Water Borne Resistivity Imaging for Surface-groundwater Interaction (HERBI) and on-farm-based TEM Aquifer Mapping (AgTEM)

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Abstract

In the Australian context, there have been opportunities to apply geophysics in agriculture. Two tools have been prototyped and progressively improved since 2002. The first is HERBI (Hydrographical Electrical Resistivity and Bathymetry Imager) which conducts multi-depth substrate electrical resistivity imaging beneath freshwater and brackish waterbodies using a streamer of electrodes. It is used principally to guide seepage remediation work on irrigation canals but also detects saline inflow into rivers and drains. The second is AgTEM-cart (Agricultural Transient Electromagnetics cart) which is a towed TEM platform for on-farm aquifer mapping. It is specifically designed for quick, easy and robust farm aquifer mapping.

Waterborne Resistivity Imaging

Seepage beneath earth irrigation canals and reservoirs can either be treated as a loss or a recharge opportunity but whichever way it is managed, geophysics is important for revealing the complicated recharge pathways through which seepage escapes. Resistivity imaging is useful for this purpose as seeped water will always be about the same salinity, thus resistivity, as the surface water. It will contrast either with salinity concentration in soils (in low flow regime alluvium that holds saline moisture within clay) or with resistivity of air voids between gravel (in high flow regime glacial alluvium that cannot hold soil moisture). Either way the seepage pathways are usually resolved.

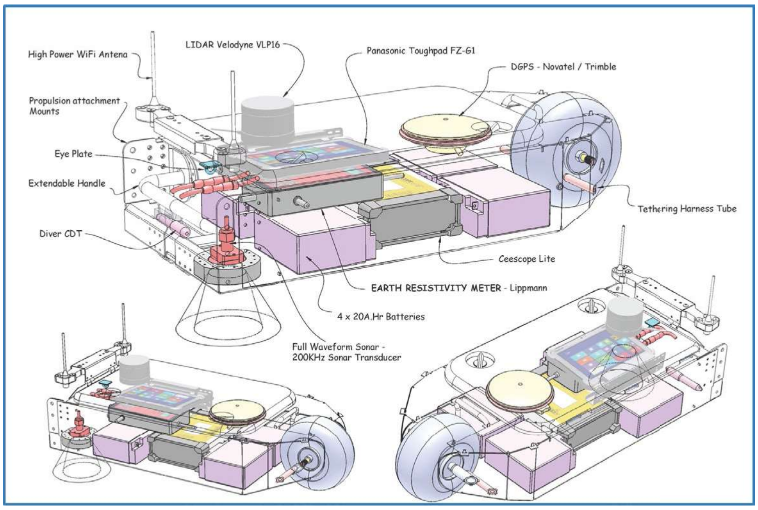


Figure 1: The HERBI system in the PlatypusUSV with propulsion system and tether removed.

Figure 2: HERBI survey using a fold-in boom extending from the side of a vehicle and occasional detachment and manual manoeuvring.

Irrigation canals are managed with varying degrees of attention yet typically have numerous obstacles along them including:

- Flow control gates such as flume gates or drop boards
- Fences,
- Water weed,
- Some exceptionally shallow water
- Bridges, &
- Culverts.

Any technology designed for use on all but the biggest of canals must be designed to work efficiently around such obstacles. Remuneration for canal geophysics can be low such that it may not even be considered if efficiency at passing obstacles is not impressive.

HERBI and Platypus USV solutions

The solution of Groundwater Imaging P/L has been to create a compact, lightweight geo-electric, full-waveform sonar and DGPS payload (HERBI – Hydrographical Electrical Resistivity & Bathymetry Imager) which is typically mounted within a fully watertight unmanned boat (PlatypusUSV) (Figures 1 and 2) that is easily manoeuvred around obstacles and relaunched by one or two people. Control is via WiFi link. On irrigation canals it is typically dragged along using ropes, either by a fold in boom protruding from a 4wd (Figure 2) or by persons walking on each bank carrying telescoping poles for passing ropes around in-water obstacles. The payload is also used from manned boats. The PlatypusUSV is designed with an optional clip-on propulsion system which can be useful in some situations. For bathymetry alone, the clip-on propulsion system is very practical. Typically, for geo-electric surveys, the pull-by-rope system is preferred due to its light weight and simplicity, and because only a low drag streamer can be pulled by the battery powered propulsion system. With the whole system delivered in a half-pallet box, a crew using the pull-by-rope system may achieve 6km/day on the most obstructed, abandoned, overgrown canals or easily attain 20km/day where bank access is maintained. Using the system in Figure 2, a single operator has achieved 28km/day.

