GUARDIAN RESOURCES

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WHITE PAPER - WILLOWSTICK TECHNOLOGIES

Willowstick Technologies In Conjunction With Guardian Resources

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1. Executive Summary

1.1 The Problem: Characterizing Subsurface Groundwater

Subsurface groundwater does not follow predictable, uniform pathways. It migrates preferentially through zones of highest hydraulic conductivity — fractures, fault planes, permeable formations, and construction defects — that are effectively invisible to surface observation and poorly resolved by conventional geophysical averaging methods. Without a technology capable of directly imaging these preferential flow paths in three dimensions, engineers and asset owners cannot make fully informed decisions about groundwater risk, remediation design, or infrastructure monitoring.

Accurate characterization of subsurface groundwater flow is a foundational requirement across a wide range of industries — mining, dam engineering, environmental remediation, hydroelectric power, and large-scale civil construction. The ability to identify, map, and model preferential groundwater flow paths with precision directly determines the quality of engineering decisions, the efficacy of remediation programs, and the long-term integrity of critical infrastructure assets.

Despite the fundamental importance of this capability, the methods most commonly relied upon for groundwater characterization — borehole drilling, resistivity surveys, and conventional electromagnetic geophysics — share a critical limitation: they provide either point-source data with no spatial continuity, or volumetrically averaged responses that lack the resolution to resolve the discrete flow paths on which engineering and remediation decisions depend.

The industries that rely on groundwater characterization collectively manage assets of enormous value and consequence: earthen dams storing billions of gallons of water, tailings storage facilities containing the mineral extraction byproducts of active and historical mine sites, and aquifer systems that support municipal, industrial, and agricultural supply. The documented consequences of inadequate subsurface characterization — structural failure, environmental contamination, regulatory liability, and loss of life — have elevated the standard of care expected of asset owners and operators across all of these sectors.

Guardian Resources, in partnership with Willowstick Technologies, LLC, addresses this gap through the deployment of the Willowstick Instrument — a patented geophysical system specifically engineered to map, model, and predict preferential groundwater flow paths in two and three dimensions. The methodology is non-invasive, operable across a wide range of terrain and hydrologic settings, and produces data of a resolution and density that is not achievable by conventional alternative methods.

1.2 Global Water Demand and the Growing Imperative for Precision

The global demand for reliable subsurface water characterization has intensified significantly in recent decades, driven by converging pressures across infrastructure, resource extraction, and environmental management sectors.

According to the U.S. Geological Survey (USGS), irrigation withdrawals — one of the largest sectoral demands on groundwater — have remained at historically elevated levels, with mining withdrawals increasing between the most recent USGS reporting periods. Major aquifer systems across the American West and globally are experiencing accelerating rates of depletion. While total aggregate withdrawals have declined due to efficiency improvements in thermoelectric power generation, per-sector demand stress in mining, irrigation, and industrial applications continues to grow — precisely the industries where the Willowstick Instrument is most frequently deployed.

Concurrent with rising demand, the infrastructure responsible for managing water is aging. Many large earthen structures in the United States and globally were constructed in the mid-twentieth century and are approaching or have exceeded their design lifespans. Seepage, internal erosion, and liner degradation in these structures represent both an asset management challenge and a public safety obligation. Regulatory bodies, insurers, and project oversight committees increasingly expect asset owners to demonstrate that available non-invasive characterization technologies were employed before invasive or remedial action was initiated.

1.3 The Willowstick Instrument: A Purpose-Built Solution

The Willowstick Instrument is not a repurposed general-purpose geophysical tool. It is a purpose-designed, patented system developed specifically for the characterization of preferential subsurface groundwater flow. Its physical operating principles, signal processing architecture, and data interpretation framework are all oriented toward a single goal: delivering a precise, defensible, three-dimensional picture of where groundwater flows beneath the surface.

The instrument operates by introducing a controlled alternating electrical current directly into the groundwater medium of interest — not into the bulk subsurface volume as conventional methods do. Because groundwater conducts electricity substantially better than dry earth materials, this current preferentially follows the exact pathways of interest. The instrument then measures, with high sensitivity, the magnetic field generated by that current flow across a dense grid of surface measurement stations. The resulting dataset — which may comprise hundreds of thousands of discrete readings — is processed through a proprietary suite of inversion algorithms and modeling tools to produce two- and three-dimensional Electric Current Distribution (ECD) models that directly image subsurface groundwater flow paths.

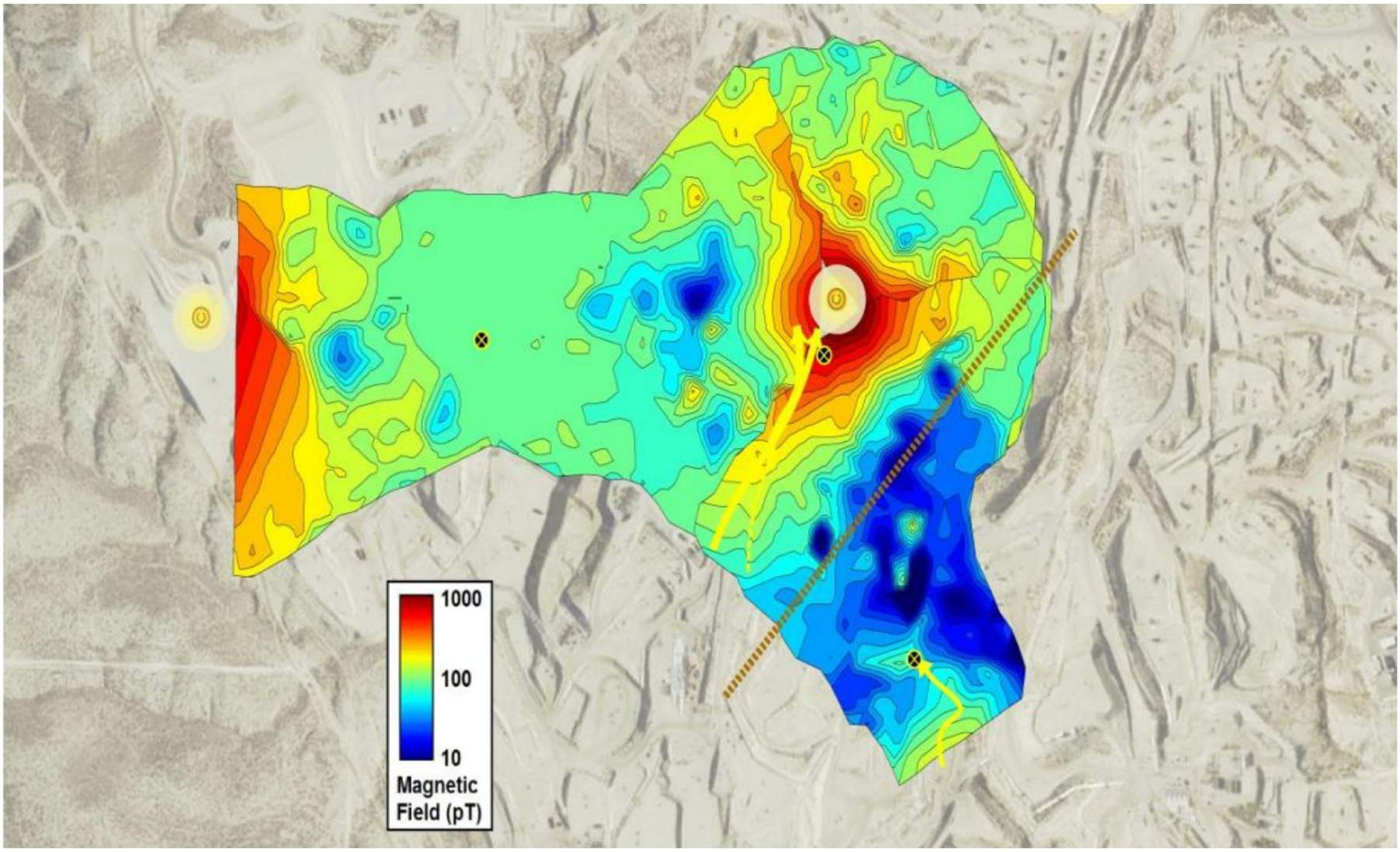

Figure 2 — Sample 2D Vector Correction Map produced by the Willowstick survey process. Warm tones (red/orange) indicate zones of concentrated current flow corresponding to preferential groundwater pathways. The map is overlaid on site aerial photography for engineering context.

