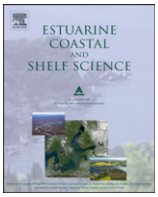
Estuarine, Coastal and Shelf Science 92 (2011) 415–423

Contents lists available at ScienceDirect

Estuarine, Coastal and Shelf Science

journal homepage: www.elsevier.com/locate/ecss



Intertidal and submarine groundwater discharge on the west coast of Ireland

R.R. Cave*, T. Henry

Earth and Ocean Sciences, School of Natural Sciences, National University of Ireland, Galway, Ireland

ARTICLE INFO

Article history:
Received 7 November 2010
Accepted 25 January 2011
Available online 19 February 2011

Keywords:
Ireland
Galway bay
submarine groundwater discharge
karst
hydrogeology
nutrients

ABSTRACT

Submarine Groundwater Discharge is now a phenomenon of global interest, as studies show that it represents both a significant proportion of the fresh water input to the ocean, and a significant contribution to the loads of many substances. At present, little monitoring of groundwater in Ireland is carried out at its point of entry to seawater, and consequently the volumes of fresh water, and the loads of nutrients and contaminants being carried into Irish coastal waters by submarine and intertidal groundwater discharge (SiGD), are unknown. SiGD is the principal source of fresh water entering Irish coastal waters between the major west coast estuaries of the Corrib and the Shannon. Calculations of the volume of submarine SiGD delivered to southern Galway bay in winter indicate it equals 10–25% of the discharge of the R. Corrib, and that its nutrient load may be of the same order of magnitude as that from the R. Corrib. This coastal karst area includes important commercial shellfish waters, which may be strongly impacted by SiGD.

1. Introduction

Submarine groundwater discharge (SGD) is now recognised as an important component of the fresh water runoff from land to the oceans, and submarine groundwater systems are important for the cycling of trace elements in coastal waters. From early papers by researchers such as Manheim (1967), Zekster et al. (1973) and Johannes (1980), SiGD research has progressed to being the subject of a SCOR Working Group in 1998/99 (WG-112, 'Magnitude of Submarine Groundwater Discharge and its Influence on Coastal Processes.'), which published a final report in 2004 (SCOR/LOICZ, 2004); and a special issue of Biogeochemistry in 2003. Taniguchi et al. (2002) provided a comprehensive report on the published studies on SGD worldwide up to that time, highlighting the significant contribution of SGD to total runoff, while Burnett et al. (2006) reviewed the multiple methods in use to quantify SGD. A broad-ranging review of SGD and its effect on the oceans was published by Moore (2010).

The bulk of the research to date has been concentrated in coastal areas of the USA (e.g. Bugna et al., 1996, Burnett et al. (2001), Schwartz (2003), Laws et al., 2004; Nuzzi and Waters, 2004; Charette and Buessler, 2004; Paytan et al., 2004; Michael et al., 2005), Mexico (e.g. Carruthers et al., 2005; Mutchler et al., 2007; Gonzalez et al., 2008; Young et al., 2008), Australia (e.g. Johannes and Hearn, 1985; Smith and Nield, 2003; Westbrook et al., 2005; Lamontagne et al., 2008), and Japan (e.g. Uchiyama et al., 2000, Suzuki and Zhang, 2003, Taniguchi et al., 2003. Windom et al. (2006) reported on some of first studies of SGD inputs to the South Atlantic, and a Special Issue described SGD studies in south-eastern Brazil (ECSS, 2008 vol. 76 iss 3).

Few studies have been conducted in European waters, with the exception of some karst areas of the Mediterranean (e.g. Moore, 2006; Povinec et al., 2006, review by Fleury et al., 2007), and the focus is more on the salination of coastal aquifers than on discharge, and in low-lying areas of northern Europe where inundation is a threat (e.g. Collection of papers in the Journal of Coastal Research, 2008, vol. 24 iss. 2).

Here we report on the first studies of intertidal and submarine groundwater discharge (SiGD) into Irish waters, from a coastal karst area along the Irish west coast.

1.1. River Basin Districts in Ireland

Ireland is currently working towards fulfilling its obligations under the European Water Framework Directive (Directive, 2000/60/EC). Detailed information on the progress of this work can be found on www.wfdireland.ie, and it forms the subject of a recent Special Issue of the Proceedings of the Royal Irish Academy (Royal Irish Academy, 2009). As part of this process, the island of Ireland has been divided in 8 River Basin Districts (RBD), four wholly inside the Republic of Ireland, 3 shared with N. Ireland and therefore designated as International River Basin Districts (IRBD), and one wholly

---

* Corresponding author.
E-mail address: rachel.cave@nuigalway.ie (R.R. Cave).

0272-7714/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ecss.2011.01.019

within N. Ireland. Two districts, the Western RBD (12×10^3 km^2) and the Shannon IRBD (18×10^3 km^2), have coastlines on the North East Atlantic Ocean, with coastal and transitional water areas of 4882 km^2 and 1487 km^2 respectively (EPA and River Basin Districts, 2005). 40.4% of the area of the Western River Basin District of Ireland and 26.6% of the area of Shannon river basin district are underlain by karstic groundwater bodies, with a much higher proportion of karst than in the other RBDs. In many places, these karstic aquifers (where conduit flow dominates) intersect the coastline, leading to the possibility of both intertidal and submarine groundwater discharge, and to salination of aquifers from a combination of over-extraction and rising sea levels.

River basin districts are further subdivided into hydrometric areas, which contain one or more river catchments. Of these, areas 29 in the Western RBD and its neighbouring area 28 in the Shannon IRBD (Fig. 1), are underlain by calcareous bedrock, with Dinantian pure bedded limestone, greatly karstified throughout area 29 and the northern part of Area 28, and with Namurian sandstones and undifferentiated Namurian rock underlying the remainder of area 28 (EPA and River Basin Districts, 2005). In both these hydrometric areas groundwater drainage predominates, surface drainage is minimal. The hydrometric area to the north, area 30, is the drainage basin of the River Corrib, part of the Western RBD, average discharge 99 m^3 s^{-1} (Table 1). To the south is hydrometric area 27, part of the Shannon IRBD, which drains into the estuaries of the Fergus and the Shannon. Average discharge from the Shannon, Ireland's largest river system, which is controlled by a weir providing water to Ardnacrusha hydroelectricity station, is 206 m^3 s^{-1} (OSPAR Commission, 2006).

Table 1

Rainfall and surface area for the R. Corrib catchment, the R. Shannon catchment and hydrometric areas 28 and 29. The Potential Runoff in m^3 s^{-1} is calculated from the Effective Rainfall (precipitation minus evaporation) over the catchment area. In brackets are the volumes calculated from rainfall alone, i.e. the maximum possible runoff. Gauged runoff data are 30 yr averages from the Office of Public Works (OPW), except for the Shannon which is from data given by the ESB. Evaporation rates are also taken from the OPW. The gauged runoff for Areas 28 and 29 are from gauges on the few surface rivers that exist in these areas (see Table 2). The difference between Potential and Gauged values in areas 28 and 29 is the expected intertidal and submarine groundwater discharge. Mills (2001) calculates an average depth of rainfall for runoff for the Shannon of 535 mm, with a drainage area of 11,250 km^2, compared to our 543 mm below, with a drainage area of 11,903 km^2.

