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Regional scale assessment of Submarine Groundwater Discharge in Ireland combining medium resolution satellite imagery and geochemical tracing techniques

Jean Wilson *, Carlos Rocha

Biogeochemistry Research Group, School of Natural Sciences, Geography Department, Trinity College Dublin, Dublin 2, Ireland

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ABSTRACT

This paper sets the foundation for the use of freely available Landsat Enhanced Thematic Mapper (ETM+) thermal infrared (TIR) imagery in a regional scale assessment of submarine groundwater discharge (SGD) to coastal waters. A comprehensive, tiered, three-step approach is proposed as the most effective and affordable means to determine the spatial extent and scale of SGD from coastal aquifers to the coastal margin. As the preliminary step, Sea Surface Temperature (SST) values derived from Landsat ETM+ TIR are used to successfully detect plumes of colder water eventually associated with SGD in close proximity to the shoreline. Subsequently, potential sites of SGD are linked to geological features on land acting as possible sources, by combining within a Geographical Information System (GIS), mapped temperature anomalies with ancillary on-shore spatial datasets describing bedrock geology including aquifer fault lines. Finally, nearshore surveys mapping the activity of ^{222}Rn (radon) and salinity are carried out to verify the presence of SGD and provide a qualitative assessment of fresh groundwater inputs to the coastal zone.

Practical application of the complete approach in the context of coastal zone management is illustrated through a case-study of the Republic of Ireland. As part of this study, over 30 previously unidentified links between aquifers on land and the sea are shown along the Irish coast, hence illustrating the tight coupling between coastal waters and groundwater inputs at an unprecedented spatial scale. The study demonstrates the potential of the combined applications of remote sensing methods and geochemical tracing techniques for a cost-effective regional-scale assessment of groundwater discharge to coastal waters.

1. Introduction and background

1.1. Overview

SGD is defined broadly as any and all flow of water across the seabed from land to sea (Burnett et al., 2003) and encompasses several components of subsurface flow including terrestrial freshwater and recirculated seawater (Moore, 1999). Groundwater will seep persistently into the sea through permeable sediments wherever an aquifer with positive head relative to sea-level is hydraulically connected to a surface water body (Johannes, 1980) Accordingly, SGD is a ubiquitous feature of coastlines worldwide. SGD is extremely variable both spatially and temporally but occurs predominantly in the form of nearshore seepage, offshore seepage and submarine springs (Burnett et al., 2001). Submarine seepage occurring offshore is generally related to extensive networks of underground caves and channels including local fracture systems (Shaban et al., 2005) which facilitate the transport of groundwater from land aquifers to points several kilometres away from the shoreline.

Groundwater in transit from land to sea can become contaminated with a variety of substances including nutrients and heavy metals (Lee et al., 2009; Swarzenski & Baskaran, 2007) hence SGD has been defined in the literature as a potentially significant source and pathway of nutrients, dissolved substances and diffuse pollution to coastal areas particularly when originating from contaminated continental aquifers (Leote et al., 2008). While fresh groundwater discharge is considered to be less than 10% of the total freshwater flux to the ocean, the inputs of associated nutrients and contaminants may be far more significant because concentrations in groundwater often exceed that of surface waters (Slomp & Van Capellen, 2004). Therefore, relatively small groundwater discharge rates can deliver comparatively large quantities of solutes including nutrients to coastal areas. For example, nutrient supply via SGD has been linked to eutrophication and suggested as a potential precursor of harmful algal blooms (Hu et al., 2006; Lee & Kim, 2007) or increased bacterial concentrations (Boehm et al., 2004).

Despite acknowledgement of its potential impact on coastal ecosystem functioning SGD remains a poorly-understood and often overlooked process when implementing coastal monitoring and management programmes. For instance, EU directives such as the Water Framework Directive (2000/60/EC) aimed at improving the quality of the water environment do not acknowledge SGD as a

* Corresponding author. Tel.: +353 1 8961121; fax: +353 1 6713397.
E-mail address: jewilson@tcd.ie (J. Wilson).

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potential nutrient source for assessment or monitoring. This is because the spatially and temporally heterogeneous nature of groundwater discharge from an essentially invisible source renders locating and quantifying rates of SGD an appreciable challenge. Consequently, the quantitative distinction between SGD and easily gauged surface runoff sources may be impaired when implementing coastal management policy based on current nutrient monitoring programmes for example.

In recognition of both the significance of groundwater discharge as a potential source of contamination and the challenges to locating and quantifying the contribution of groundwater discharge to the coastal zone, a comprehensive cost-effective methodology to facilitate a regional assessment of SGD is presented here, using Ireland as a case-study. This work is based on the premise that relatively cool groundwater discharging to warmer coastal waters manifests in the thermal band of Landsat ETM+ TIR imagery acquired during summer months. The overarching goal of this study, the first of its kind in Ireland, is to identify and characterise locations of SGD through the integration of satellite thermal remote sensing (Landsat ETM+ TIR), ancillary geological and hydrogeological data and geochemical tracing (Radon-222, salinity) techniques.

1.2. Thermal remote sensing and geochemical tracing for SGD detection

Remote sensing methods for SGD detection are applicable wherever temperature gradients form between coastal marine waters and discharging terrestrial groundwater. Temperature has been used successfully to study groundwater discharge by comparing the relatively constant temperature of groundwater with that of surface waters which fluctuate with season (Dale & Miller, 2007). In general, groundwater between approximately 5 m and 100 m depths maintains a nearly constant temperature of 1–2 °C higher than mean annual air temperature (Anderson, 2004).

