Research Programme
- Short Calls, Final Report -

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Host Organisation name	NUIG
Project Title	Geophysical Remote Sensing of subsurface properties for sustainable agricultural management
Contract Number	2017-sc-033

Date: 16/11/18

This report covers the period November 1st 2017 to October 31st 2018

2. (a) Project information:

Final project report (*max **2500**words, excluding figures and headings*):

This proof of concept project starts by integrating airborne and ground geophysics with satellite remote sensing to access surface and subsurface permeability variations over a Teagasc Agricultural Catchment (ACP) which is covered by existing Tellus data, in the context of agricultural management. Acquisition of subsurface data for agricultural purposes is traditionally achieved by *in-situ* sampling over limited target areas (farm-scale ~1km^2) and time periods. This approach is inadequate to enable integrated regional scale (water catchment scale ~100 km^2) management strategies which require an understanding of processes varying over several days for surface zones to several decades in the transition zone (~ 10's m) from surface to bedrock. The project is exploring the best methods to then upscale to Water Framework Directive (WFD) scale catchments and the tools and international collaborations needed to build a functional land management tool for the sustainable management of agricultural intensification envisioned in Food Harvest 2020 and Food Wise 2025.

Increasingly, geophysics and remote sensing are used to provide a multidimensional suite of tools to image the subsurface, and monitor fluid dynamics and biogeochemical processes (e.g., Binley et al., 2015). Attempts have been made to compare Tellus Border airborne EM and geochemical data to published geological information to improve soil mapping (Holdstock 2015). However, little work has been undertaken nationally or internationally to extract more quantitative information (e.g., permeability or clay content as a function of depth) from such datasets, with all the implications for monitoring biogeochemical surface and subsurface processes (Binley et al 2015). Therefore, this seed project combines airborne and ground geophysics with remote sensing technologies to investigate surface and subsurface permeability variations (a parameter that controls many soil functions and groundwater vulnerability) at multiple spatial scales, and as a function of depth. Research questions include how soil texture heterogeneity in surface and subsurface pathways affects the movement (e.g. time lag), concentration and load of groundwater and pollutants migrating through these pathways from farm to regional scale water catchments defined by the Water Framework Directive (WFD). These questions have important consequences for the sustainable management of agricultural intensification envisioned in Food Harvest 2020 and Food Wise 2025, and in light of the EU Habitats and Water Framework Directives, and Clean Air Policy and Soil Thematic Strategies. Subdivision of agricultural landscapes into high and low areas of permeability would allow for the concept of functional land management (O'Sullivan et al., 2015) to become a reality. To achieve this ambitious goal a pilot site with data at multiple spatial scales is required as a starting point.

(i) *Progress* of objectives and scientific/engineering targets beyond the state of the art & *methods* used

Establish a test site within an ACP catchment.

There are six ACP catchments around the country with varying soils types, geology and land use. At the time of writing this proposal only two had coincident Tellus airborne data coverage, Corduff Co. Monaghan and Dunleer in Co. Louth. The Dunleer catchment (Figure 1) had the most comprehensive axillary dataset available and its geology and hydrogeology are well understood (e.g., Thomas et al 2016). The ACP team have carried out high resolution soil type mapping across the catchment and installed monitoring wells and a weather station over the last 8 years. It is approx. 950ha in size, and soils are classified as poorly drained. In this catchment the influence of past glacial movement is apparent with its undulating landscape dissected by ditches and streams and many different deep soil types derived from glacial drift underlain by greywacke, mudstone and limestone geology. The dominant soils in this catchment are typical and stagnic luvisols. In the better drained areas on the head slopes well drained luvisols belonging to the Dunboyne soil series dominate, however, these are often interspersed by smaller areas of brown earths. On the hill slope and foot slope areas, stagnic luvisols belonging to the Fethard soil series, are more prevalent. It has some existing ground geophysics data in two fields within the catchment carried out by the ACP programme in 2010 (Figure 4). The area is also covered by Tellus Boarder geophysical data with the orientation of the catchment providing optimum data coverage (Figure 1).

