



**Research Programme
- Short Calls, Final Report -**

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Host Organisation name	Trinity College Dublin
Project Title	Submarine groundwater discharge from the Burren plateau into Galway Bay
Contract Number	2017-sc-001

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

1. (a) Project information:

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

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

The original objectives of the project, as set out below, have been partially met.

1. *Develop and apply novel tracer techniques suitable to trace groundwater from onshore karst features to offshore groundwater discharge locations*

This has been successfully completed:

- Insoluble solid tracers were developed in the form of floating wood chips which are neutrally buoyant in freshwater but buoyant in sea water, using the wood Keruing;
- The application of fluorescent dyes (rhodamine, fluorescein) in the context of groundwater-sea water interaction;

2. *Successful application of tracer techniques to prove hydraulic connections between the Burren (Bell Harbour catchment) and the sea (Galway Bay/Atlantic Ocean).*

This has been partially successful. Fluorescent dyes have indeed been successfully used to trace from Poll Gonzo cave and Deelin Pot out into Galway Bay. However, the solid wood chips (injected at the same time as the fluorescent tracers) could not be recovered in the sea; hence, that method /



application of this tracer can not be considered to be a success in the context of this study;

3. *Prove and define locations/areas of significant SGD in Galway Bay/the Atlantic Ocean by using artificial tracers linked to continuous profiles of temperature/spec. electrical conductivity anomalies*

Locations/areas of significant SGD in Galway Bay/the Atlantic Ocean were successfully delineated by using artificial tracers linked to continuous profiles of temperature/spec. electrical conductivity anomalies.

Progress of the scientific/engineering targets beyond the state of the art and methods used.

Until now, to the knowledge of the research team, there has been no systematic approach reported which links the study of SGD/SiGD with artificial tracer tests. This seems to be remarkable given the prevalence of tracer studies in onshore catchment hydrogeology, and the clear need to effectively link the qualitative or quantitative assessment of SGD/SiGD to its catchment. Therefore, the purpose of this research was to propose a method to a) locate potential offshore areas of SGD, b) apply artificial tracers, and c) monitor onshore and offshore for artificial tracers along with the natural tracer electrical conductivity (EC) to establish a hydraulic connection between onshore injection points and offshore SGD locations.

Two different tracers were used for this study: the conservative tracer uranine, and the non-conservative tracer rhodamine. The two different dyes were injected at two different sites on 14 April 2018. Uranine was injected into the underground stream within Poll Gonzo upstream a waterfall at approx. 70 masl and 56 m below ground level (see Fig. 1a). Access to the injection point was only possible with full speleological equipment. A team of six persons descended into the cave and transported the necessary equipment, abseiling three pitches on fixed ropes. The uranine was dissolved in-situ within a 100 l inflatable swimming pool. Additionally, 16 bags of wood chips were injected at the bottom of the waterfall, where two professional speleologists abseiled down another pitch with extremely difficult access. Rhodamine was injected into the bottom of Deelin Pot, where a 1 m³ carbon-fibre tank with a release valve at its bottom was installed to dilute the dye in-situ (see Fig. 1b).