	Rainfall mm yr^{-1}	Evaporation mm yr^{-1}	Area km^2	Potential Runoff m^3 s^{-1}	Gauged Discharge m^3 s^{-1}
Corrib 30061, 1950–2004	1331	452	3111	87 (131)	99
Shannon (ESB)	1024	481	11,903	205 (387)	206
Area 28 see Table 2	1330	481	990	27 (41)	9
Area 29 see Table 2	1100	462	900	18 (31)	9

1.2. Groundwater drainage in the study area

Discharges of groundwater around and off the west coast of Ireland have been noted previously, e.g. Mullan (2003) who lists caves and mentions groundwater resurgences including some off the coast of county Clare.

An investigation by Smyth (1996) and the Office of Public Works (OPW, 1997) concerning flooding in the Gort-Ardrahan area found three levels of karst, a shallow depth karst (15–25 m

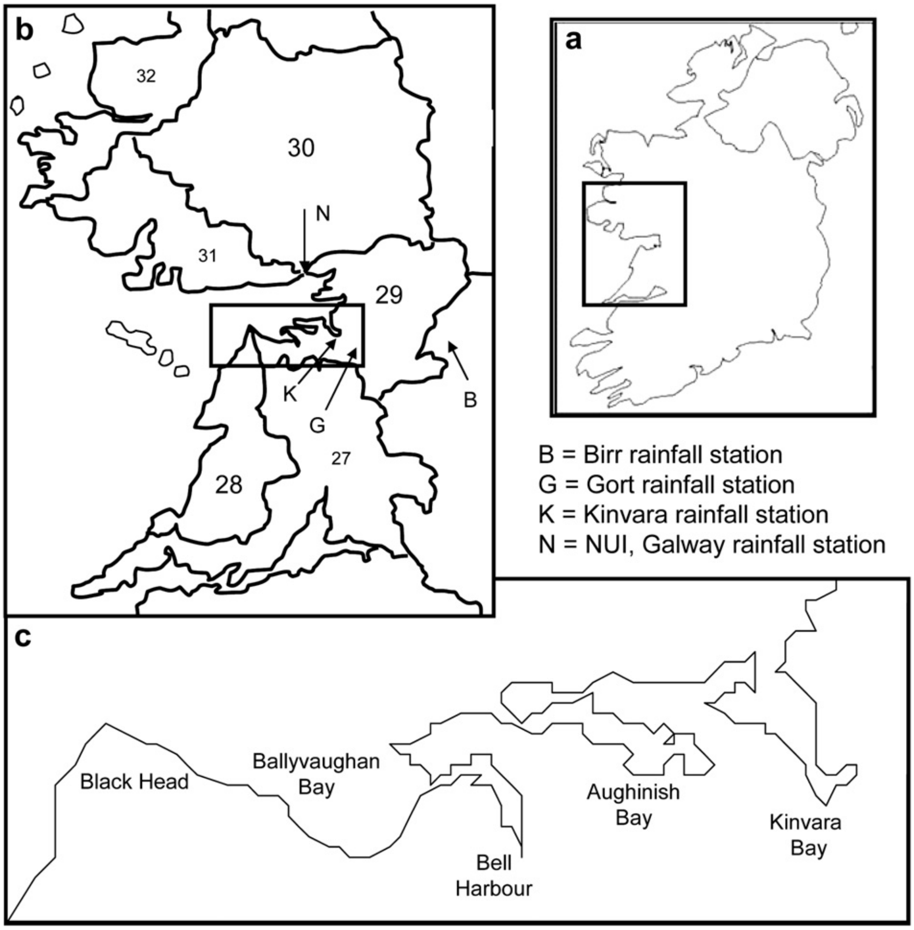


Fig. 1. Location maps. (a) Ireland, (b) relevant hydrometric areas on the western seaboard, (c) bays with submarine groundwater discharge draining hydrometric area 29.

below ground level), an intermediate (40–50 m bgl) and a deep (70–80 m bgl) karst in the Kinvara area. The shallower two appear to transmit rapid throughflow waters at high groundwater levels but are susceptible to saline intrusion at low water levels. The deepest karst appears to be a palaeo-karst and contains older groundwater. The karst underlying Kinvara drains quickly through large conduits, some of which are active only during wet periods. Dye tracing work indicates that Kinvara Bay is the focal point for a large part of the underground drainage from the Gort-Kinvara lowlands, which make up most of hydrometric area 29 (Fig. 2, after Boycott et al., 2003). However it also shows that groundwater from a given site may take several different paths to the sea (Fig. 2). Groundwater discharge is clearly visible at low tide at several sites around the head of Kinvara bay, and even at high tide the inner waters of the bay show low salinities, and water can be seen bubbling up even during long spells of dry weather. A small lake at Caherglassaun, about 5 km inland (Fig. 2), rises and falls by a few centimetres over a tidal cycle, with a lag of about 2 h, while remaining fresh, but the municipal well between this lake and the sea, about 2 km inland, occasionally pumps salt water when long dry periods coincide with spring tides (pers. comm. Tom Kavanagh, Galway Co. Council).

Tynan et al. (2007) carried out an extensive review of all the existing data on karstic areas in Ireland, and in turloughs in particular, as part of Ireland's commitment to the implementation of the Water Framework Directive. Their review focussed particularly on the extensively karstified areas of counties Galway and Clare, where our study area is located. Their study of turloughs included a number of hydrological indicators which were compared to turlough vegetation patterns, including residence time and response time. In particular, Tynan et al. (2007) looked at flood duration, represented by frequency-duration curves, and recession, i.e. the rate at which water level naturally decreases during periods of little or no rainfall, represented by a recession constant. Recession constants of 10 or higher, indicating very fast recession rates, were found in all 8 of the turloughs studied across our catchment area (Fig. 2 and Table 3). Their work indicates that there is a very rapid flow through of water throughout the catchment area, with seasonal flooding of the turloughs, so that storage only occurs at times of heavy and persistent rainfall, when the precipitation exceeds the drainage capacity.

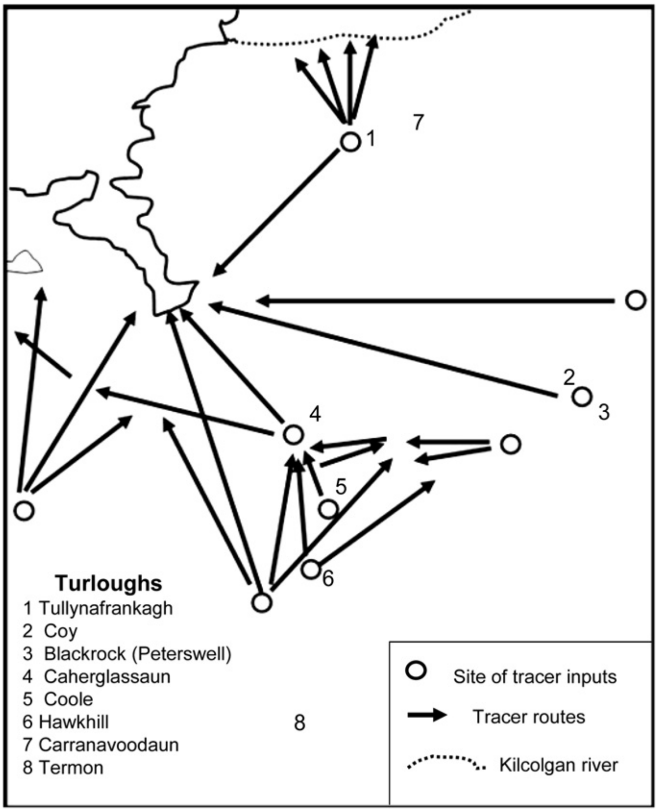


Fig. 2. Routes of groundwater tracers around Kinvara. After Boycott et al. (2003). Numbers 1–8 designate turloughs in this catchment for which Tynan et al. (2007) calculated recession constants. 1–6 were also tracer input sites.