PlatypusUSV is designed with a wheel in its nose which is very important, not so much for rolling around obstacles but more so for rolling PlatypusUSV down steep banks into the water without needing to climb down and up the banks. The top of PlatypusUSV is designed, when antennae are temporarily folded flat, to pass under low bridges and through flume gates (under the control mechanisms) so that it, and the streamer do not have to be removed so frequently. The DGPS antenna is incorporated into the hatch so that it is not exposed to inundation. This design also makes it suitable for use in rapids in upland rivers for connected waters studies (for what it was originally intended).

HERBI is normally used with a 40m or shorter submarine streamer that is dragged on the canal bed. This reveals 8 layers beneath the bed with effective depths ranging from 0.14m to 6m. Each layer uses a quadrupole (set of 4 electrodes) in the streamer as presented in Figure 3. Normalized depth of investigation curves indicate investigation depths of each quadrupole and these are presented in Figure 4.

HERBI uses the Lippmann 4-point light earth resistivity meter, Geotest hydrographic extension, and Cee Hydrosystems CeescopeTM full waveform sonar and DGPS system. The Lippmann earth resistivity meter has proved to be effective in this context as demonstrated by examples given below. Independently adjusting gain for each quadrupole measurement, it quickly switches through all quadrupoles without suffering from the amplification and noise rejection impediment of tying all channels to a common ground such as is done in some other systems.

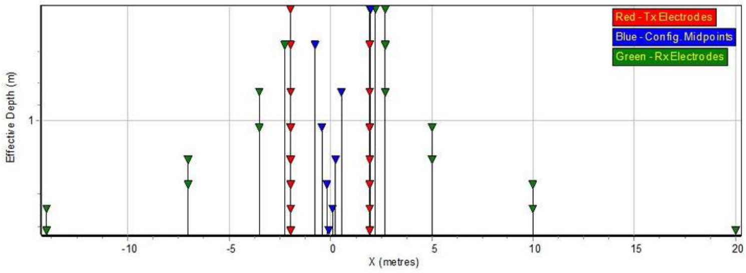


Figure 3: Electrode positions of quadrupoles, plotted on the y-axis at their respective effective depths, of a 40m long 11 electrode submarine streamer typically used with the HERBI system.

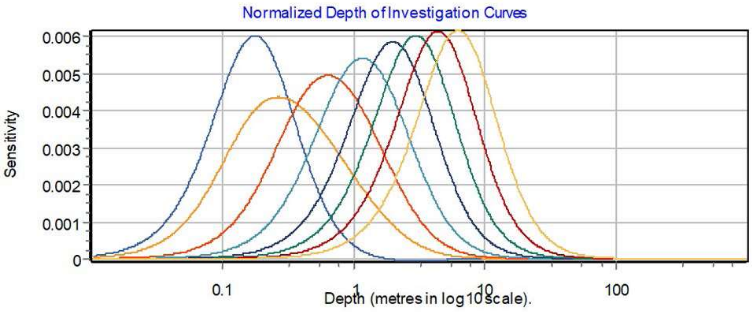


Figure 4: Normalized depth of investigation curves for a 40m long 11 electrode submarine streamer typically used with the HERBI system.

On rivers, a low-drag floating streamer 100m long is often deployed with HERBI and can image 30m deep but only from the water surface. With inversion software that incorporates the water depth into the inversion it is still possible to get reasonable near bottom resolution and this is very useful for detecting saline groundwater upflow, and potential upflow where there is still a thin fresh waterlogged sediment layer at the river bed. On irrigation infrastructure, the survey purpose is usually seepage remediation and for this purpose detail just beneath the bed is important so a submerged streamer is used instead. Water in canals typically ranges from 0.5 to 3m deep and it is easy to submerge a streamer to the bed in such depths. Reservoirs may be 6m deep and more and are more challenging to survey as a weight needs to be added to the streamer in front of the first electrode. For seepage projects presentation of data as submerged apparent resistivities with respect to effective depth suffices and keeps costs low however inversion can be conducted.

