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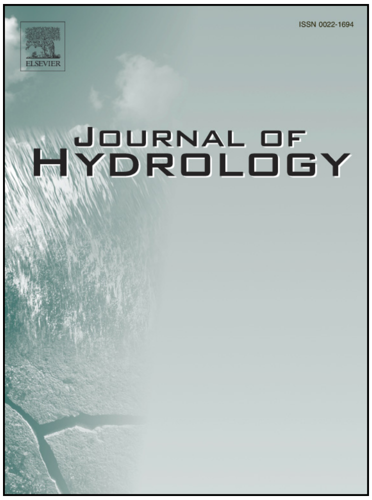

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Quantification of Submarine/Intertidal Groundwater Discharge and Nutrient Loading from a Lowland Karst Catchment

McCormack T., Gill, L.W, Naughton O., Johnston, P.M.

Department of Civil, Structural and Environmental Engineering, Trinity College Dublin, Dublin 2, Ireland

Corresponding Author: Ted McCormack, email: mccormte@tcd.ie, tel: +353 18962781

Abstract

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 – 15 m^3/s with a mean value of 7.6 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 1.1 m^3/s, thus the total mean discharge from both Kinvara Springs was determined to be 9.75-10 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 964 kg/day N and 19.8 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.

KEYOWRDS: Submarine groundwater discharge, Karst, Modelling, Salinity, Nutrient Loading, Ireland

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).

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 north-west from the mountains across the Gort Lowlands to the sea at Kinvara (see Figure 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 60-1000 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).

Figure 1: Geology and relief map of study area displaying turloughs, raingauges, boreholes, Kinvara, river gauging stations and approximate subcatchment boundaries for the river/allogenic recharge subcatchment, the modelled subcatchment, the Kinvara East subcatchment and the Cloonteen/Burren subcatchment.

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 Figure 1 for approximate subcatchment area). Tracer studies have shown that these external waters join the conduit network at some point between Caherglassaun turlough and Kinvara (Southern Water Global, 1998). The total area of these additional subcatchments is approximately 90 km^2 (roughly 18-20% of the total 483km^2 catchment for the Kinvara springs).

Kinvara Bay is protected as part of the Galway Bay Complex SAC/SPA (Special Area of Conservation and Special Protected Area for birdlife) due to the presence of several habitats and species listed in the

EU Habitats Directive (European Parliament and Council, 1992). The bay also includes some commercial/licensed shellfish production zones. Due to its protected status and the commercial interest in its conservation, the role of nutrients entering the bay is of key importance. Significant quantities of nutrients entering the bay are thought to originate from agricultural practices within the Gort Lowlands catchment (Smith and Cave, 2012). As well as nutrient loading from the springs, Kinvara Bay is also subject to untreated wastewater discharge from an outfall pipe discharging approximately 100 m off the end of the quay. Approximately 286 m^3/d (dry weather flow) of untreated sewage from the town of Kinvara is discharged into the bay during ebb tides (Environmental Protection Agency, 2010) and is likely to be a significant source of fixed nitrogen within the bay. Due to the lack of treatment, and the consequent organic enrichment and faecal contamination, the bay is at risk of losing its SAC conservation status. To combat this, a new wastewater treatment plant with a new outfall located approximately 300 m further from the town and projecting 170m into the bay has been proposed to promote dilution and produce a treated effluent with significantly lower associated ecological impacts.

Figure 2: Map of Kinvara Bay showing locations of springs (inset) and CTD diver positions.

2 METHODOLOGY

A variety of different field data were collected for the project in order to develop and validate the modelling approach as well as determine the nutrient mass balance in the bay.

2.1 Turlough Water Level

Turlough water level time series were collected at hourly resolution between September 2009 and June 2013 using Schlumberger Mini-Diver® DI501 and DI502 pressure transducers. Compensation for the variation in prevailing air pressure was made using a BaroDiver® (DI500) which was installed at ground level near Lough Coy turlough.

2.2 Rainfall and Evapotranspiration

High-resolution (15 minute) rainfall data were collected using two tipping bucket ARG100 rain gauges (Environmental Measurement Ltd) installed at the upper end of the catchment. They were installed at Kilchreest, 70 meters above ordinance datum (mAOD), and Francis Gap (250 mAOD) (Figure 1). Hourly rainfall and evapotranspiration data were obtained from climatic weather stations run by the national meteorological service, Met Éireann.

