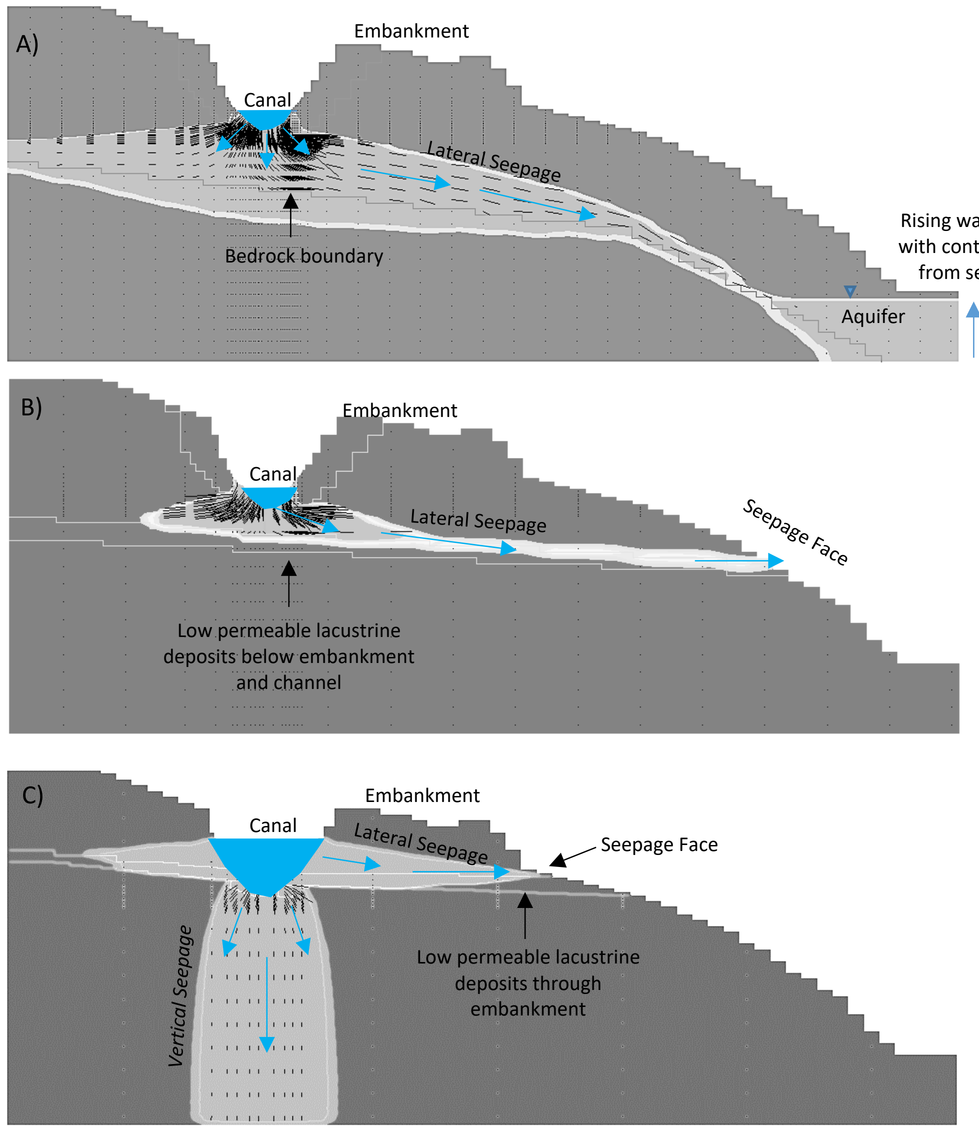


Figure 10 - Conceptual models used for seepage estimation using VS2DH (Hsieh et al., 200) with A) bedrock boundary and an seep created by a rising water table, B) lateral flow above a low permeable layer with seepage flowing through embankment material and creating a seepage face, C) lateral and vertical flow seepage patterns created during high stage where lateral flows above a low permeable layer creates a seepage face at the toe of the embankment. At low stage for conceptual model C), lateral seepage may not occur at toe of embankment due to insufficient hydraulic gradients. Vertical seepage occurs through the bottom section of the canal where lacustrine deposits were removed by canal construction or by channel incision.

At each transect, thermal and hydraulic properties, canal cross-section geometry, and stage were needed as inputs to seepage models (VS2DH; Hsieh et al., 2000). The subsurface sediments were idealized into soil zones based on lithology determined from existing geologic descriptions and through soil cores collected from bottom of the canal (Figure 11 a and b). Soil testing was performed to determine fitting parameters for the van Genuchten infiltration parameters used in the seepage models. Because seepage models are highly sensitive to thermal properties, field measurements of thermal conductivity were made monthly using a hand-held device (Figure 11c).

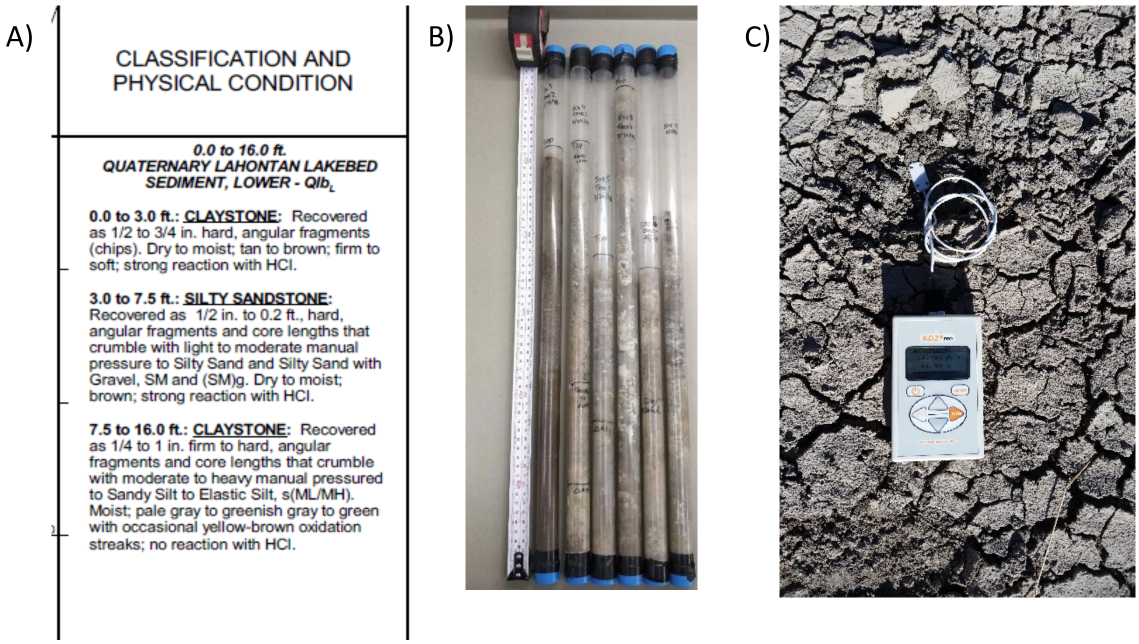


Figure 11 – A) Example geological descriptions from boreholes drilled through embankment material on the Truckee Canal (USBR, 2015a), B) soil-core samples collected from the bottom of the canal down to 3 ft and C) a portable thermal conductivity sensor used to parameterize seepage models.

For groundwater flow models, parameter-estimation model, PEST++ (Welter et al., 2015) can be used to calibrate the model by adjusting hydraulic and thermal properties until model simulations are within agreement of the observed temperatures (Figure 12). On the Truckee Canal, 14 temperature observations, collected over 2500 hours (35,000 observations in total) were used for model calibration per transect. Once initial hydraulic and thermal properties for the transect models have been defined, model calibration is performed to refine the most sensitive parameter (typically Ks) values. This is typically achieved by manual adjustments to parameters or using separate programs designed to automate the process by comparing simulated to observed or best-estimates of published values. Model calibration using PEST code will aid in the refinement of the initial estimates of hydraulic conductivity, anisotropy, and thermal conductivity. Upon completion of model calibration, assessment of calibrated parameters and seepage estimates can be further evaluated for model sensitivity and uncertainty. In transect models with data collected over an irrigation season, parameter verification can be tested against data beyond the calibration period to determine whether siltation or scour has affected the hydraulic or thermal properties throughout the irrigation season (Naranjo and Smith, 2016). For the Truckee, model verification will take place on the remaining 2,000 hours per transect for the irrigation season. Model performance will then be compared to observations during the second irrigation year monitored.

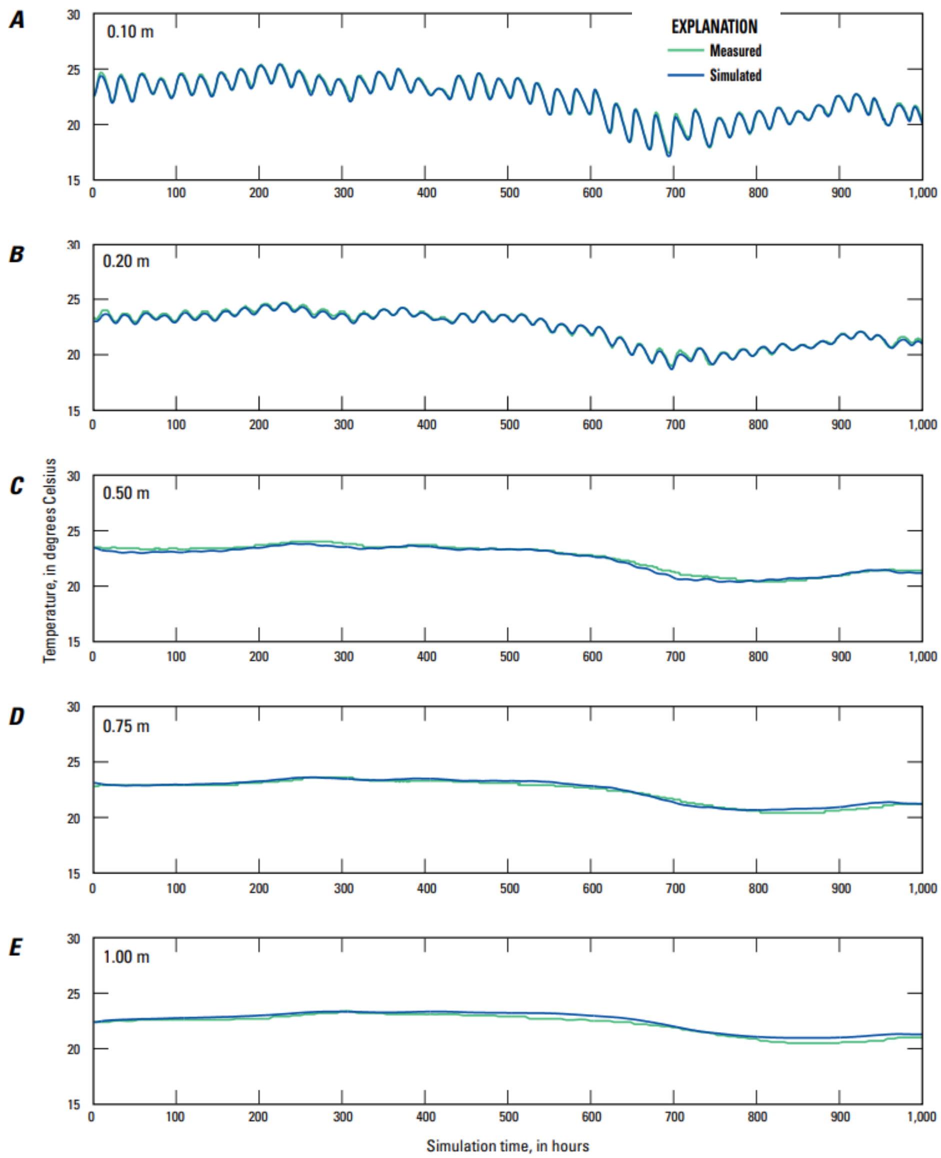


Figure 12 - Example of measured and simulated thermographs within canal sediments located in the Campbell Ditch, NV at depths of A, 0.10 m, B, 0.20 m, C, 0.50 m, D, 0.75 m, and E, 1.0 m for the 1000 hour calibration period (Naranjo and Smith, 2016).

Results

The use of heat as a natural tracer to estimate seepage across the sediment-water interface has been widely accepted because temperature is easy to measure and relatively inexpensive to record. Moreover, natural thermal forcing at the land surface typically provides large diel signals during the irrigation season. The application of heat-as-a-tracer for the Truckee Canal provides a unique opportunity to advance understanding of loss rates along the entire reach of canal during operations. Results from the on-going study also will provide new information on the role of low permeable materials in the subsurface that induce lateral flow and cause seeps within embankment and at distal areas away from the canal. The long-term data will provide insight into changes the effects of sediment temperatures on seepage rates due to changes in viscosity of water (Figure 13). Seepage-stage regression equations developed from this effort will be used to improve forecasts of water deliveries using operations models and more effectively manage water resources.

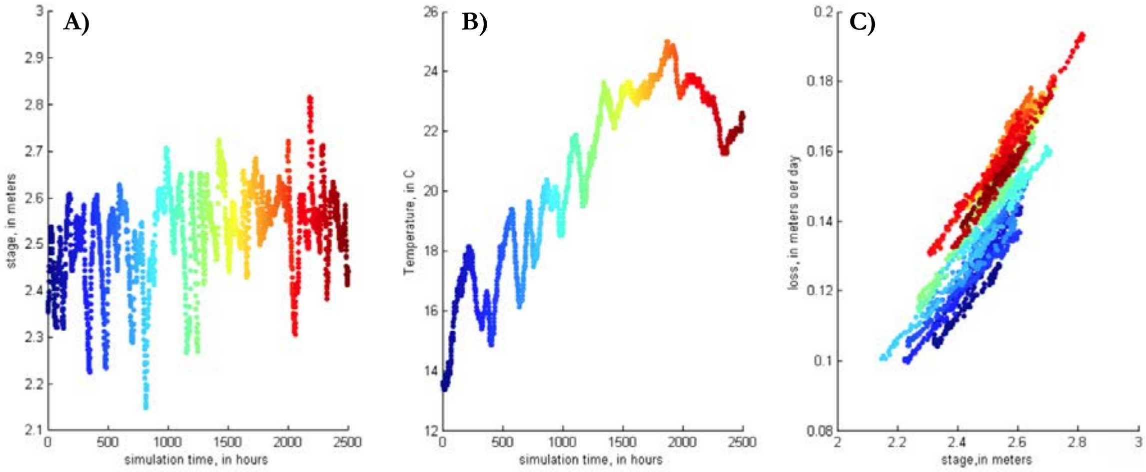


Figure 13 - The effect of temperature on simulated seepage rates relative stable canal stage. In this example, A) variable stage, and B) increasing temperature were input into VS2DH to develop the C) stage-seepage loss relationship over hypothetical 4-month irrigation period. Regression models developed for stage-seepage in canals would need to account for the effect of temperature on viscosity and seepage rates. In VS2DH, viscosity and temperature are accounted for in the hydraulic conductivity term. Dots are colorized by time.

Schedule and Cost

The costs associated with equipment for site-scale investigations are relatively low per transect. Cross-sectional surveys are needed for channel geometry using differential GPS or other survey equipment, staff gages, piezometers with stage recorders (e.g., pressure transducers), and temperature logging probes are required. Temperature sensor installation can ideally be done before normal operations using simple hand tools (Naranjo, 2019). At each transect, a field crew of two people could install temperature probes and piezometers and initiate recording data in less than four hours. Measurement frequency (stage and temperature) will depend on site conditions, but 0.5-hour time intervals are typically sufficient for main canals and laterals.

Monthly data retrieval ensures sensors are actively collecting with no loss of information due to sensor malfunction or damaged caused by rodents or the public. Monthly manual tape measurements at staff gages, piezometers and wells provide the data necessary to correct measurements collected by pressure transducers. At each transect, data retrieval will take less than an hour.

Compiling temperature and water-level data can easily be done with knowledge of simple spreadsheets. Seepage models require knowledge of unsaturated and saturated groundwater flow modeling. For a single transect, a numerical model can be constructed within a day with parameter estimation methods used to estimate seepage rates requiring 1-2 days to complete.

The relative cost in Table 1 is for a single transect for an entire irrigation season spanning 8 months (March to November). This includes equipment (temperature sensors, a pressure transducer, piezometer materials), labor for surveying, collection, model construction, and analysis.

Indirect Detection and Characterization Methods: Geophysics and Remote Sensing

Geophysical methods measure or image physical and chemical properties and processes in the subsurface; canal seepage detection using geophysical methods typically relies on the interpretation of contrasts in bulk electrical conductivity (reciprocal of electrical resistivity) related to soil moisture and lithology.

When the contrast in electrical conductivity is diminished, interpretation of the data may be complicated or become ambiguous, where contributions to spatial variations in resistivity could be caused by some combination of lithologic and water saturation factors. For example, geophysics can be useful for locating wet zones in regions where there is a contrast with a dry zone, or seep areas that have existed for some time that are now associated with increased presence of dissolved solids deposition and mineralization within pore spaces that increase conductivity of soils. In regions with a fully saturated clay or sand layer, it would be difficult or impossible to distinguish where a seep is discharging without these associated dissolved solids or salts to create adequate conductivity contrasts. Conversely, conductivity anomalies that might indicate higher water content than the surrounding soils may be caused by lateral changes in lithology (e.g., clay versus sand layer) or natural water saturation levels and are not necessarily associated with canal seepage locations.

Ground truthing geophysics with drilling or other direct investigation methods is an important part of any exploration. By being thoughtful in the approach taken with invasive (drilling) and non-invasive (geophysics) methods, an invasive field investigation can confirm the interpretations made from the non-invasive methods and ensure the accuracy of the analysis.

Surface-Based Geophysical Methods

Overview

Many surface-based geophysical methods are helpful for canal seepage investigations because they can gather data over large distances and small spatial scales non-intrusively and are sensitive to variations in subsurface hydrogeologic conditions. Surface-based geophysics is recommended to be done in a phased effort, where the first phase would involve rapid reconnaissance-type geophysical profiling techniques (e.g., electromagnetic and magnetic profiling, continuous capacitively coupled resistivity profiling, ground penetrating radar profiling), and the second phase involves more detailed geophysical mapping and subsurface imaging techniques (e.g., 2D electromagnetic and magnetic mapping, focused galvanically-coupled 2D direct current electrical resistivity tomography, seismic refraction tomography, detailed 3D ground penetrating radar surveying, and 1D self-potential profiling or 2D mapping surveys) at select target seepage areas/features. Surveys should be performed during both de-watered and watered-up conditions, when feasible, to better evaluate geophysical anomalies or data patterns related to dynamic water saturation processes as opposed to static soil properties. In general, adequate time should be allowed after dewatering or after watering up of canals and other structures, so that subsurface hydrologic conditions have time to stabilize during the associated hydraulic loading conditions.