The CeescopeTM is a product with a wide market and rapid ongoing development. Its DGPS and full waveform sonar are already being used in HERBI effectively. Extended telemetry facilities, fully autonomous operation, and other sensor integration are possible with this product. Some experimentation using LIDAR to map irrigation canal bank profiles and freeboard during HERBI survey has occurred leading to the conclusion that it is technically feasible but not within the budget of typical seepage surveys.

Waterborne Case Studies

Four case studies of HERBI survey are given:

- **I.** A single irrigation canal,
- **II.** Sludge characterization,
- **III.** A reservoir, &
- **IV.** An entire irrigation district.

Case study I: A Single Irrigation Canal

Figure 5 presents a HERBI survey along a single irrigation canal. Data is projected 10m up from the canal within Google Earth in a compact KMZ file that the layman can generally open and manipulate. For seepage remediation here, the resistive areas extending from the canal bed right through past 10m are targeted. Resistive features closed off at depth are reported by local farms as soaks while those that are not closed off are typically unknown seepage losses as they are not causing localized waterlogging problems. Other resistive features are covered by conductive clay and also are of little concern. Thin resistive layers such as above sample site K13 can be wind-blown sand which can cause lateral seepage.

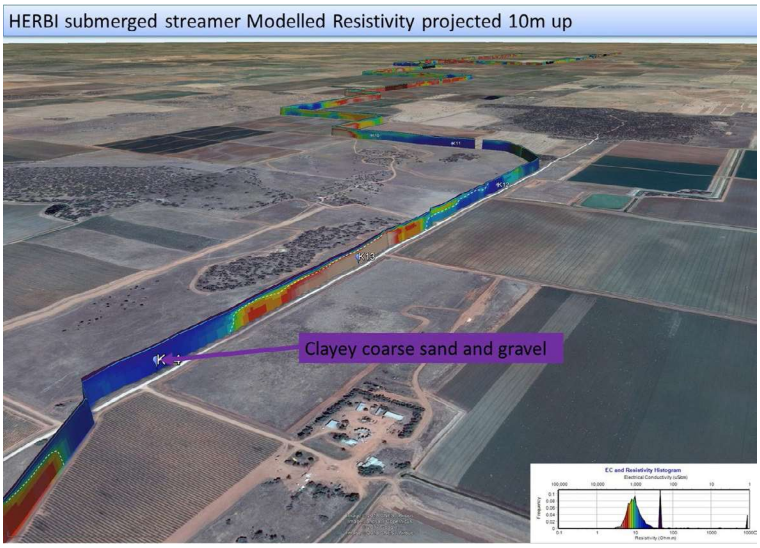


Figure 5: A sample of HERBI submerged streamer resistivity data collected along an irrigation canal. Data is projected 10m up and an aqua colour line indicates water depth.

Figure 6: A sample of sludge thickness characterization using full waveform sonar. Conversion to actual thickness requires localized calibration.

Case Study II: Sludge Characterization

Figure 6 presents a sample of data where sludge thickness has been characterized from full waveform sonar data. A pattern can be observed as the boat passed from bank to bank which can only be caused by sludge differences. Typically sludge is cleaned by long reach excavators working from one bank. The excavator reach, when not sufficient, leaves sludge along one bank. The pattern presented in this example does not reflect bathymetry.

Case Study III: A Reservoir

Figure 7 presents a survey across a reservoir. A dense line spacing of 10m was selected for this survey which feels frustratingly trivial while surveying but the whole survey was still completed in 2 hours on-water time. The dense line spacing proved to be highly useful as the sedimentological features of the site are of less than 20m width. Without such detail they would not have made sense. Remediation of a site like this involves cutting into the clay portions and lining the siltier (higher resistivity portions). Potentially, the resistive end could be partitioned off and developed into a dedicated recharge pond.

