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Quantification of submarine/intertidal groundwater discharge and nutrient loading from a lowland karst catchment

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SUMMARY

Submarine groundwater discharge (SGD) is now recognised to be a process of significant importance to coastal systems and is of increasing interest within oceanographic and hydrologic research communities. However, due to the inherent difficulty of measuring SGD accurately, its quantification at any particular location is a relatively slow process often involving multiple labour intensive methods. In this paper, the SGD occurring at Kinvara Bay, the outlet of a lowland karst catchment in Western Ireland, is estimated using a hydrological model of the karst aquifer and then further verified by means of a relatively simple salinity survey. Discharge at Kinvara predominantly occurs via two springs, Kinvara West (KW) which serves as the outlet of a major, primarily allogenically fed, karst conduit network and Kinvara East (KE) which discharges water from more diffuse/autogenic sources. Discharge from these springs occurs intertidally and as such, their flow rates cannot be measured using traditional methods. Using the hydrological model, flow rates from KW were seen to vary between 5 and 16 m^3/s with a mean value of 8.7 m^3/s. Through hydrochemical analysis, this estimated discharge was found to be supplemented by an additional 14–18% via sources not accounted for by the model. Mean discharge at KE was also estimated as approximately 2 m^3/s, thus the total mean discharge from both Kinvara Springs was determined to be 11.9–12.3 m^3/s. Overall, the range of discharge was found to be lower than previous studies have estimated (as these studies had no means of quantifying attenuation within the conduit network). Combining this discharge with nutrient concentrations from the springs, the nutrient loading from the springs into the bay was estimated as 1230 kg/day N and 24.3 kg/day P. This research illustrates the benefits of a numerical modelling approach to the quantification of SGD when used in the appropriate hydrological scenario.

1. Introduction

Submarine groundwater discharge (SGD) has been defined as any and all flow of water on continental margins from the seabed to the coastal ocean, regardless of fluid composition or driving force (Burnett et al., 2003). SGD thus comprises both the discharge of terrestrial freshwater (driven by hydraulic gradient) and recirculated seawater (driven by tidal pumping and wave set-up). Globally, the majority of SGD has been found to occur as recirculated seawater (Burnett et al., 2006). However, in karstic regions, which frequently exhibit high permeability and reduced surface drainage capabilities, SGD is primarily composed of terrestrial freshwater (Garcia-Solsona et al., 2010b; Weinstein et al., 2011). SGD has been acknowledged as a significant source of nutrients to coastal waters (Slomp and Van Cappellen, 2004; Paytan et al., 2006; Garcia-Solsona et al., 2010a; Einsiedl, 2012; Rodellas et al., 2014) as well as being a source of trace metals and contaminants (Boehm et al., 2004; Windom et al., 2006; Beck et al., 2007); as such, SGD has become a topic of substantial research interest (Moore, 2010). SGD research has traditionally been focussed on coastal areas of North America, Australia, Japan and the Mediterranean Sea (Taniguchi et al., 2002). More recently however, studies have begun to investigate SGD in regions such as South America (Windom et al., 2006; Povinec et al., 2008) and Ireland (Cave and Henry, 2011; Wilson and Rocha, 2012; Smith and Cave, 2012). In most regions, submarine springs developed in response to changes in sea level caused by the periodic glacial events throughout the Quaternary. In other areas, SGD can be of a more ancient origin such as in the Mediterranean where the occurrence of submarine springs is thought to be linked to a dramatic reduction in sea lea level 6 million years ago when the Mediterranean became isolated from the Atlantic (Fleury et al., 2007).

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The main techniques used to measure SGD include thermal imaging, tracer techniques (often using natural radium isotopes), electromagnetic techniques or seepage meters. For best results, multiple techniques are often combined, for example, see Mejías et al. (2012), Wilson and Rocha (2012) or Durand et al. (2011). Another technique which can be used is a water balance calculation using hydrological modelling although it is a technique that is less often used to quantify karstic SGD compared to other measurement techniques. One problem associated with such an approach is that water budgets only account for terrestrial freshwater and do not account for recirculated seawater, which can create significant uncertainties in some situations (Burnett et al., 2006). However, in the case of the karst aquifer targeted in this study, SGD is primarily freshwater derived principally from two intertidal springs which drain a major lowland karst network. Hence, it was the aim of this study to use a distributed hydrological model in conjunction with hydrochemical analysis to estimate the intertidal and submarine discharge and nutrient loading entering Kinvara Bay. The SGD discharge rates were also confirmed by a targeted hydrochemical (salinity) study of Kinvara Bay.

1.1. Area description

Carboniferous limestone is the most common rock type in Ireland. It underlies almost half the land surface in Ireland (making it the primary aquifer in the country) and is heavily karstified in certain regions. Unlike the situation in most of Europe, Irish karst terrain is primarily lowland with over 90% of the limestones below 150 m above sea level (asl) and much of it less than 100 masl (Drew, 2008). Lowland karst is characterised by considerable interaction between ground and surface waters. Karstic features such as losing and gaining streams, swallow holes, estavelles, springs and ephemeral lakes (known as turloughs) are evidence of this close relationship.