As a starting point, the 1-D inversion algorithm (UBC-GIF) was used to invert the Airborne Electromagnetic (AEM) apparent conductivities along 17 flight lines for electrical conductivity vs depth across the entire catchment (Fig. 3 and 4). The conductivities across the catchment vary from 0.5 to < 30mSm-1 probably reflects contrasts in superficial deposits which can be correlated with the national soils & subsoils maps for the area which indicate firm to stiff overburden with clay and weathered Mudstone and Greywacks overlying a Mudstone/Greywacky bedrock. This is in agreement with the interpretation of the land based ERT profiles (Fig. 4), taken by Teagasc in 2010, along with seismics profiles as part of the ACP study and known geology of the area. The aim of this inversions was to select possible coincident field sites for field scale land geophysics surveys directly beneath Tellus flights and 3 suitable lines were selected for surveying (Figure 2).

As the AEM dataset has limited resolution in the near surface (<5m). A CMD EXPLORER was used to acquire multi-receiver EM data from the upper 6m in June 2018 across the width of the catchment. As field work was delayed from March to June due to bad weather only the mostly westerly flight was covered with ground geophysics due to crop height and tramline directions. The CMD EXPLORER has three receiver coils at a spacing of 1.4, 2.82 and 4.49m with resultant investigation depth ranges of 2.2, 4.2 and 6.7m. Five lines at a spacing of 12m centred on the Tellus flight line and covering the whole catchment where acquired so as to sample the same footprint as the airborne survey (Figure 3 for example). Each line was surveyed twice (horizontal and vertical coplanar configurations) at a walking pace. This provided resolution in both the shallow and deeper extents of the upper 6m. Several 30m ERT profiles at a 1m electrode spacing were also acquired to ground truth the CMD EXPLORER data during the inversion stage.

The acquired apparent conductivity data are currently being inverted using the EM4SOILS code, a 1D laterally constrained inversion for conductivity with depth. The final inversion of the CMD Explore data has been slowed by an unexpected shift in the raw CMD-EXPLORER data. The reason for this shift is attributed to an internal and unreported calibration within the CMD instrument. An ERT line has been used to calibrate an EM line and a correction can be derived. Testing is ongoing to ensure that the correction is applicable for all EM data acquired. It is recommended that an ERT calibration line be acquired alongside any future CMD-EXPLORER acquisitions. Preliminary results show conductivities varied from 3 to 23 mS/m in agreement with the existing ERT data. Note the low conductivity near surface layer (<1m) reflecting the extent of the dried-out layer during the drought. Once this inversion is complete, we intend to begin forward modelling the airborne EM response and incorporate it into the AEM inversions.

Explore potential research avenues for upscaling

A literature review was carried during the project looking into how joint geophysical inversion strategies coupled to petrophysical modelling (Slater 2007; Hoyer et al., 2015), stochastic modelling (Gunnink and Siemon, 2014), artificial neural networks to relate point or ground-based data sources to regional and airborne geophysical datasets (Gunnink et al., 2012; Kirkwood, 2016), and multiscale power law EM modelling (Beskardes et al., 2017).

The artificial neural networks approach looks the most promising for improved soil type mapping and mapping surface permeability pathways. This is the approach we will apply to the Dunleer dataset and potentially another ACP catchment with contrasting soils and land use. This will include combining near surface multi-receiver EM data with Sentinel 2 imagery and the Tellus radiometric data layers by expanding on the technique presented in (Zara et al 2014). Very little cloud free satellite data hyperspectral data was available prior to 2015 or concurrent with the flight times of the Tellus Boarder survey in 2012. However, the dry summer this year meant we now have high quality Sentinel -2 imagery over the entire catchment. There is also the possibility of including the apparent conductivities of the 24KHz Tellus AEM data (Figure 2) as there are several correlations between the apparent conductivities and the traditionally acquired soil maps (by Teagasc) across the catchment.

The identification of subsurface permeability pathways part of the project is being mapped with the AEM inversions and the next step is to forward model the airborne EM response of the ground-based Geophysics (multi-receiver EM) gathered in Dunleer and then incorporating it within the airborne AEM inversion to improve near surface resolution. However further work is required to investigate the effect of near surface moisture (water content) variations on the EM responses.