This approach is scientifically rigorous, grounded in established electromagnetic physics, and fully transparent in its physical basis — while the specific instrumentation design, signal processing methods, and inversion algorithms that make it possible represent proprietary innovations protected under U.S. Patent No. 8,688,423 B2, with additional patents pending.

1.4 Why Investigate Before Drilling or Remediating?

Guardian Resources advocates a diagnostic-first philosophy: conduct a comprehensive non-invasive geophysical characterization using the Willowstick Instrument, establish a verified three-dimensional model of subsurface groundwater conditions, and then direct all subsequent investigative and remedial expenditures to precisely defined target locations.

a. Reduce cost and time while increasing accuracy. The Willowstick Instrument produces a cost-effective, timely, and verified image of current subsurface conditions. Engineers and asset owners are equipped to make well-informed decisions at the outset of a project, rather than iterating through expensive and inconclusive trial-and-error drilling programs.

b. Minimize the number of observation wells required. In the majority of projects, a Willowstick investigation identifies areas requiring further investigation without requiring a broad drilling program across the entire site. Where drilling is subsequently needed, it is directed to the locations of highest diagnostic value — reducing well count, cost, and site disturbance.

c. Detect subsurface changes early. A Willowstick investigation typically represents a fraction of the total cost of site characterization by conventional means, and an even smaller fraction of the cost of remediating an undetected problem. Decisions based on interpolations from sparse borehole data routinely fail to capture significant subsurface changes that can develop rapidly between monitoring intervals.

d. Enable proactive asset management. The Willowstick Instrument's non-invasive operational profile makes it well suited to periodic re-investigation of high-value assets. Sequential surveys at the same site — conducted with identical electrode configurations and measurement parameters — enable direct temporal comparison of groundwater conditions, supporting early detection of emerging issues before they become critical failures.

e. Direct remediation to the right location. Implementing groundwater remediation — whether involving cut-off walls, grout curtains, drainage systems, or injection wells — without prior non-invasive characterization is analogous to invasive medical intervention without prior diagnostic imaging: technically possible, but associated with an unnecessary and avoidable level of risk, cost, and uncertainty. The Willowstick Instrument eliminates that uncertainty by defining the precise location and geometry of the target before remediation design is finalized.

1. The Willowstick Instrument

2.1 Instrument Overview

The Willowstick Instrument is an integrated system of purpose-built hardware and proprietary software components, designed from the ground up for one specific application: mapping preferential subsurface groundwater flow paths in two and three dimensions. The system enables highly trained survey technicians and geophysicists to collect, process, and model the magnetic field generated by a controlled electrical current injected into the groundwater medium of interest — producing maps and models that directly reflect the geometry and extent of subsurface flow.

The hardware components of the system include the current-injection source and electrode apparatus, the high-sensitivity magnetic field measurement instrument mounted on a surveyor's pole, and the GPS-based positioning system that defines each measurement station's precise geographic coordinates. The instrument is hand-carried to each station, enabling surveys across a wide range of terrain types — including steep slopes, water surfaces, and areas inaccessible to vehicle-mounted equipment — without requiring any surface preparation or ground disturbance.

The software components encompass the full data processing and modeling workflow: normalization of measured magnetic field data against the theoretically predicted homogeneous baseline model; application of proprietary filtering algorithms that isolate the groundwater signal from cultural electromagnetic interference; generation of the Ratio Response Map and Predicted Magnetic Field Map; and execution of the three-dimensional inversion algorithms that produce the Electric Current Distribution (ECD) models delivered to clients.

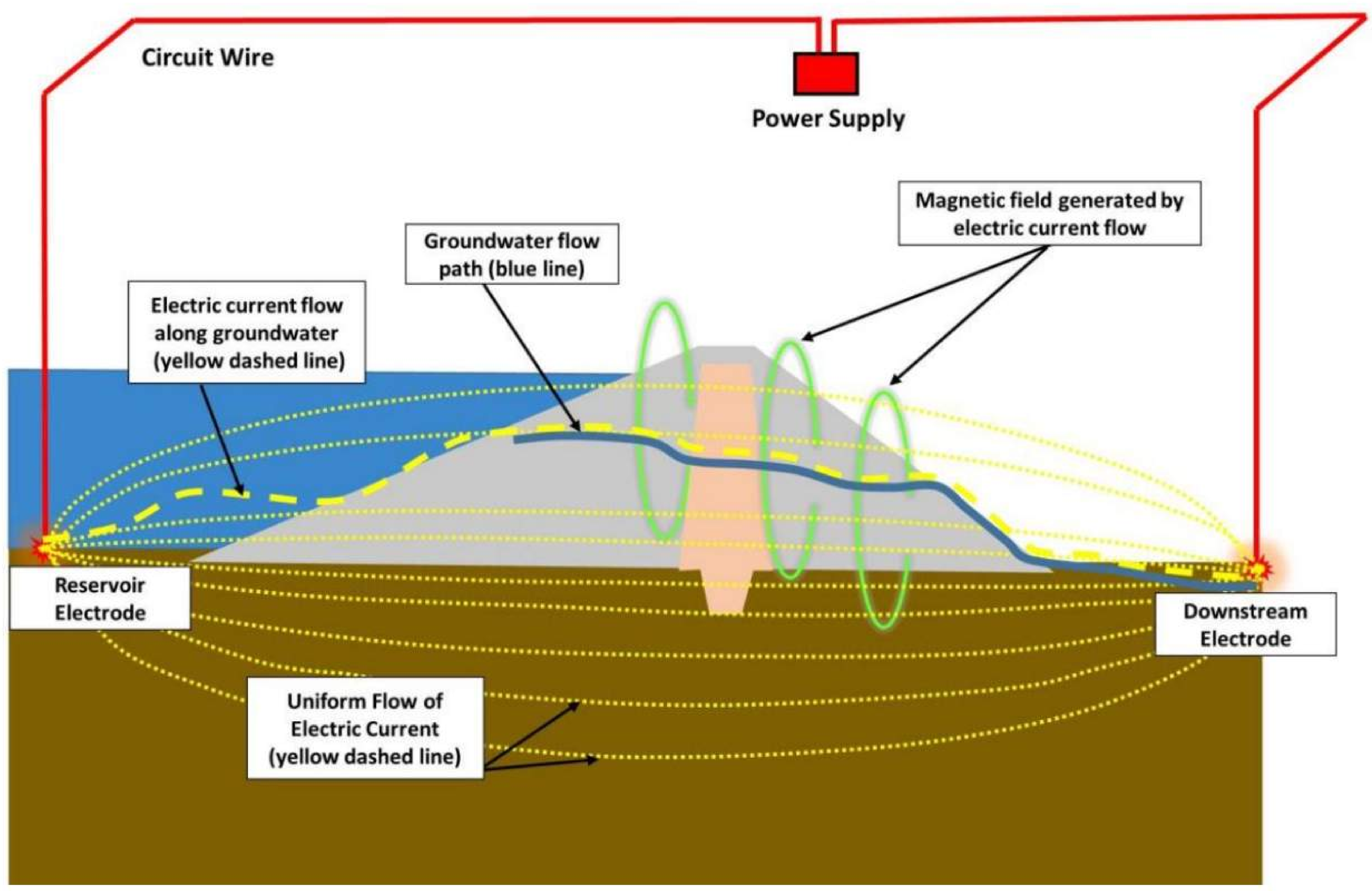

Figure 3 — Schematic of a typical Willowstick dam seepage investigation. The reservoir electrode (upstream) and the downstream electrode establish the AC electric circuit. The current follows the highest-conductivity (groundwater) pathways; the resulting magnetic field is measured at surface grid stations to map the seepage path in plan and cross-section.

2.2 Scientific Foundation: Why the Physics Works

The Willowstick method is grounded in two well-established principles of classical physics, applied in a novel combination through purpose-designed instrumentation.