As discussed above, canal seepage detection using geophysical methods typically relies on the interpretation of contrasts in bulk electrical resistivity. According to Bhatt and Jain (2014), the solid phase (e.g., mineral grains) in soils and rocks are essentially nonconductive compared to the saturating fluid in a porous medium, with the exception of some metallic minerals. The majority of electrical conduction in electrolytic mixtures (e.g., moist soils and water bearing rocks) occurs as the movement of ions, governed by the electrical resistivity which has been demonstrated to be an effective predictor of various soil properties including salinity (Rhodes et al., 1976), porosity, and water content (Dannowski and Yaramanci, 1999; Tabbagh et al., 2002; Binley et al., 2002).

Primary factors that influence bulk resistivity of soils and other earth materials include 1) level of saturation of interconnected pore spaces, electrical resistivity (e.g., salinity) of the saturating pore fluid, grain size and mineralogical content of soils (e.g., the amount of clay versus sand), and the fraction of metallic minerals (e.g., hematite particles or iron oxides) (McNeill, 1980; Groover et al., 2017). Secondary factors include compaction/density, temperature, and secondary porosity. As discussed in Groover et al. (2017), "extensive discussions about the theory and applications of the electrical properties of earth materials are widely available in the literature (Archie, 1942; Telford et al., 1990; Reynolds, 1997; Binley and Kenma, 2005; Minsley et al., 2010)." Additional detailed theory and discussions can be found in Keller and Frischnecht (1966) and Locke (2000).

Figure 14 presents examples of observed variations in bulk DC electrical resistivity (SI units of ohm-m) of different soil-types as a function of water saturation (%). In most cases, laboratory testing and field surveying data indicate that resistivity changes are on the order of several tens to hundreds of ohm-m between a dry and partially saturated soil type. When considering the electrical conductivity (SI units of S/m) we see that the absolute value of changes are generally much smaller and within a single order of magnitude simply due to the reciprocal relationship with resistivity values. For example, plot A in Figure 14 shows the resistivity of a sand decreasing from approximately 350 ohm-m to 150 ohm-m as saturation is increased from 20% to 80%. This resistivity change corresponds to an increase in electrical conductivity from 2.8 to 6.7 mS/m. Similarly, the tomogram in the bottom plot of Figure 14 shows lower resistivity values in the immediate vicinity of and below an unlined irrigation canal that suggest increased water saturation of soils due to vertical and lateral seepage losses from the canal. The absolute variations in resistivity between different pairs of points 1 through 5 are as follows; points 1 to 2=14 ohm-m (35 mS/m), points 3 to 4=150 ohm-m (23 mS/m), and points 3 to 5=765 ohm-m (27 mS/m).

In practice, similar magnitudes of conductivity variations on the order of 10's of mS/m are commonly observed at known or otherwise suspected seepage locations along canals (Rittgers, 2018). These electrical conductivity variations related to water saturation levels are well within the sensitivity (approximately 0.1 mS/m) and accuracy levels (approximately +/- 5% at 20 mS/m) of most relevant resistivity and FDEM instruments (Geonics Limited, 2020a, 2020b; GF Instruments, 2019; Advanced Geosciences Inc., 2009, 2011).

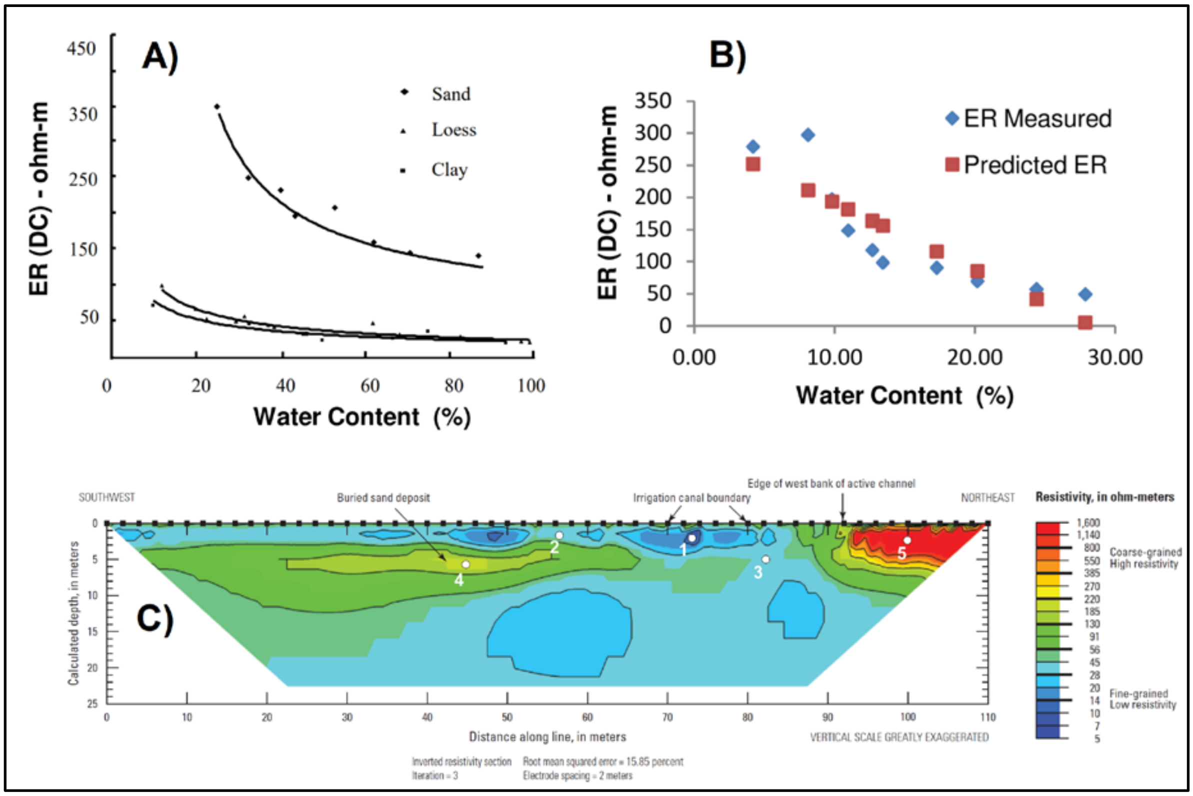


Figure 14. Examples of observed variations in bulk DC electrical resistivity (ohm-m) of soils as a function of percent water saturation (%): A) lab-tested resistivity values for three common types of soils versus water saturation [modified from Hong-jing et al., 2014], B) for a clean sand [modified from Bhatt and Jain, 2014], and C) from an electrical resistivity tomography survey conducted across an unlined irrigation canal located within an alluvial depositional setting consisting of surficial flood-plain deposits and tilled soils overlying hydraulically permeable silty sands [modified from Groover, et al., 2017].

Details: Phase I (Rapid Geophysical Profiling Techniques)

As stated above, there are several "rapid" geophysical profiling techniques that may be useful in canal seepage detection and hydrogeologic characterization efforts across long segments of canal systems, depending on various site-specific factors, logistical considerations, and project objectives. These profiling techniques may include the following:

- Vehicle or hand-towed ground-penetrating radar (GPR) profiling
- Vehicle-towed or hand-carried time-domain electromagnetic induction (TEM) instruments
- Vehicle-towed or hand-carried frequency-domain electromagnetic induction instruments (FDEM)
- Vehicle or hand-towed continuous capacitively-coupled electrical resistivity (CCR) profiling

GPR and TEM:

While GPR and TEM are included in the above list, these geophysical techniques are generally not considered to be practical rapid seepage detection tools.

GPR provides images of shallow stratigraphic layering, and images hyperbolic anomalies that are caused by perpendicular utilities/voids or point-reflectors such as voids, tree roots, animal burrows, or cobbles that may be of seepage-related interest. Lateral variations in signal attenuation versus depth could be used to interpret spatial changes in moisture content, but this interpretation schema is rather difficult and ambiguous. There has been significant research in relating soil water saturation θ estimation directly from measured values of the dielectric constant ε' (an electrical property of all matter and empty space) which can be derived from GPR wave propagation velocity measurements (see Mukhlisin and Saputra (2013) for a detailed review). Several empirical and semi-empirical models have been developed via nonlinear regression fitting of datasets for a variety of soil types and to account for multi-phase mixtures (e.g., air, soil, water). Some of these models attempt to predict θ using ε' as a single independent variable, while other models have two or three independent variables, including bulk density and porosity. In these multivariate cases, prior knowledge or otherwise assumed constant values of these parameters are required for each constituent material type (Dannowski and Yaramanci, 1999).

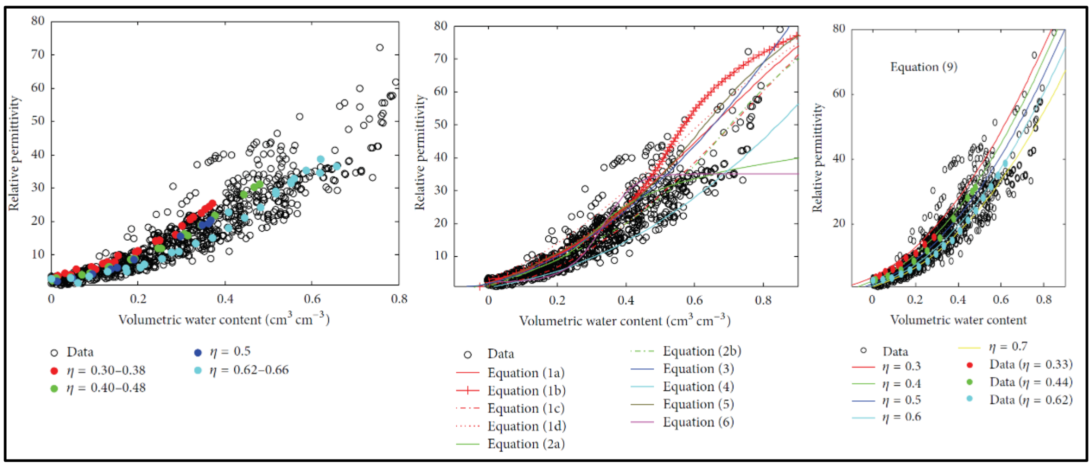


Figure 15. Plots of measured dielectric constants versus volumetric water content for various soil types amalgamated from various studies: Data plotted with secondary data of porosity indicated with color-filled circles (left) and with results of various single-parameter prediction equations plotted as line-plots(center), and with results of various two-parameter prediction equation that accounts for porosity plotted as line-plots (right). Modified from Mukhlisin and Saputra, (2013).

As seen in Figure 15, there is clearly a positive correlation between increases in permittivity and increases in water saturation levels (mainly due to the relatively high dielectric constant of water). However, there is a variable range of measured volumetric water content values associated with any given dielectric constant value, where this range (and associated prediction uncertainty) increases with increasing permittivity values. The center and right plots of Figure 15 show the results of applying various prediction models, where the center plot shows predicted values for single-parameter models (only measured ε') and the right plot shows predicted values for two-parameter models (measured ε' and porosity). While these data demonstrate that it is possible to accurately predict volumetric water content using multi-parameter prediction equations, this approach requires knowledge of porosity to avoid significant errors. As a result, GPR is not considered practical for rapid seepage detection, especially along tens or hundreds of miles of canal alignments. The technique is deemed more appropriate for site-specific detailed survey applications.

Rapid TEM techniques capable of imaging the uppermost ~0-10m in detail (typical depths of interest related to canal seepage processes) are still in development, current system electronics limitations have significant impacts on TEM's ability to resolve shallow hydrogeologic responses of primary interest. As depicted in Figure 16, the tTEM system by Aarhus University Hydro-Geophysics Group and similar TEM systems are useful for deeper explorations on the order of tens of meters in depth (up to 100m or more), but lack in near surface vertical (approx. 5m) and lateral (approx. 5-10m) resolutions and sensitivity to near-surface conditions generally required for most rapid canal seepage detection applications (Auken et al., 2018).

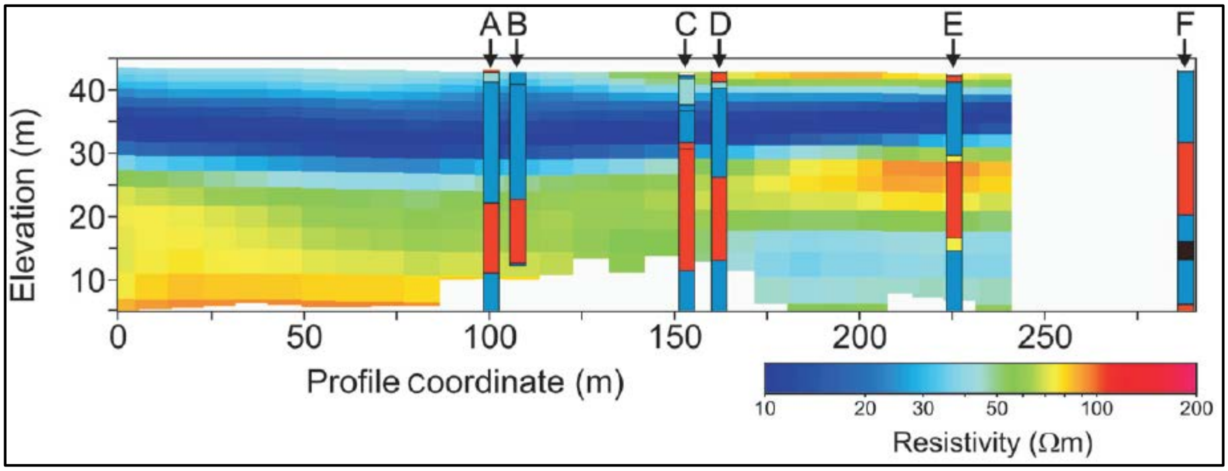


Figure 16. Example of tTEM electrical resistivity profile showing correlation between modeled resistivity values lithology stick-logs. Modified from Auken et al. (2018).

As depicted in Figure 17, the size and configuration of the tTEM system also presents practical limitations in its use for rapid canal inspections over long distances. Here, the system is approximately 15m (50ft) long and is mounted on low-clearance sleds that are rope-tethered and dragged across the ground surface. This physical configuration requires a relatively flat and smooth ground surface, and straight or gently curving survey lines with no significant vegetation or obstacles. This is often not the case for canal alignments and access roads and may pose logistical issues related to the use of similar platforms.

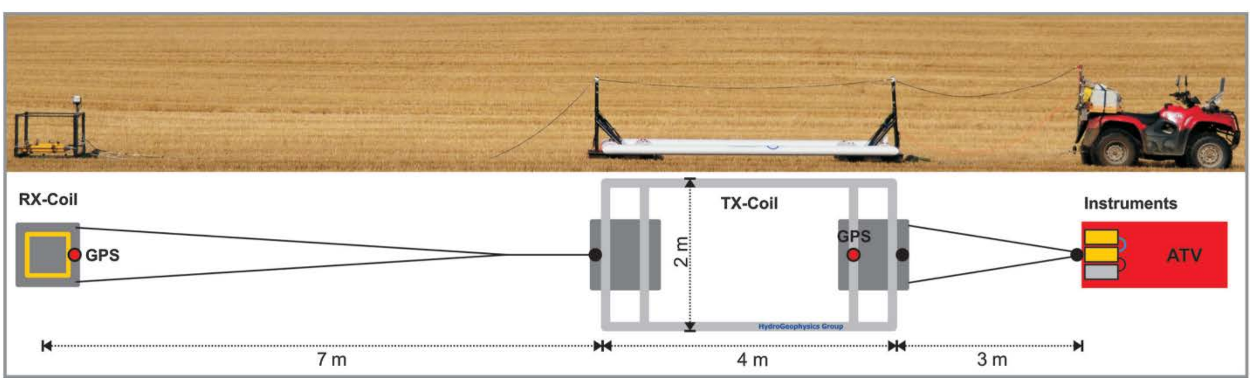


Figure 17. The tTEM system, with a side-view photo (top) and a plan-view of the system layout (bottom). (modified from Auken, et al., 2018).

FDEM:

Figure 2 depicts conceptual models of under-seepage and through-seepage, and Figure 18 depicts a conceptual model of related seepage detection using FEDM. In Figure 18, there is typically an increase in the water saturation within and underneath the embankment, as well as immediately downhill of the embankment with the eventual development of vegetation at a seep location. In under-seepage conditions, the embankment slope surface can be devoid of vegetation and moisture while there is standing water and lush vegetation along the downstream toe. Conversely, through-seepage can lead to shallow wetting-fronts within the embankment, and wet-spots and vegetation can develop further up along the slope.

Conveniently, the seepage-related conditions depicted in Figure 2 and Figure 18 can be targeted for seepage detection purposes. Specifically, the increase in electrical conductivity (a corresponding decrease in resistivity) due to increases in water saturation can be targeted with geophysical techniques, and the spatial variations in vegetation along a canal can be used as an indirect indication of seepage. Hence, there is an opportunity to combine both normalized difference vegetation index (NDVI) remote sensing data images with ground-based FDEM and magnetic gradiometry profiling surveys conducted along canal embankments to more accurately detect and map embankment seepage in comparison to utilizing a single data type only.

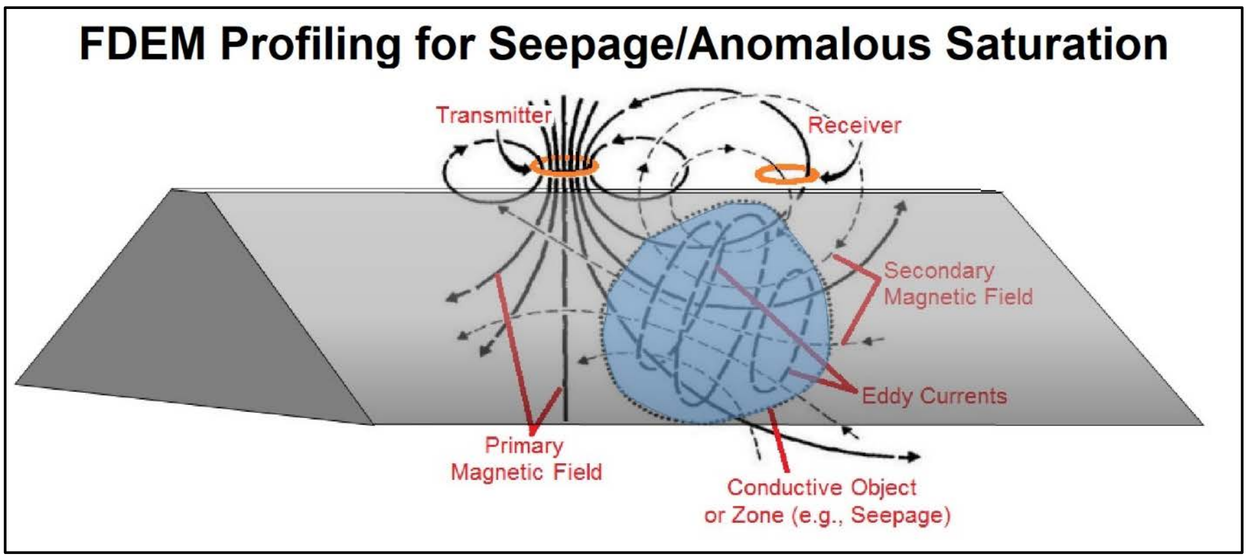


Figure 18 - Frequency-domain electromagnetic (FDEM) coupling with electrically conductive zones related to seepage. Seepage zone identified in blue.