(ii) Implementation (please include any issues with timelines, milestones, management etc. or deviations from the original implementation plan)

In order to establish the site in Dunleer, existing ACP groundwater boreholes and soil mapping (physical and chemical characterisation) was collated during Q4 2017 and Q1 2018. Existing ground geophysics data and Lidar was provided by Teagasc in Q1 2018. Very little cloud free satellite data hyperspectral data was available prior to 2015 or concurrent with the flight times of Tellus boarder survey in 2012. However, the dry summer this year meant we now high-quality Sentinel -2 imagery over the entire catchment which we will be able to link with the Tellus dataset (Q3 2018). AEM inversions where completed in Feb 2018 and field sites selected.

As fieldwork was delayed from March 2018 (bad weather) to the start of June only the most westerly of the Tellus flight lines (Line 1799) was accessible due to crop height and tramline orientation. It was intended to carry out a radiometric survey over the same footprint as the ground EM but we had problems with the instrument stabilisation in the field and this was not done. The ground EM data is still being inverted and we are working on the calibration factor for the CMD instrument.

A Poster was presented at 7th annual international workshop on airborne electromagnetics (AEM2018) in Denmark June 16-20th, organised by the Aarhus Hydrogeophysics Group. The poster was very well received and got lots of input from Geoscience Australia and the USGS. We attended a two-day workshop on AEM inversions just before the start of the conference and are considering if the Aarhus method is a more suitable inversion code to the UBC for our needs.

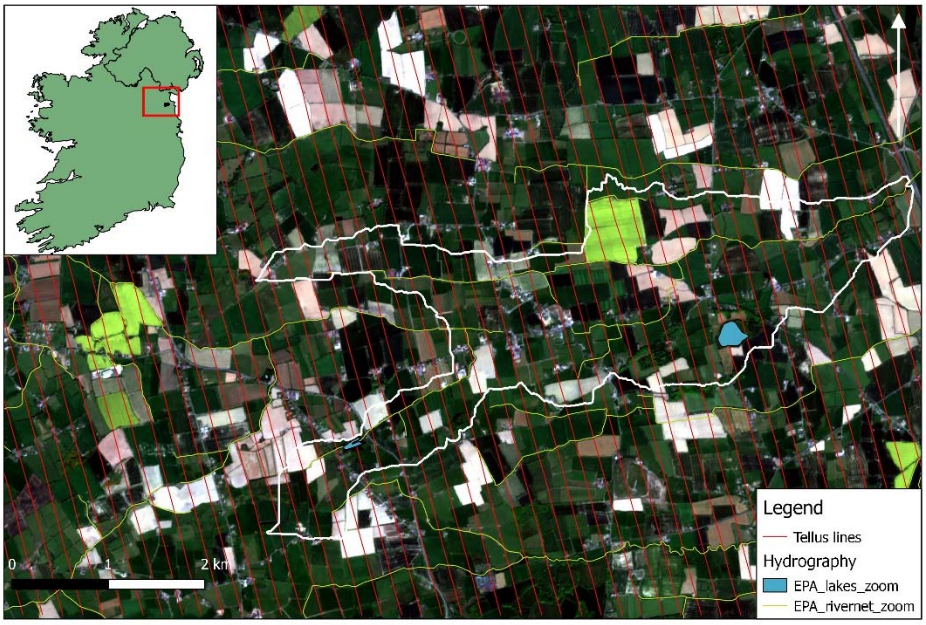

Figure 1: Dunleer Co. Louth ACP catchment location with Tellus survey lines in Red.