2. Objectives

The objectives of this study were (i) to estimate the water available for runoff via submarine groundwater discharge in hydrometric areas 28 and 29, (ii) to measure the actual fresh water discharge from Kinvara Bay (the focal point for much of the discharge from hydrometric area 29), (iii) to make preliminary estimates of the nutrient loads entering Kinvara Bay via the groundwater system, and (iv) to examine the relationship between the rainfall in the catchment and the rate of SiGD into the bay.

3. Methods

3.1. Annual water balance calculations

To generate a water balance, we require values for precipitation (P), evapotranspiration (E), runoff (R) and fluctuations in the water stored in soil or aquifers (S), where $P - E - S = R$. Mills (2000) published a water budget for the island of Ireland, using land use and meteorological data from 1960–1990. The 30-year estimate for Ireland gives 1150 mm/yr of precipitation, 450 mm/yr of evapotranspiration and 700 mm yr^{-1} of runoff (MacCarthaigh, 1996), which translates into a potential total fresh water discharge into coastal waters of the island of Ireland of $\sim$1874 m^3 s^{-1}, or 59×10^3 km^3 yr^{-1}. A comparison between estimated and measured runoff from the Shannon between 1961 and 1990 showed that the measured runoff was in most cases somewhat higher than that estimated by the model (Mills, 2001).

In hydrometric areas 28 and 29, average annual rainfall is between 1050 and 1350 mm, and evapotranspiration between 450 and 480 mm. The amount of storage within the system is not known, but because western Ireland has regular rainfall and rarely suffers drought, the storage is only enough to smooth out the discharge by maintaining relatively high discharge rates even during periods of low or no rainfall. The catchment contains a mix of epikarst (typically 0–15 m below the surface, Pracht et al., 2004), fractured areas and conduits (Table 3, Tynan et al., 2007), and the recession constants from turloughs across the catchment are high, indicating fast flow through of water, with turloughs filling in late Autumn/eary Winter and during periods of sustained precipitation outside the winter months. Even in winter, a dry spell of two to three weeks is enough to fully drain the turloughs. The storage term is therefore neglected here, and Effective Rainfall (ER), that is the long-term measured average rainfall minus evaporation ($P - E$), converted to Potential Runoff by multiplying ER × surface area of the catchment, is used as a first approximation of the volume of water available for runoff (Table 1). Groundwater is a major source of domestic water supply in these regions but it is assumed that water extracted for domestic use is returned to the system via soakaways and sewage outfalls. Industry is largely limited to farming and fishing. Drainage is largely underground, with surface drainage limited to a few small rivers in each area (Table 2).

3.2. *Daily rainfall and potential runoff*

Daily rainfall data from NUI Galway (coast), Gort (mid-catchment) and Birr (inland) stations have been averaged to provide values for daily rainfall over the catchment for hydrometric area 29 (see Fig. 1 for station locations). Rainfall data from the station at NUI Galway are used as a proxy for the coast at Kinvara, as data for the Garda station at Kinvara are only available from 1966 to 1997, when the measurements were discontinued. The patterns for the two stations, which are on either side of Galway Bay (see Fig. 1a), follow each other closely. Rainfall data have been collected by the University in Galway city (NUIG) since 1861 to the present day, with a break in measurements from 1952 to 1965 (Gaffney, 2006). The 32 year average from 1966 to 1997 shows that Galway city received an average of 1166 mm of rain annually, while Kinvara received 1078 mm, a difference of 88 mm over the course of a year. Over this 32 year period, the annual difference ranges from ~200–0 mm. Only twice in this period has Kinvara annual rainfall exceeded that of Galway, and then only by a few millimetres, and the patterns for the two stations follow each other closely. Fig. 3 shows monthly rainfall totals for NUIG for 2006/07.

During winter months, evaporation in this region is negligible – the mean monthly potential evaporation data for the Met station at Birr, the closest station to the catchment which measures this parameter, is 3.6 mm (Nov), −0.7 mm (Dec), 2.1 mm (Jan) and 14 mm (Feb). For the calculation of the daily potential runoff for hydrometric area 29 from Nov–Feb, the duration of this study, the evaporation term is therefore neglected and the daily PR is calculated by multiplying the average of measured rainfall from 3 rainfall stations by the surface area of the catchment.

3.3. *Microcat data and the calculation of fresh water removed on the ebb*

Two Microcat SBE-37 instruments, measuring temperature and salinity, were deployed from 9th Nov 2006 to 6th March 2007, in Kinvara Bay, hanging from rafts and sampling water approximately 1.5 m below the water surface (Fig. 4). Microcat 3114 was removed in March 07, but Microcat 3115 continued to be deployed until May 07, when it was taken out and Microcat 3114 was redeployed in its place. Microcat 3114 was then retrieved in July 07. Measurements were recorded at 10 min intervals, and the instruments were visited and downloaded about once a month. The salinity values of the two Microcats overlap at high tides (Fig. 5), but 3115 generally shows lower salinity values than 3114 at low tides, due to its position closer to the inner bay (Fig. 4). Here we present the winter data, and Microcat 3114 has been used to calculate the ebb fresh water output, as we believe it better represents the outflow from the bay. Changes in the recorded salinity clearly reflect diurnal tides, neap-spring cycles and fresh water input.

Table 2
Data from the surface rivers in areas 28 and 29. The lowest reach of the Kilcolgan river is an artificial channel having been dug and lined in the early part of the 20th century, where previously it disappeared underground before reaching the sea. Numbers and years below the river name indicate the OPW hydrometric station and the years over which the gauged runoff data are averaged. Data for all stations on the OPW network can be found at http://www.opw.ie/hydro.

Area 28	Rainfall mm yr^{-1}	Evaporation mm yr^{-1}	Area km^2	Potential Runoff m^3 s^{-1}	Gauged Discharge m^3 s^{-1}
Caher	n/a	n/a	15		ungauged
Aille	n/a	n/a	33.5		ungauged
Annagh	n/a	n/a	22		ungauged
Inagh 28001, 1972–2004	1332	481	168	4.5	5.9
Doonbeg 28002,	1188	481	136	3	n/a
Area 29					
Oranmore 29015, 1983–85	1100	462	40	0.8	0.6
Clarin 29004, 1973–86	1100	462	123	2.5	2
Kilcolgan 29011, 1983–2003	1100	*462*	373	7.5	6.7

Table 3
Karstic flow system around turloughs across the catchment with recession constants (numbered as in Fig. 2), taken from data in Tynan et al. (2007).

Turlough Name	Recession constant	Karstic flow system and overland inputs
1. Tullynafrankagh	10.01	Shallow epikarst
2. Coy	10.8	Fracture/conduit
3. Blackrock (Peterswell)	11.67	Fracture/conduit
4. Caherglassaun	11.28	Deep epikarst conduit, overland flow at high stage
5. Coole	11.19	Deep epikarst conduit, overland flow at high stage, river inputs
6. Hawkhill	10.25	Shallow epikast, deep epikarst conduit, overland flow at high stage from Coole
7. Carranavoodaun	10.02	Shallow epikarst
8. Termon South	10	Shallow epikarst

The total volume of water in Kinvara Bay, at the mean high water level, has been calculated from LIDAR data as 21.7 × 10^6 m^3 with a surface area of 5.19 km^2 (pers. comm. Dr Garret Duffy, NUIG). Parts of the estuary dry out at low tide (Fig. 4), giving a mean low water volume of 8.3 × 10^6 m^3. The estuary is shallow throughout, with no part deeper than about 8 m at high tide. Tidal curves for Galway city were produced using Belfield™ software and aligned with the salinity data. There is no tide gauge in Kinvara Bay so actual heights have not been measured. However, heights from a tide gauge installed subsequently on the Aran Islands by the Marine Institute compare very well with the data for Galway city. The tidal curve also correlates well with salinity data (Fig. 5).