The first principle is the differential electrical conductivity of wet and dry geological materials. Water bearing dissolved mineral ions — as virtually all naturally occurring groundwater does — is a substantially better conductor of electricity than the dry or partially saturated materials surrounding it. This conductivity contrast is the physical basis for the technology's ability to differentiate preferential flow paths from background geology: when an electric current is introduced into a system containing both water-bearing and dry zones, the current concentrates preferentially in the water-bearing zones, in proportion to their conductivity relative to the surrounding matrix.

The second principle is the Biot-Savart Law, a foundational relationship in electromagnetism that describes how a magnetic field is generated by a moving electric current. Every electric current — regardless of the medium through which it flows — generates a surrounding magnetic field. The spatial distribution and intensity of that field is a direct function of the spatial distribution and intensity of the current that produces it. This means that by precisely measuring the magnetic field at the surface, it is possible to infer the distribution of the electric current below the surface — and therefore the distribution of the groundwater that the current is following.

Key Physical Principle - Because the Willowstick Instrument measures magnetic fields rather than electrical potentials, it is not subject to the signal attenuation that limits conventional DC resistivity methods in the presence of conductive overburden. A magnetic field generated by current flowing through a deep water-bearing zone propagates to the surface without significant attenuation by overlying conductive layers — enabling reliable characterization of groundwater at depths exceeding 300 meters (approximately 1,000 feet).

The combination of these two principles — conductivity-driven current concentration and magnetically encoded current distribution — is what makes the Willowstick Instrument uniquely capable of producing high-resolution, three-dimensional images of subsurface groundwater flow paths. Conventional resistivity and electromagnetic methods share the first principle but do not exploit the second in the same way: they typically measure electrical potential differences or secondary electromagnetic fields at the surface, both of which are subject to the averaging effects that limit their spatial resolution. The Willowstick Instrument's approach to magnetic field measurement, at the station density made possible by its proprietary hardware design, yields a fundamentally different quality of subsurface information.

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2.3 The Measurement Process

A Willowstick survey begins with the establishment of the electric circuit. Two electrodes are placed in locations selected to maximize the diagnostic value of the resulting current flow: typically one in the upstream water body or groundwater source of interest, and one at a downstream location in contact with the water or seepage discharge to be characterized. A controlled alternating current is then introduced into the circuit through the Willowstick power supply, at an operating level of 0.3 to 1.7 amperes and a proprietary signature frequency of 380 Hz.

The 380 Hz operating frequency is not arbitrary. It is selected to avoid the harmonic frequencies of both 50 Hz and 60 Hz power distribution systems in common use globally, minimizing interference from power infrastructure while remaining within a frequency range that provides the desired depth of investigation and sensitivity to the conductivity contrasts of interest.

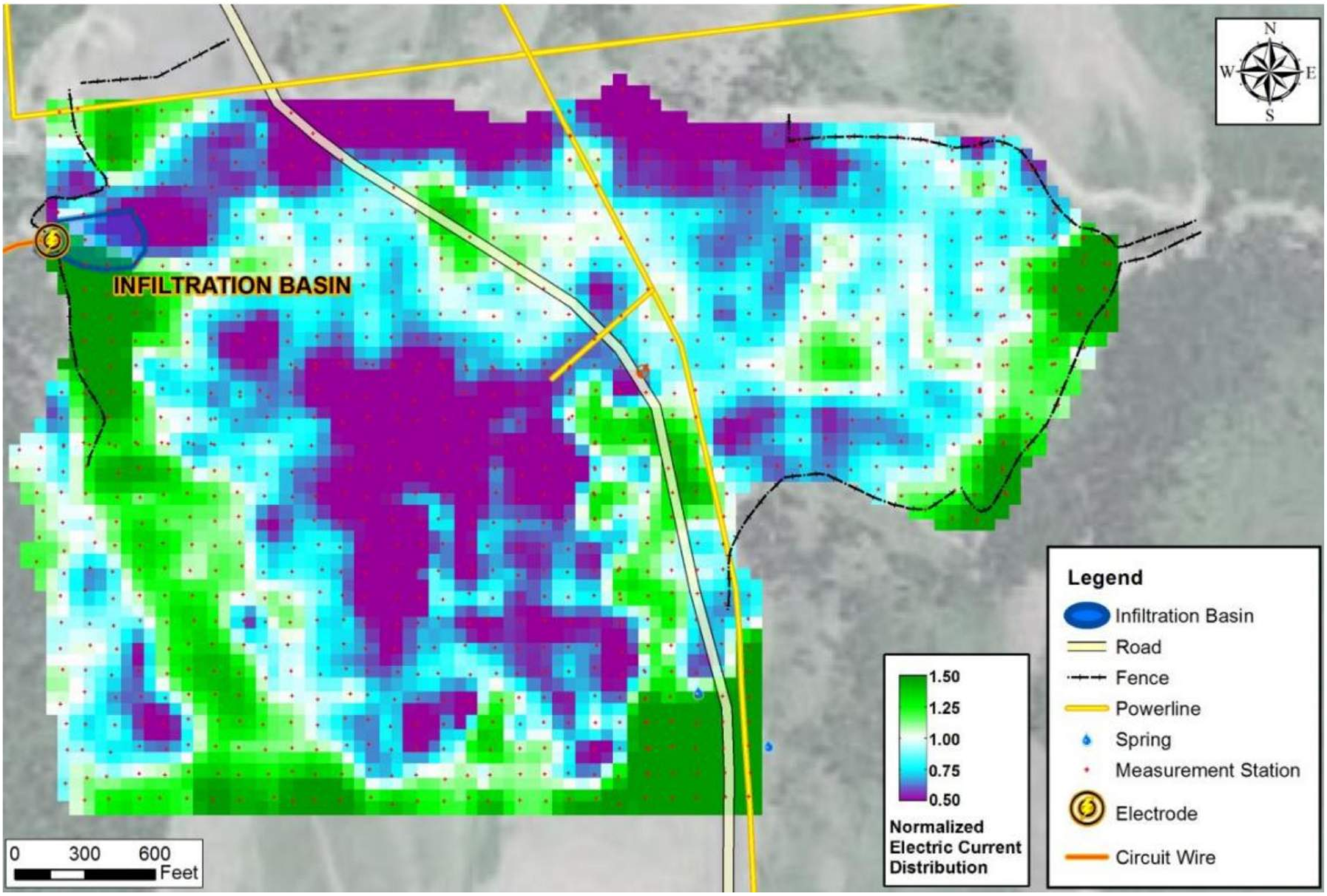


Figure 3- Electric Current Distribution Model (Elevation slice taken below the surface at a mine site)

Once the circuit is established, the survey team carries the Willowstick Instrument to each measurement station in turn, following a predefined grid. At each station — spaced as closely as 2.5 meters apart in high-resolution surveys — the instrument acquires a complete magnetic field measurement and records the station's GPS coordinates. The instrument is sensitive to magnetic fields produced by as little as one-tenth of an ampere of current flowing through the subsurface from a distance of up to one mile, enabling detection of very subtle groundwater anomalies at significant depth.
This measurement density — the number of stations collected per unit area — is a key differentiator of the Willowstick approach. Many surveys in the technology's history have produced datasets of hundreds of thousands of readings. This data density is what enables the three-dimensional inversion models to resolve the precise geometry and depth of preferential flow paths, rather than producing the broad statistical averages characteristic of lower-density conventional surveys.

2.4 Data Processing and Model Generation

Raw magnetic field data collected by the Willowstick Instrument undergoes a structured processing workflow before the final interpretive models are produced. This workflow is executed using proprietary software developed and refined by Willowstick Technologies over successive generations of the instrument.

The first processing stage involves normalization of the observed magnetic field against the predicted field from a theoretically homogeneous subsurface model. The homogeneous model — which assumes uniform electrical conductivity throughout the subsurface volume — provides a stable physical baseline. Because this baseline is derived from fixed physical laws rather than empirical calibration, it does not vary with time, temperature, or local conditions. Deviations of the measured field from this baseline are therefore interpret-able as genuine subsurface heterogeneity rather than measurement artifact.

This normalized dataset is rendered as the Ratio Response Map — a two-dimensional plan view that shows, for each measurement station, the ratio of observed to predicted magnetic field intensity. Zones where the ratio exceeds the baseline indicate elevated current concentration, corresponding to zones of higher-than-average electrical conductivity, in most cases reflecting preferential groundwater pathways. Zones below the baseline indicate reduced current density, corresponding to lower-conductivity or dry material.