FDEM can be utilized to detect and map out the locations of anomalous electrically conductive zones related to canal seepage, as depicted in Figure 18. Similarly, magnetic gradiometry surveys can be performed to detect the presence of subsurface ferrous metallic infrastructure (e.g., corrugated metal pipes at canal take-outs) that produce FDEM data signatures similar to that of seepage areas. These magnetic data can help to avoid false positives when analyzing the FDEM data.

Most typically, FDEM surveys are conducted by hand-carrying the system, as depicted in images A through E in Figure 19. While this approach to data collection is ideal for difficult terrain, densely vegetated areas, or for smaller surveying areas requiring 2D mapping data coverage, cart-mounted systems and configuring the data loggers for continuous data collection with differential global positioning system (DGPS) antennas can allow for much more rapid data coverage along profiles (e.g., along canal crest roads or along the downstream toe of embankments). Examples of cart-mounted FDEM and magnetometer systems configured in this fashion are depicted in images F and G in Figure 19.

With cart-mounted FDEM and magnetometer systems, tens of miles of data can be collected very rapidly in a single field day, allowing for more comprehensive data coverage along canals and other linear structures such as levees or even subsurface pipelines for other applications (e.g., leak detection). These systems can be configured to collect up to a 10Hz data sample rate, allowing for very dense data coverage (<3ft) along canals even while driving at relatively high speeds (e.g., 10-15mph).

Furthermore, due to the relatively inexpensive nature of this approach, repeated surveys can be performed at differing stages of hydraulic loading of canals in order to help identify time-lapse changes related to the "turning on" and "turning off" of seepage at specific points or segments of canals. Rapid geophysical profiling provides an opportunity for more detailed analysis of canal seepage by the following:

1) cataloging the spatial variations in electrical conductivity within the uppermost 50 feet or more related soil moisture distributions,
2) conducting time-lapse analyses for temporal change detection
3) identifying spatio-temporal changes following operations and maintenance events along canals (e.g., watering-up of a canal system, or pre/post embankment lining or repair efforts), in order to help evaluate changes in performance and hydrologic conditions along the embankment.

Figure 19 - Various commercially available FDEM systems being hand-carried (images A – E) or cart-mounted (images F and G) for data collection. Each system has a varying depth of investigation, where

shorter/smaller systems have relatively shallow depths of investigation, while larger FDEM systems (e.g., the EM34 system depicted in image B) have larger depths of investigation.

CCR:

Figure 20 shows the OhmMapper system, a CCR profiling system being deployed with a five-receiver setup and being vehicle-towed. While this system is useful for collecting continuous 2D resistivity tomography profiles, it has several limitations related to depth of investigation, resolution and sensitivity in conductive soils, practical logistical and safety concerns in rough and uneven terrain or along curved or uncleared survey lines. Due to the length of the cable and the fact that it needs to be dragged across the ground surface, data collection is commonly limited to flat and straight or gently curving survey lines that are clear of vegetation and other obstacles, and typical data collection rates similar to a slow walking pace of approximately 2 km/hr (1.2 miles/hr).

Similar systems can be deployed as water-borne floating arrays and can be boat-towed along the centerline of canals to help infer grain-size distributions beneath the canal invert (Ball et al., 2006). This approach to inferring soil-types based on electrical CCR profiling surveys makes the assumption that subsurface water salinity and saturation levels are homogeneous along the length of the survey and that any lateral or vertical variations in bulk electrical resistivity are only due to corresponding changes in grain size distributions underlying the canal. This can be a reasonable assumption if data are collected inside a canal while watered up or dewatered for adequate time as to allow water saturation levels to reach steady-state equilibrium. Conversely, this may not be a reasonable assumption in more complex hydrogeologic settings where water saturation is expected to vary significantly within the survey area (e.g., along the downstream toe of canal embankments, or across larger areas with variable surface and groundwater conditions). In these more complex hydrogeologic conditions, mapped variations are most often due to both lateral changes in grain-size and water saturation levels or depth to the phreatic surface.

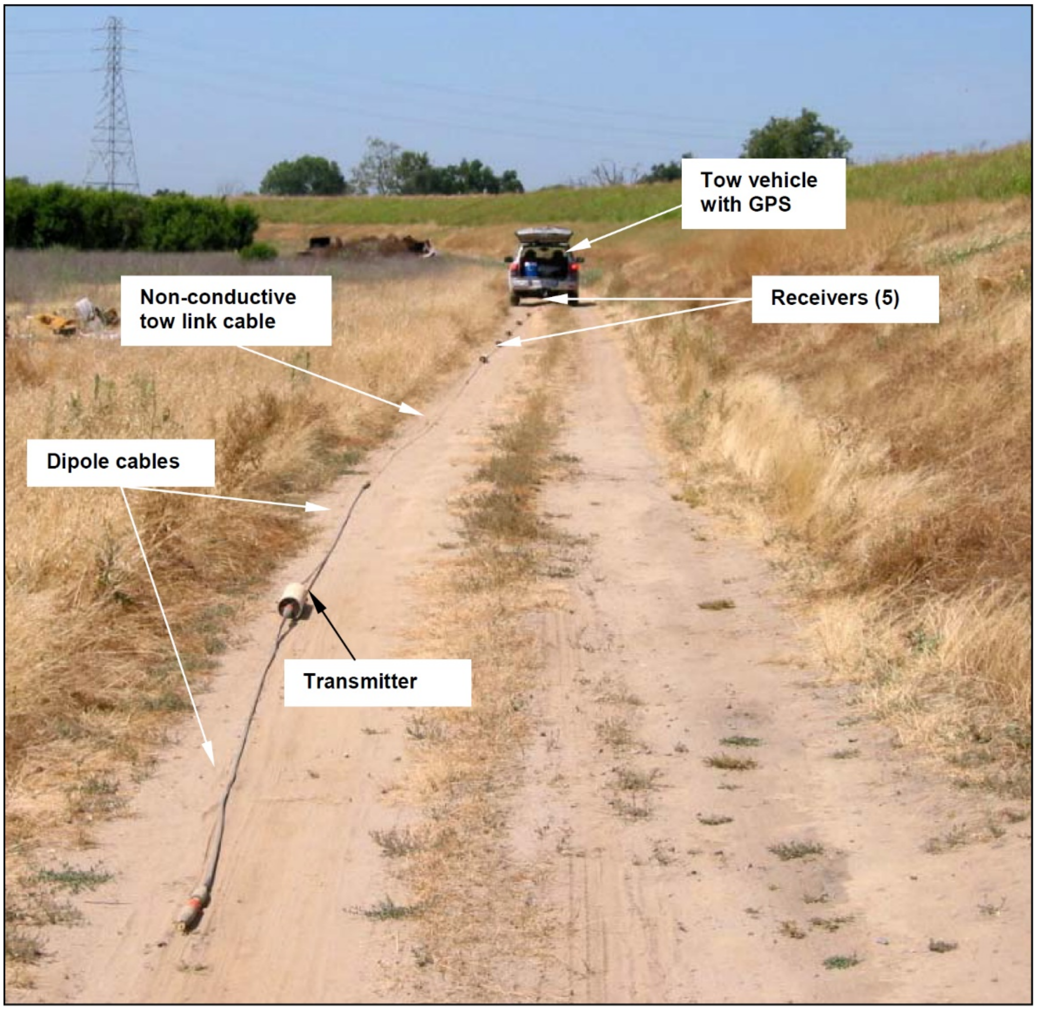


Figure 20. Photo of the Geometrics Ohm-mapper CCR profiling system being vehicle-towed. Here, the "a" spacing or dipole length was set to 5 m and "n" factors of 3.0, 3.5, 4.0, 4.5, and 5.0 were used. Using this configuration, the length of the array was in excess of 35 m (115ft), (Llopis and Simms, 2007).

Results

The results of these types of rapid geophysical profiling surveys include the following major contributions to seepage detection and structural health characterization and monitoring:

1. Continuous data coverage along entire lengths of long canals embankments collected in a short amount of time (days).
2. Identification of anomalous conductivity zones indicative of seepage locations.
3. The ability to identify and map locations of subsurface metallic infrastructure (e.g., abandoned takeout structures, corrugated metal pipes (CMPs), or illegal perforations through embankments), and the ability to differentiate between these features and seepage related data signatures.
4. The ability to image lithologic layering and interfaces at depth that may be of interest to seepage characterization.
5. The production of a unique set of geospatial data that can be used subsequently with other complimentary data types to help improve seepage detection and structural health assessments.

6. The ability to help guide more focused techniques at identified anomalous locations along canals.

Schedule and Cost

Rapid profiling techniques are generally very inexpensive when compared to other approaches to geophysical data collection with similar spatial data coverages. In some cases, what can be achieved with rapid profiling in a matter of days would take months to achieve the using other techniques over the same lateral coverage. Depending on the scale of a given survey, and the logistics involved in site access, 100 miles of canal embankment could be surveyed in three days with a crew of two people. The entire workflow, including mobilization of gear and personnel, field surveying and data collection, data processing and analysis, and report generation can be completed in a month. Relative costs are provided in Table 1.

Details: Phase II (Focused High-Resolution Geophysical Mapping and Imaging Techniques)

In addition to rapid geophysical profiling techniques described above, several more focused and higher-resolution geophysical mapping and imaging methods are available for seepage characterization efforts. Some of the most common geophysical tools applicable to seepage characterization include the use of FDEM systems for 2D spatial mapping across grids or areas rather than simply profiling along canal alignments, electrical resistivity tomography (ERT) imaging techniques, spontaneous-potential or self-potential (SP) mapping, seismic refraction tomography and seismic surface-wave techniques, and ground penetrating radar imaging. These techniques are typically more labor and time intensive and thus only offer limited spatial coverage. Therefore, these methods are best suited for focused surveys at identified or otherwise suspected seepage locations that require detailed investigations and analysis.

These focused geophysical techniques can be implemented in specific areas of known seepage for various reasons, including the following:

1. Areal mapping of linear electrical conductivity anomalies caused by shallow seepage pathways,
2. Imaging anomalous patterns of electrical resistivity within the subsurface that are generated by seepage zones at depth to help visualize their depth and spatial extents,
3. Imaging subsurface geologic structures and material types (e.g., sand and clay lenses or depth to bedrock) that may be related to and influence local seepage conditions and processes at specific points along canals.
4. To help differentiate between canal seepage and the presence of natural groundwater conditions at various points along canals (e.g., where canals cross natural drainages).

Detailed FDEM Mapping & Imaging

Similar to rapid profiling with FDEM systems, as discussed above, the same instruments can be either towed or hand-carried in a grid-like fashion, with data collected along tightly-spaced parallel or crossing survey lines. For example, Figure 21 shows the results of hand-carrying a FDEM system along several parallel survey lines that cross approximately perpendicular to a suspected seepage pathway. This approach to focused data collection offers detailed information about subsurface electrical conductivity patterns related to seepage phenomena at a specific location.

The top image in Figure 21 shows apparent conductivity values in map-view for a given instrument or FDEM coil configuration that has a specific depth of investigation range. This image can be thought of as a depth-slice through the subsurface (conductivity across some constant depth below ground surface). The bottom image in Figure 21 shows the result of inverse modeling of several colinear data layers, each recorded with a different FDEM system or coil configuration (different transmitter-receiver spacings and/or orientations relative to vertical). Here, each data layer provides a unique depth of investigation that can be used to help constrain the inversion process. The result is a model of 2D or 3D distribution of electrical conductivity of the shallow subsurface. This data product is similar to the results of an electrical resistivity tomography survey or a 3D tTEM survey, where an image (model) of the subsurface conductivity is produced. This helps to inform the depth to various features of interest, such as an electrical conductivity anomaly associated with a seepage zone or seepage pathway.

While the apparent conductivity mapping results and corresponding inverted 3D resistivity model depicted in Figure 21 have certain levels of ambiguity related to the "possible seepage pathways" labeled on the figure, the main purpose of this figure is to demonstrate the ability of FDEM to map conductivity patterns related to hydrogeologic conditions with high spatial resolution and sensitivity levels. Here, the southern low conductivity half of the top plot corresponds to a topographic bench comprised of silty sands and gravels above the water table, and the northern higher conductivity half of the top plot corresponds to a low-laying flood-plain with finer-grained soils, lush vegetation, and surficial expressions of higher saturation conditions associated with a shallow water table (e.g., the frog pond indicated with a star). The linear trends of high conductivity values in the top plot of Figure 21 are associated with old abandoned irrigation ditches that extend to the Truckee River located just north of the dataset. FDEM data collected within these ditches are interpreted to indicate increased saturation and associated conductivity values, where the FDEM system was in closer proximity to the phreatic surface within the topographic low points.

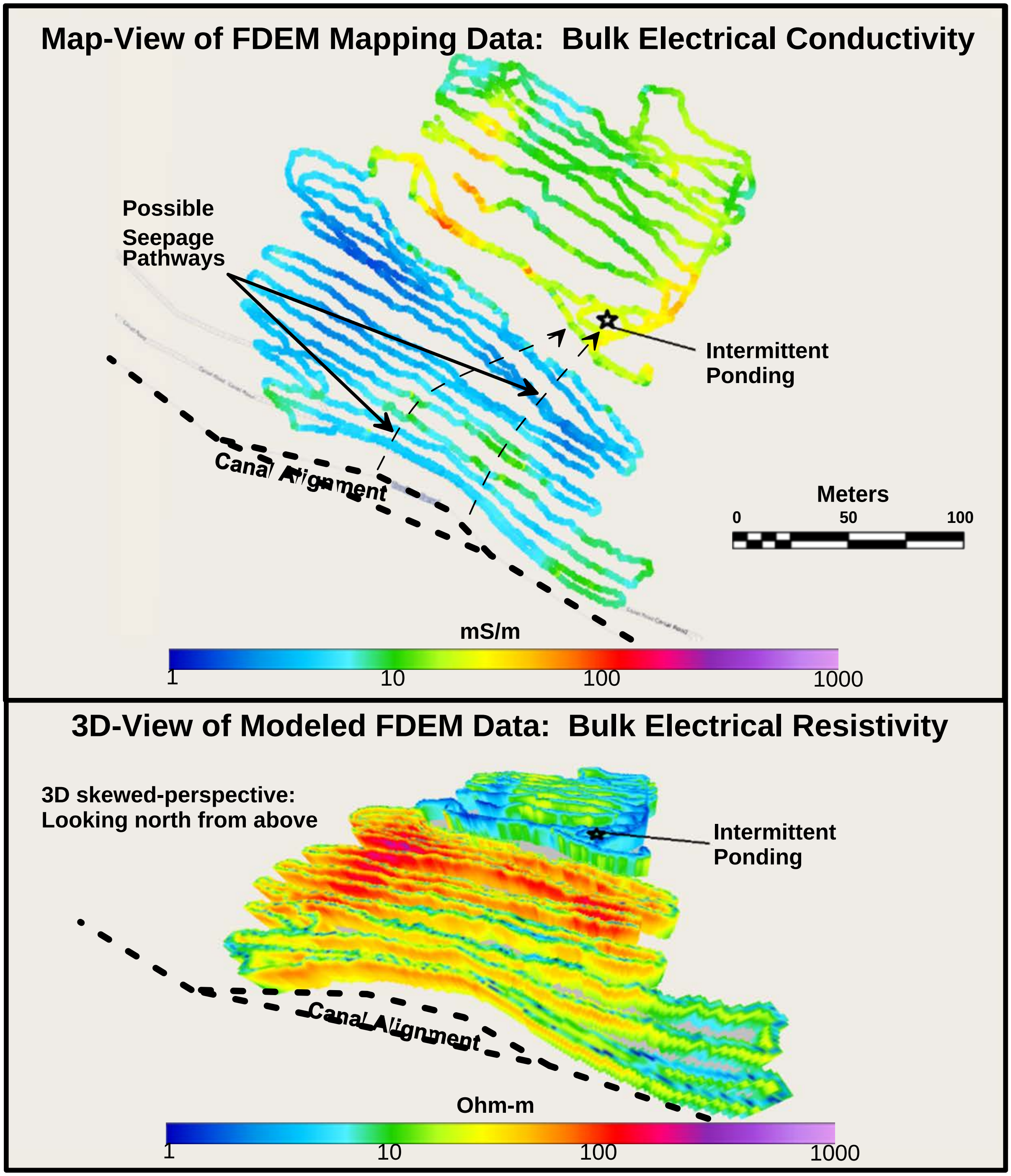


Figure 21 - Example of a detailed FDEM mapping survey data set, with electrical conductivity values plotted in map-view on the top image, and with the inverse modeled subsurface electrical resistivity distribution plotted in 3D in the bottom image.

FDEM mapping surveys should generally be performed while seepage is known or otherwise suspected to be actively occurring, in order to maximize the technique's sensitivity to seepage locations. These surveys could be performed just once during watered-up conditions or could be repeated at various times during an irrigation cycle to verify interpretations and to monitor for changes in seepage conditions, as needed. For example, collecting FDEM data during watered-up and during dewatered conditions should help reveal changes in conductivity anomalies caused by seepage, as depicted in Figure 22.

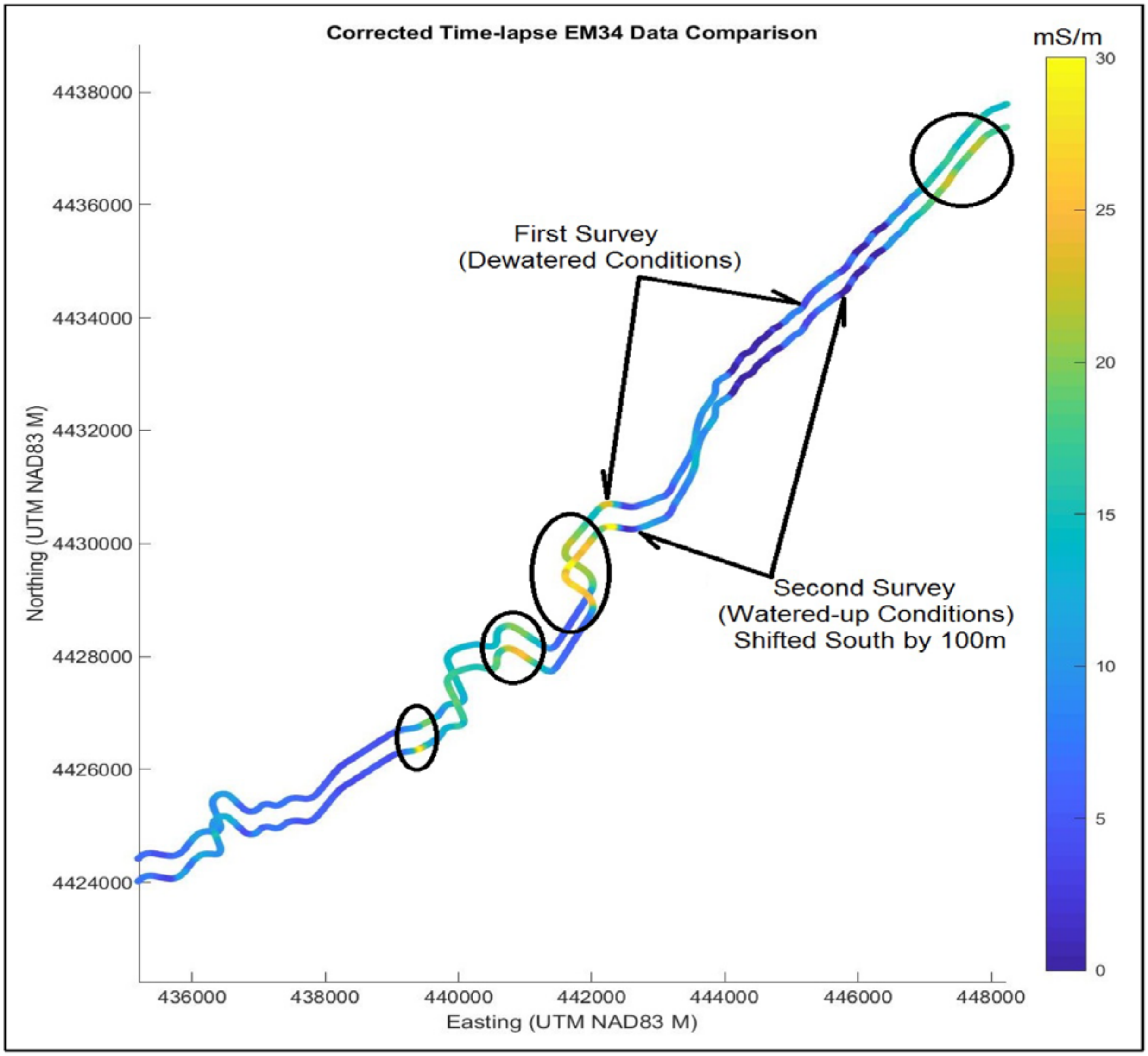


Figure 22 - Example of time-lapse conductivity changes related to canal seepage locations from repeated FDEM surveys collected during watered-up and dewatered conditions. The second survey's data track has been shifted 100m to the south for visualization and comparison sake.