3.4. *Calculation of fresh water taken out by the ebb*

The amount of fresh water taken out by each ebb tide has been calculated from the 10-min Microcat 3114 salinity data as follows. First, the salinity of water between each high to low tide is averaged. Then two different values of seawater salinity are used, to put an upper and lower limit of the amount of fresh water contained in the ebb. For the upper limit, the averaged salinity value is divided by a seawater salinity of 33.5 to get the maximum proportion of fresh water contained in the ebb water (Eq.(1) (upper limit)). Data from the underway thermosalinograph on RV Celtic Voyager, taken on transits

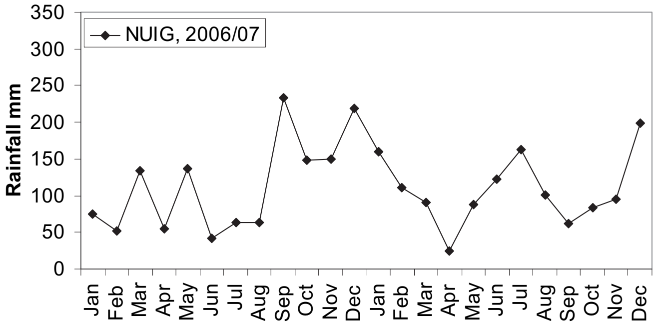


Fig. 3. Monthly rainfall for 2006/07 from the NUI Galway weather station, provided by Frank Gaffney. Rainfall measurements at Kinvara ceased in 1997, so the NUIG station is used to represent the coastal part of the catchment, as the patterns and quantities are very similar.

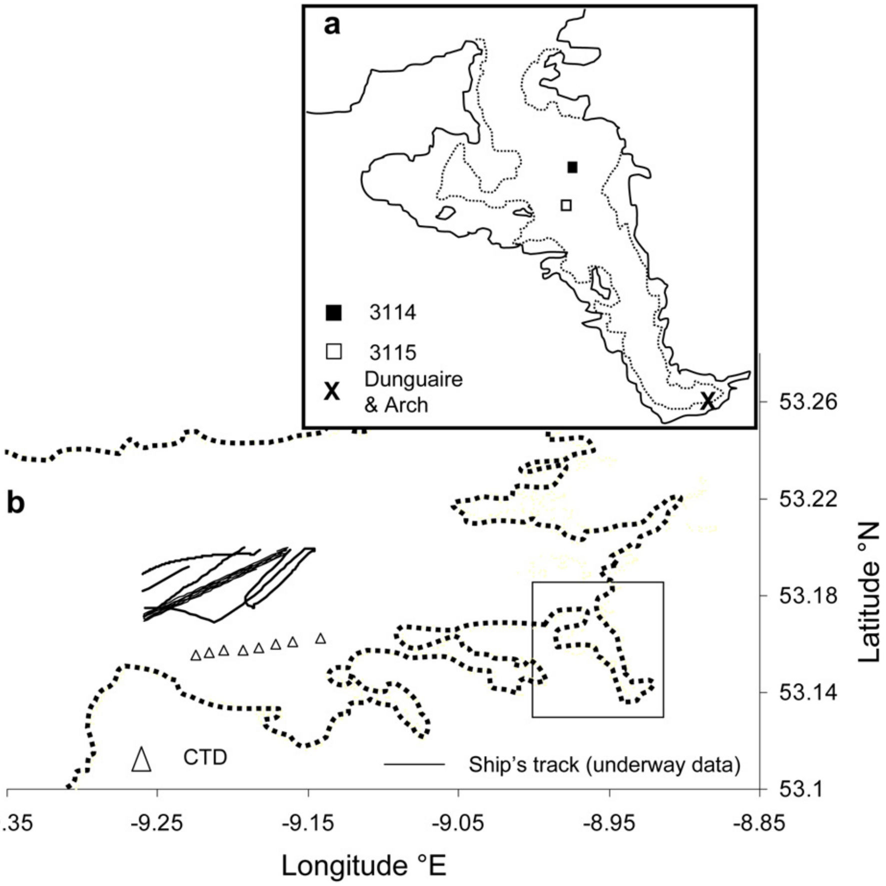


Fig. 4. (a) Kinvara Bay mean low and high tide contours, with positions of Microcats 3114 and 3115, and the sampling locations at Dunguaire Castle and the nearby ruined Arch (b) map of Galway bay showing Kinvara bay (inset) and the location of underway data from RV Celtic Voyager and Celtic Explorer in winter 2006/07, and CTD casts from Feb 2007.

through the inner bay between Dec 2006 and March 2007, and on a series of 1 day surveys in mid-February 2007 which collected CTD data from the inner bay (Fig. 4), indicate that the salinity of the top 10–15 m of seawater at high tide outside Kinvara Bay is 33.5 ± 0.3. Deeper water further out in Galway bay reaches salinities of 34.9. However, as Kinvara is a shallow bay, in general only seawater from the upper part of the water column is likely to enter it. This equation assumes that the residual flow pattern of Galway bay means that none of the ebb water is brought in by the following flood tide.

For the lower limit of the ebb fresh water volume, the averaged salinity of the ebb is divided by the maximum salinity measured on the previous flood tide (Eq. (2) (lower limit)). This allows for some ebb water being returned to the bay on the following flood tide.

The height of low water in metres is subtracted from the height of high water for that tide, and the result multiplied by the surface area of the estuary, to get the total volume of water brought out on the ebb tide. The total ebb tide volume is then multiplied by the fresh water proportion to get the volume of fresh water removed on each ebb tide (Eqs. (1) and (2)).

$$(S_{HW} - S_{LW})/33.5 \times (H_{HW} - H_{LW}) \times \text{Surface Area} \tag{1}$$

$$(S_{HW} - S_{LW})/\text{max. salinity of flood tide} \times (H_{HW} - H_{LW}) \times \text{Surface Area} \tag{2}$$

For both calculations, it is assumed that the water in the estuary is well mixed, and that the Microcat salinity values are therefore representative of the water column. The Microcats were located close to the midline of the bay, about two-thirds of the distance between the head of the bay and the open sea (Fig. 4a). Salinity surveys of the bay indicate that the water column is well mixed vertically, but less well mixed horizontally, and therefore while the data recorded should be representative of the whole water column at that point, it may not accurately reflect the salinity gradient across the estuary.

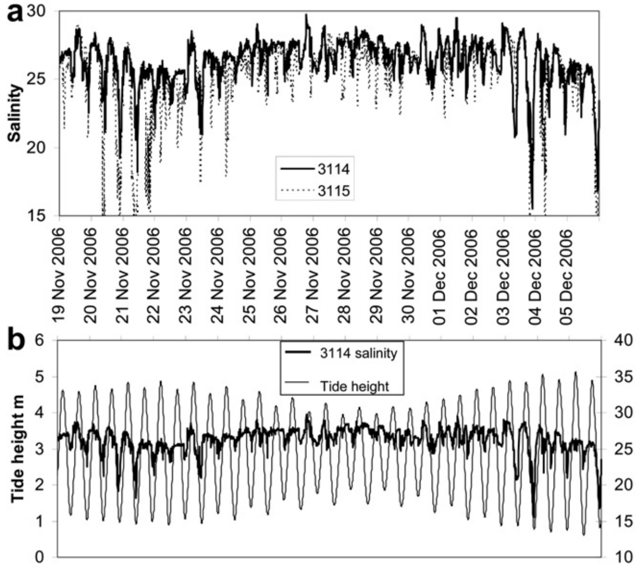


Fig. 5. (a) Salinity of Microcats 3114 and 3115 over a spring-neap-spring cycle, showing their close correlation, with 3115 showing greater influence of fresh water, (b) Tidal curve with 3114 salinity overlain.

