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A combined remote sensing and multi-tracer approach for localising and assessing groundwater-lake interactions

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ABSTRACT

The combination of thermal imagery and geochemical tracing has been demonstrated as an affordable and effective technique to identify potential groundwater discharge sites in coastal areas on a regional scale. In this paper, a combined multi-tracer approach is evaluated in its applicability to lakes and verified as an appropriate and powerful means to localise and assess groundwater-lake interactions, demonstrated through a case study of Lough Mask in the west of Ireland.

Surface water temperature patterns generated from Landsat 7 Thermal Infrared (TIR) images were used to locate groundwater inputs captured as anomalous cold plumes visibly emanating from shallow lake margins during summer months. Radon-222 was used to confirm the presence of groundwater and to detect localised seepage points or groundwater "hotspots". Conductivity was used as a secondary tracer in support of radon to identify areas of active groundwater inflow.

Radon results show that groundwater enters the lake through carboniferous limestones adjacent to the north and east of the lake and no groundwater inflows were observed from the west characterised by Ordivician sandstones and mixed volcanics. The observed strong anti-correlation between mapped radon and satellite derived temperature values implies that decreases in surface water temperatures are associated with increases in radon activity and hence groundwater inputs to the lake. Moreover the spatial pattern of mapped temperature anomaly displays a positive correlation to the mapped radon and conductivity anomalies which further suggests that the tracers are inextricably linked and support a common groundwater source.

The study demonstrates the suitability of a multi tracer approach as a comprehensive and cost-effective preliminary screening tool for groundwater-lake interactions with the potential for application elsewhere. This information is important and can be used in support of national water policy and legislation by helping to identify for example, lakes at risk of failure to comply with Water Framework Directive (2000/60/EC) water quality objectives particularly where mapped inputs are linked to groundwater bodies classified as less than good status as per the requirements of the Groundwater Directive (2006/118/EC). Evaluating the potential occurrence and understanding where groundwater discharge occurs is the first step towards more in-depth geochemical surveys that seek to clarify the role played by groundwater in lacustrine biogeochemical budgets.

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1. Introduction

1.1. Overview

The Water Framework Directive (WFD) was adopted in 2000 and established an integrated approach to the protection, improvement and sustainable use of all water bodies. Under Article 8 (1) of the Directive, EU member states must establish a programme of monitoring of water status to achieve the objectives of the WFD which include the attainment and retention of "good status" (i.e. both good chemical and good ecological status) or better (Official Journal of the European Communities, 2000).

The Irish Environmental Protection Agency (EPA) is implementing a national programme of water body monitoring in compliance with the WFD (EPA, 2006). This is conducted primarily through surveillance and operational monitoring programmes which provide an assessment of overall surface water status as well as identifying water bodies "at risk" of failing to meet WFD environmental objectives.

While individual monitoring programmes are in place, assessments of groundwater-surface water interactions are not

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undertaken as part of the general monitoring procedure in Ireland. This is because groundwater discharge to lakes is often patchy and diffuse and very difficult to estimate using traditional techniques including seepage metres and piezometers (Lee and Cherry, 1978).

Since, most lakes generally receive groundwater inflows through their bed or loose water via seepage to the aquifer; the resultant groundwater-surface water interactions may significantly impact lake water chemistry, water quality, biology and ecology (Shaw et al., 2013). Indeed, contaminants from a variety of sources at and below the surface may be transported via groundwater exchange flows and recent studies have identified groundwater inputs as one of the main drivers of eutrophication in lakes (Zhu and Schwartz, 2011). Groundwater-lake interactions therefore could have a disproportionally greater influence on water quality and ecology potentially sufficient to threaten risk of failure to comply with WFD objectives.

In recognition of the significance of groundwater as a potential pollution pathway and the challenges to localising and assessing inputs that are diffuse and highly variable, here, a robust methodology to facilitate a regional scale assessment of groundwater discharge to coastal waters (Wilson and Rocha, 2012) is evaluated in its suitability for application to lakes. The overall goal is to investigate groundwater-lake interactions using satellite remote sensing coupled with natural environmental tracers and analyses that both verify and qualify the technique. The proposed multi tracer approach has the potential to be applied as a preliminary screening tool for groundwater-lake interactions elsewhere to help inform requirements for future monitoring programmes in support of WFD objectives.

1.2. Remote sensing for groundwater detection

The utility of heat as a groundwater tracer was recognised in the early 1900's (Anderson, 2005) and remote sensing methods for groundwater detection are applicable where temperature gradients form between surface water bodies and discharging groundwater. Traditionally, remote sensing of surface water temperatures has been undertaken using sensors that operate in the infrared (IR) portion of the electromagnetic spectrum, where emissivity of large water surfaces is close to zero.