2.3 River Gauging

River gauging stations were present on the three primary rivers draining off the Slieve Aughty Mountains. Four Office of Public Works gauging stations were located on the three main rivers, the Owenshree, Ballycahalan and Owendalulleegh, with an additional station located on the Beagh River near the outlet of Lough Cutra. Rating curves were developed for each gauging station using the mid-section velocity depth surveying method. Approximately 15-20 flow measurements were recorded for each river between 2009 and 2012 using an acoustic digital ultrasonic current meter (OTT ADC). For high stage events, the rating curves were extended using the velocity-area method (Shaw, 2011).

2.4 Hydrochemistry

Between March 2010 and March 2013, monthly sampling was carried at the turloughs as well as KW and KE springs. Boreholes were sampled to collect groundwater samples from within the carboniferous aquifer surrounding the turlough network (see Figure 1 for borehole locations). Samples were tested for alkalinity based on Standard Methods (APHA, 1999), specific-conductivity (conductivity corrected to 25°C) using an electrical conductivity (EC) meter (WTW® Cond.197i), Total nitrogen (TN) using cell test kits by Merck (range 0.5-15 mg/l) and Dr. Lange (range 1-16 mg/l), and nitrate (NO_3) using Merck test kit (range of 0.1-25 mg). Quality control (QC) was carried out for TN and NO_3 using Merck Combicheck standards for each batch of monthly samples. If the tested QC sample did not lie within the given range of values (5±0.7mg/l for TN, 9±0.9mg/l for NO_3), the batch of samples, and the QC were retested. Total phosphorus concentrations were determined by acidic persulphate digestion of samples at 120°C and subsequent measurement of phosphate by colorimetry in accordance with the Standard Methods (APHA, 1999). Total dissolved phosphorus concentrations were obtained similarly but with the added step of filtration directly after sampling using a 45 micron filter. QC was carried out for P by running a QC sample with each batch of P analyses. This solution was prepared to a specific concentration (0.025 mg/l TP) at the onset of laboratory testing and kept in individual bottles in a freezer. Duplicate samples were also collected and tested to rule out sampling error.

2.5 Spring Discharge Measurement

In order to assess the accuracy of the modelled outflow at Kinvara, a measurement of outflow was needed over the course of the modelling period. However, the intertidal nature of the Kinvara springs renders direct flow measurement impossible. As such, it was necessary to conceive of an alternative methodology which could be used to calculate the outflow at Kinvara. The technique chosen was a salinity mass balance (similar to that of Null et al. (2014)). CTD-Diver® (DI271) monitors were used to measure the altering depth and specific conductivity within the bay between May 2012 and February 2013. CTDs were placed in three locations within the bay: the springs, the approximate midpoint of the bay and the outlet (Figure 2). The CTDs were positioned on the base of the bay using a concrete platform and, in some cases, at a depth of approximately 1 m within the water column, suspended from the buoy-platform rope. The CTD placed at the spring was positioned far enough out into the bay so as to pick up the combined flow from KW and KE springs. Long term water level data from Galway Port (required for model calibration) were obtained from the Irish Marine Institute. This dataset was offset by 72 minutes to allow for a tidal delay between Kinvara and Galway Port. Specific Conductivity (mS/cm) was converted into salinity (practical salinity units or 'psu') by an approximate factor of 0.61 (Schemel, 2001). The premise behind the method was that, in theory, for each tidal cycle, the input of freshwater at Kinvara should result in a slightly reduced salinity value for the bay. When the tide comes in, the freshwater at Kinvara is held back (in dry periods, the freshwater is even pushed back into the aquifer). On the out-going tide, the freshwater is released and should cause a measurable dip in salinity across the bay.

Salinity transects of the bay were also carried out using a boat on the 11th of February 2013. Transects were run between the springs and the outlet of the bay while the tide was coming in. CTDs were rigidly suspended from the boat at depths 10 cm and 90 cm below the surface.