The fresh water volume removed on the ebb tides for each day was then compared with daily Potential Runoff (PR) data for the catchment.

3.5. Nutrient sampling

Groundwaters discharging into the intertidal zone at the two principal known locations at the head of Kinvara bay (Dunguaire and Archway sites, Fig. 2) were sampled for nutrients between Oct 2005 and Jan 2006, and again between Sept and Nov 2006, to gain some idea of the variability of nutrient concentrations in SiGD in autumn/winter (Table 4, Fig. 6). A YSI multimeter was used to check the salinity of the discharge, salinities of less than 2 were recorded in all cases. Samples were collected in cleaned polyethylene 100 ml bottles, stored frozen and analysed on a Lachat QC8000 Flow Injection Analysis (FIA) instrument, using OSIL nutrient standards.

4. Results and discussion

Table 1 shows the annual potential runoff and measured discharge for the R. Corrib and R. Shannon, which drain hydrometric areas north and south/west of the area of interest. Daily discharge data for Irish rivers are available from gauging stations maintained by the Office of Public Works (OPW) and the Environmental Protection Agency (EPA). For the Shannon, data are collected by the Electricity Supply Board (ESB), who control the river flow into the Shannon estuary via the Ardnacrusha hydroelectric power station.

It can be seen that while the first-order discharge calculation for the Shannon is very similar to long-term gauged discharge, the first-order calculation for the Corrib underestimates the gauged discharge by about 12% (Table 1). One reason for the discrepancy may be the paucity of weather stations collection evaporation data, and this may therefore be overestimated for the Corrib catchment. There are very few surface rivers in hydrometric areas 28 and 29, and only the larger ones are gauged (Table 2). The effective rainfall calculation for these areas therefore differs greatly from the total of the gauged discharges, and the difference here is expected to be intertidal and submarine groundwater discharge (SiGD).

Table 4
Winter nutrient loading to Kinvara Bay from SGD, compared with loading from the R. Corrib. Concentrations of TON (nitrite + nitrate) for the Corrib are based on the average concentrations from the winter months of 1997–2001. Concentrations for Kinvara are based on average concentrations measured in intertidal groundwater discharge at the head of Kinvara bay in winter 2005/6 and 2006/7. Discharge data for the Corrib was provided by the OPW. For calculations of SiGD from Kinvara, see text.

		Av. Flow $m^3\ s^{-1}$	Av. TON $mg\ L^{-1}$	Av. TON $kg\ d^{-1}$
Corrib	Nov-06	162	1.0	13960
	Dec-06	306	1.0	26434
	Jan-07	269	1.0	23240
	Feb-07	189	1.0	16358
Kinvara				
Min SGD low TON	Nov-06	14	1.4	1666
	Dec-06	23	1.4	2809
	Jan-07	31	1.4	3732
	Feb-07	17	1.4	2084
Min SGD high TON	Nov-06	14	3.2	3809
	Dec-06	23	3.2	6421
	Jan-07	31	3.2	8530
	Feb-07	17	3.2	4763
Max SGD low TON	Nov-06	41	1.4	4979
	Dec-06	61	1.4	7376
	Jan-07	96	1.4	11563
	Feb-07	35	1.4	4180
Max SGD high TON	Nov-06	41	3.2	11380
	Dec-06	61	3.2	16859
	Jan-07	96	3.2	26431
	Feb-07	35	3.2	9554

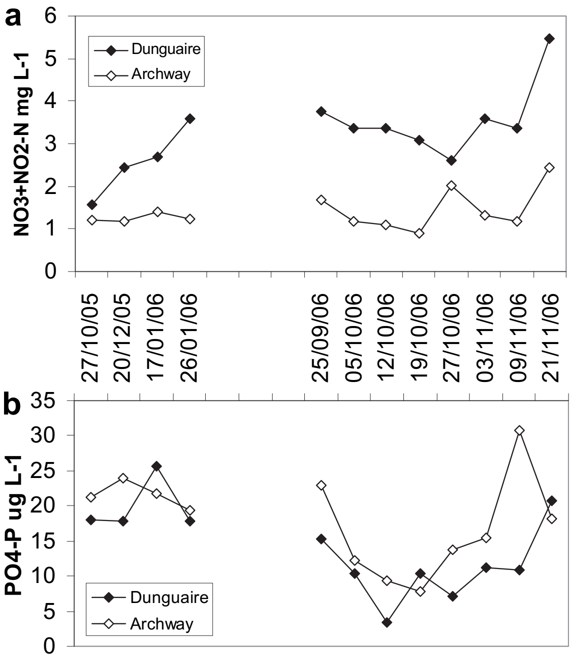


Fig. 6. Nutrient data from the two main known SGD sources in Kinvara Bay in winter 2005 and 2006.

Rainfall is measured daily at a range of stations throughout the hydrometric areas and so water volumes calculated from rainfall have high accuracy. However, evaporation (losses) data are collected at very few stations, one or two per hydrometric area, and so are much less representative. Table 1 above indicates that there are on average 35–40 $m^3\ s^{-1}$ of ungauged runoff entering the sea from hydrometric areas 28 and 29. It should be borne in mind that peak discharges on gauged river systems in the west of Ireland commonly reach double the average discharge in wet periods, and half the average in dry periods, so that submarine groundwater discharge into coastal waters from hydrometric areas 28 and 29 could be expected to vary from 10 to 80 $m^3\ s^{-1}$ over the course of a year.

A key distinction between karst areas and catchments served by surface rivers is that karst has a finite natural flow capacity, due to the bounded flow channels, unlike river systems which are free to rise to any height. In groundwater systems, a maximum discharge rate, governed by the permeability of the aquifer and the cross-sectional area of the discharge points, if known, can be arrived at, which cannot be exceeded, however much rain falls. This is particularly evident in karst systems. Increasing rainfall and runoff therefore has the tendency to extend the length of time the system will discharge at its maximum rate, rather than continually increasing the discharge. Water will back up in the system, filling turloughs and flooding surrounding land, but not necessarily significantly increasing the head of water (which would increase the rate of discharge), as it will tend to spread out at the lowest level. Thus flow through a karst aquifer to the sea will reach a maximum discharge, dependent on the head of water, which may be sustained over periods of weeks by storage further up the system, whereas for rivers the discharge is effectively unlimited, and ongoing precipitation is required to sustain high flows over periods longer than a few days.

Unlike the Corrib river system, where flow rises and falls smoothly with a slight lag time as rainfall rises and falls, high rainfall in a karst area following a dry spell can lead to a more episodic output, as parts of the groundwater system fill initially, with no increase in output, and then overflow into previously dry channels which discharge into the sea. However, if another wet spell occurs before the system has time to empty, then the response may be much quicker. Surface storage of water in turloughs can lead to an extended drainage period, as the outflow is limited by the diameter of the natural 'pipework'. A further complication arises in that the catchment of a karst groundwater system is much more difficult to define than that of a river system. In some instances, as the water table rises, groundwater from one system may spill over into another. It is quite possible for example that water from the Fergus catchment (hydrometric area 27, Fig. 1) may feed or be fed by water originating in hydrometric areas 28 and 29, during very wet periods. For example, at Kilfenora (Co. Clare) discharges under normal conditions are to the Fergus catchment, but during wet periods discharges are split between the Fergus catchment (to the east) and the Dealagh catchment (to the west).