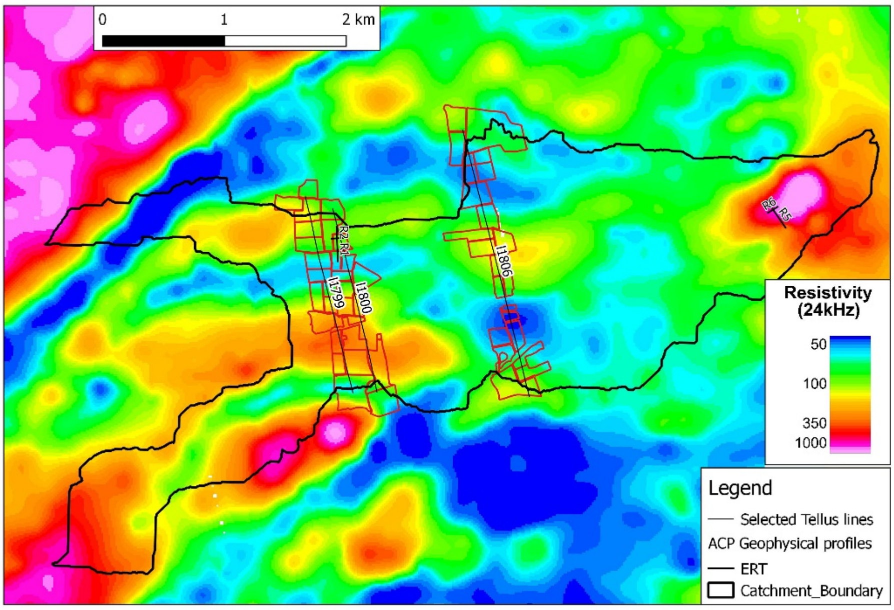

Figure 2: 24KHz Tellus apparent conductivity map. With 3 Tellus flight lines superimposed and field boundaries in Red.

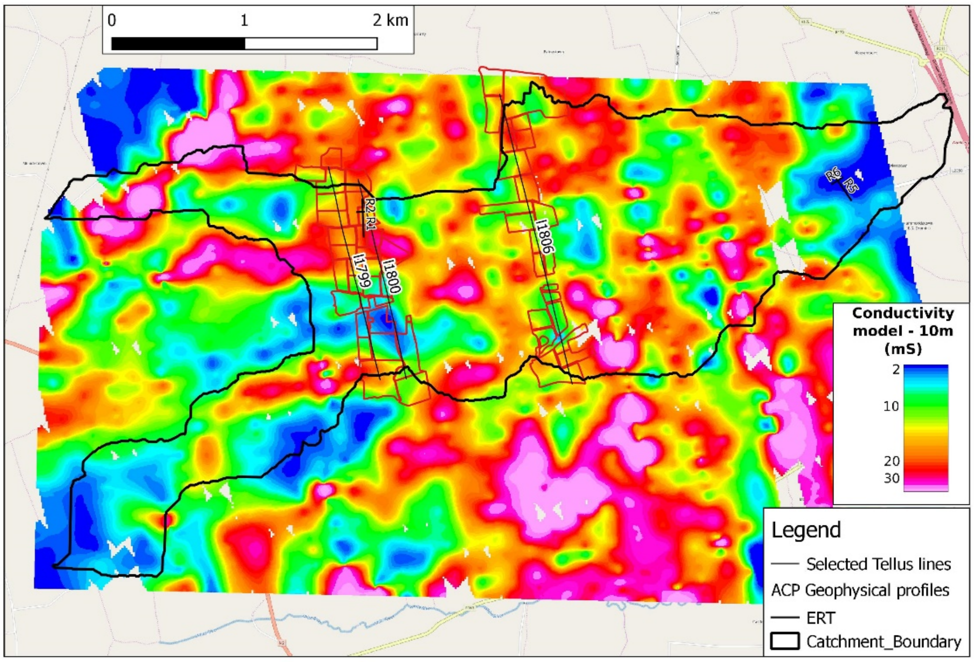

Figure 3: 10m Depth slice through The I-D inversion of the Tellus airborne data over the catchment.