3.0 Hydrological Model

A hydraulic/hydrological model of the main conduit flow system in the Gort Lowlands, built using Infoworks CS version 8.5 (Wallingford Software), was used to estimate discharge from the main conduit network to the spring at Kinvara West (Gill et al., 2013). This software package is designed for management of urban drainage networks and incorporates the Hydroworks modelling engine. The model simulates the hydraulic behaviour of a pipe network under varying conditions of rainfall, land use, population, inflows etc. As the model is capable of modelling the hydraulic conditions in both open channel and pressurised flow channels, it is highly suitable for modelling a well-developed karst conduit network such as that of the Gort Lowlands. The model represents the main conduit flow system in the Gort Lowlands as a complex network of pipes (representing conduits) and tanks (representing turloughs) fed by three allogenic river inputs, discharging at an outfall (KW). Internal storage within the system was represented using five ponds with the same stage-volume characteristics as the surveyed turloughs. These storages operate as surcharge tanks, relieving pressure from the conduit system during periods of high flow. Diffuse autogenic recharge was incorporated into the model using a conceptual epikarst fracture system represented by sub-catchments draining into the main conduit system via permeable pipes. This was achieved using a combination of runoff-routing model, Groundwater Infiltration Module (GIM) and use of SUDS (Sustainable Urban Drainage) applications in the Infoworks modelling suite. The rainfall falling on a subcatchment was first subjected to evapotranspiration losses and initial wetting and storage losses. The water was then routed down through the soil into the conceptual epikarst fracture system which was represented by pipes with permeable characteristics (with flow calculated via Darcy's Law), which then link to the main open conduits. A schematic illustration of the model and the locations of its major elements is shown in Figure 3. For a complete description of the construction and calibration of the original model see Gill et al. (2013).

Figure 3: Conduit network model Schematic.

It should be noted that the outfall for the hydrological model represents only the discharge at Kinvara West; the more diffuse karst-fed Kinvara East spring is not accounted for by the conduit network model.

The model was updated and refined for the purposes of this study in order to improve model accuracy and certainty in SGD estimates (McCormack, 2014). Airborne LiDAR topographic data were used to extend the original turlough stage-volume relationships derived using field GPS surveys (Gill, 2010; Naughton et al., 2012). Using a combination of GPS data for lower basin levels, together with LIDAR data for the upper reaches of flooding, turlough stage-volume relationships were determined to a much greater degree of accuracy than had previously been available. In addition, the original rating curves for the three rivers feeding the catchment/model suffered from uncertainty at high flows due difficulties in obtaining flow measurements under those conditions. During 2012 additional high flow data were collected which created significant improvements to the rating curves for higher flow estimates for each river. The model was re-calibrated and validated using an extended 6 year water level time series.

3 RESULTS

3.1 Simulated flows at Kinvara West spring

After a successful simulation, a large range of output data were available from the model at a 15 minute time step such as flow, velocity, water level, hydraulic gradient etc. for any node or link in the network. Figure 4 shows an example of observed vs modelled results for Coole turlough between 2010 and 2013. The simulated water levels/volumes show good correlations with the measured water levels/volumes, particularly for the lower three turloughs, Coole, Garryland and Caherglassaun.

Figure 4: Observed vs modelled results for Coole turlough between 2010 and 2013.

The goodness of fit, or model efficiency, was assessed using the Nash-Sutcliffe criterion for all turlough water levels and volumes across the entire dataset (2010-2013) with results presented in Table 1.

Table 1: Efficiency of model results for turlough water level and volume data.

	Water Level	Volume
Blackrock	0.888	0.813
Coy	0.891	0.889
Coole	0.933	0.963
Garryland	0.961	0.974
Caherglassaun	0.963	0.962

Using this calibrated model, the discharge at Kinvara West was then determined for the entire modelling period. Figure 5, a time series of modelled flow between 2010 and 2013, shows that the flows at Kinvara

West ranged between approximately -5 and 15 m^3/s with a mean value over this three year period of 7.6 m^3/s. Negative flow values indicate tidal intrusion into the karst network during low flow periods at high tides. Such saltwater intrusion has been shown to influence groundwater levels in boreholes up to 5 km from the coastline (Petrunic et al., 2012).

Figure 5: Modelled outflow at Kinvara West between May 2010 and March 2013. Note: the 'thickness' of the line representing discharge is due to daily tidal variation.