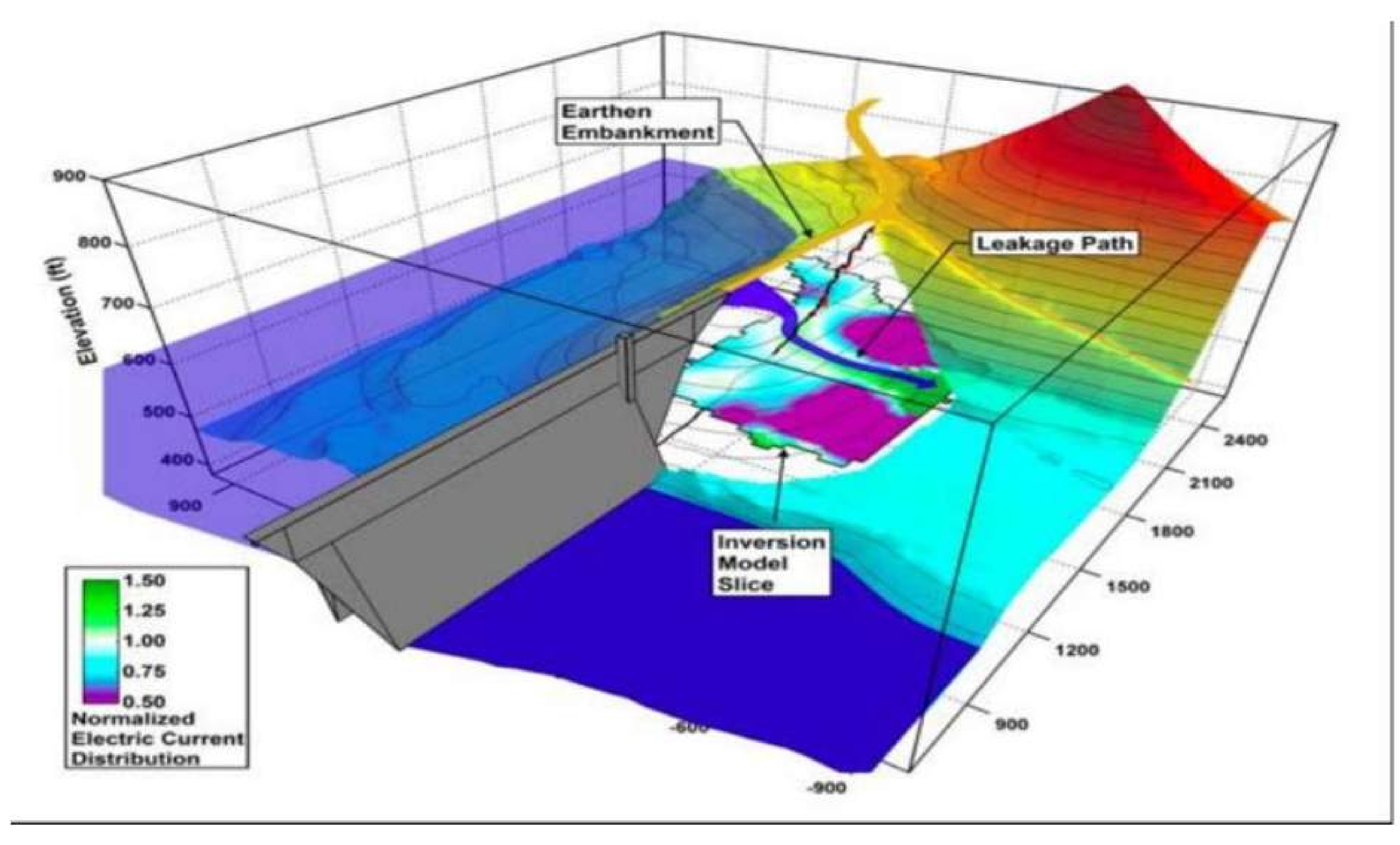


Figure 4 — Sample 3D Electric Current Distribution (ECD) Model of an earthen embankment. The leakage path (warm tones on the inversion model slice) is delineated against the background model, with elevation (ft) on the vertical axis. This model provides the precise location, depth, and geometry needed to target remediation work.

The three-dimensional Electric Current Distribution (ECD) model is generated by applying a suite of proprietary inversion algorithms to the full dataset. Inversion modeling is a well-established mathematical approach in geophysics: it involves iterative adjustment of a subsurface model until the predicted surface response of that model matches the observed data within a defined tolerance. The Willowstick inversion algorithms have been developed and calibrated over more than two decades and across more than 230 projects, producing models that reflect the actual distribution of electric current — and therefore groundwater — throughout the subsurface volume of interest.

The output of the processing workflow is a suite of maps and models — Ratio Response Maps, Predicted Magnetic Field Maps, ECD plan-view slices at selected elevations, and three-dimensional volumetric representations — that together constitute the interpretive foundation for the Final Report delivered to the client.

2.5 The Willowstick Survey Layout

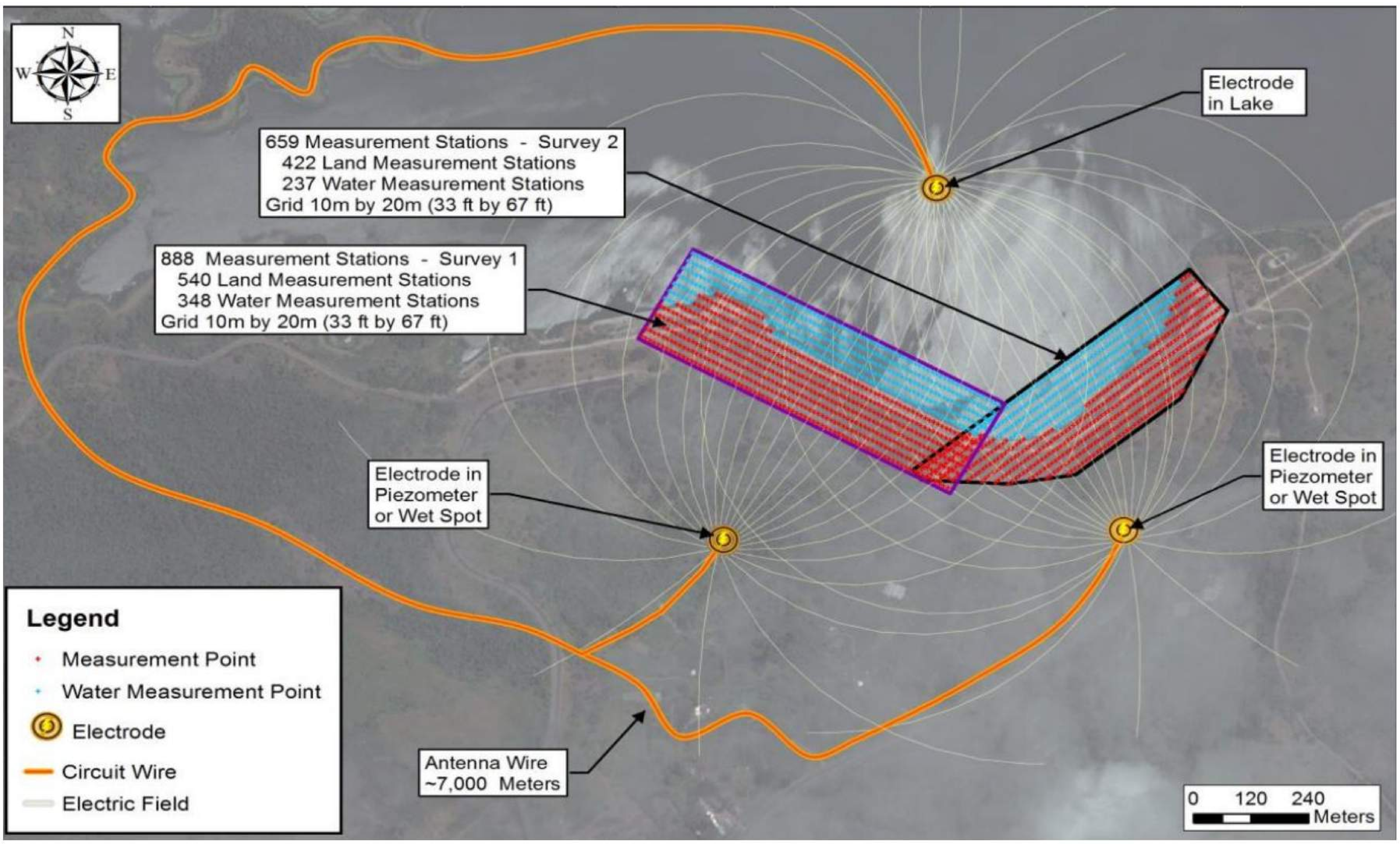


Figure 6 — Sample layout of two concurrent Willowstick surveys with three electrodes (two on land, one in the reservoir), showing the circuit wire (~7,000 m), measurement grid (10 m × 20 m stations), and resulting magnetic field distribution. Survey 1: 888 stations; Survey 2: 659 stations.