The literature reports on the successful deployment of remote sensing technologies to delineate groundwater discharge to lakes but mostly with reference to high resolution airborne (Lewandowski et al., 2013), handheld (Duarte et al., 2006) or ground-based thermal imaging systems (Schuetz and Weiler, 2011). These systems while effective tend to be extremely costly and certainly not suitable for a regional scale assessment or continued monitoring of groundwater discharges across lakes for water management purposes.

The USGS series of Landsat satellites measure thermal radiation across the 10.4 μm to 12.5 μm range of the electromagnetic spectrum with a spatial resolution of 60m for the Enhanced Thematic Mapper Plus (ETM+) sensor (Jensen, 2007). Given that the Landsat archive spans four decades and is available to download for free from a number of sources such as the USGS GLOVIS facility (USGS, 2013), the unique opportunity to complete cost-effective regional scale assessments of groundwater inputs to lakes using thermal imagery is potentially afforded. Few published guidelines exist however for the application of Landsat imagery to localise groundwater inputs to lakes as a consequence of limitations that include the presence of cloud, scan-line errors or poor temporal and spatial resolution for example. Despite these shortcomings, Tcherepanov et al. (2005) examined ground-surface water interactions across lakes in the Nebraska Sand Hills using a series of Landsat TM and ETM+ scenes with some success. Their results highlighted a number of areas with consistently cooler temperatures subsequently inferred but were not verified as zones of potential groundwater discharge. To actually confirm groundwater—lake interactions the observed temperature gradients must be substantiated and validated as consequences of local groundwater inflows using ancillary datasets (Becker, 2005). For lakes we propose this is best achieved using Landsat data in combination with natural environmental tracers such as radon and conductivity.

1.3. Radon (^{222}Rn) and Conductivity as natural environmental tracers of groundwater

The distinctive and measurable difference that exists between radon concentrations in groundwater relative to surface water is the fundamental basis for using radon as an environmental tracer for groundwater discharge to surface water bodies. Radon, a non-reactive noble gas has a half-life of 3.82 days, is produced through the decay of Uranium, a naturally occurring mineral in rocks and soil. Concentrations of radon are several orders of magnitude higher in groundwater compared to surface water which normally results in a very sharp concentration gradient at the surface- groundwater interface (Schmidt et al., 2008).

Radon has been used very successfully in studies seeking to evaluate groundwater-surface water interactions (Burnett et al., 2008) and the application to lakes is gaining increased attention in the literature (Dimova and Burnett, 2011; Schmidt et al., 2009). Other natural tracers of groundwater such as conductivity can be used to support radon surveys in localising sites of groundwater seepage into lakes (Dimova et al., 2013). In particular, specific conductivity (25 °C) measurements serve as an excellent tracer of water movement because of the near conservative behaviour of the ionic constituents that contribute to measured conductivity.

Groundwater generally has greater concentrations of total dissolved solids than lake waters as a result of bedrock weathering processes and thus, greater ionic strength and higher electrical conductivity. Consequently, when groundwater discharges into surface water of lower electrical conductivity, measurable anomalies will occur and discharge zones may be identified by their elevated electrical conductivity relative to that of the receiving waters (Harvey et al., 1997).

In this study, the applicability of a combined earth observation and multi-tracer approach for localising and evaluating groundwater-lake interactions is demonstrated through a case study lake (Lough Mask) in the west of Ireland. The specific objectives are to:

1. Map the spatial variability of groundwater discharge into a lake using thermal anomalies observed in surface temperature patterns generated from 60 m resolution Landsat ETM+ TIR data.
2. Map the spatial distribution of surface water radon activity concentrations and conductivity to confirm the presence, and provide a qualitative assessment, of groundwater inflow patterns.
3. Verify and qualify the suitability of a multi tracer approach as a means to localise and assess groundwater-lake interactions.

2. Study area

Lough Mask (53°36′N, 9°22′W) situated within the Corrib catchment (Fig. 1), is part of the 'Great Western Lakes' system in Co. Mayo, Ireland, approximately 30 km east from the Atlantic coast. Mask at 82 km^2, is the second largest lake of a chain of lakes draining from Lough Carra in the upper reaches of the system through Lough Corrib into Galway Bay. Mask is designated under the EU Habitats Directive 92/43/EEC and EU Birds Directive 79/409/EEC and supports a diverse range of habitats including many important

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