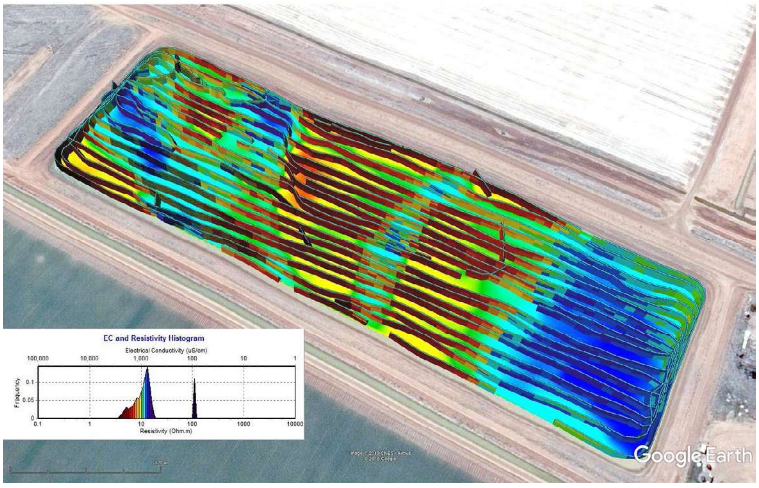


Figure 7: A 10 hectare farm dam surveyed with HERBI submerged streamer at 10m line spacing. Resistivity data is projected 10m up. The histogram indicates a separate peak for surface water.

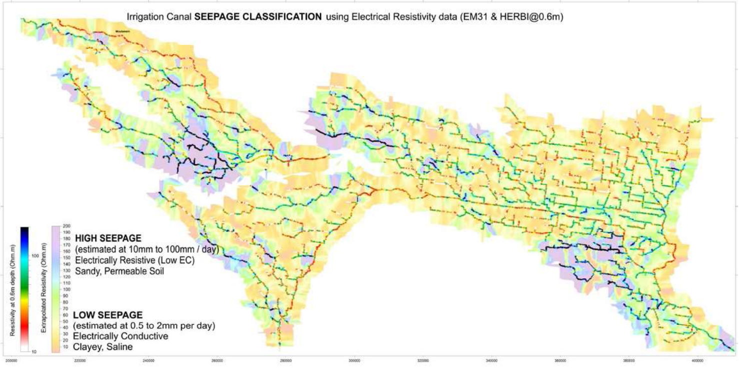


Figure 8: HERBI data combined with EM31 data using histogram calibration for 3000km of irrigation channels in a 220km wide irrigation area.

Case Study IV: An Entire Irrigation District

Figure 8 presents the highly beneficial result of surveying all the canals in an entire irrigation district. There are 3000km of canals in this example. A characterization of all the high recharge areas emerges and the sedimentary connections between them become evident. Classification by means of resistivity becomes robust when completed on such a scale. In order to cover this area within a suitable budget, many smaller canals had to be covered simply by driving a frequency domain electromagnetic bulk soil electrical conductivity meter (Geonics EM31) on a quadbike along at speed somewhere in the vicinity of the canal. Such data is of low quality for various reasons yet could be integrated with the robust HERBI data collected along backbone canals using a method of calibration dependent upon comparison of histograms of data collected in common areas. At this scale, the level of detail cannot be appreciated but the overview is equally important.

On-farm TEM Aquifer Mapping

Towed transient electromagnetic imaging is effective for mapping shallow aquifers and their connectivity with the surface. It is particularly good for detailing recharge heterogeneity and recharged water flow pathways, which can often be irreducibly complicated, much to the frustration of surprised engineers trying to design recharge works. In Australia towed TEM is used presently mainly for coal mine approvals (identifying recharge heterogeneity) and for siting bores but has tremendous potential for designing managed recharge projects on farms. Legal impediments to agricultural managed aquifer recharge presently prevent such projects where recharged water rights transfer to the Commonwealth government as the water recharges.

The great advantage towed TEM has for designing recharge works is the rapid mapping of the substrate at a level of detail necessary to define sedimentological and other geological features. Permeability of a point bar sand deposit may contrast with that of a floodplain clay by around six orders of magnitude so for recharge works design, all such features need to be mapped in three dimensions. Towed TEM can traverse terrain to give detail at much less than 10 metres horizontally and less than 2 metres vertically when required.

Just like with canal imaging, farm mapping is only cost effective if the numerous obstacles on farms can be passed practically and efficiently. These include (not all on the same site):

- Abundant farm gates,
- undulating ground (often with tussocks of grass on the top of humps),
- ploughed ground,
- sensitive and tall row crops,
- regularized orchard tree spacing,
- public roads with traffic,
- native tree and weed regrowth,
- rocks, stumps and trenches hidden in long vegetation,
- tyre puncturing thorns,
- creeks, &
- bogs.