A plot of the net flows into system (rivers) and out of the system at KW spring as predicted by the model simulations for the period between May and June 2012 is shown in Figure 6 which shows the damping effect that the network of linked pipes and turloughs has on the input signals. The outflows from the system maintain at between approximately 5 to 10 m^3/s for most periods whereas the inflows show higher peaks and faster recessions. Over the three year study period, the maximum flow modelled at KW only reached 14.8 m^3/s whereas the maximum combined river input was 69 m^3/s. The results also show the temporal effect of tides as well as the monthly impact of spring tides (range ≈ 5 m) and neap tides (range ≈ 2 m) on groundwater discharge into bay. Overall, the modelled outflow at KW was 17% greater than the combined river input due to the contribution of rainfall on the diffuse/epikarst sub-catchments.

Figure 6: Karst Lowland aquifer: allogenic river inflow vs modelled spring outflow (May 2012 – Sept 2012).

3.1.1 Contribution of water from non-Gort lowland systems

The modelled outflow at KW takes account of the three rivers feeding the Gort Lowlands and any rainfall that falls within the catchment. It does not however, take account of the contribution of water from separate systems such as Cloonteen to the south and the North-Burren to the west. Tracer studies have proven a hydrological link between these systems and the intertidal springs at Kinvara (Southern Water Global, 1998). These external waters can be observed linking onto the Gort Lowlands conduit network between Caherglassaun and Kinvara West spring via hydrochemical sampling, specifically the measurement of alkalinity.

The variation in alkalinities of Caherglassaun and KW (Figure 7) shows very similar patterns over time, although with relatively elevated concentrations at KW. The mean concentration of KW is 155.6 mg/l $CaCO_3$ while the mean concentration of Caherglassaun is lower at 121.3 mg/l $CaCO_3$. These concentrations are both relatively low for karstic catchments due to the allogenic nature of the water feeding the conduit network. Samples taken from boreholes within the catchment show much greater alkalinity concentrations (350 – 400 mg/l $CaCO_3$) as the samples are more representative of the diffuse/epikarst aquifer which surrounds the conduit network. As the discharge volumes of water are so great and the time of travel so short (in the order of hours to days) between Caherglassaun and Kinvara, dissolution of the carbonate aquifer (as well as other non-conservative processes) are unlikely to contribute significantly to alkalinity concentrations. Instead, the increased alkalinity at Kinvara suggests the addition of water with a higher alkalinity from a separate system.

Figure 7: Alkalinity comparison between Caherglassaun and Kinvara West (May 2010 – Mar 2013).

The hydrological model predicts that over a three year study period, the amount of water that flowed from Caherglassaun to KW was approximately 680,470,000 m^3 whereas the amount of water discharging at KW was approximately 684,950,000 m^3. The model includes a diffuse autogenic recharge contribution of 0.7% from this area. A mass balance using the mean measured alkalinity of the diffuse/epikarst water in the catchment of 365.1 mg/l $CaCO_3$ shows that this additional water to KW would cause an increase in alkalinity from 121.3 mg/l $CaCO_3$ at Caherglassaun to just 123 mg/l $CaCO_3$ at KW. This value is considerably lower than the recorded mean of 155.6 mg/l $CaCO_3$ (standard deviation: 25, standard error: 5) which suggests that there is a significant contribution from additional diffuse recharge systems not accounted for by the model.

The amount of additional water (with alkalinity between 350 and 400 mg/l $CaCO_3$) required to enhance KW to the recorded level would be between 96,000,000 and 121,900,000 m^3, i.e. an increase of 14–18% (an unsurprising figure considering this subcatchment takes up approximately 18-20% of the total catchment size). This mass balance calculation includes the assumption that external groundwater originates from sources with similar alkalinity values as the diffuse groundwater within the Gort Lowlands (350 – 400 mg/l $CaCO_3$, mean: 365.1 mg/l $CaCO_3$). This is a reasonable assumption considering that the two likely sources of external water are from the Cloonteen catchment and the north-Burren, and both of these areas are known to have alkalinity values typical of diffuse/epikarst water. Thus based on this mass balance calculation, the mean modelled outflow at Kinvara increases from 7.6 to approximately 8.7-9.0 m^3/s due to the addition of flow from these adjacent areas.