Table 1 provides a relative cost for a typical detailed (1 day) FDEM mapping survey.

Electrical Resistivity Tomography and Seismic Tomography Imaging

ERT and seismic refraction tomography or surface-wave imaging techniques (e.g., multi-channel analysis of surface waves, or MASW) can be a useful set of geophysical techniques for imaging subsurface material properties related to canal seepage. These methods involve the installation of surface-mounted sensors (electrodes and geophones) that are used to collect data along linear arrays (for 2D, cross-sectional imaging below each line) or 2D aerial grids (for 3D imaging below each grid of sensors). Figure 23 shows a photo of two linear sensor arrays placed along the top of an engineered earthen embankment for data collection during an induced through-seepage failure experiment. Here, stainless steel electrodes are inserted in the ground and connected by a special cable (yellow cable on left), and the geophones (blue sensors) are placed similarly and connected to a different specialized cable and recording instrumentation (black cable on the right).

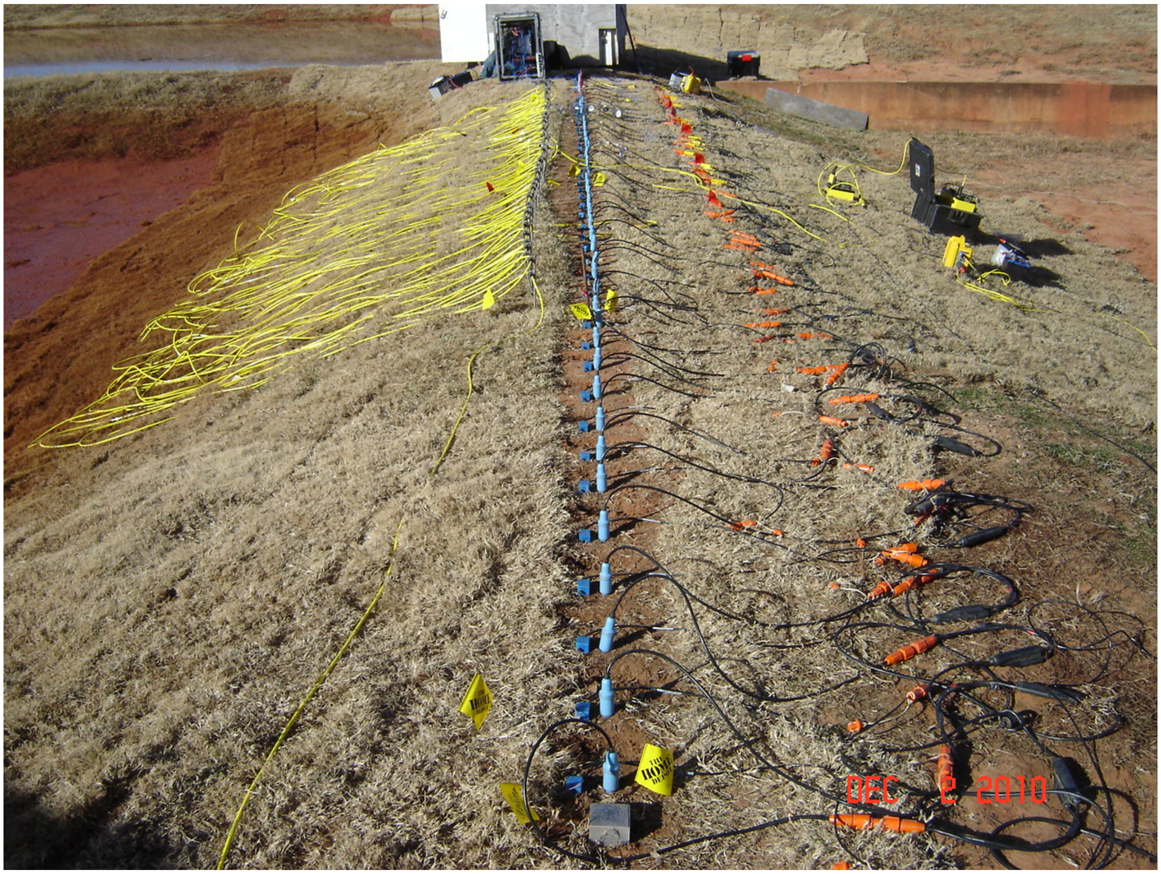


Figure 23 - Photo of an induced through-seepage embankment failure experiment with arrays of resistivity electrodes (left) and geophones (center) placed along the crest of the engineered embankment. These sensors were used to perform repeated 2D seismic and resistivity tomography surveys for time-lapse monitoring of the embankment failure process (Rittgers et al., 2016).

Electrical resistivity surveys result in an image of the subsurface electrical resistivity distribution beneath the sensor array, which offers useful information related to hydrogeologic conditions beneath the survey line. Specifically, the depth to and topology of bedrock or other aquicludes can often be imaged, and seepage zones can be identified by anomalously low electrical resistivity (high conductivity values) related to increased saturation (and sometimes increase sediment mineralization in the case of long-existing seeps with salty or high TDS water).

Similarly, seismic imaging techniques are used to image the seismic wave propagation velocity distribution within the subsurface beneath a survey line or grid. Both compression wave (p-wave) and shear-wave (s-wave) surveys can be performed to measure the velocities of the respective wave types. This survey type and resulting image of the subsurface has several useful applications related to investigating canal seeps, where the distributions of seismic velocities are related to hydrogeologic conditions. As depicted in the top plot in Figure 24, seismic surveys are very useful for imaging depth to and topography of bedrock, and can also indicate more unconsolidated zones within overburden materials and fractured zones within bedrock that may be more permeable and act as preferential seepage pathways. Collected simultaneously, these two methods can offer valuable information related to specific seepage pathways, including the location, lateral extent, the depth of a seepage zone, and any local geologic structures that may be controlling observed or suspected seepage.

These survey types should generally be performed while seepage is known or otherwise suspected to be actively occurring, in order to maximize the techniques' sensitivities to the seepage location. These surveys could be performed just once during watered up conditions or could be repeated at various times during an irrigation cycle to verify interpretations and to monitor for changes in seepage conditions, as needed. For example, collecting ERT during watered up and during watered down conditions should help reveal changes in resistivity anomalies caused by seepage. In most cases, there would not be any changes expected in the seismic velocity distributions.

In Figure 24, a borehole log is superimposed on the plots to show the locations of geologic contacts. Here, the seismic velocity model shows the depth to bedrock and, in some cases, helps to identify low-velocity zones created by shear-zones, fractures, and loose materials associated with seepage pathways. The resistivity model clearly shows pockets of low resistivity (high electrical conductivity) associated with increased water saturation in the vicinity of seepage pathways at depth (dashed black circles), (USBR, 2016). Table 1 provides a relative cost for a typical detailed (1 day) tomography survey.

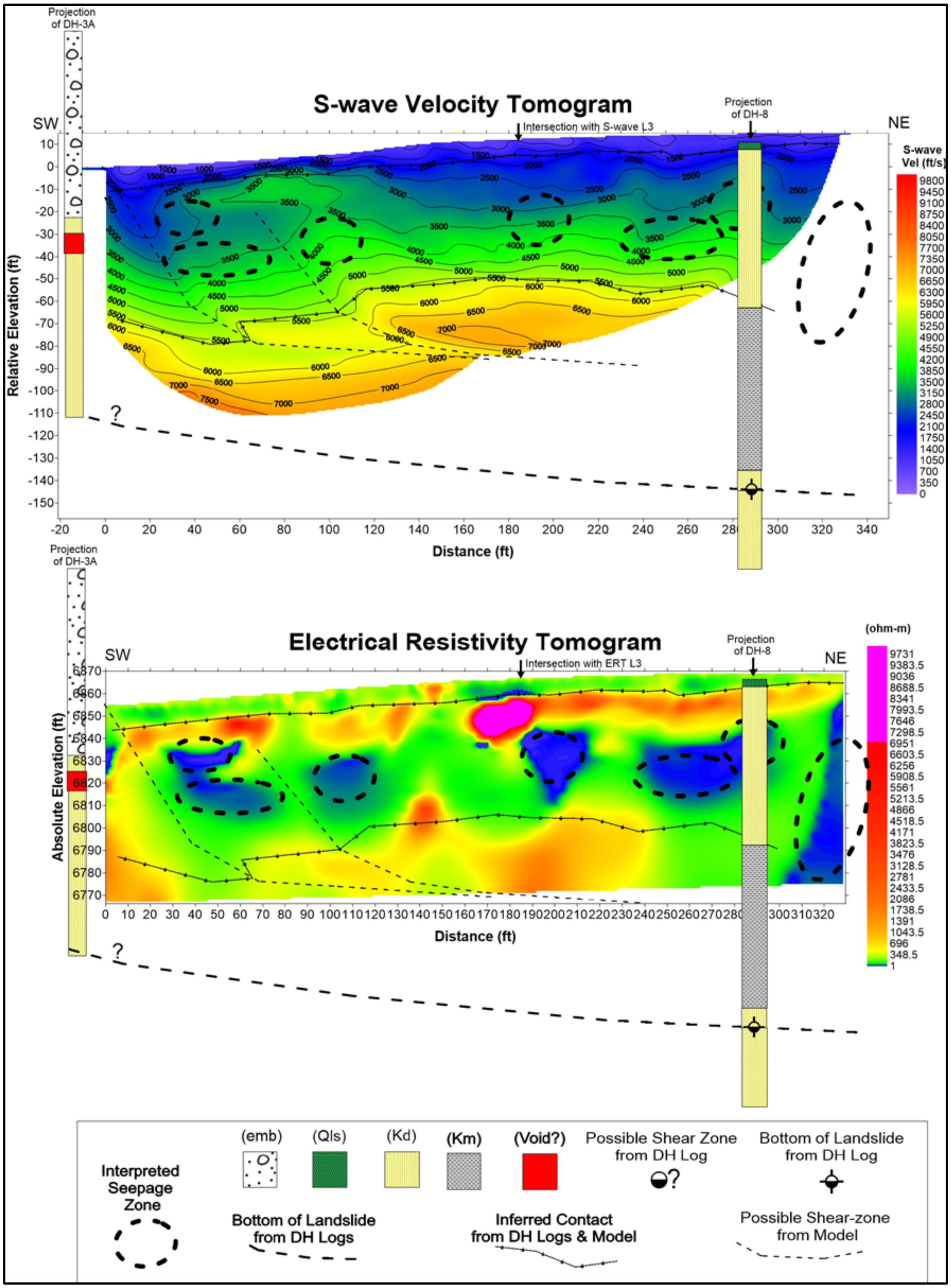


Figure 24 - Co-located 2D seismic shear-wave refraction tomography model (top plot) and ERT model (bottom plot). Dashed-black ellipses indicate the locations of interpreted seepage pathways through landslide debris, characterized by localized low resistivity and low seismic velocity properties.

Self-Potential Mapping and imaging

Self-potential (SP) mapping and imaging, sometimes also referred to as "spontaneous potential" or "streaming potential," is a passive electrical geophysical surveying technique that is sensitive to the flow of water through porous media such as earthen embankments and their foundations. The method is rather simple, and generally consists of measuring electrical voltage distributions across the ground surface relative to some far away reference point (a fixed reference electrode). Measurements are taken using non-polarizable electrode half-cells and a high-impedance voltmeter. The resulting data can help to reveal the location and orientation of subsurface seepage or groundwater flow, due to the resulting separation of electrical charges in solution (i.e., negative ions flow downstream preferentially, while positive ions tend to stay in the upstream direction, creating a localized dipolar electric field in the vicinity of the seepage). Figure 25 depicts a typical positive SP anomaly at the location of seepage.

SP data are typically just plotted and interpreted after minor processing, but these data can also be used in tandem with electrical resistivity models to create subsurface images of the source current density distributions (electrical currents that result in the observed SP anomalies) (Ikard et al., 2014). These models can help to reveal the location, depth, orientation, and relative concentration of seepage within the subsurface, but this is not standard practice.

Table 1 provides a relative cost for a typical detailed (1 day) SP mapping survey.

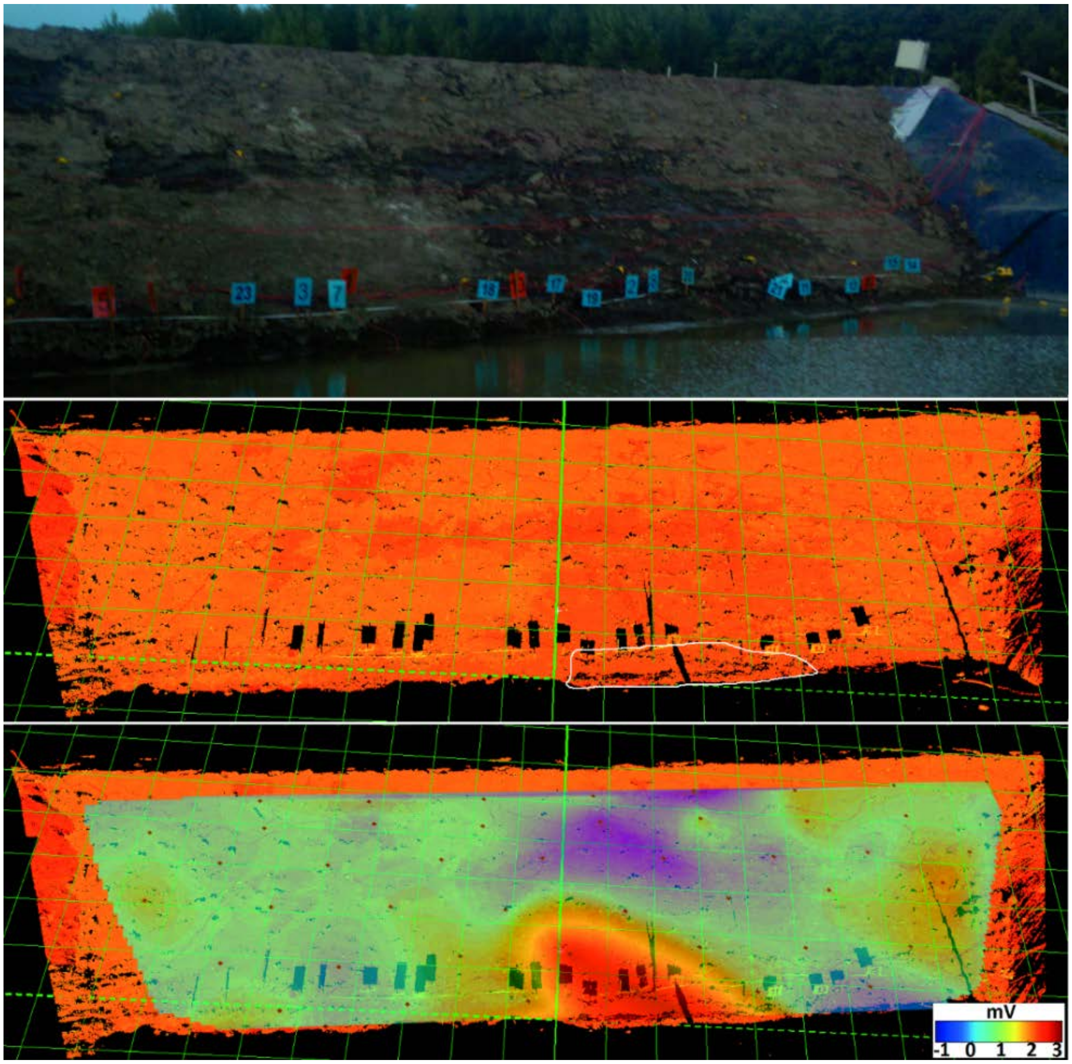


Figure 25 - Photo of a full-scale earthen embankment failure experiment with induced concentrated under-seepage (top), a LIDAR scan of the downstream face of the embankment showing slumping (outlined in white) at the downstream toe at the location of induced under-seepage just prior to failure (center image), and SP data superimposed on the LIDAR image showing a positive voltage SP anomaly that was observed to develop at the same location throughout the 7-day experiment. (Rittgers et al., 2015).

Ground Penetrating Radar Imaging

GPR is a high-frequency electromagnetics (EM) technique that operates based on the propagation and reflection/diffraction of EM waves in materials. GPR systems consist of a transmitter and receiver antenna pair and controller electronics. The transmitter antenna emits a pulse of EM energy that propagates downward into the subsurface where the wave interacts with objects and interfaces between materials of differing dielectric permittivity (a function of electrical conductivity, magnetic permeability, and density of materials). These waves then diffract and reflect back up to the ground surface and are recorded by the receiver antenna that is usually placed at a fixed distance from the transmitter antenna (~commonoffset).

GPR is an extremely high-resolution geophysical imaging technique but has very limited depths of investigation in most soils (typically no more than 10-15ft using 250MHz or 100MHz antennas commonly used for hydrogeologic applications) and is the exact EM analog of seismic reflection techniques. There are much lower-frequency GPR options that can be used to extend the depth of investigation at the expense of spatial resolutions. However, these lower frequency GPR systems typically do not have useful applications for canal seepage detection/characterization within typical depths in interest (uppermost 30ft). Lower-frequency antennas are also quite large and impractical in most related scenarios.