Fig. 7a shows potential runoff (PR) over hydrometric area 29, plotted against the calculated fresh water outflow from Kinvara Bay, with Fig. 7b showing the PR as a 3-day moving average. The lower limit calculation for ebb fresh water outflow (based on the highest salinity for a given tide), indicates it represents 34% of the PR for hydrometric area 29 for Nov–Feb, while the maximum calculation (based on a seawater salinity of 33.5) indicates it represents 92% of the PR. Over the winter of 2006/7 therefore, the minimum SiGD from this bay alone ranged from 4 to 87 $m^3\ s^{-1}$, while the upper limit of the maximum SiGD rose as high as 198 $m^3\ s^{-1}$. Over the same period, discharge from the R. Corrib, a catchment over 3 times the size of hydrometric area 29, varied from 124 to 392 $m^3\ s^{-1}$ (data from OPW, Fig. 8a). This indicates that the SiGD from Kinvara bay represents a significant proportion of the fresh water budget of Galway bay. Work being undertaken in neighbouring Aughinish Bay (Smith and Cave, in prep) will help to constrain the maximum SiGD from Kinvara.

The data show that even following extended periods of high rainfall, the part of the system discharging into Kinvara Bay is able to quickly ramp up the discharge volumes, returning to background levels of discharge once there a few consecutive days of dry weather. This indicates that there are a number of additional pathways for the discharge of groundwater into the bay that come into use in wet periods.

Groundwater discharges in the intertidal zone were measured at Kinvara over the autumn/winter of 2006 using a Global Water FP101 Global Flow probe to measure velocities. Discharge was then calculated using the mean section method (Shaw, 1994). Intertidal groundwater discharges of 3.5–5.9 $m^3\ s^{-1}$ were recorded flowing into the bay at low tide from sites between Dunguaire Castle and Kinvara Pier. It should be noted however that these are the lower end of the observed scale, as the flow velocity and depth at much higher discharge rates made it unsafe to take measurements. These intertidal flows are indicative of the type of flow volumes we may expect at other submarine discharge points in the bay, which cannot be measured directly.

Groundwater sampled at the coast contains relatively high levels of nutrients (Table 4). If the concentrations in these waters are representative of the concentrations in groundwater throughout this area, then SiGD represents a significant source of nutrients to these coastal waters. Nutrients entering groundwater have the potential to accumulate rather than diminish with time, due to the lack of light for photosynthesising organisms that might otherwise take them up. The concentration of nitrite + nitrate (TON) in the water sampled at the Dunguaire outflow at the head of Kinvara bay are consistently higher than those sampled at the Archway, less than 150 m away

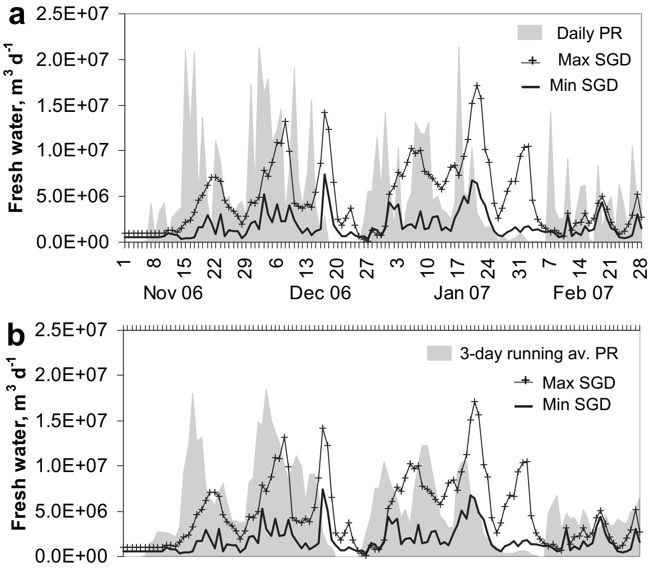


Fig. 7. (a) Min and Max amounts of SiGD daily removed on the ebb tide, compared to rainfall over the catchment. The min calculation indicates that 34% of the potential runoff (PR) to the catchment over the Nov–Feb period is removed by SiGD. The max calculation indicates that 92% of the PR to the catchment over this period is removed by SiGD. (b) SiGD as above compared to a 3-day running average of the PR. The max SGD peaks correspond to the PR peaks, but with a delay of several days. The min. SiGD corresponds more directly to the running average, with a delay of ~1 day.

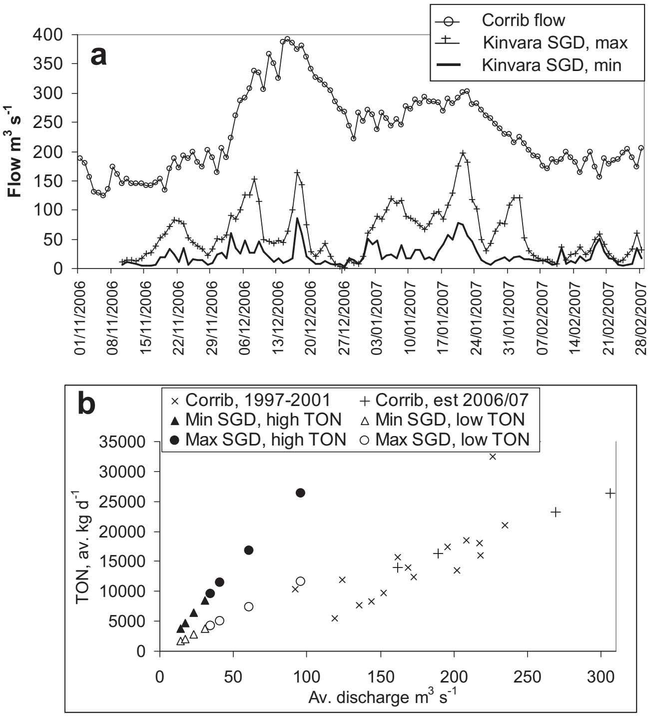


Fig. 8. (a) Daily min and max SiGD from Kinvara for winter 2006/07, compared with R. Corrib discharge over the same period. (b) Comparison of loads of TON brought into the sea via the R. Corrib, and via SiGD into Kinvara Bay, over the winter months. The nutrient concentration in Corrib waters for winter of 2006/07 is an estimate, based on the average concentrations measured in the winters of 1997–2001. Corrib discharge volumes are from daily values reported by the OPW, and concentrations for 1997–2001 are from weekly monitoring by the Western Region Fisheries Board.

(Fig. 6), while phosphate concentrations are more similar. The Archway flow tend to dry up during dry spells, while fresh water flow at Dunguaire is present at low tide even during extended summer droughts. It is likely therefore that the Dunguaire flow is from a deeper source, which may be augmented by shallower sources during wet spells, in agreement with the OPW (1997) report. TON from Dunguaire averages 3.2 mg L^{-1} while TON from the Archway averages 1.4 mg L^{-1}, giving an overall average of 2.3 mg L^{-1}. Nutrient data from the R. Corrib for this period is not available, but weekly monitoring data from the Western Region Fisheries Board for all winters from 1997/98 to 2000/01 show that TON did not exceed 1.5 mg L^{-1} except for a few samples in the winter of 1997/98, which reached a max of 2.3 mg L^{-1}.