2.5 The Willowstick Survey Layout Cont.

The flexibility of the Willowstick survey layout is one of its practical advantages. The number, placement, and configuration of electrodes can be adapted to the specific geometry of the investigation target — whether a dam embankment, a tailings storage facility, a contamination plume, or a geothermal field. Multiple overlapping surveys can be conducted with different electrode configurations, providing independent confirmation of identified anomalies and enabling triangulation of flow path geometry in three dimensions.

Survey grids are designed to provide full coverage of the investigation area at the station density required to meet the resolution objectives of the project. In dam and embankment seepage investigations, grids typically span the full crest width and extend a sufficient distance upstream and downstream to capture the full extent of the seepage path. In mine site and tailings investigations, grids may cover several square kilometers at standard resolution, with higher-density patches deployed over areas of particular interest.

2.6 Technology Development and Generations

The Willowstick Instrument is currently in its eighth generation of development. The foundational scientific principles have remained constant since the initial application at the Midnite Mine, Wellpinit, Washington in the 1990s — documented in a U.S. Bureau of Mines Report of Investigations1 — but the instrumentation, software, and operational methodology have undergone continuous refinement since Willowstick Technologies, LLC was formally established in 2004 under AMP Capital Partners.

Successive generations of the instrument have delivered improvements in measurement sensitivity, reduction of cultural electromagnetic interference, integration of high-precision GPS positioning for replicable survey layouts, and — most significantly — the development of the proprietary three-dimensional inversion algorithms and volumetric modeling capabilities that differentiate the current system from its predecessors. The advent of modern high-performance computing has been central to this evolution: early implementations of the technology required up to 15 minutes per measurement station; the current system acquires a complete, GPS-registered magnetic field reading in approximately 10 seconds, enabling the data densities that make high-resolution three-dimensional modeling possible.

The process patent covering the fundamental Willowstick method was granted as U.S. Patent No. 8,688,423 B2. Additional patents covering specific innovations in instrumentation design, signal processing, and data interpretation are pending with the U.S. Patent and Trademark Office. These protections reflect the substantial proprietary innovation embodied in the current generation of the system and are actively maintained by Willowstick Technologies, LLC.

2.7 What the Willowstick Instrument Does Not Do

A precise understanding of the Willowstick Instrument's performance envelope is as important as an understanding of its capabilities. The method is not appropriate in the following circumstances:

- Groundwater bodies where dissolved ionic content is near zero — an extremely rare condition representing less than one percent of groundwater systems characterized to date. In the absence of dissolved ions, the conductivity contrast between water and dry material is insufficient to concentrate the injected current in a way that is detectable.
- Applications where the primary deliverable is a volumetric flow rate measurement. The Willowstick Instrument characterizes the location, geometry, depth, and relative conductivity of groundwater flow paths; it does not directly measure discharge volume or velocity.
- Survey configurations where the target flow path is located at depths several hundred meters below the practical measurement surface elevation — for example, in extreme mountainous terrain where the vertical separation between the accessible surface and the target exceeds the effective operating depth.

These are narrow constraints that apply to a small minority of real-world groundwater characterization problems. In the vast majority of dam seepage, tailings management, mine site hydrology, contamination assessment, and water resource investigation contexts, the Willowstick Instrument is fully applicable and produces results of a quality that no conventional alternative can match.

It is equally important to note that the boundaries of what the Willowstick Instrument can achieve have consistently expanded beyond initial expectations. Projects have been successfully completed in geological settings, terrain configurations, and application types that were not originally envisioned as within the technology's scope. Each successive generation of the instrument — and each project undertaken in difficult or unconventional conditions — has extended the performance envelope further. Guardian Resources and Willowstick Technologies approach every investigation with the intent to push that boundary. Clients have repeatedly benefited from capabilities that the technology's own early specification history would not have predicted, and that commitment to continuous expansion of what is possible remains central to how we operate.

2.9 Comparative Performance Against Other Geophysical Methods

A rigorous evaluation of the Willowstick Instrument's performance relative to conventional alternatives requires an understanding of why the conventional alternatives fall short of the resolution and precision required for definitive groundwater characterization.

Passive geophysical methods measure naturally occurring fields and do not introduce any controlled signal into the subsurface. Their fundamental limitation for groundwater characterization is that naturally occurring field variations reflect a broad range of subsurface properties — density, mineral composition, redox chemistry — and cannot be used to selectively identify or map groundwater flow paths. Even where passive anomalies may be consistent with groundwater presence, they provide no information about flow path geometry, depth, or direction.

DC resistivity and electromagnetic induction methods are the most widely deployed conventional alternatives for groundwater investigation. Both methods introduce a controlled signal into the subsurface and measure its surface response. Their limitation is structural: they energize large volumes of subsurface material uniformly, and their measurements reflect the aggregate electrical response of the entire energized volume. From this aggregate response, the contribution of a specific narrow, discrete flow path cannot be reliably resolved — particularly where conductive overburden or cultural interference is present. The result is an averaged picture of subsurface conductivity from which preferential flow paths can sometimes be inferred, but rarely confirmed with the precision required for engineering decision-making.

The Willowstick Instrument overcomes this limitation by injecting current directly into the water medium of interest, rather than into the bulk subsurface volume. The current follows the groundwater; the instrument tracks the current. This targeted approach produces data of fundamentally higher relevance and resolution than bulk-energization methods.

Ground Penetrating Radar achieves high spatial resolution in favorable conditions but is limited to investigation depths of a few meters in typical geological settings. It is not applicable to the characterization of flow paths at the depths relevant to most engineering and mining applications.

Three-dimensional seismic surveys provide excellent characterization of large-scale geological structure — stratigraphy, faulting, basin geometry — but are not designed to resolve discrete preferential groundwater flow paths within those structures. Acquisition costs are high and logistical constraints significant, limiting applicability in routine groundwater investigation contexts.

Borehole data are accurate, physically verifiable, and provide samples and direct measurements that geophysical methods cannot replicate. The limitation of drilling is its fundamental character as a point measurement: it provides information only at the precise location of the borehole, and the characterization of a site to the spatial resolution required for engineering decisions requires a large number of wells whose placement cannot be optimally determined without prior spatial knowledge of subsurface conditions.

Guardian Resources and Willowstick Technologies do not position the Willowstick Instrument as a replacement for drilling. Rather, it is the optimal precursor: it defines where to drill, how many wells are needed, and what to expect — transforming a trial-and-error process into a targeted, evidence-based program. In this context, the Willowstick Instrument reliably reduces overall program cost, improves data quality, and shortens the timeline from investigation to confident action.

3. Summary

3.1 Instrument Overview

The Willowstick Instrument represents a purpose-built application of established electromagnetic physics to one of the most consequential unsolved problems in applied geophysics: the direct, non-invasive characterization of preferential subsurface groundwater flow paths in three dimensions.

Its scientific foundation — the differential conductivity of water-bearing versus dry geological materials, combined with the magnetic encoding of subsurface current distribution as described by the Biot-Savart Law — is well understood and independently verifiable. Its implementation through purpose-designed instrumentation, proprietary signal processing software, and field-validated three-dimensional inversion modeling represents a significant and protected technical innovation that has been refined through more than 230 completed projects across a diverse range of applications and geological settings.

The instrument delivers what conventional methods cannot: a spatially continuous, three-dimensional picture of subsurface groundwater distribution at the density and resolution required to make definitive engineering decisions. It is the foundation upon which all Guardian Resources groundwater characterization programs are built, and the reason our clients consistently achieve better outcomes — lower costs, fewer surprises, more targeted remediation — than programs that rely on conventional approaches alone.