As water is almost opaque in the TIR, thermal remote sensing of surface water temperatures only provides spatially distributed values of radiant temperature in the "skin" layer or top 100 μm of the water column (Handcock et al., 2006). Daily observations of both regional and global SST (Kilpatrick et al., 2001; Parkinson, 2003) provide for example direct insight into the spatial and temporal variability of upper ocean currents, water mass boundaries and mixing (Thomas et al., 2002). This is an established practice in oceanography: ocean temperatures have been studied extensively since the late 1970s from a variety of satellite sensors including NOAAs Advanced Very High Resolution Radiometer (AVHRR) (Fox et al., 2005); NASA's Geostationary Operational Environmental Satellites (GOES) (Menzel & Purdom, 1994); NASAs Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) (Abrams, 2000), ENVISATs Advanced Along-Track Scanning Radiometer (AATSR) (Corlett et al., 2006) and NASAs Moderate Resolution Imaging Spectroradiometer (MODIS) (Esaias et al., 1998). While global measurements of sea surface temperature gathered by these satellites facilitate effective observations of ocean-basin scale circulation patterns, the relatively coarse spatial resolutions of these sensors (≥1 km) will not resolve fine-scale SST gradients important for the study of oceanographic features of nearshore coastal zones (Fisher & Mustard, 2004). Indeed, a spatial resolution of 1 km is not sufficient to discriminate thermal gradients in water bodies less than 3 km in width or water masses located less than 2 km from the shoreline (Wloczyk et al., 2006). However, satellite sensors with spatial resolutions appropriate for tracking small scale thermal patterns such as Landsat (Clark, 1993; Gibbons & Wukelic, 1989; Tcherepanov et al., 2005), are limited by both their spectral and temporal resolution. For example, atmospheric correction of surface temperature values generated from image data, requires at least two thermal bands (Wloczyk et al., 2006) and as both Landsat Thematic Mapper (TM) and ETM+ record thermal emissivity in one waveband with a repeat cycle of 16-days, inherent atmospheric correction and resolution of temporal variability on scales shorter than seasonal are precluded (Thomas et al., 2002). Moreover, an error with the scan-line corrector (SLC) aboard the ETM+ sensor means that post-May 2003 images include large data gaps and consequently some of the available archived images may be unusable. While an obvious solution to the problem of low spatial, spectral and temporal resolution associated with medium resolution satellite systems is to use airborne systems, these tend to be extremely costly (Dave, 1998) and economically unsuitable for a regional scale assessment of potential SGD locations.

Despite the shortcomings to the use of Landsat TIR for SST retrieval, there have been some encouraging results. Thomas et al. (2002) quantified the variability of SST along the coastline of Maine using a time series of Landsat Thematic Mapper (TM) thermal band data. Differences in seasonal patterns of SST (spatial resolution of 120 m) observed during summer months in four adjacent bays were attributed to residual circulation, tidal mixing and freshwater influence. Fisher and Mustard (2004) developed a sea surface climatology tracking SST as a function of year-day, from a combination of Landsat TM and ETM+ TIR data for a study area in Southern New England. As expected, their results revealed that isolated and shallow water bodies undergo more extreme temperature variation than deeper embayments. Moreover, the spatial pattern of the climatology revealed anomalous patterns associated with anthropogenic thermal input from a large power plant, supporting the application of Landsat thermal data to smaller scale studies. Wloczyk et al. (2006) calculated sea and lake surface temperatures in Northern Germany from Landsat TIR data and compared them to *in-situ* measurements and an empirical model developed by Germany's National Meteorological Service. Root-mean-square (RMS) deviations of 1.4 K and 2.2 K respectively, were reported.

The successful deployment of thermal remote sensing to delineate groundwater discharge to the coastal ocean documented in the literature to date, centres predominantly on the acquisition and analysis of high resolution TIR imagery acquired from aerial (airborne) surveys. For example, Banks et al. (1996) used airborne Thermal Infrared Multispectral Scanner (TIMS) images to identify the location and the spatial extent of groundwater discharge to creeks on a peninsula in Chesapeake Bay, USA. The presence of tonal differences in the TIMS imagery verified by water temperature measurements in the field were interpreted to locate sites of SGD. Portnoy et al. (1998) used aerial TIR imagery and shoreline salinity surveys to characterise groundwater discharge to an estuary in Cape Cod, USA. Other examples from the US include McKenna et al. (2001), Roseen et al. (2001), Ullman and Miller (2004) and Johnson et al. (2008) who used airborne TIR imagery to identify groundwater discharge in Delaware's Inland Bays, the Great Bay Estuary (New Hampshire), Delaware Bay (Delaware), Waquiot Bay (Massachusetts) and Hawaii respectively. The presence of SGD was verified in the examples given through salinity and temperature measurements in the field. Elsewhere, Shaban et al. (2005) and Akawwi et al. (2008) conducted aerial TIR surveys along the Lebanese and Jordanian coastlines respectively to identify potential sites of SGD.

The application of Landsat TIR for SST retrieval is neither extensive nor widespread and although far less frequently reported, satellite derived SSTs have been applied with limited success to identify and characterise coastal SGD. Wang et al. (2008) used two Landsat thermal images acquired in 2000 and 2002 to successfully locate groundwater discharge areas in Rehoboth Bay, Indian River and Indian Bay, Delaware. The accuracy of the satellite derived temperatures was verified through comparison with *in-situ* data and reported to be within 1 °C of *in-situ* water temperatures. Varma et al. (2010) used a combination of satellite (Landsat, ASTER and NOAA) thermal images to examine the utility of remote sensing methods for detection of known but previously unmapped locations of SGD in Geographe Bay, Bunbury, Western Australia. Within their study, evidence of SGD