The TON concentrations of measurements made at Dunguaire and the Archway have each been averaged over the measurements made in winter 05/06 and 06/07 to calculate monthly minimum and maximum loads of fixed nitrogen entering Kinvara bay from SiGD (Table 4), and are compared with the Corrib winter month averages for 1997–2001 (Fig. 8b), and with an estimated value for the Corrib for winter 2006/07 (Table 4). The winter of 2006/07 was wetter than those of 1997–2001, with average discharge from the Corrib in December 2006 reaching 306 $m^3 s^{-1}$. It can be seen that the loads of fixed nitrogen being brought into Kinvara bay by SiGD are approaching the same magnitudes as those brought into Galway bay by the Corrib. If the concentrations of fixed nitrogen in the SiGD at Kinvara (which we calculate above to fall between 31% and 83% of the SiGD for area 29) are representative of SiGD along this coastline, and we scale the SiGD discharge up to its full volume, then the loads of fixed nitrogen brought in by SiGD from hydrometric area 29 alone are likely to be of the same order as are brought in by the Corrib.

Kinvara Bay waters are designated as shellfish waters, with attendant requirements for water quality monitoring. Groundwater wells on the landward side are monitored under the Drinking Water regulations, but these allow TON concentrations of up to 50 mg L^{-1}, orders of magnitude more than would be found in normal seawater conditions. If a well fails to meet the regulations for drinking water, it will be closed for human consumption, but no action is taken at present to prevent contaminated groundwater from entering the sea. Kinvara Bay waters are monitored under the Shellfish Waters Directive regulations, which include a range of contaminants as well as oxygen levels, but do not include nutrient monitoring. Groundwater entering the bay itself is not routinely monitored by any agency.

SiGD has the potential to pose significant hazards to the shellfish industry, as there is no clear link between the agencies monitoring groundwater in coastal areas, and the agencies monitoring seawater. Any contaminants in groundwater may enter the sea via SiGD without warnings being communicated across agencies, and adversely impact shellfish directly, while high nutrient loads, generally beneficial to phytoplankton growth, may, if unchecked, lead to the development of eutrophic conditions. A third issue is that prolonged exposure to low salinity water affects the quality of the shellfish, as they remain closed and therefore do not feed. It would be of great benefit to shellfish harvesters to have a system which could help them predict the likely occurrence of low salinities in shellfish water, so that harvesting could be optimised.

Further work remains to be done to characterise SiGD waters for other dissolved constituents including organic carbon, as SiGD needs to be included in the calculations of the amount of dissolved organic carbon entering seawater from land-based sources.

A report by Smyth (1996) concerning flooding in the Gort-Ardrahan area stated that “the hydrological/hydrogeological regime is only partially understood. There is a lack of data concerning detailed geology, flow rates, rainfall (particularly on Slieve Aughty), turlough levels, groundwater levels, groundwater flow paths, aquifer parameters, structural and geomorphological influences on the hydrogeological flow regime, and hydrochemistry”. The study by Tynan et al. (2007) addressed turlough levels and storage in the system, while this paper, and ongoing research at NUI, Galway, funded by the Geological Survey of Ireland Griffiths programme, are beginning to address some of the remaining gaps in our knowledge. On the wider scale, collaborative work on tracing SiGD is being carried out in conjunction with Michael Schubert and Kay Knöller from the Helmholtz Centre for Environmental Research-Ufz in Leipzig, and Florian Einseidl at the University of Copenhagen (radon and radium isotopes), and with Matt Charette at the Woods Hole Oceanographic Institution in the USA (trace metals), while research is ongoing at Trinity College, Dublin to assess whether thermal imaging can be used to identify areas of SGD around the Irish coastline (Wilson and Rocha, pers. comm.), funded by the Environment Protection Agency STRIVE programme.

5. Conclusion

This study quantifies for the first time the groundwater inputs to coastal waters along a stretch of the west coast of Ireland. Such inputs have not previously been taken into account in hydrodynamic modelling in this region. This is a karst limestone area, with large focussed submarine and intertidal groundwater inputs, however the principle can be applied to most coastal waters where there is a coastal aquifer. It shows that the inputs of fresh water and nutrients from SiGD to coastal waters can be of the same order as riverine inputs, and that SiGD needs to be taken account of in hydrodynamic and hydrochemical models for coastal waters. SiGD has the potential to contribute large fluxes of nutrients and contaminants to coastal waters, in exactly the same way as rivers, and should therefore be accounted for when calculating inputs to coastal waters for the purpose of fulfilling EU Water Framework Directive monitoring obligations, and when making River Input Discharge returns to OSPAR. Agencies monitoring groundwater in coastal aquifers, and those monitoring coastal waters, including designated Shellfish and Bathing waters, should maintain close contact for the regular exchange of monitoring data, and to set up contingency plans to deal with the impacts on seawater of contamination in coastal groundwater systems.

Acknowledgements

This research was funded by a National University of Ireland, Galway, Millenium Fund grant to R.R. Cave and T. Henry. Mr. Rainier Krause very kindly permitted us to hang our instruments from his rafts in Kinvara Bay. A number of NUI Galway undergraduate students participated in some of the survey work for this project, including Barry Ryan and David Killeen (Environmental Science), Brian Clancy and Joey O’Connor (Marine Science). Rainfall data were provided by Met Éireann (Birr and Gort), Frank Gaffney (NUIG), and An Garda Síochana (Kinvara Garda Station). Flow data for the river Corrib were provided by the OPW and nutrient concentration data by the Western Region Fisheries Board. Flow data for the Shannon were provided by the ESB. The Marine Institute of Ireland funded the surveys that collected the salinity data in Galway Bay. The manuscript benefited from comments from three anonymous reviewers.

References

Groundwater and pore water inputs to the coastal zone. Biogeochemistry 66, 2003, 1–2. Special Issue.

Boycott, T., Bruce, C., et al., 2003. In: Mullan, G. (Ed.), Caves of County Clare and South Galway. University of Bristol Spelaeological Society, Bristol.

Bugna, G.C., Chanton, J.P., et al., 1996. The importance of groundwater discharge to the methane budgets of nearshore and continental shelf waters of the northeastern Gulf of Mexico. Geochimica Et Cosmochimica Acta 60 (23), 4735–4746.

Burnett, W.C., Taniguchi, M., et al., 2001. Measurement and significance of the direct discharge of groundwater into the coastal zone. Journal of Sea Research 46 (2), 109–116.

Burnett, W.C., et al., 2006. Quantifying submarine groundwater discharge in the coastal zone via multiple methods. Science of the Total Environment 367 (2–3), 498–543.

Carruthers, T.J.B., van Tussenbroek, B.I., et al., 2005. Influence of submarine springs and wastewater on nutrient dynamics of Caribbean seagrass meadows. Estuarine Coastal and Shelf Science 64 (2–3), 191–199.

Charette, M.A., Buesseler, K.O., 2004. Submarine groundwater discharge of nutrients and copper to an urban subestuary of Chesapeake bay (Elizabeth River). Limnology and Oceanography 49 (2), 376–385.

Epa and River Basin Districts, 2005. The Characterisation and Analysis of Ireland's River Basin District. National Summary Report (Ireland) 2005.

Povinec, P.P., Burnett, W.C., de Oliveira, J. (Eds.), 2008. Submarine groundwater discharge studies along the Ubatuba coastal area in south-eastern Brazil. Estuarine Coastal and Shelf Science 76 (3), 259. Special Issue.

Fleury, P., Bakalowicz, M., et al., 2007. Submarine springs and coastal karst aquifers: a review. Journal of Hydrology 339 (1–2), 79–92.