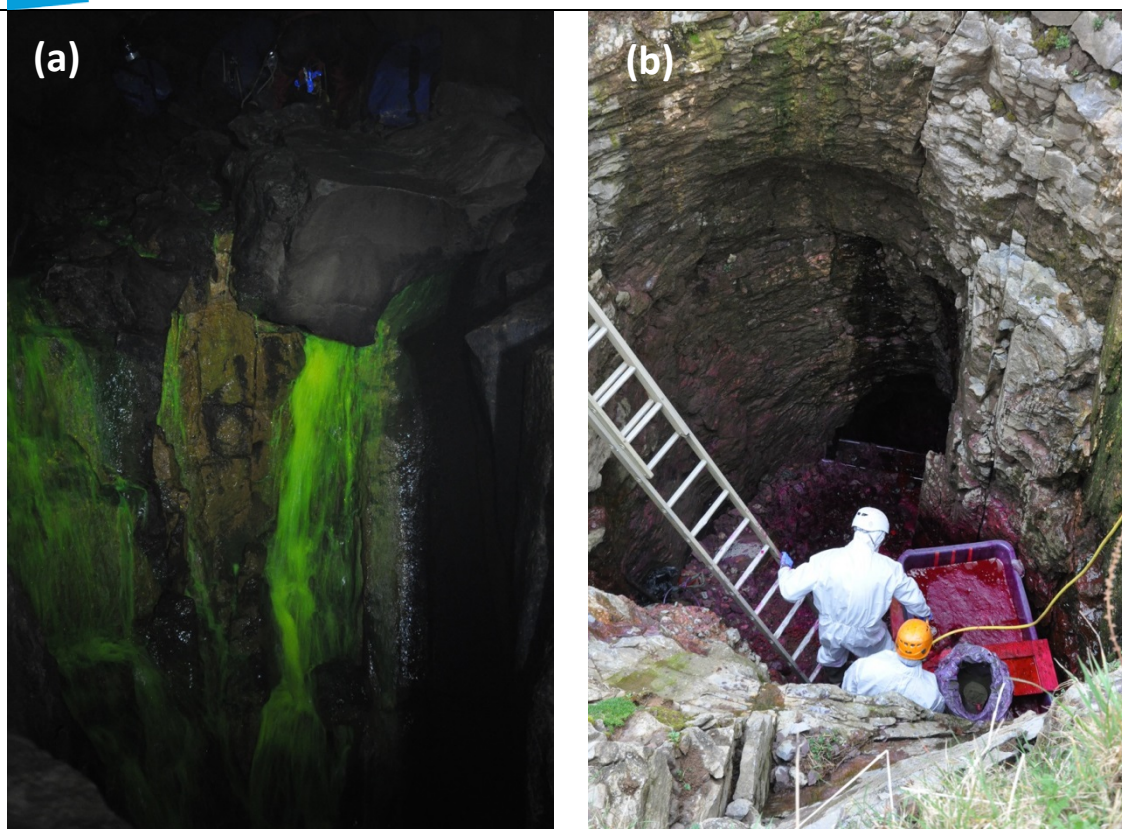


Figure 1. a) Injection of uranine tracer in Pollí Gonzo and **b)** rhodamine tracer at Deelin Pot.

Sampling for the tracers at potential outlets was conducted in the traditional way as ‘stationary’ at individual discrete locations on land, as well as ‘mobile’ over an area within the sea of Galway Bay. Mobile monitoring was necessary to account for the multiplicity of potential SGD locations in the bay. Detection of tracers was done qualitatively using nylon bags of activated charcoal (technical grade, AppliChem Panreac) and (semi-)quantitatively using three GGUN-FL30 field fluorometer (Albillia Co., Switzerland). The smallest detectable concentration variation in clear water is 0.02 ppb for uranine and ≤ 0.2 ppb for rhodamine. Stationary sampling was conducted at 10 different sites, at all nearby springs, both to the north and south.

Four Landsat images were chosen as most suitable to estimate the sea surface temperatures dating 11 Jul 2013, 24 Nov 2016, 2 Jan 2017 and 8 Apr 2017. These images revealed localised areas of colder temperature anomalies off the shore interpreted as the potential influence of SGD, which provided target areas for the mobile sampling. The mobile sampling was conducted in transects from a vessel in the sea, rather than deploying a fluorometer fixed at one location in the sea. The vessel was iteratively and systematically passing over the areas of potential SGD while monitoring for fluorescence. Based on estimated mean travel times, it was decided to start sampling 36 h after injection lasting for 3–4 days for as many hours as possible per day. The fluorometer was tied on ropes to be pulled in the back of the vessel (see Fig. 2b) while being connected via cable to the data logger and a computer on board. Additional weights were installed on the ropes to make sure the fluorometer did not float too close to the water surface, keeping it between 3 and 0.5 m below the surface. A CTD (LTC M200 Levellogger, Solinst) diver was attached close to the fluorometer to sample for depth, temperature, as well as conductivity as indicators for SGD. In order to obtain the spatial



reference of each reading of the CTD and the fluorometer, both instruments were synchronised with a hand-held GPS (GPSmap 60CSx, Garmin) recording the geographic position of the vessel in 3 sec intervals.