The GPR technique is excellent at detecting and imaging the location and depth of target features of interest, such as tree roots, or open air or water-filled voids. Other typical targets of GPR surveys are sinkholes, utility lines, and conduits. A very common application is for measuring the thickness of concrete slabs on grade and identifying sub-slab voids related to spillway seepage pathways resulting in backward erosion piping. Point reflectors (small objects or linear features oriented perpendicular to a given GPR survey line) tend to create hyperbolic data patterns or anomalies, as depicted in Figure 26. Open subsurface voids tend to generate a very strong amplitude "ringing" pattern that is indicative of a hollow cavity where EM waves get trapped and bounce back and forth off the top and bottom of the cavity. Interpreting GPR data is challenging and requires some a priori knowledge of the subsurface.

GPR data can be recorded along single survey lines, where the resulting data can be thought of as a vertical slice into the subsurface directly beneath the survey line (see image D in Figure 26). Alternatively, several adjacent GPR survey lines or grid patterns of data coverage can be collected in order to produce 3D images of the subsurface. The resulting data is then pre-processed and "migrated" to convert from time to depth, and to help "focus" the subsurface images. The resulting images can then be plotted in 3D and interpreted using various approaches such as transparency thresholding, as depicted in Figure 27.

GPR surveys should be performed to help identify the exact location and orientation of suspected shallow voids or erosion piping pathways. Voids are more prominent when air-filled, so GPR surveying results may be more successful at imaging these features if collected during dewatered conditions. Here, GPR data signatures related to air-filled voids are typically quite apparent, where the GPR waveform is observed to "ring" and the waveform polarity flips if the overlying material has a higher relative dielectric permittivity (always the case with air-filled voids, usually with water-filled voids). The data signature of a void referred to as "ringing" is a data pattern caused by the EM wave getting trapped in the void space and bouncing up and down, transmitting a portion of the EM wavefield energy back up to receiver antenna each time it "hits" the upper side of the void. GPR surveys can be repeated to monitor for shallow subsurface changes, if needed.

One limitation to GPR imaging, is that the antennas need good coupling with the ground surface. Therefore, a relatively smooth ground surface is most typically required along survey lines (e.g., not extremely rough ground surface, riprap, thick vegetation, or other frequent obstacles that prevent pushing or pulling the system along a survey line). A cart mounted system is the most typical configuration, where an encoder wheel tells the system when to transmit and record. This cart must be able to be pushed or pulled while in constant contact with the ground surface. If not, the data quality is severely impacted. Finally, there must be some contract in dielectric properties in the substrate or there will be nothing to reflect the EM waves. This is a common issue in arid soils with low water contents. However, this is also a potential advantage in locating seeps.

Table 1 provides a relative cost for a typical detailed (1 day) GPR mapping survey.

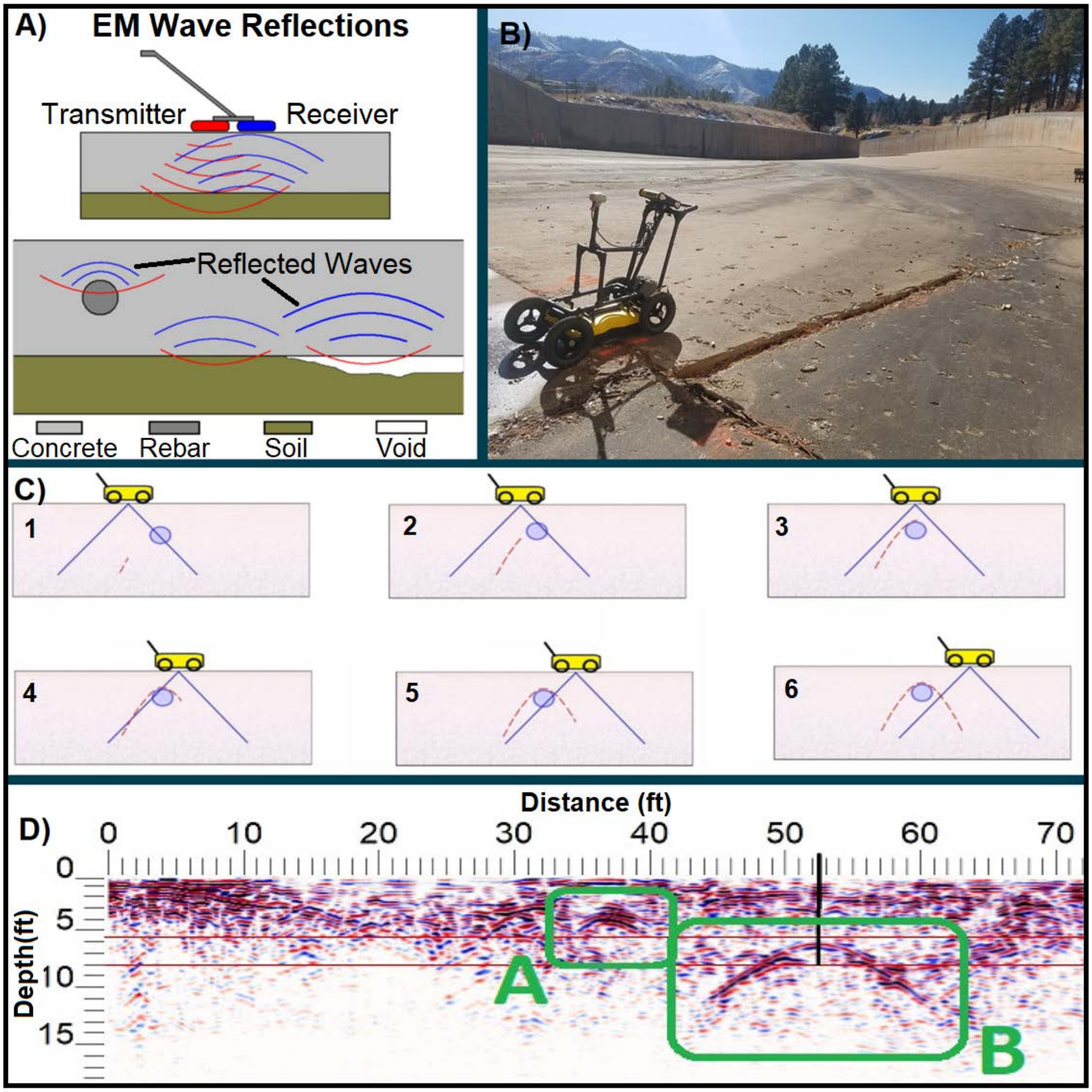


Figure 26 - Schematic of a GPR system with transmitter and receiver antennas and EM waves propagating and reflecting off of subsurface objects and interfaces (image A), photo of a typical cart-mounted GPR system (image B), schematic of the sequential construction of a hyperbolic reflection anomaly while passing over the top of an air or water-filled void (image C), and raw GPR data showing two different hyperbolic reflection anomalies from two objects/targets at different locations and depths (image D).

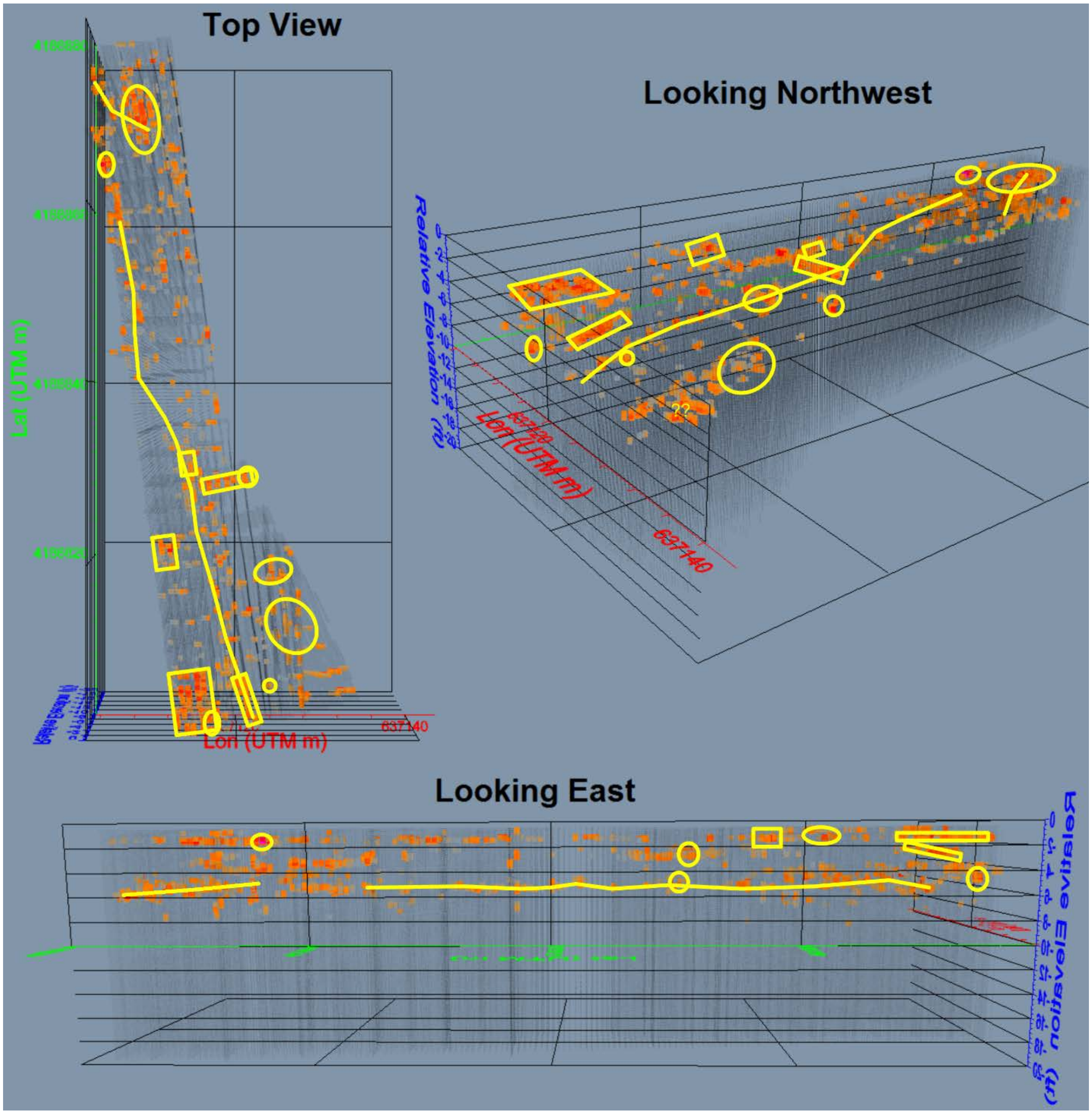


Figure 27 - Three different perspectives of a 3D GPR data volume/model plotted with amplitude transparency thresholding to help reveal the 3D positions and orientations of subsurface anomalous features and objects. Similar large-amplitude GPR reflections are oftentimes observed from air and water-filled voids (e.g., animal burrows, stoping sinkholes, or erosion piping features), and from tree roots or other embankment perforations (e.g., metallic and non-metallic conduits) (USBR, 2018).

Results

Results of implementing focused and high-resolution geophysical mapping and imaging surveys can help tremendously with seepage detection and characterization efforts. These survey types are most typically performed at pre-selected locations of known or otherwise suspected seepage issues (e.g., a single seepage point or segment of canal where seepage-related performance issues are identified), due to the amount of time and logistics involved in collecting data. The results of these survey types provide images of the subsurface that can be used to map out the location and orientation and depth (and severity in some cases) of seepage pathways. Also, these surveys can be repeated in order to better understand spatio-temporal variations in hydrogeologic conditions related to seepage.

It is important to note that while these techniques provide information about the seepage locations and can help refine the conceptual model, they do not provide a direct quantification of seepage rate.

Schedule and Cost

The cost and schedule of these types of surveys mostly depends on the site conditions and required spatial coverage of a given surveying method. Vehicle access is usually required due to the amount of equipment involved. For a typical seepage area, most data types can be collected in a single day.

A single 2D resistivity tomography (or 2D seismic tomography) survey can be placed along a canal crest road or along the toe of the embankment such that it is centered on the identified or otherwise suspected seepage location, and will thus have adequate length to capture and image the seepage zone at depth. This field effort usually takes approximately 3 to 4 hours per survey to complete with a crew of two or three people. Alternatively, several adjacent 2D surveys can be performed to develop a 3D tomographic model of the area, if imaging of the entire seepage pathway is required. This of course increases the required time and cost of the overall field effort.

A FDEM mapping survey can typically be conducted in less than a single field day, depending on the area being surveyed, and the number of systems being used (e.g., repeated surveying with different instruments and configurations).

GPR data can be collected relatively quickly (at walking speed). Therefore, a GPR survey is typically conducted within a single field day, depending on the area or length of embankment being surveyed. Similar to FDEM, GPR data can be collected along single survey lines, or in a grid-like fashion to produce 3D images of the subsurface.

Processing and interpreting these various data types can be completed in hours or up to a week after data collection is complete, depending on the volume and complexity of the data (can take longer, depending on complexity of the data, level of integration of other data types, and project needs/goals). The relative cost in Table 1 was developed assuming a single seepage survey location with a day's worth of data collection for each of the five detailed data types described above. This approximation assumes one mobilization, and includes system rentals, shipping costs, labor and non-labor associated with travel and data collection, analysis, and processing.

Remote Sensing Data from Satellites or Aircraft Flyovers

Overview

Various remote sensing data types and data products are available from satellite or aircraft-based sensors. With regards to seepage detection, normalized difference vegetation index (NDVI) is a notably useful remote sensing data product, as it is mainly sensitive to the presence of lush green vegetation which is often observed to be coincident with canal seepage locations. While this approach has its merits, there are inherent limitations to the use of NDVI for seepage detection. For example, this approach requires data to be collected during an irrigation season, requires seepage to exist long enough to affect vegetative growth patterns. Additionally, not all lush vegetation is going to be directly associated with canal seepage but can instead be attributed to naturally occurring shallow water table conditions or with irrigation watering activities adjacent to canals. Furthermore, seepage from canals can result in rather large areas of ponding water or increased saturation below canals embankments, and so the surficial expression of vegetative growth may not be indicative of the exact location of seepage loss points (Rittgers, 2018).

For most canal seepage detection applications using NDVI, it is recommended that stakeholders first acquire any existing satellite-based remote sensing data for use in calculating NDVI data for the canal segments of concern. These NDVI data can subsequently be used to help guide collection of ground-based geophysical data types or can be used in conjunction with geophysical data to help provide a more robust assessment of seepage locations and conditions along canals. Generally, the interpretation of both datasets together is perhaps more robust than only one or the other alone, helping to avoid false positives or false negatives (see Rittgers (2018) for more details).

Details

There are several free satellite remote sensing data products available today. For NDVI dataset creation, NASA Landsat satellite imagery is commonly used for acquiring the necessary input data layers for subsequent development of an NDVI dataset. This approach is relatively nuanced and not trivial, requiring experience with imagery pre-processing (e.g., often requires geometric, atmospheric, and radiometric corrections of each data layer prior to calculation of NDVI values on a per-pixel bases). Alternatively, NDVI data products derived from Sentinel and Landsat satellites imagery can be obtained for free directly from Climate Engine (http://climateengine.org/).

Also, the United States Department of Agriculture (USDA) National Agriculture Imagery Program (NAIP) produces a high-resolution (<3m spatial resolution) NDVI product that is typically provided annually from satellite data collected ideally during the primary nation-wide agricultural irrigation season (i.e., summer months). NAIP acquires aerial imagery during the agricultural growing seasons in the continental United States. A primary goal of the NAIP program is to make digital ortho photography available to governmental agencies and the public within a year of acquisition. This image layer provides access to the most recent NAIP imagery for each state and is updated annually as new imagery is made available. This imagery is published in 4-bands (red, green, and blue and near infrared), where available, with the option to display the imagery as false color to show the IR band or to display the NDVI showing relative biomass of an area.

NAIP imagery data can be downloaded for free as a fully processed NDVI GeoTIFF data product and converted to an XYZ data base with relatively simple scripting efforts, or with the use of freeware such as GRASS GIS (geographic information system) software used for geospatial data management and analysis, image processing, etc.). NAIP NDVI data are available for download at https://datagateway.nrcs.usda.gov/GDGHome_DirectDownLoad.aspx.

Figure 28 shows the spatial and temporal coverage of most recent USDA NAIP data, along with information on inter-pixel spatial resolutions by State and year acquired. Most of these reported resolutions are more than adequate for most seepage-related applications, especially for incorporation into rapid reconnaissance type analysis efforts to optimize further investigations. Unmanned aerial vehicles (UAVs) (discussed in a following section) can improve data resolution dramatically while using the same imaging techniques, if needed.

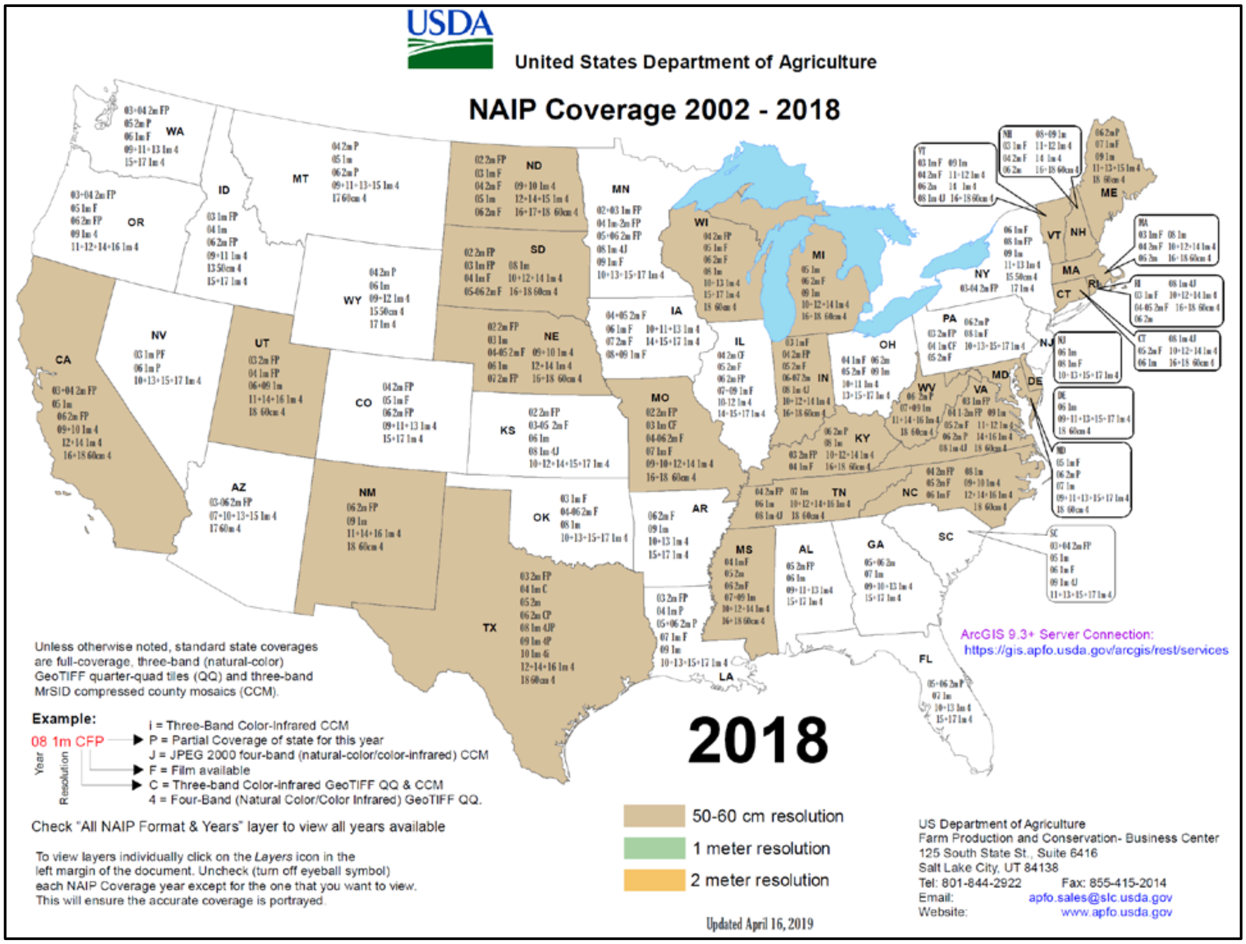


Figure 28 – Free open-access NAIP NDVI data coverage and resolutions by State and year acquired (USDA, 2020).