Survey results from the Willowstick Instrument are always interpreted in conjunction with all available site information — existing well data, geological mapping, geotechnical reports, and operational records. This integrated approach produces the highest possible confidence in the resulting subsurface model and the strongest possible foundation for the decisions that follow.

4. Selected Case Studies and Field Validation

Overview

The following case studies illustrate the performance of the Willowstick Instrument across representative investigation types. These examples demonstrate the instrument's ability to identify, map, and model preferential flow paths under real field conditions and to directly support engineering and remediation decision-making.

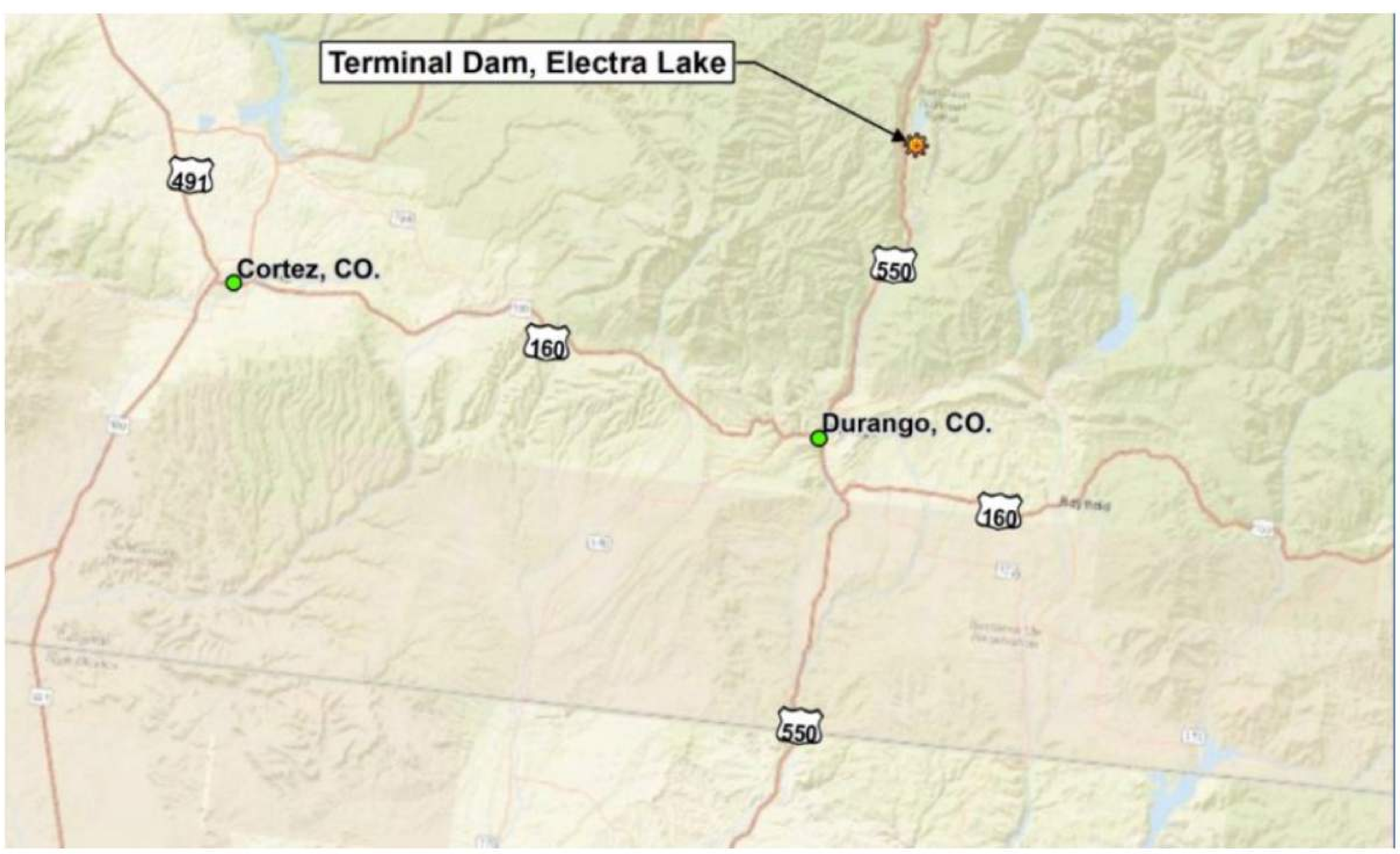
Find more at our website: https://willowstick.com/library

4.1 Dam Seepage Investigation — Terminal Dam, Electra Lake, Colorado (2019)

Client: Xcel Energy (Tacoma Hydropower Project)

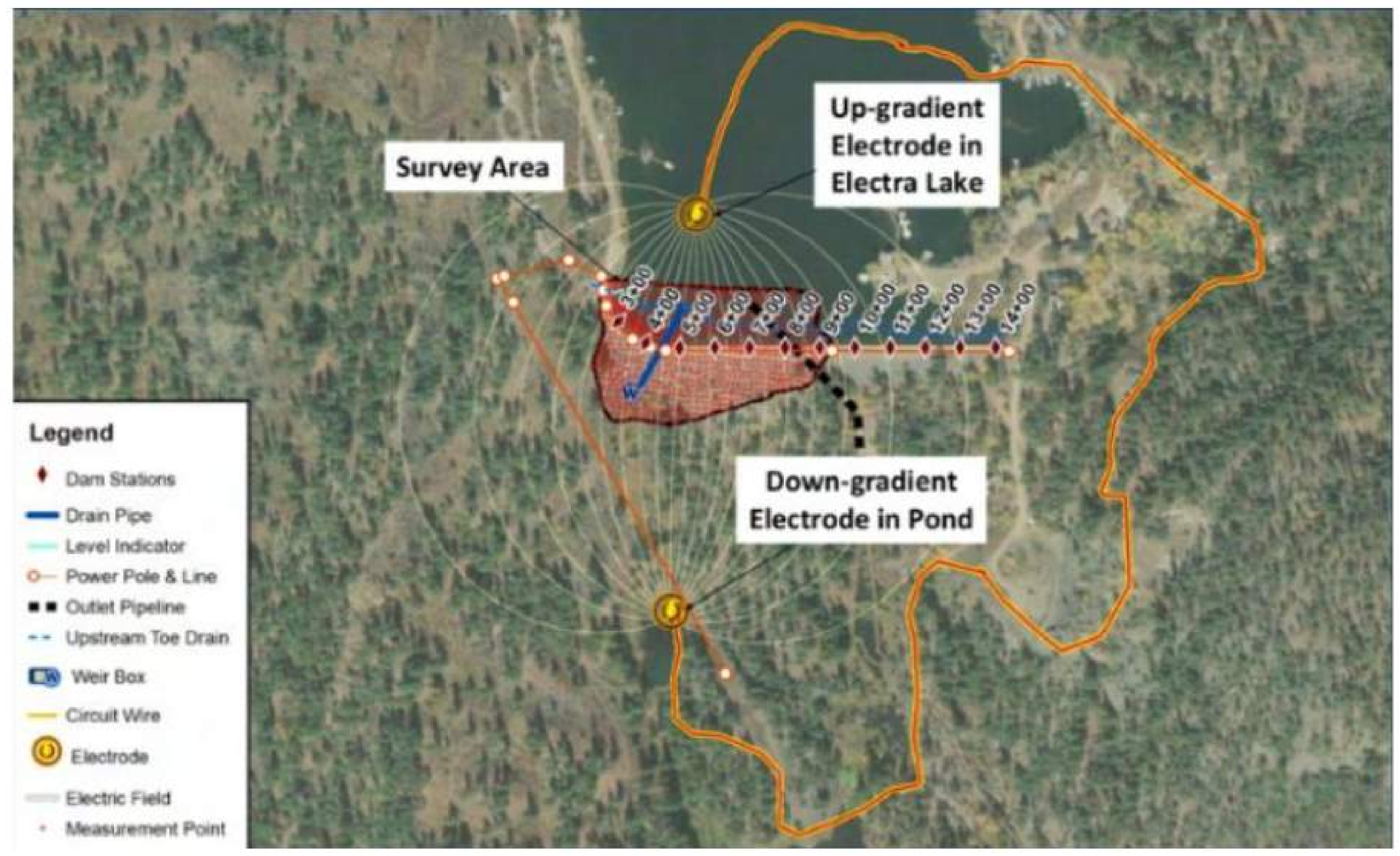
Partners: Willowstick LLC / W.W. Wheeler & Associates, Inc.