Gaffney, F., 2006. Climate of Galway 1966–2005. Measurement of Temperature, Sunshie and Rainfall. National University of Ireland Department of Experimental Physics Report.

Gonzalez, F.U.T., Ilveira, J., et al., 2008. Water quality variability and eutrophic trends in karstic tropical coastal lagoons of the Yucatan Peninsula. Estuarine Coastal and Shelf Science 76 (2), 418–430.

Johannes, R.E., 1980. The ecological significance of the submarine discharge of groundwater. Marine Ecology Progress Series 3 (4), 365–373.

Johannes, R.E., Hearn, C.J., 1985. The Effect of Submarine Groundwater Discharge on Nutrient and Salinity Regimes in a Coastal Lagoon Off Perth, Western- Australia. Estuarine Coastal and Shelf Science 21 (6), 789–800.

Collection of papers on the implications of sea-level rise for Europe's coasts. Journal of Coastal Research 24 (2), 2008.

Lamontagne, S., La Salle, C.L., et al., 2008. Radium and radon radioisotopes in regional groundwater, intertidal groundwater, and seawater in the Adelaide Coastal Waters Study area: implications for the evaluation of submarine groundwater discharge. Marine Chemistry 109 (3–4), 318–336.

Laws, E.A., Brown, D., et al., 2004. Coastal water quality in the Kihei and Lahaina districts of the island of Maui, Hawaiian Islands. Impacts from physical habitat and groundwater seepage: implications for water quality standards. International Journal of Environment and Pollution 22 (5), 531–546.

MacCarthaigh, M., 1996. An Assessment of the 1995 Drought. Environmental Protection Agency, Wexford.

Manheim, F.T., 1967. Evidence for submarine discharge of water on the Atlantic continental slope of the southern United States, and suggestions for further research. Transactions of the New York Academy of Sciences Series 2 29 (7), 839–853.

Michael, H.A., Mulligan, A.E., et al., 2005. Seasonal oscillations in water exchange between aquifers and the coastal ocean. Nature 436 (7054), 1145–1148.

Mills, G., 2000. Modelling the water budget of Ireland—evapotranspiration and soil moisture. Irish Geography 33 (2), 99–116.

Mills, G., 2001. Ireland's water budget—model validation and a greenhouse experiment. Irish Geography 34 (2), 124–134.

Moore, W.S., 2006. Radium isotopes as tracers of submarine groundwater discharge in Sicily. Continental Shelf Research 26 (7), 852–861.

Moore, W.S., 2010. The effect of submarine groundwater discharge on the ocean. Annual Review of Marine Science 2010 (2), 59–88.

Mullan, G. (Ed.), 2003. Caves of County Clare and South Galway. University of Bristol Spelaeological Society, Bristol.

Mutchler, T., Dunton, K.H., et al., 2007. Isotopic and elemental indicators of nutrient sources and status of coastal habitats in the Caribbean Sea, Yucatan Peninsula, Mexico. Estuarine Coastal and Shelf Science 74 (3), 449–457.

Nuzzi, R., Waters, R.A., 2004. Long-term perspective on the dynamics of brown tide blooms in Long Island coastal bays. Harmful Algae 3 (4), 279–293.

OPW, 1997. An Investigation of the Flooding Problems in the Gort Ardrahan Area of South Galway – Final Report, vols. 1–12 Office of Public Works/ Jennings O'Donovan and Southern Global Water.

OSPAR Commission, 2006. Data Report on the Comprehensive Study of Riverine Inputs and Direct Discharges (RID) in 2004, Assessment and Monitoring series. 186 pp.

Paytan, A., Boehm, A.B., et al., 2004. Bacterial contamination and submarine groundwater discharge-a possible link. Environmental Chemistry 1 (1), 29–30.

Povinec, P.P., Aggarwal, P.K., et al., 2006. Characterisation of submarine groundwater discharge offshore south-eastern Sicily. Journal of Environmental Radioactivity 89 (1), 81–101.

Pracht, M., Lees, A., Leake, B., Feely, M., Long, B., Morris, J., O'Connell, B., 2004. Geology of Galway Bay: a Geological Description to Accompany the Bedrock Geology 1:100000 Scale Map Series, Sheet 14, Galway Bay. GSI, Dublin.

Royal Irish.Academy, 2009. Biology and environment: proceedings of the Royal Irish Academy. 109B3(2009): Water Framework Directive Special Issue. doi:10.3318/BIOE.2009.109.3.

SCOR/LOICZ, 2004. Submarine Groundwater Discharge, Management Implications, Measurements and Effects Prepared for International Hydrological Program (IHP), Intergovernmental Oceanographic Commission (IOC) by Scientific Committee on Oceanic Research (SCOR), Land-Ocean Interactions in the Coastal Zone (LOICZ). IHP-VI, Series on Groundwater No. 5, IOC Manuals and Guides No. 44.

Schwartz, M.C., 2003. Significant groundwater input to a coastal plain estuary: assessment from excess radon. Estuarine Coastal and Shelf Science 56 (1), 31–42.

Shaw, E., 1994. Hydrology in Practice, third ed. Taylor & Francis.

Smith, A.J., Nield, S.P., 2003. Groundwater discharge from the superficial aquifer into Cockburn Sound Western Australia: estimation by inshore water balance. Biogeochemistry 66 (1–2), 125–144.

Smyth, T., 1996. A Case Study in the Gort/Ardrahan Area of South Galway. Office of Public Works, Dublin.

Suzuki, M., Zhang, I., 2003. Submarine groundwater spring and its impact on the marine environment in Toyama Bay, Japan. Geochimica Et Cosmochimica Acta 67 (18), A459. A459.

Taniguchi, M., Burnett, W.C., et al., 2002. Investigation of submarine groundwater discharge. Hydrological Processes 16 (11), 2115–2129.

Taniguchi, M., Uchida, S., et al., 2003. Periodical changes of submarine fluid discharge from a deep seafloor, Suiyo Sea Mountain, Japan. Geophysical Research Letters 30 (18) art. no.-1917.

Tynan, S., Gill, M., Johnston, P., 2007. Water Framework Directive: Development of a Methodology for the Characterisation of a Karstic Groundwater Body with Particular Emphasis on the Linkage with Associated Ecosystems Such as Turlough Ecosystems (2002-W-DS-8-M1). Final Report. Prepared for the Environmental Protection Agency by Department of Civil, Structural & Environmental Engineering, Trinity College Dublin (TCD). Available for download from. http://www.epa.ie/downloads/pubs/research/water.

Uchiyama, Y., Nadaoka, K., et al., 2000. Submarine groundwater discharge into the sea and associated nutrient transport in a sandy beach. Water Resources Research 36 (6), 1467–1479.

Westbrook, S.J., Rayner, J.L., et al., 2005. "Interaction between shallow groundwater, saline surface water and contaminant discharge at a seasonally and tidally forced estuarine boundary. Journal of Hydrology 302 (1–4), 255–269.

Windom, H.L., Moore, W.S., et al., 2006. Submarine groundwater discharge: a large, previously unrecognized source of dissolved iron to the South Atlantic Ocean. Marine Chemistry 102 (3–4), 252–266.

Young, M.B., Gonneea, M.E., et al., 2008. Characterizing sources of groundwater to a tropical coastal lagoon in a karstic area using radium isotopes and water chemistry. Marine Chemistry 109 (3–4), 377–394.

Zektser, V.A., Ivanov, I.S-, Meskheteli, A.V., 1973. The problem of direct groundwater discharge to the seas. J. Hydrol 20 (1), 1–36.