Results

The immediate result of collecting and inspecting NDVI data images is a comprehensive view of vegetative vigor along entire canal systems. These images provide an indirect indication of where seepage has been occurring for long enough to support anomalous vegetative growth, and can even offer some insights into the geometry of seepage pathways (e.g. shallow or deeper pathways that are daylighting on or immediately adjacent to a canal embankment, or if the seepage is deeper and daylighting further away from the embankment toe). An example of NDVI data is shown in Figure 29, where a 100m wide swath of NDVI data values have been extracted from a larger satellite image and plotted with a color scale. Here, areas of bright yellow indicate the locations of lush green vegetation, while darker brown and green and blue colors are areas of either dead vegetation, bare ground, roadways, or water (e.g., the canal). NDVI image data can also be integrated into other analysis workflows and compared with other data types for sake of better identifying where seepage is occurring (Rittgers, 2018).

This seepage detection and characterization tool is very simple to use, is very inexpensive, and can offer immediate benefit to seepage detection and characterization efforts. Ideally, NDVI data should be collected during watered-up conditions so that local vegetative growth has had time to respond to seepage and become lusher and greener relative to background signatures in areas not experiencing seepage.

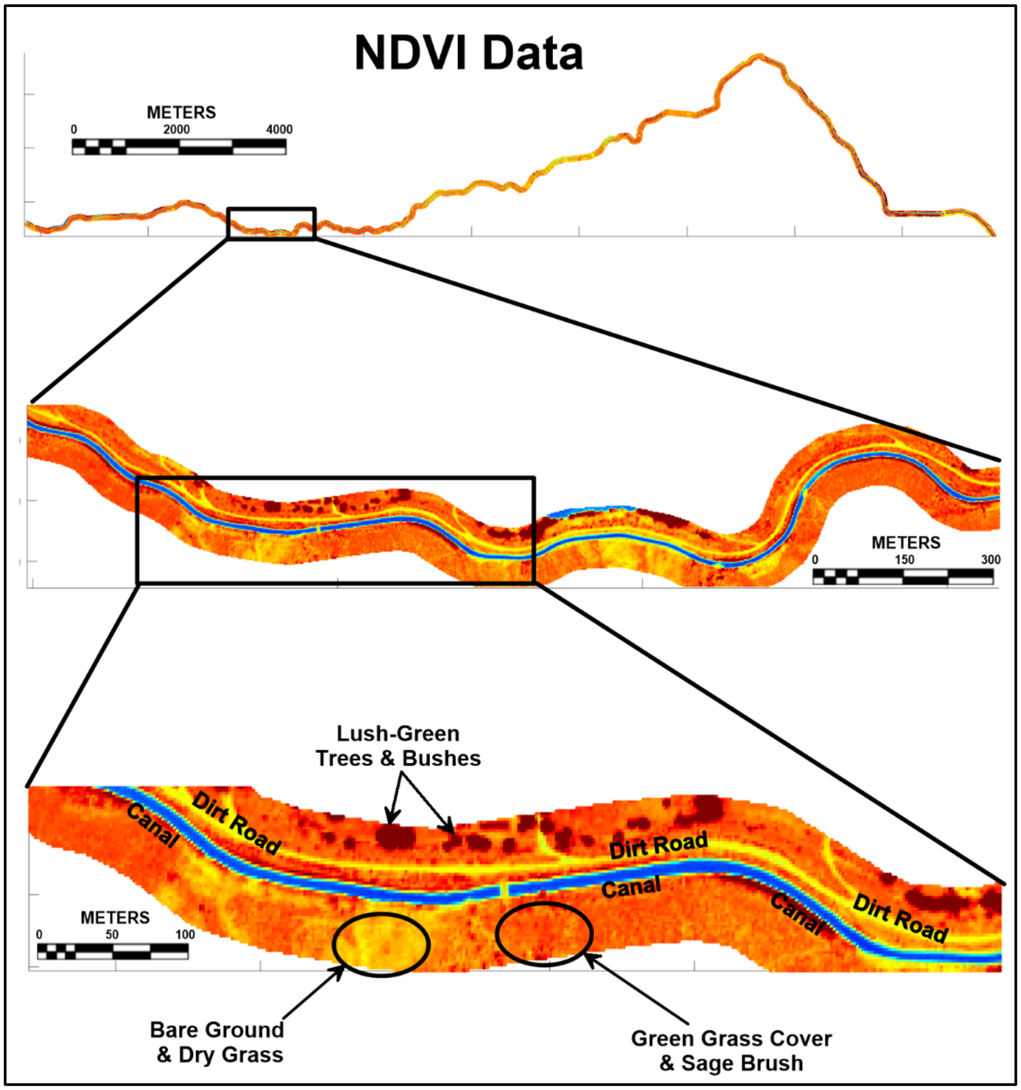


Figure 29 - Example of NAIP-NDVI data extracted for a 100m swath centered along a canal alignment.

In Figure 29, subsequent zooming in on the NDVI data reveal the level of detail contained within the free NAIP imagery, where warm colors (oranges and yellows) indicate high NDVI values associated with increasingly lush green vegetation, and cooler colors indicate areas of bare soil, dead vegetation, or bodies of water. At the highest level of detail, individual trees and shrubs can be identified.

Schedule and Cost

Acquiring free NDVI data is extremely quick and can be done in less than a single day. If high-resolution NDVI data is required, or no free data is available for the required location or timeframe, then purchasing data can become expensive and sometimes result in a waiting period (e.g., need to schedule or wait for a flyover to be performed). There are several free software options for viewing and exporting NDVI data, so the associated costs can be limited to the time and labor of the analysts involved. For a typical canal system (say 40 miles long), NDVI data can be acquired, inspected, and potential seepage locations identified in just a few days, depending on the level of detail needed by analysts to inspect or utilize the data.

Table 1 provides a relative cost for a detailed NDVI analysis effort and assumes free data and 10 days of analysis and reporting.

Remote Sensing Using UAV/Unmanned Aerial System (UAS)

Overview

UAVs typically are line-of-sight systems that include visual-spectrum and near infrared (IR) data collection capabilities, but also can include multispectral data collection. Surveys should be flown at least once per irrigation season, ideally twice: once during dewatered conditions, and once during watered-up conditions. UAS-based photogrammetry surveys of canals should be performed during dewatered conditions. These topography surveys should be conducted no more than annually, unless there are specific issues or target segments of canals that have poor structural health performance.

Details

There are many options for UAV systems and camera sensor payloads—together, referred to as an UAS. Depending on specific project objectives and the UAS and sensor type used, all required data can be collected in a single pass or may require multiple flyovers using different sensors or the same sensors deployed at different times of the day or irrigation season. For example, two common UAV sensor payloads (multi-spectral cameras) are shown in Figure 30, where the Altum camera (right) is the same as the Rededge camera (left) except that the Altum camera added capability of an integrated radiometric thermal IR sensor. With the RedEdge camera, thermal IR data must be flown separately. In both cases, the flight plan can be designed to achieve the necessary spatial resolution versus spatial data coverage (e.g., decreasing the flight altitude to improve spatial resolution at the expense of spatial coverage per flyover/swath of data). As a rule of thumb, higher resolution datasets require lower altitudes and more flyovers to generate a mosaic of images with the same spatial coverage as higher/lower-resolution flyovers.

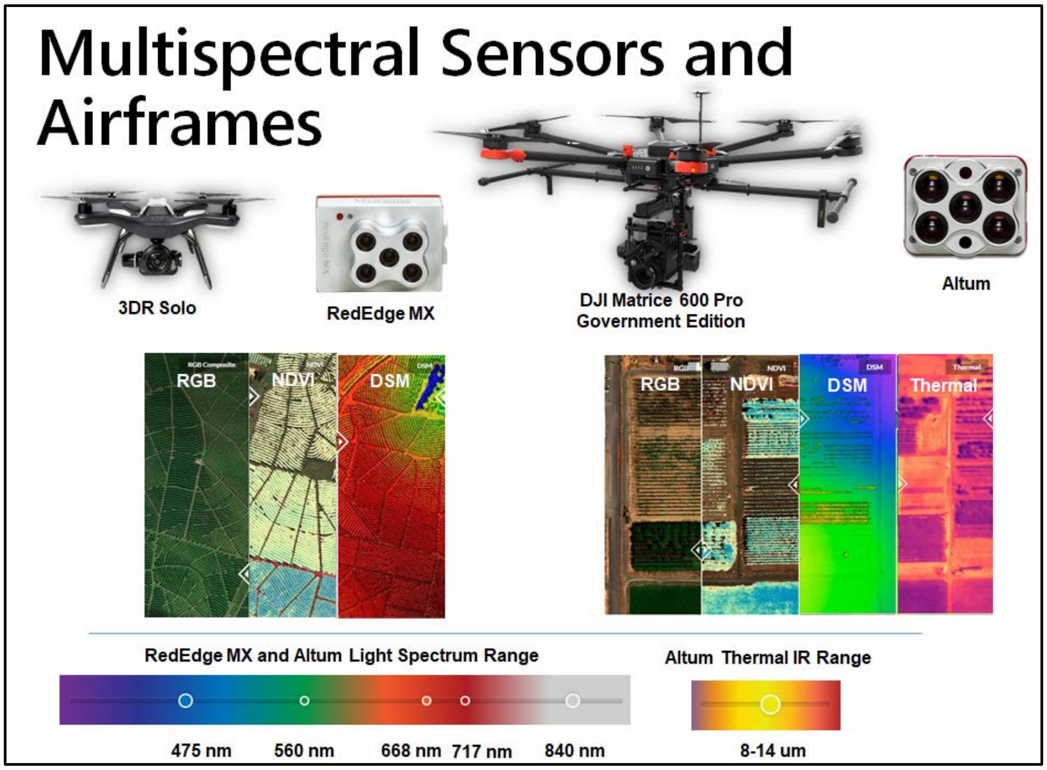


Figure 30 - Typical UASs and payloads used by Reclamation for performing high-resolution remote sensing surveys along canals and other structures. Note that this report does not recommend any specific system or configuration, rather the manufacturer's names are provided solely for reference. DSM refers to a digital surface model and is not discussed herein.

With the use of visible-spectrum and near-infrared remote sensing data, analysts can develop high-resolution NDVI images if deemed useful. There is also the possibility to collect repeated IR data within a 24-hr period to help identify time-lapse thermal anomalies associated with near-surface voids and seepage zones associated with increased saturation of downstream surface soils and any standing surface water. These time-lapse IR surveys should be performed during daytime and either at sunrise or slightly after sunset, so that the different solar loading and resulting thermal expressions of wet areas can be more easily distinguished. Here, wet areas appear cooler than surrounding dry areas in the first several hours of thermal heating during early-to-mid morning. Conversely, wet/saturated soils retain more heat and appear warmer than surrounding dry areas during the early evening and nighttime hours, after the sun has set and the ground surface has begun to cool off. This phenomenon can be used to help map seepage areas but requires both adequately bare and non-vegetated ground surfaces and adequate solar exposure.

Figure 31 shows that similar to satellite-based systems, NDVI data can be collected using a UAS-mounted multi-spectral camera (or repeated flyovers with single-band sensors) to collect the required visible and near-infrared spectral images to detect healthy and lush vegetation possibly associated with seepage (top image). The resulting NDVI data from UAV surveying; dark green pixels indicate areas with healthy vegetation (bottom image).

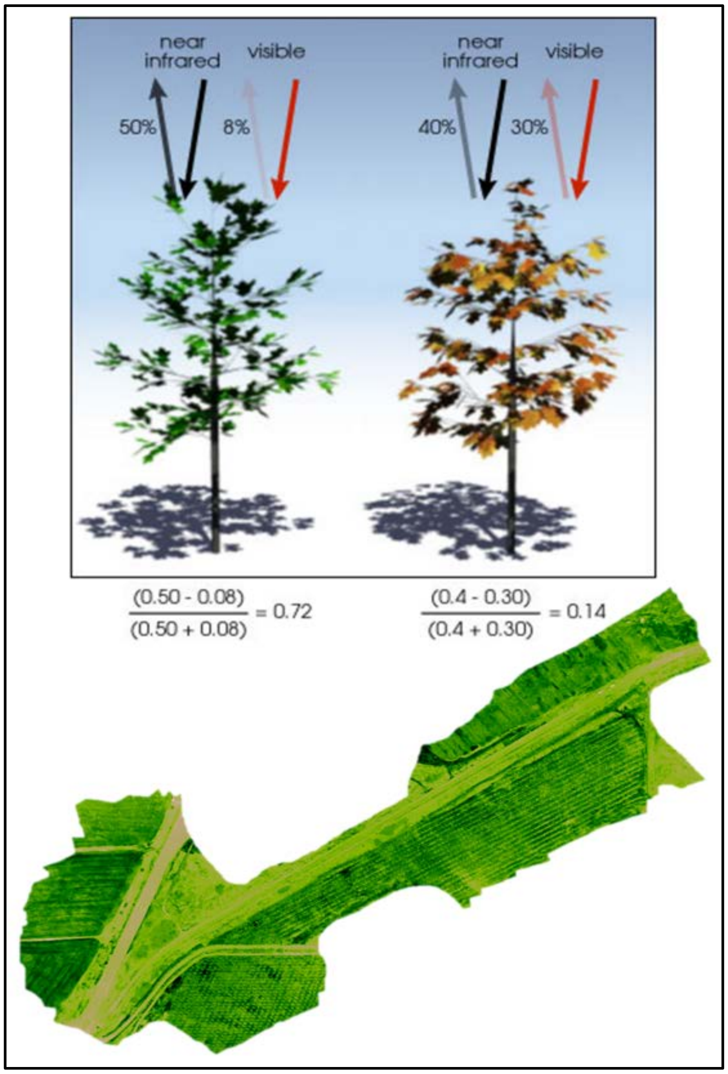


Figure 31 – NDVI from a UAS. Top image demonstrates the calculation to determine NDVI, bottom image shows the NDVI image developed from a UAS fly-over.

Figure 32 shows a thermal image (thermogram) providing the location of wet soils during a nighttime flyover experiment. Similar phenomena have been seen on embankments with sufficiently bare soils along the downstream face of the structure. Note that night flights can be difficult or impossible to permit with the FAA.

Figure 32 - Thermal IR image from UAS where white pixels are warmer.

Additionally, UAV-based photogrammetry can be performed to develop 3D topographic data and extracted topography cross-sections at various locations along a canal embankment. Temporal differencing of topography can be a useful tool for detecting subtle changes in the topography/geometry of canal embankments that may be related to subsidence, slope-stability issues, seepage, surface scour erosion, and animal burrowing. Figure 33 shows an example of a topographic profile extracted from photogrammetry data collected along a Reclamation canal during dewatered conditions. Here, the topographic profile reveals subtle features, including (from left to right) the downhill field, a footpath and crest road on the canal embankment, the canal invert, and the uphill field with thicker/rougher vegetative cover. Note how the thicker vegetation causes multiple layered surfaces and some ground surface data gaps on the right side of the profile. This is one of the primary challenges of implementing photogrammetry in vegetated areas, where the ground surface is the target of interest.

Figure 33 - Detailed view of an extracted photogrammetry DEM profile of ground surface topography across a Reclamation canal during dewatered conditions (top) and the same extracted profile superimposed on aerial imagery. Note vehicles for scale with a 1: 1 horizontal to vertical ratio.

Results

One of the most obvious results from the use UAVs for remote sensing surveys is the high resolution that can be achieved with this technology. When compared with the same types of remote sensing data products available from open-source data repositories, UAV surveys can achieve up to an order of magnitude higher spatial resolution (e.g., centimeter per pixel resolution compared with 1 meter, or greater, pixel resolutions available in most airborne and satellite data products). In most cases the sensor sensitivity (data value accuracy) is comparable to these other options.

The results of using UAS technology for remote sensing surveys along canals can be summarized with the following:

- Expedited data coverage where needed
- Customizable and extremely high-resolution (per-pixel spatial resolution) imagery of target areas
- Decreased cost and time-frame for acquiring data where and when needed.
- Independent capabilities for data collection that doesn't depend on satellite orbit fly-overs or ordered aircraft flyovers
- The ability to quickly repeat surveys for time-lapse analysis in specific locations based on previously recorded autonomous navigation waypoints

Schedule and Cost

Depending on the amount of remote sensing data coverage and the number of types of data and associated repeated flyovers needed, most UAS surveys can be performed along long segments of canal within a few days. This timeline does not include permitting for special requirements by the Federal Aviation Administration (FAA). It is worth noting here, that special requirements by FAA and other federal and State authorities need to be considered when designing flight plans and operating UAS's, particularly at night. At the time of this report, the Department of Interior and other federal agencies are not permitted to fly UAS's for non-emergency, non-national security or military applications due to ongoing security reviews of the systems.

The processing and reporting of UAS remote sensing surveys is relatively streamlined in most cases. However, this process can be more complicated and time-consuming based on the amount of data collected, the processing workflow being implemented, and the associated computational costs involved. Additionally, site-specific conditions can lead to more difficult and complex processing, such as the filtering of vegetation and canopy horizons from photogrammetry models (e.g., filtering the elevation/geometry of the tree canopy versus the ground surface topography).

Table 1 provides a relative per project cost.

Satellite-Based Synthetic Aperture Radar (SAR)

Overview

The SAR satellites data has been widely used in (1) water-related applications such as snow depth estimation, river channel mapping, soil moisture retrieval, and aquifer volume changes, and (2) deformation-related applications such as volcano monitoring, earthquake damage mapping, ice stream motion, landslide monitoring, and land subsidence due to sink holes and waste-water disposal activities. The C- and L-band SAR remote sensing technology can assist in identifying seepage locations or channel planform changes at canal, river, and levee structures.

A primary benefit of this technology is that, in most cases, a significant amount of historical data exists which can be used to "hind-cast" previous performance. These data can then be used to inform locations and techniques for more detailed investigations or can be used to constrain models.