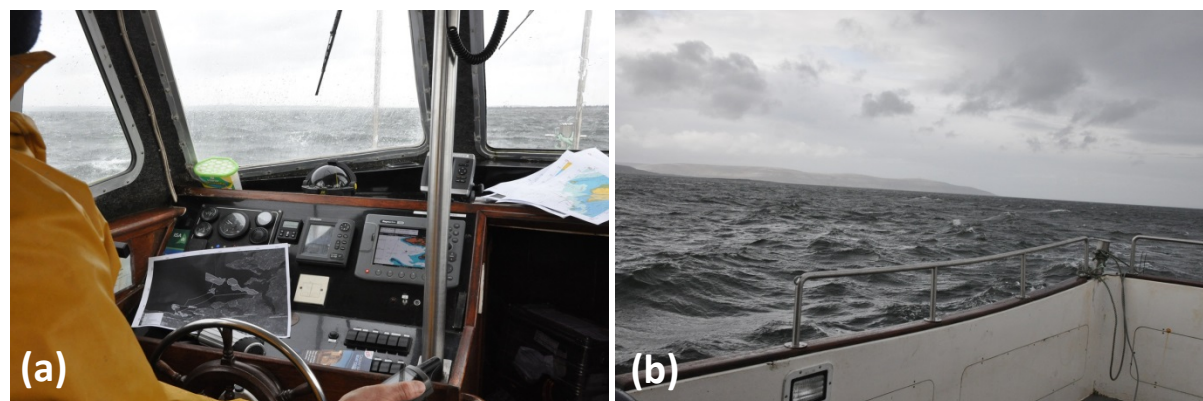


Fig 2. a) Locating target areas for mobile sampling, **b)** fluorometer being towed behind boat.

Charcoal bags were collected on 19 April 2018, five days after the injections. The charcoal samples were then analysed the following day using different eluents for uranine and rhodamine. The analysis was carried out at the GSI using a Cary Eclipse Fluorescence Spectrophotometer (Agilent Technologies). Neither a visible emission peak of 586 nm for uranine, nor an emission peak of 516 nm for rhodamine b is present in any of the samples. As a result, all charcoal samples are interpreted to be free of any of the two dyes.

The results of the mobile offshore sampling over a period of four days revealed positive concentrations of uranine and rhodamine at peaks on day 2 after sampling in location that correlated with low EC levels in the sea. In general, tracer was recovered in a relatively large geographical area, with three distinct clusters visible, 1.) in the south-west off Ballyvaughan, 2.) in the centre off Aughinish, and 3.) in the east (see Fig. 3).. These clusters are defined based on the rhodamine readings, yet, cluster 2 and 3 also contain uranine readings. Further, cluster 2 contained concentrations of low EC readings especially in the western part, which is indicative of SGD. In fact, only in cluster 2 is there a spatial and temporal correlation between dye readings and EC values. Importantly, both, rhodamine and uranine were recovered there, including their peak values. Therefore, it is this area in which the main SGD outlet for the Bell Harbour catchment is believed to be located. However, an additional tracer study is planned in order to confirm this conclusion, and further broaden the geographical sampling area. Finally, no floating Keruing wood chips were picked up or seen whilst mobile sampling for four days on board of the boat.