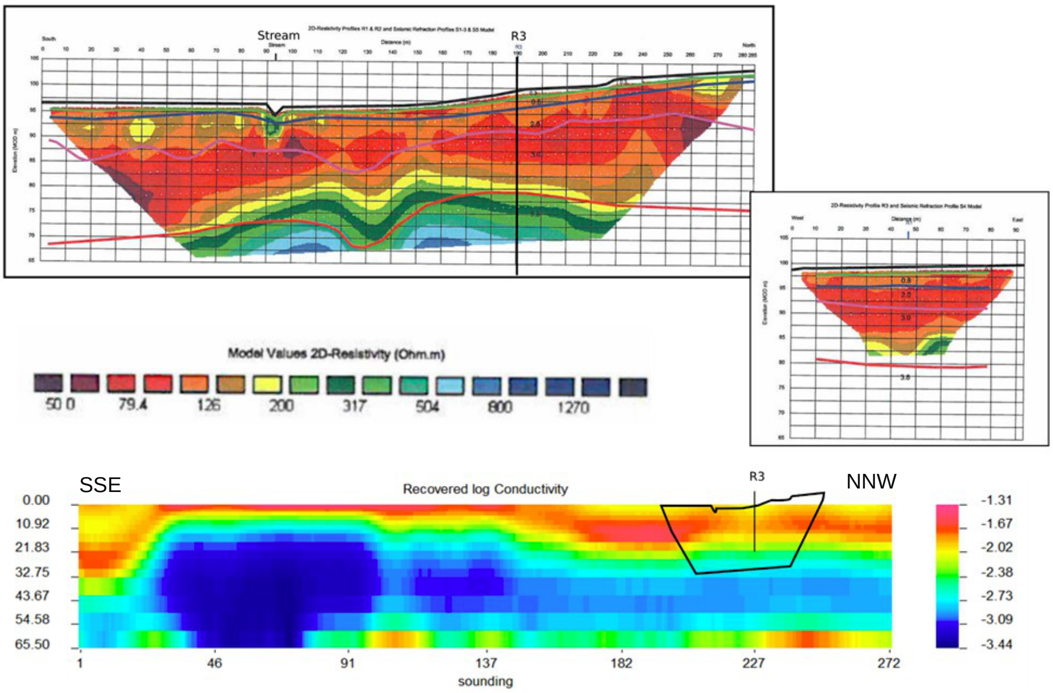

Figure 4: Comparison of coincident near surface ERT profile and Tellus flight line 1800 inversion using the inversion algorithm (UBC-GIF). The ERT was acquired by the Teagasc ACP in 2010. Location of ERT profile denoted by the black polygon on the Tellus profile.

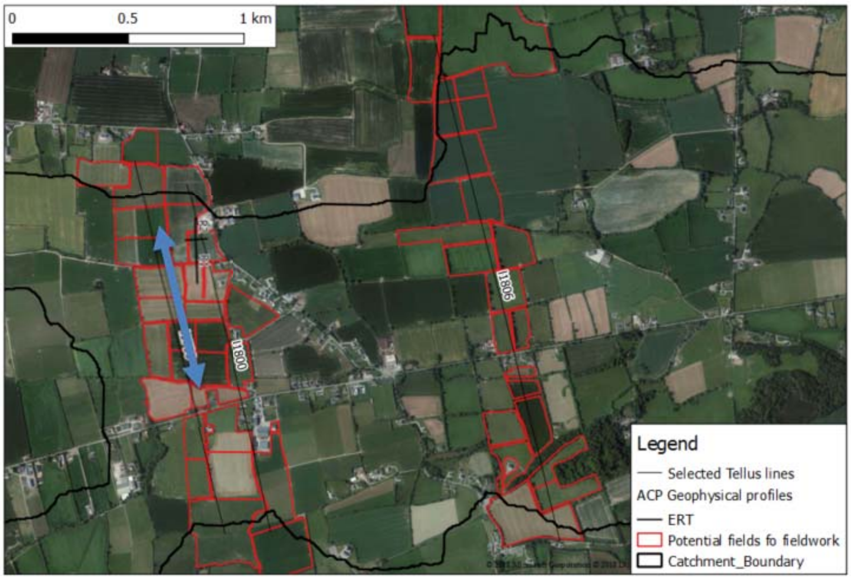

Figure 5: Dunleer Co. Louth ACP catchment location with the 3 Tellus survey lines identified for the field survey. Blue arrow denotes the location of the CMD explorer results in Figure 6&7 below. Note the whole lines was surveyed.