Terminal Dam — a 1,270-foot long, 60-foot-high asphalt-faced zoned rockfill dam near Durango, Colorado, forming part of the Tacoma Hydropower Project — experienced a sudden and significant escalation in seepage flows in July 2018. Seepage rates increased from approximately 35 gallons per minute to over 300 gpm, peaking at 450 gpm, prompting Xcel Energy to initiate reservoir draining procedures. Initial investigations — including dive exploration and dye testing — narrowed the source to the lower portion of the reservoir but failed to identify the specific defect.

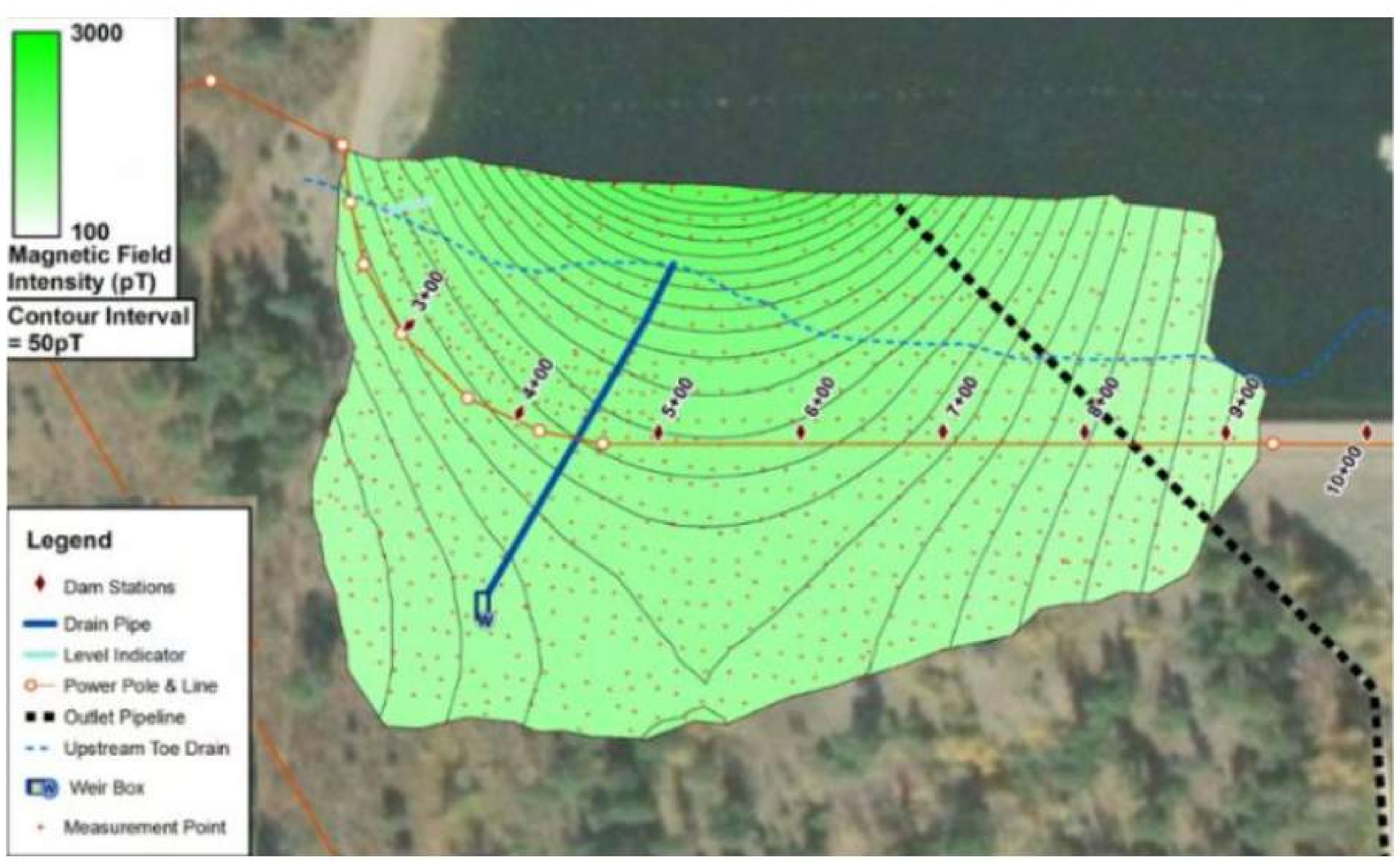


Terminal Dam at Electra Lake, near Durango, Colorado — project location overview.

A Willowstick geophysical survey was conducted in September 2019. The up-gradient electrode was placed in Electra Lake and the down-gradient electrode in the collection pond downstream. Magnetic field measurements were collected across a dense grid spanning the full dam footprint. Two-dimensional and three-dimensional ECD models were constructed and analyzed against all available site information.

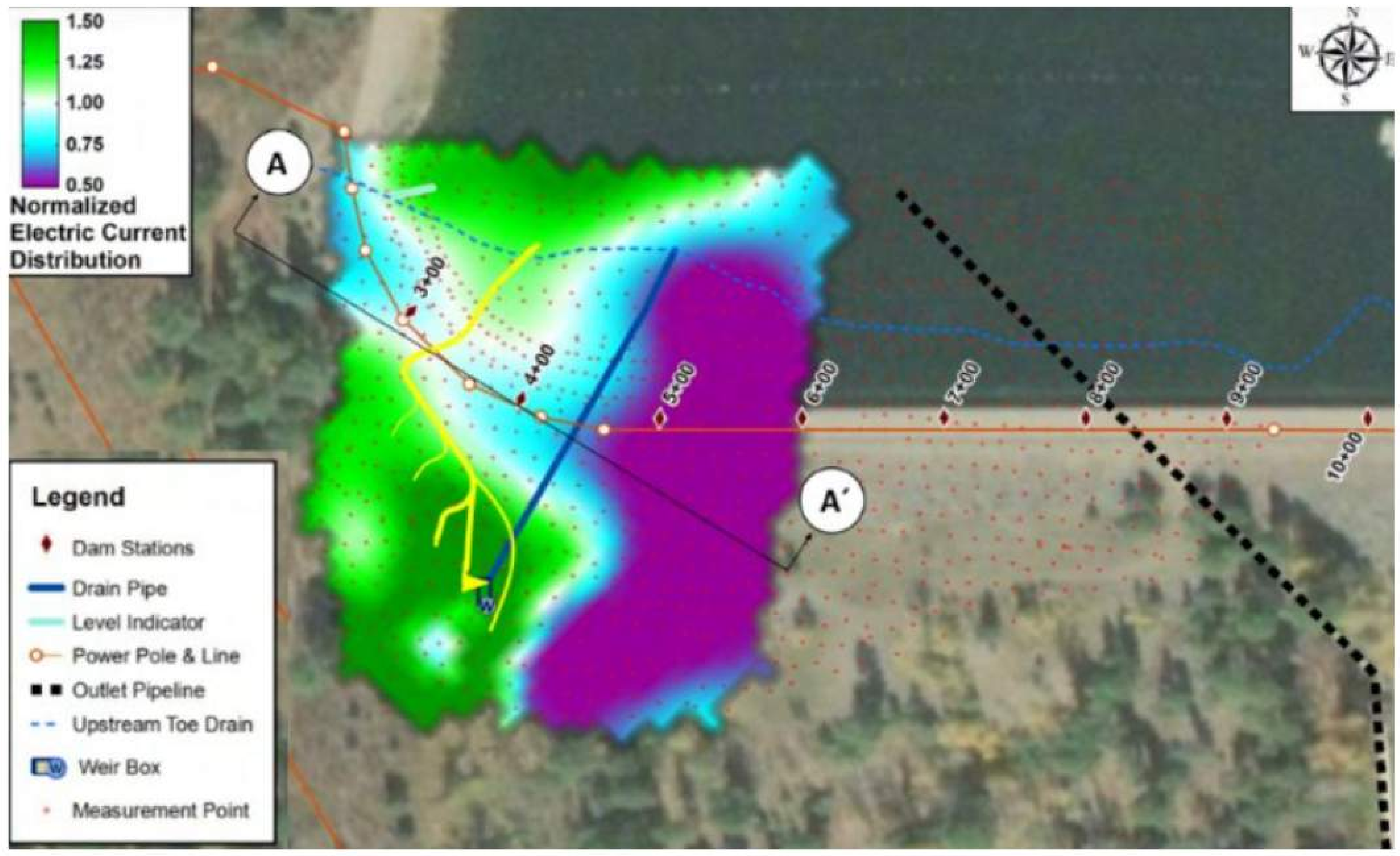


Terminal Dam Survey Layout — electrode positions, circuit wire, measurement grid, and infrastructure overlay.