Details

Satellite-based radar has better capability than optical/thermal infrared in detecting wetness under vegetation and topsoil. There are three key practical considerations necessary to monitor canal seepage remotely: spatial resolution, temporal resolution, and spatial coverage. The SAR data at 10-m spatial resolution estimates surface volumetric water content (VWC) of soil near canals allowing for estimates of canal seepage that can be compared with field/lab test results. However, speckling noise from backscattering of thermal, vegetation, and surface roughness might cause challenges in mitigating potential errors in the SAR data. There are multiple possible causes of the missed detection, includingrain events that may cause speckling noise or a radar signal associated with wetting may be too small. Reduction of the missed detections will be investigated in the future using the following approaches: 1) multi-temporal despeckling method, which has not been implemented, may reduce the noise, 2) a spatial feature may be enhanced by the nonlocal mean filter, 3) the vegetation effect may be systematically removed using the physical model approach that worked effectively for soil moisture studies, 4) the subsurface seepage may be identified by examining longer wavelength observations such as L-band ALOS satellite data or NASA's L- or P-airborne data, 5) the soil moisture may be derived using the approaches for the Soil Moisture Active Passive mission (SMAP) which could provide more detailed information of wetting due to seepage, and 6) the ground-range detected (GRD) data product may be spatially multi-looked to reduce speckle noise and Sentinel Application Platform (SNAP) satellite software provided by European Space Agency (ESA) could be used to filter potential speckling errors.

The upcoming NASA-ISRO SAR (NISAR) is planning on launching a dual-frequency synthetic aperture radar in September 2022 that is expected to have advanced radar imaging to observe and understand natural processes on ground surface. Our goal is to utilize the radar ability to detect under vegetation and topsoil with frequent monitoring over a continental scale and apply it towards operational monitoring of canal leaks and implement more sophisticated algorithms that have been used widely in the SAR community.

The L-band SAR can provide more detailed analysis of canal seepage by: 1) cataloging the spatial variations in SAR satellite images related to shallow (≤5 cm below ground surface) soil moisture distributions, 2) conducting time-lapse analyses for temporal change detection on a per-satellite-image-pixel basis, and 3) identifying spatio-temporal changes following operations and maintenance events along canals (e.g., watering-up of a canal system, or pre/post embankment lining or repair efforts), in order to help evaluate changes in performance and hydrologic conditions along the embankment.

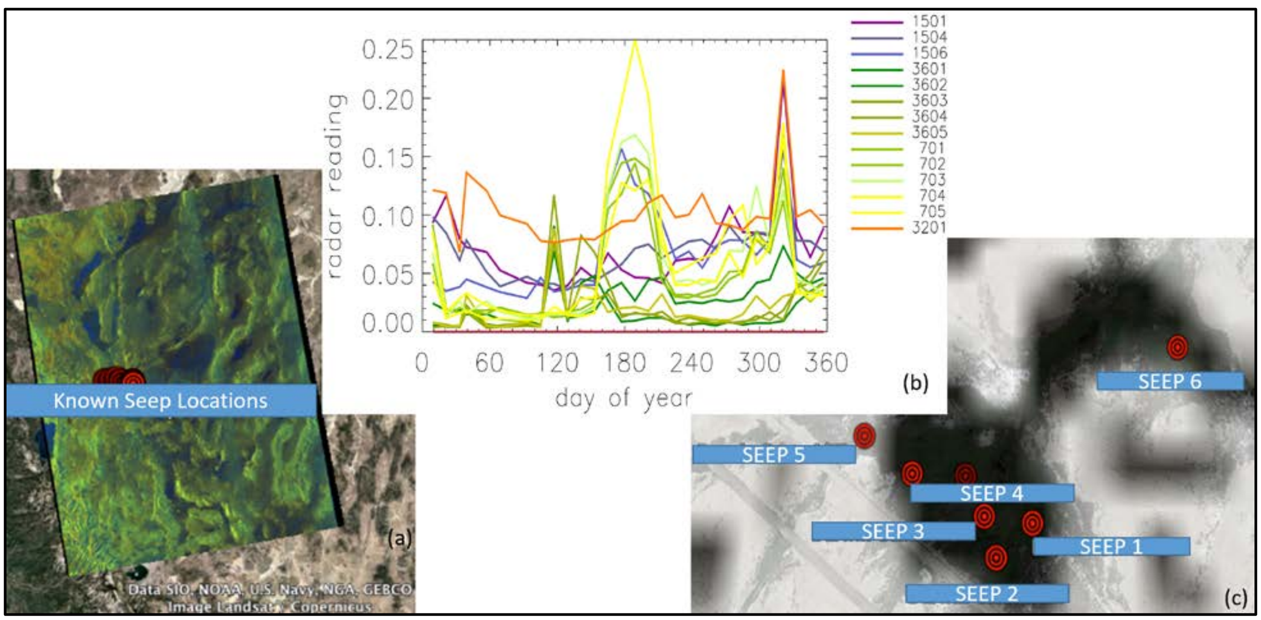


Figure 34 - SAR data processing: (a) Boundary of Sentinel-1 data at Truckee Canal study domain near Fernley, Nevada (~300km wide and 500km long); (b) Time series of radar backscattering coefficients at selected known seepage sites for 2017; and (c) Overlay of known seepage location (red) on a binary form (significant change in dark or negligible change in transparent) with the background of the Google optical map.

In a case study on the Truckee Canal, NV, the spatial and temporal resolution of Sentinel-1 data with a ~ten-day repeat time was used to identify seepage (). The time-series of radar backscattering coefficients for selected known seepage sites are shown in Figure 34 (b). The most prominent features are the 6 peaks around day 180. These peaks are deemed to be correct representation of seepage, considering that watering started in April (day 90) and it took about 60 days for leaks to develop in the Truckee sites. In 2017, the Truckee Canal watered up on April 1 (day 90 in the plot). Peak VWC occurred about 60 days following water up in the Truckee sites. A successful example of the spatial analysis to locate the seepage is shown in Figure 34 (c). The temporal difference of Sentinel images was taken before and after the period when seepage was expected based on canal stage. Each of the two images was averaged temporally to reduce the speckle noise in SAR images. The dark pattern in the figures matches the known seepage locations. These results indicate that moisture anomalies can be identified from the satellite imageries corresponding to the known seepage locations.

This seepage detection approach using the C- and L-band SAR satellite remote sensing technology provides a technique to quantify potential seepage losses by location and over time, for more rapid and global management of canal embankments.

The SAR data processing consists of five major steps: (1) SAR data collection, (2) data pre-processing, (3) interferogram generation, (4) phase unwrapping, and (5) geocording.

1. In SAR data collection, multiple-year L-band and C-band satellite image data archived from the ALOS-1(L-band) and Sentinel-1A/B (C-band) can be searched, accessed, and collected from SSARA (Seamless SAR Archive). https://web-services.unavco.org/brokered/ssara/gui.
2. In the pre-processing step, orbit data are used to compute offset vectors on pixel level from Single Look Complex (SLC) images. The processed image is resampled to the master grid. Co-registered stacks of single-look complex (SLC) data can be created to generate surface displacement time-series followed by further analysis of the phase and amplitude.
3. In the interferogram generation, interferometric products are computed to generate the complex interferogram and the coherence images. The interferometric phase can be corrected for the phase of a ground control reference point and coherence changes can be compared through time.
4. In the phase unwrapping step, original phase from the wrapped phase representation is reconstructed with a sophisticated phase unwrapping algorithm.
5. In the geocording, the unwrapped phase is converted to a height and the pixel coordinates are georeferenced. The generated products can be modified for contouring and layering with GIS programs.

SAR satellite remote sensing technology using 10-m full resolution and 30-m multi-looked data can be used to detect soil moisture content and time-lapse fluctuations in concentrated and distributed seepage. Historical and recent SAR satellite imagery from multiple missions and international space agencies are available to download for free. Multiple-year L-band and C-band SAR data archived from the ALOS-1(L-band, 46-day repeat, 2006-2011) and Sentinel-1A/B (C-band, 6- and 12-day repeat, 2015- present) satellites are readily available with more L-band data available in the future from ALOS-2 (2014-present) and NISAR (launching in 2022). Future radar missions, such as NASA-ISRO SAR (NISAR) operating at L-band are expected to have improved Radar Frequency Interference (RFI) and geolocation. SAR satellite remote sensing technology aids in effective detection of seepage loss areas on a wide scale allowing for a rapid evaluation/monitoring of canal embankment systems, and efficient cost saving to cover nationwide canal sites.

Results

The value of using L-band SAR satellite remote sensing technology to detect soil moisture content and time-lapse fluctuations related to seepage phenomena is currently being evaluated under an ongoing research project. This effort is focused on the application of this technology to canal seepage, specifically using Truckee Canal as a test-site/structure.

A year-long time-series of Sentinel SAR data for 2017 has identified seepage events and sites over the pilot study domain based on the algorithm detailed in this section. The SAR data are offered at 60 m spatial resolution every 12 days. Twenty-five known seepage locations were used to develop the detection algorithm. Two approaches have been tested to date: (1) temporal and (2) spatial detection methods. The temporal detection method identified 10 seepage events at the correct time of the year. Six of the ten seepage event locations had strong features while the other four were of small intensity. The spatial analysis located seven sites. The sophisticated algorithms applied are as follows: (1) noise filtering through minimum-variance unbiased temporal smoothing; (2) spatial feature enhancement via non-local mean filter; and (3) utilizing SAR phase information and vegetation changes (Kim et al., 2017b). These periodically collected SAR data and the time-lapse analysis results provide valuable information within a short time period for detecting seepage losses throughout the Truckee Canal test-site.

Schedule and Cost

The Sentinel-1 satellites from multiple international space agencies provide open sources for satellite imagery data that are available to download for free. A primary factor of the cost and schedule is computational cost to perform SAR data processing, generate time-series using interferometric analysis, filter scatter data, and compare coherence changes through time, and develop a SAR data monitoring algorithm. Total time and effort depend on the size of the project area and volume of satellite imagery data processed.

In general, to process SAR data of one-year duration and a few miles of canal length, and develop an SAR data monitoring algorithm based on the site conditions would likely require about a month or 2-month effort. A secondary factor for determining the cost and schedule is the time required to setup a supercomputer system and software installation to process data effectively. A system setup effort typically requires a few days. Table 1 provides a relative cost per the above level of effort.

Implementation

This section focuses on which of the investigation techniques should be considered for an unlined canal seepage investigation. Recommended improvements to the canal operations or functionality (seepage barriers, lining, etc.) and project outcomes (Figure 1) of canal seepage investigations can vary between sites as a result of multiple factors; descriptions of which improvements and outcomes are not within the scope of this report and therefore not discussed in significant detail. The goal of this report is to provide an overview of novel and proven methods and provides a general level-of-effort needed for estimated costs to plan and implement seepage investigations. This report intentionally focuses on research funded by Reclamation's Science and Technology program from about Fiscal Year 2016 to Fiscal Year 2021.

Which Technique(s) to Choose?

Each investigation should begin from a big-picture perspective and then focus in on the details required to develop and optimize a realistic and useful conceptual model for the given situation. Irrigation canal seepage losses are site specific, expert based, and should be considered a living-document, updated iteratively with increasing availability of data and new knowledge.

Table 1, at the end of the report, presents a decision matrix to guide the selection of potential investigation techniques based on data requirements and site conditions.

While many techniques are applicable to a range of site conditions, there are significant differences in the level of expertise of personnel required to perform the work, the monetary costs of obtaining the data, the time required to collect and analyze these data, and the implications of the information obtained from these data for a given situation. Additionally, the order in which the techniques are performed is important, because data from one technique can inform the additional data collection by another techniques. Typically, the techniques that cover a larger spatial area and/or provide a large time-series of data (e.g. satellite data) can be used to target site-scale investigations (geophysical investigations, heat-as-a-tracer, etc.). Thus, its consideration to techniques is as important as the order in which they are implemented.

The following section defines nine scenarios that water managers may face in making decisions on method selection, and data collection depending on field and project constraints.

When to implement the techniques?

This section provides conceptual workflows for a variety of common scenarios. The conceptual model and problem should be continually refined during each step of the process such that uncertainties are identified and mitigated in the most cost-efficient manner. It should be noted that the workflows presented below are not meant to imply that data from one source is "more valuable" or "more accurate." Rather, the data from each step can be used to inform the next step or method, thereby maximizing efficiency and costs.

The "primary" category indicates steps to consider first — these often include the use of satellite data to "hind-cast" the historical performance or may include "rapid" geophysical analysis. The "secondary" and "tertiary" steps should utilize all the information gathered in any previous steps to optimize the investigation techniques used in the next steps. Depending on the data collected and the scope of the investigation, it may not be necessary to complete all "primary", "secondary", and "tertiary" steps; nor may all of the listed techniques be applicable or appropriate. Proper judgement should be used through the process to ensure cost and data optimization considering the intended scope.

It should be noted that surface-based geophysics encompasses the full range of "rapid" to "focused," depending on the technique employed. See prior sections in this report for more detail.

Scenarios

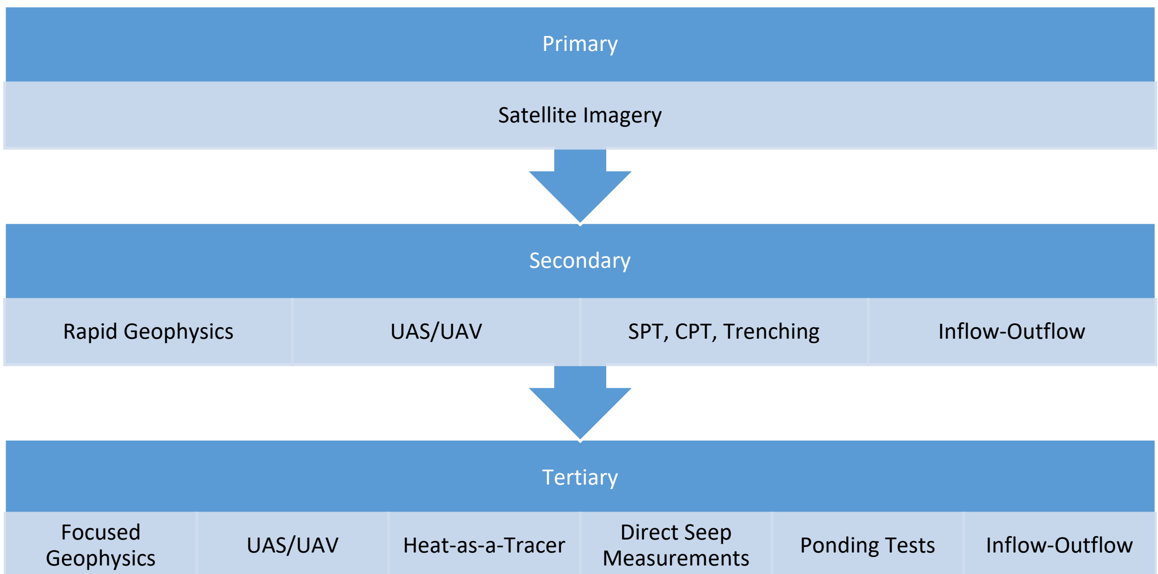
The following scenarios are discussed in more detail in this section:

1. Idealized workflow <u>insensitive to time</u> with highest quality data required
2. General workflow <u>sensitive to time</u> with highest quality data required
3. General workflow <u>insensitive to time</u> with <u>lowest cost</u> items preceding more costly techniques
4. <u>Newly developed concentrated seep</u>(s), concern about consequences (time sensitive)
5. <u>Newly developed or rapidly increasing diffuse seepage</u>, concern about consequences (time sensitive)
6. <u>Existing concentrated seep</u>(s), limited concern about consequences, <u>poor geologic</u> understanding
7. <u>Existing concentrated seep(</u>s), limited concern about consequences, <u>good geologic</u> understanding

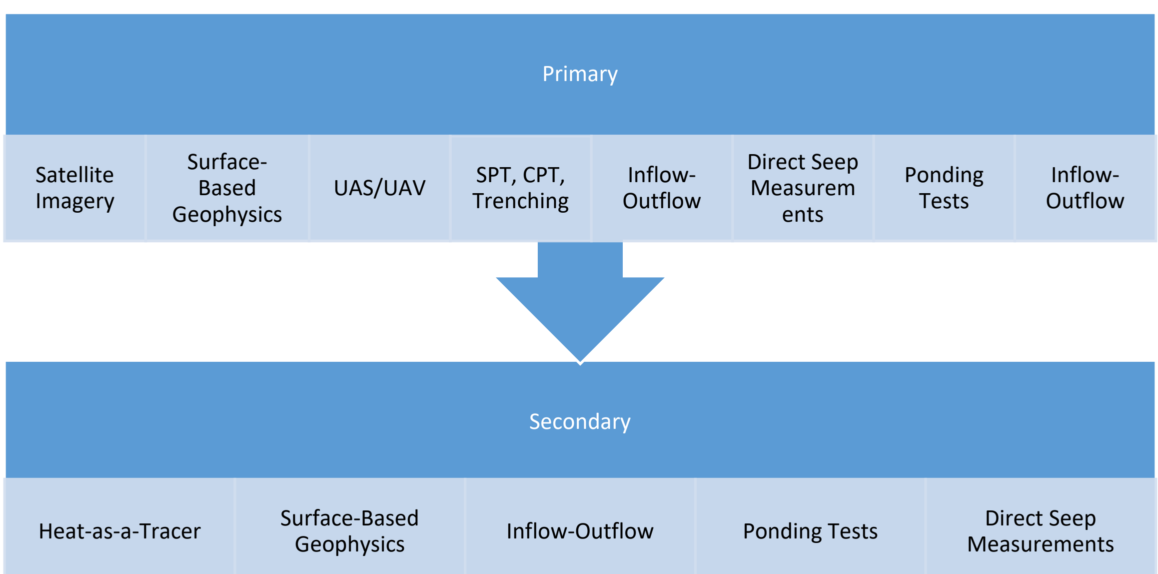
8. Existing diffuse seepage, limited concern about consequences, poor geologic understanding
9. Existing diffuse seepage, limited concern about consequences, good geologic understanding

Each investigation should start with a focused visual inspection of the canal system. This should be performed commensurate to, or shortly after discussions with personnel who spend the most time at the site (i.e., ditch riders, O&M personnel, etc.).

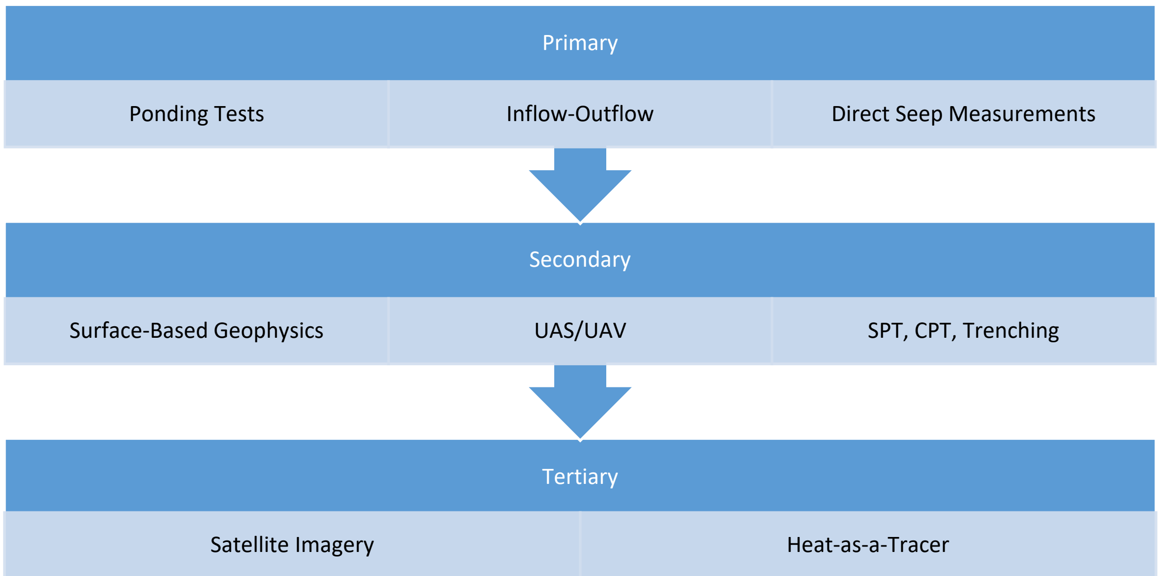
Idealized workflow insensitive to time with highest quality data required. Collect data at decreasing spatial resolution to optimize each step. Repeat some techniques between seasons to generate a robust data set.