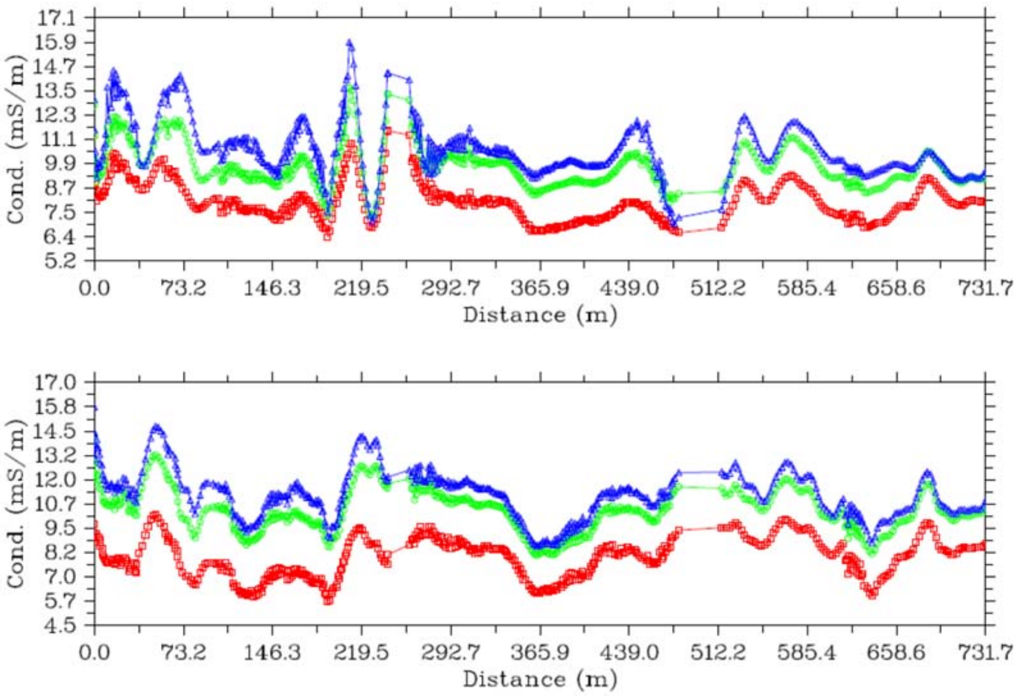

Figure 6: Recorded apparent conductivities from for horizontal (top) and vertical (bottom) coplanar configurations (below) from the CMD EXPLORER

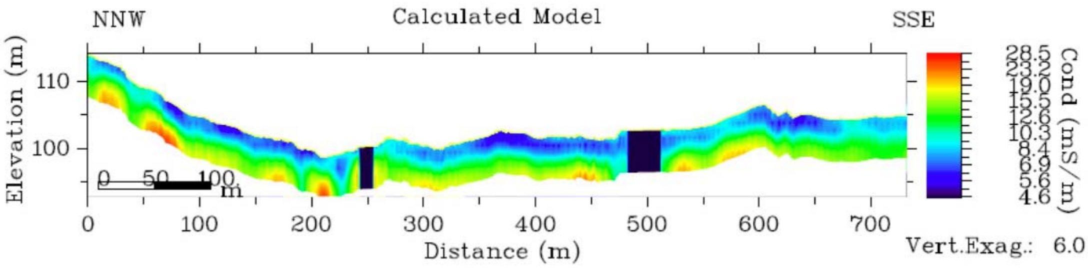

Figure 7: Preliminary inversion of a section of the Multi-Receiver CMD-EXPLORER EM data using EM4SOILS along Tellus flight line 1799. Gaps (navy) in profile are for a road and open field drain.

(iii) Outputs (please provide a short description *and* complete the table below)

One of the main objectives was to apply for PhD funding to extend the work of O'Connell et al. 2017 and develop international collaborations to upscale from ACP to WFD catchments. Dave O'Leary was successfully in his application to the IRC for a structured 4 year PhD starting on Oct 1st 2018. Dave also attended the 7th annual international workshop on airborne electromagnetics (AEM2018) in Denmark on June 16-20th. This was an excellent opportunity at the start of his project to network and he has been invited to spend time in Aarhus Hydrogeophysics Group, Denmark during his PhD working with Dr Anders Vest Christiansen who specialise in time domain EM and more recently in geostatistical modelling and catchment management. Collaboration has been established with Prof Andrew Binley of Lancaster University Environmental Centre. His research interests include groundwater-surface water interaction, fusion of hydrological and geophysical data for improved hydrological characterisation and inverse methods in geophysics. Prof Binley provided his CMD EXPLORER for the fieldwork carried out during the course of this project and is prepared to continue collaboration.

In addition, this project has:

Established a test site in Ireland with all the data needed to address the scale problem in catchment management.

Acted as a demonstration project for the application of Multi-Receiver EM surveys in Ireland. This was the first time such data was been gathered and it offers considerable advantages in the very near surface mapping in comparison to traditional ERT or EM surveying.

Provided data for a PhD student and will develop the training of this researcher in the areas of catchment management and hydrogeophysics over the next four years.

Presentation of newly developed near surface geophysical techniques to the wider environmental community and Teagasc.