The subject area of this study, Kinvara Bay, is located in Co. Galway in Western Ireland. The bay is subject to submarine groundwater discharge via a system of intertidal springs located at the inner most part of the bay. These springs are fed predominantly by the 483 km^2 Gort Lowlands catchment (Environmental Protection Agency, 2011) which is bounded to the east by the low lying Slieve Aughty Mountains and to the west by the northern edge of the Burren (one of the largest karst landscapes in Europe) and drains northwest from the mountains across the Gort Lowlands to the sea at Kinvara (see Fig. 1). Approximately half of the catchment is underlain by largely impermeable non-calcareous rocks, primarily Devonian sandstones, which underlay the Slieve Aughty Mountains to the east. The western side of the catchment is low-lying with flat topography and is underlain by pure carboniferous limestone. The three primary surface rivers which drain the mountains run along an impermeable substrate surface until they reach the western karst region where they sink underground providing allogenic recharge to the karst aquifer. This combination of allogenic recharge from the rivers and autogenic recharge occurring within the carbonate lowlands (i.e. a binary karst system) provides the catchment with unique hydrological and ecological characteristics.

The limestone of the Gort Lowlands has undergone karstification at numerous stages and under a range of climatic, geological and oceanographic changes throughout its history. The most significant dissolution occurred during the Tertiary period, during which the limestone bedrock was progressively dissolved and lowered to produce the lowlands of today (Drew, 1990; Simms, 2005). The area was also heavily glaciated during the Quaternary, with karstification occurring periodically in the warmer periods between glacial events. More recently, allogenic recharge has rapidly influenced karst development in the region, whereby the relatively acidic waters derived from the peaty catchment of the Slieve Aughty Mountains have contributed to the development of a complex network of sinking streams, conduits and turloughs (ephemeral karst lakes). Flow dynamics within the Gort Lowlands can be separated conceptually into two dominant types: conduit flow and more diffuse flow through the fractures and weathered epikarst (with matrix flow also occurring to a lesser extent). Water that enters the conduit system is transported relatively rapidly downstream towards Kinvara (or surcharges into turloughs during flooded periods). Flow velocities within this conduit network have been estimated (from tracer studies) at between 60 and 1000 m/h (Drew, 2003). Outside of the main conduit network, the water lies within a more matrix/fracture type bedrock and flow throughout this bedrock is slower and more diffuse in nature. Unlike in upland karst areas, the lowland nature of the catchment results in a relatively shallow vadose zone; consequently phreatic or epiphreatic conditions frequently occur within the epikarst zone. Hence, a significant quantity of diffuse flow through the aquifer can be through the epikarstic zone, i.e. horizontal flow occurring within epikarst rather than (the more typical) vertical flow.

The presence of ephemeral lakes known as *turloughs* is a key characteristic of Irish lowland karst regions. These lakes are described as topographic depressions in karst, which are intermittently flooded on an annual cycle via groundwater sources and have substrate and/or ecological communities characteristic of wetlands (Environmental Protection Agency, 2004). Numerous turloughs can be found within the Gort Lowlands, five of which are of particular importance to this study. These five turloughs, Blackrock, Coy, Coole, Garryland and Caherglassaun, form an interlinked chain of lakes connected via an underground conduit network which transmits the majority of water which passes through the catchment towards Kinvara. Due to the presence of these turloughs, and the close relationship between groundwater and surface water within the catchment, flooding is a major concern for the local population. The Gort Lowlands area experienced four major flood events within six years between 1989 and 1995. The damage caused by these floods combined with ecological importance of the area prompted the commissioning of an extensive investigation known as the Gort Flood Studies Report (Southern Water Global, 1998). Further and more extensive flooding within the region occurred in November 2009, causing even greater damage (Walsh, 2010).

Water flowing through the active conduit network within the Gort Lowlands emerges at Kinvara predominantly via two springs, Kinvara East (KE) and Kinvara West (KW). A third spring at Kinvara Harbour is also known to discharge water from a similar source to KW (Southern Water Global, 1998) however the discharge from this spring is significantly smaller than that of KW and as such it has not been incorporated into this study. The Kinvara springs are located at an elevation between low and high tides, discharging continuously. Thus, over a tidal cycle the springs alternate from free draining to wholly submerged springs. As such, it is important to designate the discharge from these springs as 'intertidal' rather than just 'submarine'. Kinvara West is understood to be the main outlet for the Gort Lowland conduit system whereas Kinvara East discharges water from more diffuse epikarst-type sources, and is also known to discharge water from deeper within the karst aquifer (Southern Water Global, 1998). The differing sources of water for these two springs results in contrasting hydrochemistry. Kinvara West, with its significant proportion of allogenic, low bicarbonate water has a mean alkalinity of 156 mg/l $CaCO_3$ whereas Kinvara East exhibits higher alkalinity concentrations (mean: 260 mg/l $CaCO_3$) due to its autogenic, bicarbonate rich recharge. It should be noted that KW also receives water from non Slieve Aughty derived sources such as the Cloonteen River to the south and the Burren to the West (see Fig. 1 for approximate subcatchment area). Tracer studies have shown that these external waters join the conduit network at some point between Caherglassaun turlough and