Figure 9: AgTEM towed transient electromagnetic system – an overview reveals the loop layout (the receiver loop is in the central plane).

Some of these obstacles are as much of a challenge to the towing vehicle as to the towed cart.

AgTEM-cart

The AgTEM-cart has been developed for conduct of towed TEM survey in Australia. The latest prototype is presented in Figure 9.

AgTEM-cart History

Since 2002 many prototype towed transient electromagnetic systems (AgTEM's) have been developed resulting in the current commercial version, AgTEM4. Early versions were towed sleds of slingram (receiver and transmitter loop widely separated) or central loop configuration. Most had wheels and an axle at the front of the sleds and were towed by ropes from a vehicle housing the electronics and batteries. Early versions used Zonge electronics and later versions use the Monex Geoscope TerraTEM. Work on a dedicated electronics package is underway and since currently AgTEM-cart uses off the shelf electronics systems, the rest of this paper will focus mainly on the cart design, not the electronics. More recent versions of AgTEM-cart are all mounted on wheels and have a null-mutual induction coupling arrangement between the main receiver and transmitter loops. This arrangement keeps everything in the one cart coupled rigidly with the towing vehicle such that logistics are quicker and complications at obstacles and when passing sources of interference are less drawn out. AgTEM-cart is occasionally used with a separate, additional slingram receiver as there are some benefits with this configuration.

A Comparison of Towed TEM Design Options

The simplest loop configurations (Co-incident loop and In-loop) that centre the receiver loop with or within the transmitter loop lead to extremely high primary field pickup in the receivers. This results in severe primary field overprint on data and necessitates turning amplification down so far that little useful data can be collected. In-loop configuration is, however, simple to implement in a towed trailer and has been chosen as a solution in many early towed TEM systems in Australia (Allen, 2007, Barrett et. al., 2006, Harris et. al., 2006).

Another configuration separates horizontal coplanar loops – the Slingram configuration. It is used in the tTEM towed TEM system of Aarhus University Hydrogeophysics Group (Auken, 2019), its ancestor – PATEM (Sorensen, 2000) and occasionally as an additional configuration with the AgTEM-cart.

The impediments of using a Slingram system are:

- For every setup and pack up there two sleds/carts to pack rather than one. For small jobs or jobs requiring frequent equipment pack up to pass along busy roads this can break viability.
- For every traverse near a metallic obstacle or buried insulated cable, both the receiver loop and transmitter loop must pass and all the data in between needs to be rejected. Toft, 2001, compared the response of Slingram and in-loop TEM systems to shallow three dimensional resistive and conductive bodies. He presented modelled results that revealed that 1D inversion of Slingram data (not horizontally smoothed) over such bodies results in erratic and confusing responses. In practice, Slingram data must thus be horizontally smoothed prior to submission to 1D inversion. This limits the footprint of the configuration considerably, and, as a side effect, results in the need for considerable blanking zones over buried cables and other such cultural effects. The footprint can be so wide that it cannot be used to detect small prior streams.
- If a two cart/sled system must be towed then for every farm gate or other obstacle both have to pass through. On tight bends or sloping ground the rear one tends to catch on one gate post and in the worst case will tug on the front cart/sled and overturn it, also ripping apart and stretching sensitive wiring. This can be avoided with care, frequent stopping and returning to slide the sled sideways, or by using a second person walking beside the second sled to try to direct it appropriately.
- Two cart/sled systems tend to slide down side slopes including irrigation canal banks, particularly at corners.
- Two cart/sled systems tend to drift sideways on public roads or road margins and have been lifted metres into the air by draught from passing trucks and willy-willies. Getting approval for use on roads is not appropriate.
- Two cart (not sled) systems connected only by rope can roll uncontrollably on steep hills.
- If slingram is conducted with the transmitter cart behind the towing vehicle and the receiver mounted up high in front of the towing vehicle then manoeuvrability is excellent yet such a system has increased inductive coupling with the towing vehicle which must be stable and removed in processing. With AgTEM-cart this has proved to be effective with the coil suspended in a gimbal-mount but is rarely used due to the extra setup cost.
- Most Slingram systems use skids for at least part of their support. On bitumen roads and even gravel, these wear out rapidly and require replacement frequently.