Presentation of Conference Presentations (Ryan Institute Research day, AEM2018 and Geoscience 2018).

References

Beskardes, G.D., Weiss, C.J. and Everett, M.E, (2017) Estimating the power-law distribution of Earth electrical conductivity from low-frequency, controlled-source electromagnetic responses. *Geophysical Journal International*, **208**, 639-651.

Binley, A., S. S. Hubbard, J. A. Huisman, A. Revil, D. A. Robinson, K. Singha, and L. D. Slater (2015), The emergence of hydrogeophysics for improved understanding of subsurface processes over multiple scales, Water Resources Research, 51, 3837–3866.

Gunnink, J.L., Bosch, J.H.A., Siemon, B., Roth, B., and Auken, E., 2012. Combining ground-based and airborne EM through Artificial Neural Networks for modelling glacial till under saline groundwater conditions. *Hydrology and Earth System Sciences*, **16**(8), 3061–3074.

Gunnink, J.L., and Siemon, B., 2015. Applying airborne electromagnetics in 3D stochastic geohydrological modelling for determining groundwater protection. *Near Surface Geophysics*, **13**(1), 45-60.

Kirkwood, C.,Cave, M., Beamish, D., Grebby, S., and A. Ferreira 2016. A machine learning approach to geochemical mappin. *Journal of Geochemical exploration Pages 49-61*

O'Connell, Y., Brown, C., Henry, T., Morrison, L. and Daly, E., 2017. Assessment of groundwater resources using airborne electromagnetic remote sensing (*in review.*)

O'Sullivan, L., R. Creamer, R. Fealy, G. Lanigan, I. Simo, O. Fenton, J. Carfrae, and R. Schulte. 2015. Functional Land Management for managing soil functions: A case-study of the trade-off between primary productivity and carbon storage in response to the intervention of drainage systems in Ireland. Land Use Policy **47**:42-54

Slater, L., and D. P. Lesmes, 2007. Electrical-hydraulic relationships observed for unconsolidated sediments: Water Resources Research, 38(10), 1213.

Saey, T., P. De Smedt, M. M. Islam, E. Meerschman, E. V. De Vijver, A. Lehouck, and M. Van Meirvenne (2012), Depth slicing of multi-receiver EMI measurements to enhance the delineation of contrasting subsoil features, Geoderma, 189, 514–521

Thomas, I.A., Jordan, P., Shine, O., Fenton, O., Mellander, P.-E., et al., 2016. Defining optimal DEM resolutions and point densities for modelling hydrologically sensitive areas in agricultural catchments dominated by microtopography. International Journal of Applied Earth Observation and Geoinformation, 54 . 38 - 52.

Zara E, Huang J., and Triantafilis J. 2016 Identifying soil landscape units at the district scale by numerically clustering remote and proximal sensed data. Computers and Electronics in Agriculture vol 127, P510-520

Task No.	Deliverable description	Planned delivery (as per proposal)	Expected delivery
6	Proof of PhD applications	Month 2 and 6	Month 2 and 4
9	Mid-term technical report	Month 6	Month 6
10	EAGE Conference presentation	Month 8	Month 8
12	Maps, models and databases for the GSI/Teagasc	Month 11	Month 17
14	Draft articles TResearch (Teagasc research magazine) and the GSI Groundwater newsletter	Month 12	Month 17
14	Final Report /draft international peer reviewed article	Month 12	Month 12

Publications to date:

[conference publication] Thebaudeau B[1], O'Leary D[2], Brown C[2], Fenton O[3], Mellender P-E [4] , Green S[3], Daly E[2,*] (2018) Geoscience 2018

[Conference Publication] O'Connell Y., Daly E., and Brown, C., Assessment of groundwater resources using airborne electromagnetics in Ireland. AEM2018 June 2018

[Conference Publication] Thebaudeau B1, Brown C2, Fenton O3, Mellender P-E 4 , Green S3, Daly E2,*.Geophysical remote sensing of subsurface properties for sustainable agricultural management. Ryan Institute Research day Feb 24th 2018

[Conference Publication] Daly E , Tellus Irelands national mapping programme conference talk Ryan Institute Research day Feb 24th

4. Data/outputs submitted with final report *(please list the documents, presentations, datasets etc. submitted with this report)*

a. Geoscience 2018 poster