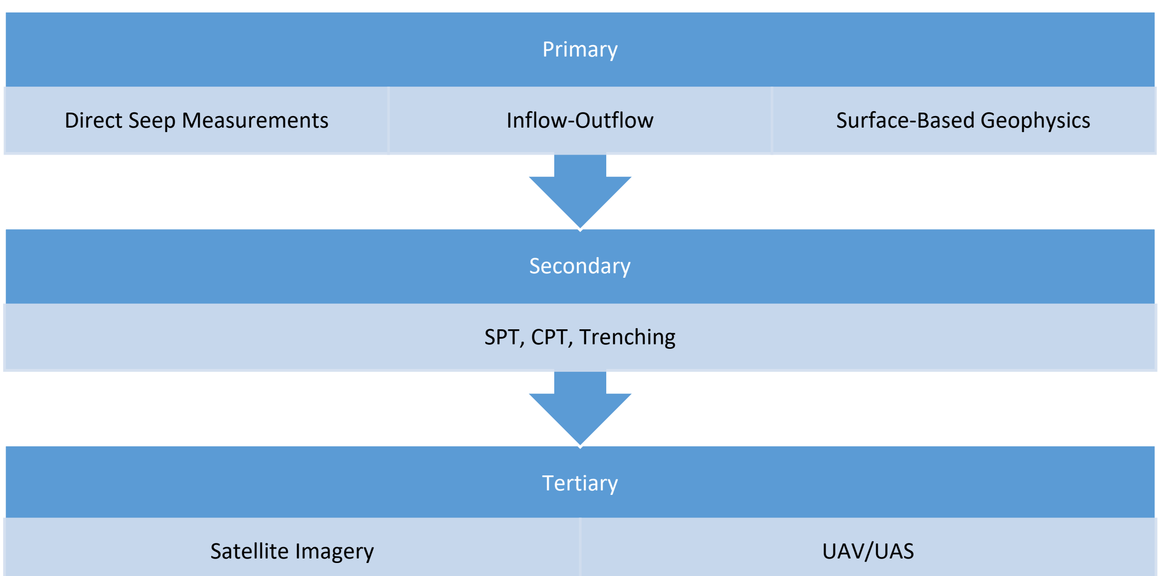
General workflow sensitive to time with highest quality data required. Collect data over two field seasons. This will reduce the potential for refinement of locations for the more targeted techniques but still provides a robust data set.



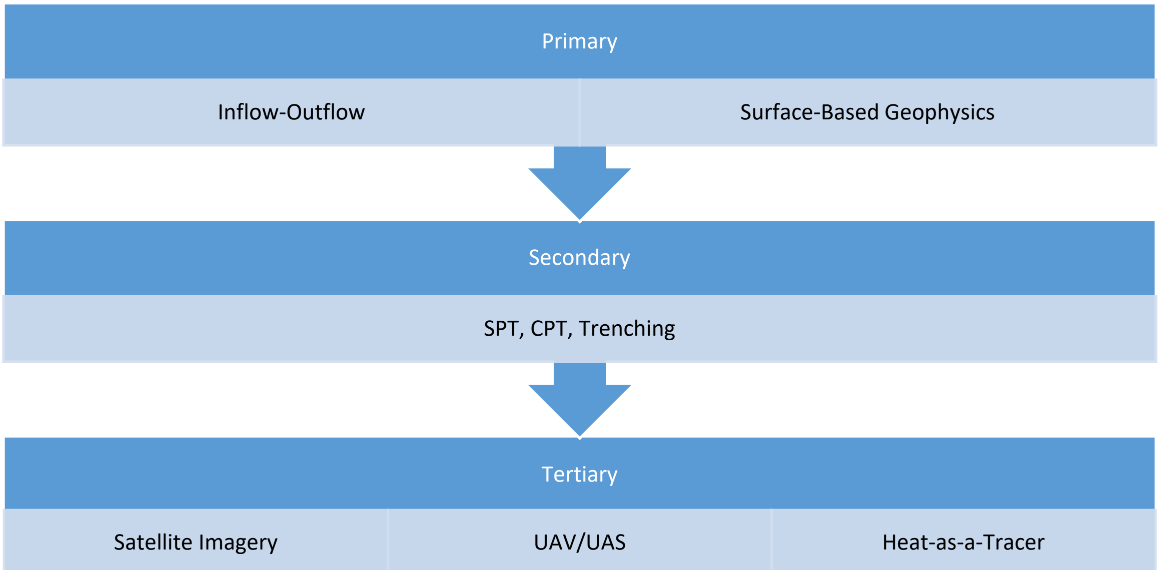
General workflow insensitive to time with lowest cost items first moving to more costly techniques. Collect data during season 1 using field personnel, resulting in lower initial costs. This scenario does not allow for refinement based on spatial resolution.



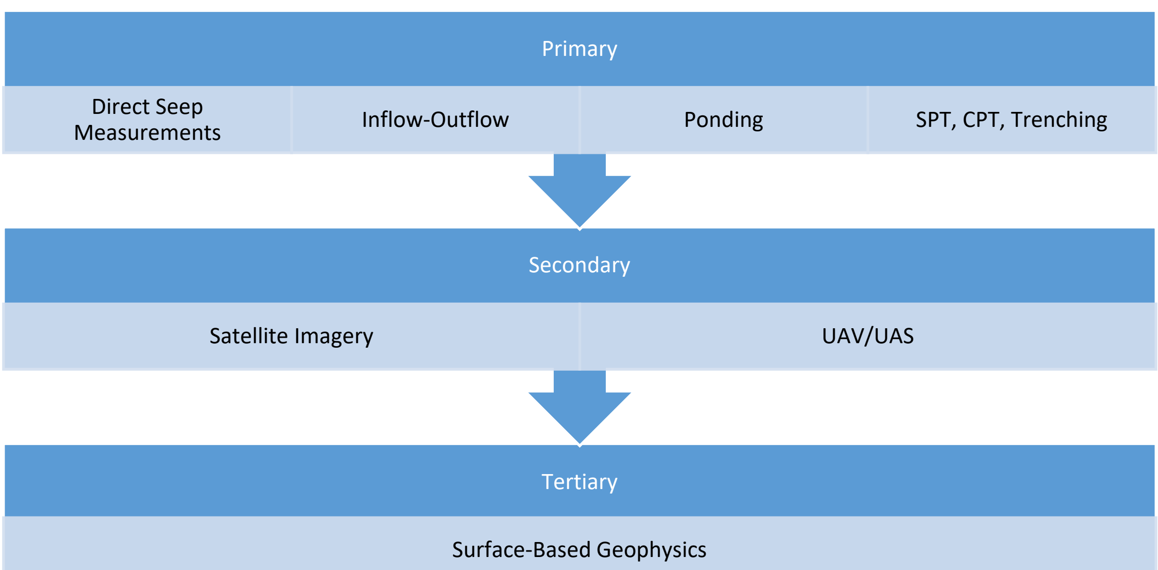
Newly developed concentrated seep(s), concern about consequences (time sensitive). Collect data in real-time during the primary step, with the ability to gather more data in later steps to further refine the model. Use the later steps to refine the geologic understanding, then move to larger spatial coverage to look for other potential problem locations.



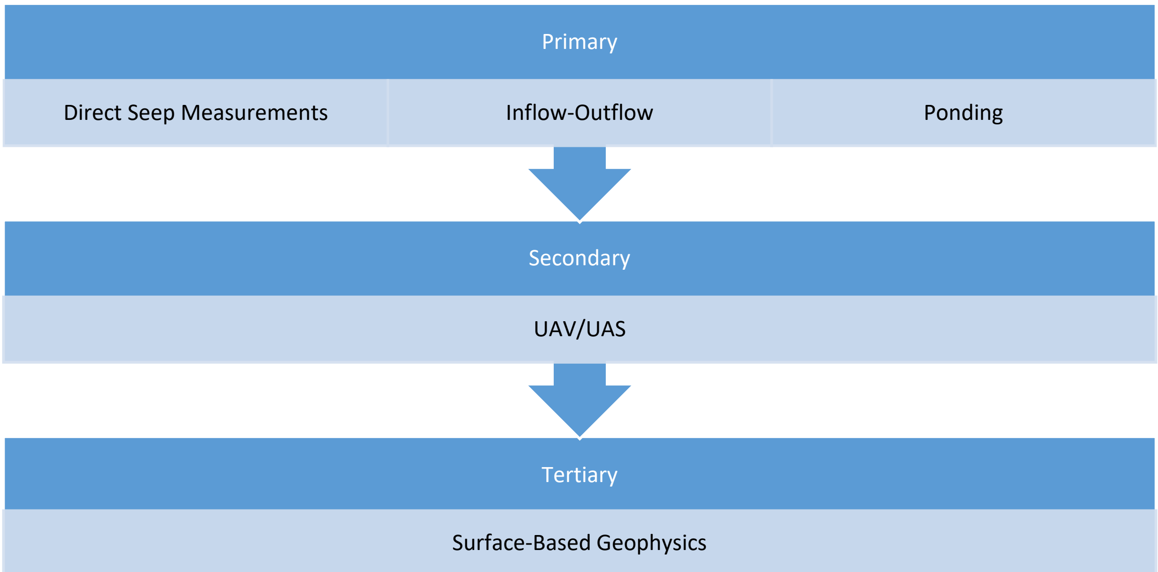
Newly developed or rapidly increasing diffuse seepage, concern about consequences (time sensitive). Use the immediate step to collect data in real-time field data, with the ability to gather more data in later steps. Use the later steps to refine the geologic understanding, then move to larger spatial coverage and targeted high-resolution data collection.



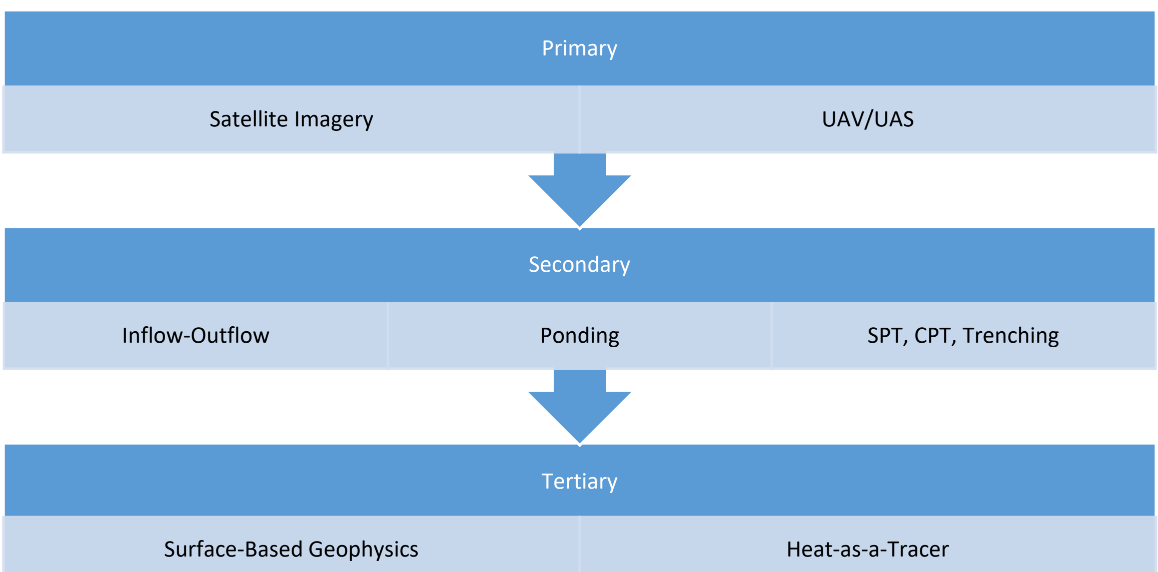
Existing concentrated seep(s), limited concern about consequences, poor geologic understanding. Collect real-time, cost-efficient data in the primary step to refine geologic understanding. Use the workflow in the next steps to broaden, then narrower spatial resolution to refine the data set.



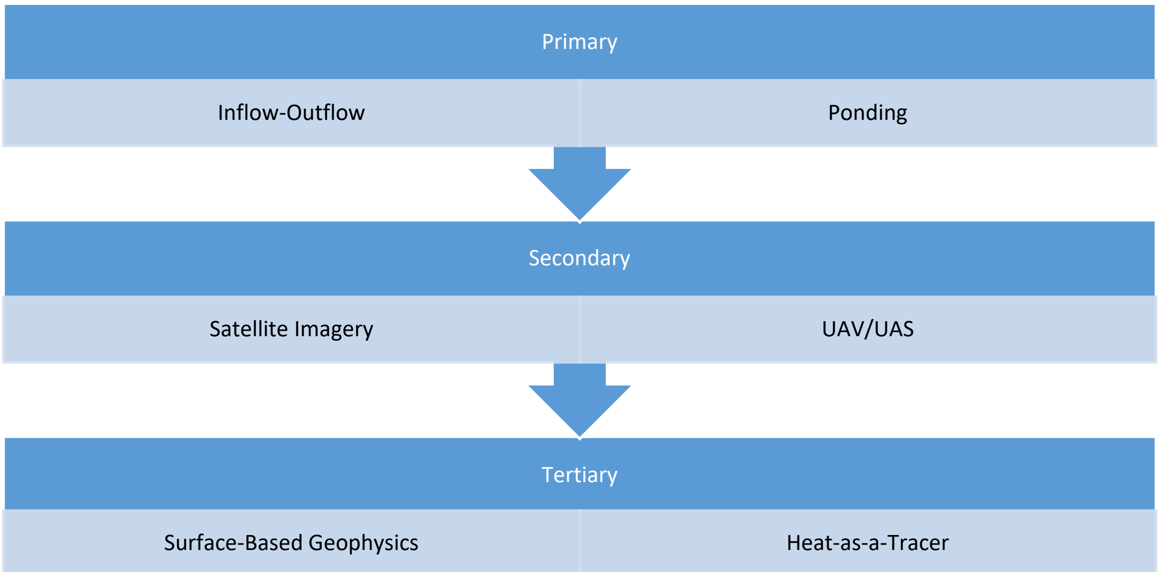
Existing concentrated seep(s), limited concern about consequences, good geologic understanding. Collect real-time, cost-efficient data in the primary step. The workflow then steps to broader, then narrower spatial resolution to refine data set.



Existing diffuse seepage, limited concern about consequences, poor geologic understanding. Collect real-time, cost-efficient data in the primary step which will help to refine the geologic understanding. The workflow then steps to broader, then narrower spatial resolution to refine data set.



Existing diffuse seepage, limited concern about consequences, good geologic understanding. Use the primary step to collect real-time, cost-efficient data. The workflow then steps to broader, then narrower spatial resolution to refine data set.



Improvements and Outcomes

Knowing the annual volumetric loss rate along sections of canal can help prioritize canal maintenance, lining improvements, and optimization of canal operations. Ranking the sections of canal by loss rates could help prioritize funding resources for improvements. The results of the seepage analysis should be used to help guide irrigation districts and water management decisions on costly upgrades to conveyance systems to improve water usage, farm productivity, and restoration efforts to improve downstream water quality and ecosystems.

A description of a canal lining experiments and outcomes are provided in Israelsen and Reeve (1944), while a description of the efficacy and cost benefit of different lining alternatives are provided in Swihart and Haynes (2002). The use of synthetic sheet piles to improve canal safety is provided in Ellis (2018). Details about construction activities and improvements at an operating canal is provided in USBR (2020).

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Table 1 - Details about field investigation methods.

Field Technique		Applicability																		Relative Cost [5]
		Sandy Soils	Clayey Soils	Excavated Prism	Prism built with fill	Unlined Canal	Lined Canal	Known Seep Locations	Unknown Seep Locations	Concentrated Seepage	Diffuse Seepage	Access Concerns - Property [1]	Access Concerns - Operations [2]	Requires Specialized Knowledge	Requires Specialized Equipment	Could be performed by field personnel	Requires Canal Unwatering	Time Series Data Collection - Fine [3]	Time Series Data Collection - Coarse [4]	
Geologic Investigations	CPT	X	X	X	X	X	X	X	X	X	X	X		X	X				X	$1,000 to $2,000 per hole
	SPT	X	X	X	X	X	X	X	X	X	X	X		X	X				X	$2,000 to $4,000 per hole
	Trenching	X	X	X	X	X		X	X	X	X		X		X	X	X		X	$1,000 per test pit
Indirect Field Methods: Geophysics and Remote Sensing	Surface-Based Systems	X	X	X	X	X	X	X	X	X	X	X	Depends on methods and site condtions	X	X		Depends on methods and site condtions			Rapid-Profiling Geophysics $35,000 FDEM Mapping $35,000 Tomography $35,000 Self-Potential $35,000 Ground Penetrating Radar $35,000 Total[6] $105,000
	Satellite NDVI	X	X	X	X	X	X	X	X	X	X			X					X	$10,000
	UAV/UAS	X	X	X	X	X	X	X	X	X	X	X		X	X					$40,000
	Satellite Based SAR	X	X	X	X	X	X	X	X	X	X			X					X	$30,000
Indirect Field Methods: Heat-as-a-Tracer	Heat-as-a-Tracer	X	X	X	X	X		X	X		X		X	X	X		X	X	X	$40,000
Direct Field Methods	Inflow-Outflow	X	X	X	X	X	X	X	X	X	X	X				X				$10,000
	Direct Seepage Measurements	X	X	X	X	X	X	X		X		X				X				$10,000
	Ponding Tests	X	X	X	X	X	X	X	X	X	X	X	X			X	X			$2,000

Notes: 1. Property access issues indicates that access to locations outside of the canal prism or right-of-way may need to be accessed requiring coordination with landowners.
2. Operations access issues indicates that regular canal operations may be need to be interrupted to install equipment or perform the investigation.
3. Fine times series data collection indicates data is collected electronically in near real-time.
4. Coarse time series indicates that temporal data is available but is not collected in real-time (i.e. satellite data collected every time the system passes over the site).
5. Relative costs developed assuming that local office does not own specialized equipment but could provide field assistance similar to O&M operations.
6. Total cost assumes that not all methods are required for each project. This is a typical cost for a project.