AgTEM-cart uses, for its primary receiver, a null-mutually coupled receiver integrated into the cart core (See Figure 9). Impediments of this system are:

- System response stability demands that the relative loop positions of parts of loops in close proximity remain constant. If they do not then system response will vary during survey and processing integrity will be affected. True pure time domain waveform propagation is a practical impossibility so system response will always need to be removed. The AgTEM cart manages the dimensional stability requirements by keeping the receiver loop and transmitter loop parts that come within 600mm of each other either within the rigid core of the cart or within taut, firmly-held wires extending from the front upper corners. When elastically held booms are folded backward to pass obstacles (Figure 11) then the null-coupling is temporarily disrupted and the result is readily detected and rejected later in processing by monitoring within the ramp. After obstacles are passed, booms spring back into their fixed positions. The transition from fixed to retracted is abrupt due to the tension in the elastic cords leading forward.
- The near-surface is highly energized in close proximity to the receiver. Any induced polarization, super-para-magnetic effect or other behaviour that responds slowly to energization will overprint late time data. AgTEM-cart keeps the transmitter loop 1.8m off the ground minimizing such problems.

AgTEM-cart Design

The AgTEM-cart is designed principally as a practical collapsible structure for suspending a 6m wide 32.52 square metre transmitter loop and for keeping it separated an acceptable distance of over 5m from the towing vehicle. Also integrated into the design is a 10 turn times 2.06 square metre null mutually coupled receiver loop in a plane 600mm below the 1.8m high transmitter loop. The drawbar for the cart is collapsible and after extending, the cart is lifted up into place by a fixed winch near the tow hitch. A patented arrangement suspends booms, pivoting from ball and tendon joints, such that they are held in exact place by the weight of the transmitter loop combined with two elastic cords extending to near the tow hitch.

Figure 10 reveals how the skid plate design in the AgTEM undercarriage handles rough terrain and hidden stumps.

Figure 11 reveals how AgTEM-cart folds to travel through narrow gaps and down roads. Indicator, brake and tail lights are installed for travelling in traffic where it may be managed in a similar manner as a portable grain auger.

Figure 10: skid plates on the AgTEM-cart undercarriage and 600mm ground clearance permit traversing of exceptional terrain.

Figure 11: AgTEM-cart booms fold backward permitting width reduction to 1.8m. Signal lights and reflectors facilitate travel in traffic.

The structure of AgTEM is made from sailing ropes (Kevlar), specialized mouldings and fibreglass. AgTEM wheels are jog cart wheels with solid urethane tyres fitted under Kevlar bead skins to prevent punctures. Suspension is instead supplied by airbags.

The cart has been tested over rough terrain yet the suspension of the transmitter loop and the angular inertial of its large dimensions dampen the impacts on the cart that affect data quality. The loop sways but as long as the critical front parts are held taut, then synchronous movement of the remainder has little effect on null coupling. All lengths sway one way then the other but loop area remains similar.

When travelling through and brushing against trees the loop is often ripped off at designed in weak joins (cable ties) which are quickly and easily replaced.

Future Towed TEM Designs

Using the same ball and tendon design as AgTEM cart, Groundwater Imaging P/L is currently building an electrically propelled single wheel system that may be manoeuvred through difficult vegetation including orchards where a regularized 6m wide space is maintained under trees for harvesting equipment to pass.

AgTEM Data Processing

AgTEM data now is primarily processed within the Aarhus Geosoftware Workbench package. Preprocessing commenced in our own software includes GIS based interactive data filtering, booms retraction affected data removal, system response estimation, system response removal, bin aggregation after cultural noise investigation and movement noise removal. We find collection of data in numerous narrow stacked time bins is very useful for cultural noise investigation but then resampling is essential prior to inversion for efficiency reasons.

Groundwater Imaging P/L also use our own software to convert results into a compact format laypersons can open and view in Google Earth.

Depth of Investigation

A 6m wide loop helps increase depth of investigation compared to a smaller loop and increasing the loop turns and current can help more but there are limits to the ranges that are possible. Further, other factors including processing filters, smoothing, lateral constraint, and system response removal all can affect depth of investigation. For this reason it is important to verify depths of investigation through geological means such as tracing a dipping feature to increasing depths. Sea water intrusion is one of easiest features to trace. Increasing power, loop area, loop turns and/or receiver sensitivity can do nothing to assist with non-geological systematic noise sources including system response, fence pick up or buried insulated cable pick up. Apart from power line noise, almost all non-geological noise sources are amplified by signal increases such that improved system performance makes no difference to depth of investigation once the noise source takes precedence. Calculated depths of investigation cannot account for such non-geological noise sources.