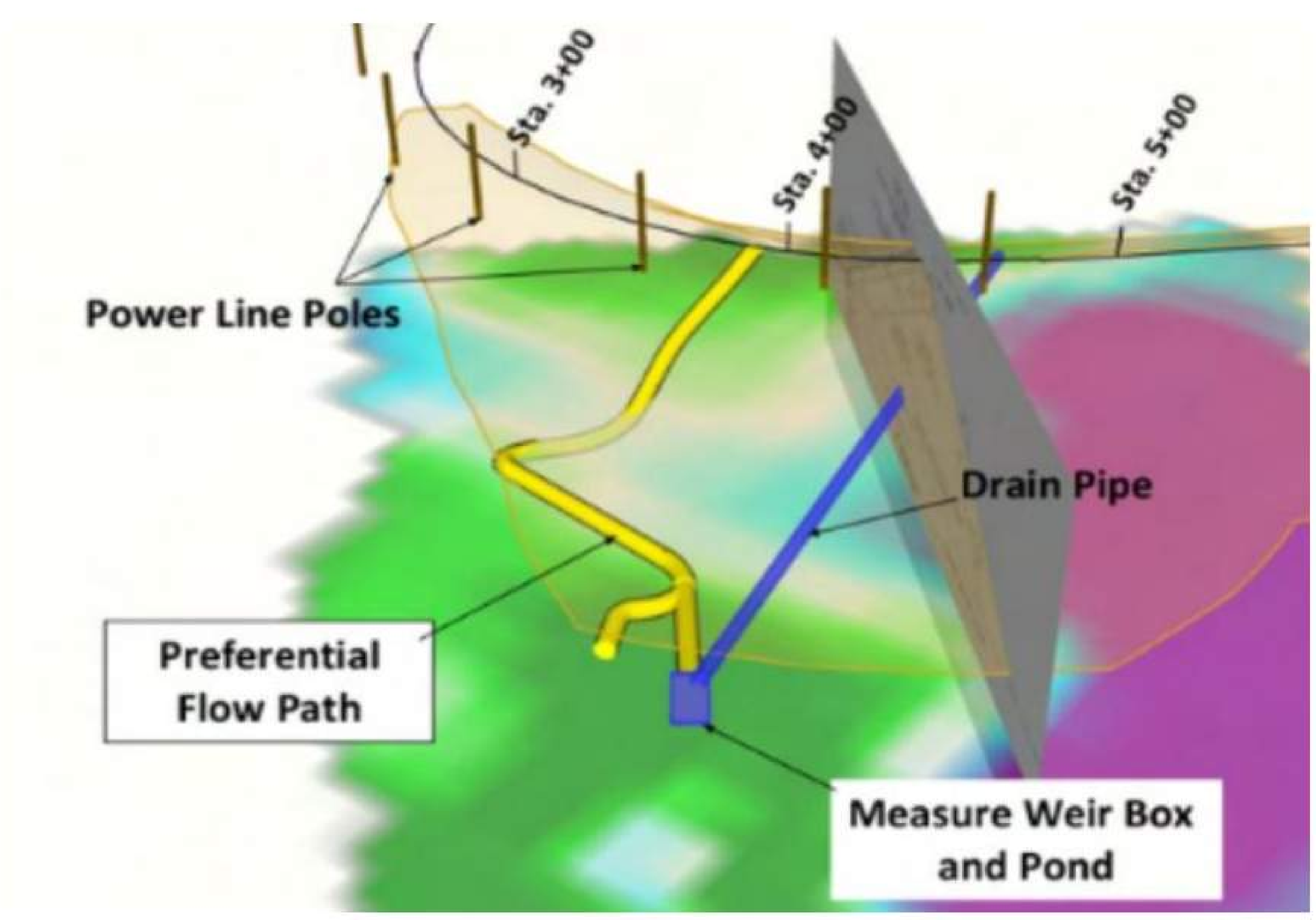
Predicted Magnetic Field Map: theoretical homogeneous model baseline used as the anomaly detection reference. Field intensity in picoteslas (pT); contour interval 50 pT.

The investigation successfully pinpointed a 12-inch diameter hole in the asphalt liner near the upstream toe of the dam. The ECD model resolved the flow path both upstream and downstream of the crest, with the expected signal attenuation beneath the crest due to the increased depth of the current path and interference from the power line along the crestline.



ECD Model Slice at 8,330 ft elevation: plan view of normalized electric current distribution. The preferential seepage path is clearly identified in the right valley section upstream and downstream of the dam crest.

The Willowstick Instrument enabled precise identification of a discrete 12-inch liner defect in a large, complex earthen dam — a result that eluded conventional investigation methods. The survey-guided repair program restored dam integrity and continuous hydropower operations, while the comprehensive investigation confirmed that no broader structural deterioration was present. The 40-year-old asphalt liner was found to be in otherwise good condition.



3D visualization of the discovered preferential flow path. The yellow trace identifies the seepage route from the upstream liner defect through the embankment to the downstream collection system.

4.2 Tailings Dam Seepage Path Mapping — Multiple Sites (IMWA 2017)

Publication: Urlich, C., Hughes, A., and Gardner, V. (2017). Tailings Seepage Paths Mapped Using Electric-Based Technology. Mine Water and Circular Economy, IMWA 2017, Lappeenranta, Finland. 2

A peer-reviewed paper presented at the 2017 International Mine Water Association Conference documented the application of the Willowstick electric-based survey method to three tailings dam seepage investigations. Authored by representatives of AECOM, Atkins Global, and Willowstick Technologies, the paper demonstrated the instrument's capability across three distinct tailings storage facility configurations.

Tailings Dam Study 1 — Fault-Controlled Seepage, Right Abutment

A valley-fill TSF with observed seepage at both dam abutments was investigated using six survey configurations. No preferential seepage paths were identified in the left abutment — current distribution was observed to be uniform across all three left-abutment surveys, providing a reliable negative result. At the right abutment, two discrete seepage paths were confirmed independently across all three survey configurations, each following the alignment of a pre-identified fault zone in native foundation materials beneath the dam.

Tailings Dam Study 2 — Foundation Seepage, Newly Constructed Dam

A newly constructed tailings dam experiencing seepage at its downstream toe was investigated to delineate flow paths and assess risk to the dam structure and an adjacent open pit. The Willowstick survey identified primary and secondary seepage paths in foundation materials beneath the dam, confirming that the dam structure itself was not implicated — internal erosion and piping of the embankment could be ruled out. Subsequent targeted drilling confirmed the survey findings. Remediation planning proceeded at significantly lower cost than would have been required without the survey.

Tailings Dam Study 3 — Complex Multi-Phase Investigation

A two-phase investigation of a TSF and associated waste rock dump was conducted to identify seepage paths through, under, and around the tailings dam, and to assess deeper seepage beneath a 2-kilometer drainage collection trench. Phase 1 identified an unexpected seepage pathway into the TSF through a buried former drainage channel beneath the dam's wing wall — a discovery that would not have been possible without the spatial continuity of the Willowstick survey approach. Phase 2 confirmed primary seepage paths beneath the waste rock dump aligning with pre-existing drainage channels.

The paper concluded that non-intrusive electric-based geophysical technology can be effectively applied in an observational approach framework — as described by Peck (1969) — to supplement conventional geological, geotechnical, and hydrological data. This approach enhances understanding of seepage conditions, informs dam design updates, and supports long-term safety and closure planning for tailings storage facilities.

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