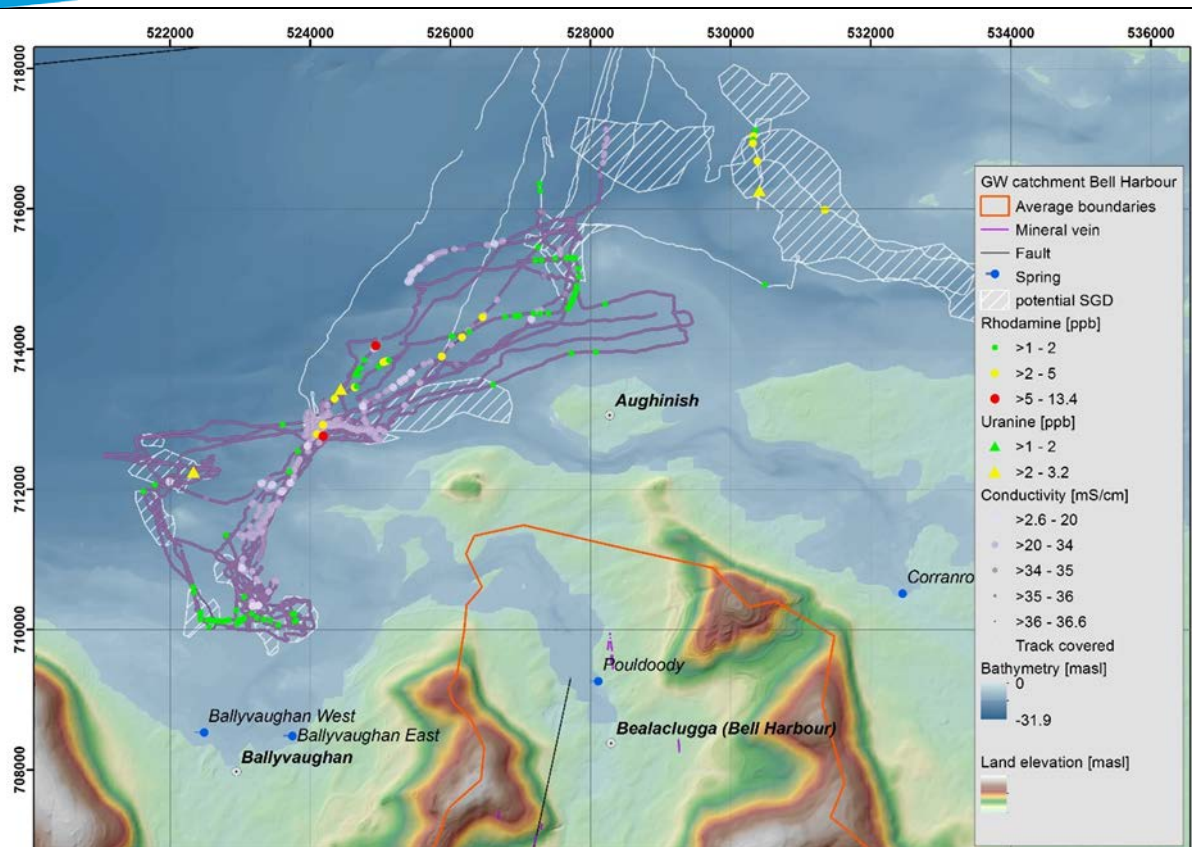


Fig. 3. Measured tracer concentration of rhodamine and fluorescein alongside measured EC.

In summary, hydraulic connections between the Burren (two injection locations) and Galway Bay were successfully established following injections on the 14th of April 2018 using both fluorescent dyes; the solid tracer using *Keruing* wood however, was not sampled in Galway Bay.

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

- Due to logistical problems with the availability of the NUIG boat, no preliminary tracer tests could be conducted, meaning that no natural background sampling for EC/fluorescence was conducted. Hence, only one multi-tracer large-scale test was therefore performed; however, a second tracer test is still planned to provide better confirmation of the SGD discharge. This could not happen prior to the drafting of this report due to the exceptionally dry summer and early autumn that was experienced in Ireland this year.
- The mobile offshore sampling could not be executed to the extent (spatially or temporally) as previously agreed on with the company galwaybaytours.com; this was partly to do with the very rough sea conditions for the first two days, but was exacerbated due to the skipper turning out to be unreliable and not willing to stick to the original work hours agreed upon.

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

- Bio-degradable insoluble solid tracers (wood fragments) were developed that can be injected into underground karst rivers where they would be neutrally buoyant but then



float once they hit sea water; ▪ A hydraulic connection between the Bell Harbour catchment and Galway bay/the Atlantic Ocean was established using artificial fluorescent tracers; ▪ 1 peer reviewed article in an international journal is in preparation.

Task No.	Deliverable description	Planned delivery (as per proposal)	Date of delivery
1	Establish bio-degradable insoluble coloured solid tracers that can be injected into underground rivers and float on the water surface after arrival in the sea	02/2018	03/2018
2	Study natural background level of fluorescence and temperature/electrical conductivity anomalies in Galway Bay/the Atlantic Ocean	Until month 10	(partly completed during main tracer study – 05/2018)
3	Establish hydraulic connection between the Bell Harbour catchment and Galway bay/the Atlantic Ocean using artificial tracers	08/2018	06/2018
4	1 peer reviewed article in an international journal, 1 article in a national journal (e.g. Groundwater Newsletter) and an international conference contribution	11/2018	11/2018

Publications to date:

- one poster publication at the annual GSI conference, *Geoscience 2018*;
- one journal publication currently being drafted for *Groundwater*

Schuler, P.; Stoeckl, L.; Bunce, C.; Gill, L.W. (2018) A new method for tracing submarine groundwater discharge from coastal karst aquifers *Geoscience 2018* Dublin, Ireland, 06-NOV-18 [Poster]



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

- a. poster presentation given at *Geoscience 2018*

SUPPLEMENTARY MATERIAL

(This section will be included in your published report unless otherwise instructed. If you have a published report, publication, etc. you may include it here).