AgTEM-cart used with 10 Amps and 1 or 2 turns in the transmitter loop and no pre-amplification has always generated useful data to around 30 metres deep (see examples below). Sea water intrusion has been traced to 90 metres deep (see the example below) but on routine high productivity surveys with such electronics generally data beyond 30m deep is treated with caution. This limit is, however, largely a limit from the 3rd party electronics that historically has been available to us. Additionally, fence effects are observed to influence data generating false conductors at very approximately the depth equal to separation from the fence. Some fences can even be straddled while others have a very strong influence. On some farms the fence network is so dense that refusal to survey is the only acceptable solution. Telephony cables have been our worst consumers of depth of investigation.

The shallow limit of depth of investigation is dependent on a combination of factors but keeping loop turns to a minimum, clamping voltage of the transmitter high, and loop proximity to each other and to the ground small are all important. AgTEM-cart keeps loops close together but the receiver remains 1.2m off the ground to help with manoeuvrability over tall vegetation. With currently available electronics this is not a limiting factor, rather sampling rate is the limit. If shallow investigation is required then frequency domain electromagnetics is recommended instead. In inverted data we obtain from AgTEM with a 6µS ramp we typically discern slight but meaningful contrast between 1 and 2m depth slices in smooth model inversions and good contrast between 2m and 4m depth slices.

Aquifer Mapping Case Studies

Two case studies of AgTEM-cart data are given:

I. A 375 Hectare reservoir survey and
II. A coastal irrigation delta.

Case Study I: 375 Ha Reservoir Survey

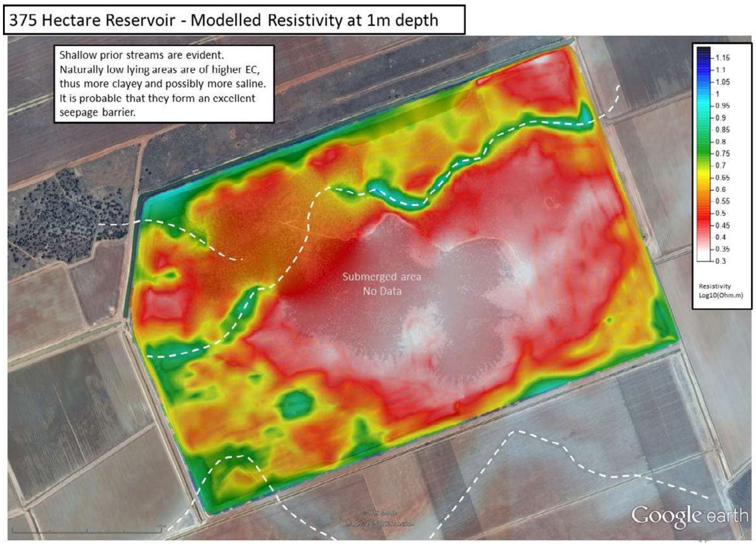
In one day, AgTEM-cart was used to survey a farm reservoir to investigate seepage losses. Figures 12 and 13 present two depth slices of interest. At 1m deep a small prior stream is observed into which water may seep. Other high resistivity features are less obvious but when the 12m depth slice and deeper slices are observed it is evident that the prior stream is closed off at depth yet the other high resistivity features open up. They are deep recharge features.

Case Study II: A Coastal Irrigation Delta

An early version of AgTEM-cart was used with a Slingram receiver to collect data over a coastal delta, principally along rural roads. In this region, farming interests dominate and extensive recharge has historically been executed for decades to abate seawater intrusion into bores used for crop irrigation. Figure 14 presents data projected 100m up. This data has revealed lenses of fresh water in sediments as an intermediate resistivity over very conductive seawater intrusion which is traced down to about 90m deep intersecting very resistive basement rock.

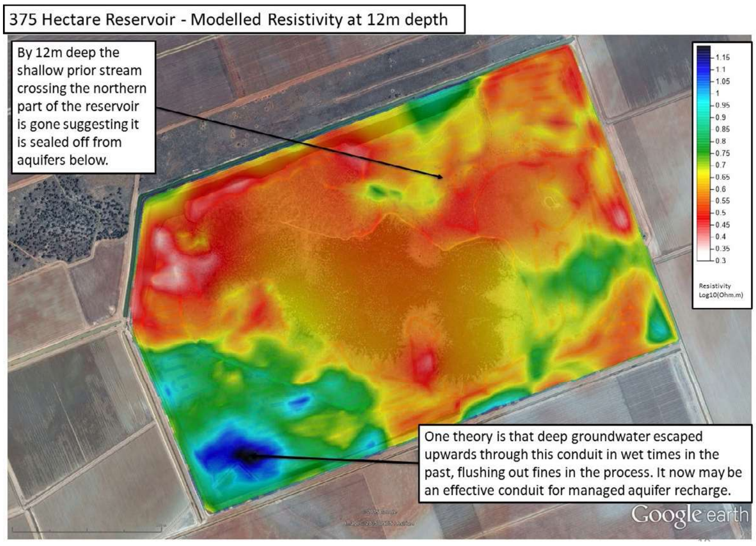
Conclusion

Two tools for investigating recharge and shallow aquifers have been presented. HERBI for investigation from inland waterways, and AgTEM-cart for investigation from agricultural land. Both


375 Hectare Reservoir - Modelled Resistivity at 1m depth

Shallow prior streams are evident. Naturally low lying areas are of higher EC, thus more clayey and possibly more saline. It is probable that they form an excellent seepage barrier.

Figure 12: A 375 hectare reservoir surveyed in one day using AgTEM – 1m depth slice.


375 Hectare Reservoir - Modelled Resistivity at 12m depth

By 12m deep the shallow prior stream crossing the northern part of the reservoir is gone suggesting it is sealed off from aquifers below.

One theory is that deep groundwater escaped upwards through this conduit in wet times in the past, flushing out fines in the process. It now may be an effective conduit for managed aquifer recharge.

Figure 13: A 375 hectare reservoir surveyed in one day using AgTEM – 12m depth slice.

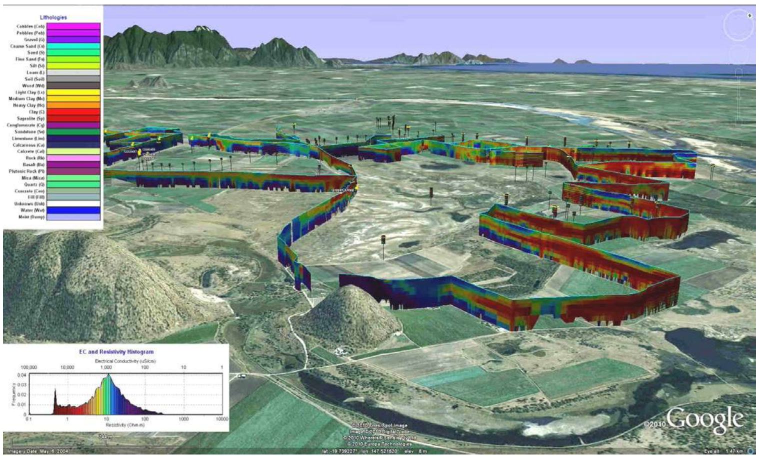


Figure 14: An example of AgTEM-cart slingram data projected 100m up. Highly conductive seawater intrusion from the right is observed extending down as far as 90 metres deep intersecting resistive basement rock near the prominent hill in the foreground. Managed aquifer recharge is exercised extensively in this area to oppose seawater intrusion to bores used for horticulture. Lenses of freshwater (intermediate resistivity) are evident above the saline layer.

are designed and tested with years of Australian and New Zealand survey experience in agricultural areas on budgets obtained principally from agricultural sources. The transition from academic geophysics to solutions that even individual farmers may afford has been achieved.

Both of these tools specialize in creating a high level of spatial and depth detail of groundwater related properties at as low as practical cost, even on small jobs. Recharge (and discharge) heterogeneity has been shown by these tools to greatly exceed that of conceptual models typically envisaged for groundwater and connected water management.

Acknowledgements

Many farmers and farmers' collectives have helped fund this effort and have provided results. Actual locations have been omitted to help protect their interests.

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