3.1.2 Estimation of Kinvara East discharge

The outflow from KE is more difficult to quantify as is it is fed primarily from the more diffuse north-western portion of the Gort Lowlands and is not included in the pipe-network model (see Figure 1). However, an approximation of diffuse flow per area of catchment can be made by taking the diffuse contribution at each timestep from the hydrological model (i.e. outflow from the sub-catchments) and dividing it by the total area of the modelled sub-catchments. Considering that these model sub-catchments are calibrated to the karst aquifer underlying the Gort Lowlands, their calibration should apply to the catchment feeding KE as much as it does KW (as the bedrock geology is the same for both catchments). Thus the 'diffuse flow per unit area' can be applied to the KE catchment in order to find an approximation of flow discharge from the KE spring. An estimate of the catchment size of KE was made based on 'recharge areas' as delineated by the Gort Flood Studies Report (Southern Water Global, 1998) approximated as 88 km^2. With this catchment area, the flow feeding KE equates to approximately 1.1

m^3/s (i.e. an increase of 11% on the total outflow from KW). Thus the total mean flow entering Kinvara Bay from both springs is estimated at approximately 9.75 – 10 m^3/s. The relative discharges from KW and KE are displayed in Figure 8. It should be noted that the discharge shown in this figure for KW is made up of modelled discharge and an additional 16% discharge (to account for the 14-18% increase in KW from separate systems).

Figure 8: Comparison between estimated KE discharge and total KW discharge (including contribution from non Gort Lowland systems), (May 2012 – Sept 2012).

3.2 Manual Measurement of Discharge

The results from a CTD positioned at the base of the spring (during mid-July) are shown in Figure 9(a) where the salinity shows downward shifts when the tide drops indicating that the CTD was in contact with freshwater. As the tide starts to rise, the salinity shows a dramatic shift back up to a value more akin to saltwater. As the tidal range decreased due to the approaching neap tide (period at which the difference between high and low tide is least), a critical point was reached on July 12th when the tide did not drop sufficiently low enough to allow freshwater to contact the CTD. It should be noted that depth on these tidal plots is presented as meters above chart datum (m ACD).

Figure 9: Water level and salinity data from the CTD's. A: Spring CTD (8th July – 14th July), B: Midpoint CTD (3rd–5th May), C: Outlet CTDs (water column – solid line, base – dashed line, 8th–14th July).

This behaviour suggests the existence of a sharp interface between saltwater and freshwater (with the less dense freshwater sitting on top of saltwater) displayed conceptually in Figure 10.The fresh water sits on top of the salt water in the form of a wedge, a well-known phenomenon associated with estuaries (Partch and Smith, 1978). The presence of this wedge indicates limited saltwater-freshwater mixing is occurring near the spring.

Figure 10: Conceptual interface between saltwater and freshwater at Kinvara spring.

This interface was less distinct in the water column at the midpoint CTD (as seen in Figure 9(b)) with data from approximately 1m depth collected during early May. From the plot, it can be seen that the wedge was still present but the interface between freshwater and saltwater has become wider and less distinct due to mixing processes. Spot samples taken during this sampling period, however, showed that pure freshwater was still present on the upper few centimetres of water. Thus at this location (2 km from the springs) the wedge was only present at the very top of the water column.

At the outlet (approximately 4 km from the springs), the interface was not evident within the water column, suggesting that the water was totally mixed at this point (solid orange line in Figure 9(c)). However, curiously, the CTD positioned at the outlet base (dashed orange line in Figure 9(c)), shows salinity approximately half that of the water column. This contrast between salinity at the outlet base and the outlet water column is difficult to explain. Perhaps the lower salinity at the outlet base is an indication that the CTD was placed within the vicinity of an unknown submerged spring. While the cause of this salinity behaviour is unknown, its occurrence suggests that water passing through Kinvara Bay outlet cannot be considered well mixed.

The spatial variability of salinity within Kinvara Bay, derived from conductivity transects carried out during a rising tide, is shown in Figure 11. In Figure 11(a) it can be seen that a distinct layer of freshwater was present to a depth of at least 10 cm and extends out to the midpoint of the bay. In Figure 11(b), no such interface was identified deeper in the water column but did show a general trend of decreasing salinity approaching the springs. These plots indicate that the conceptual wedge of freshwater is extremely shallow and can stretch far out into Kinvara Bay. Also, the saltwater layer lying beneath this wedge was not homogeneous and gradually increases in salinity with distance from the spring.

Figure 11: Salinity transect of Kinvara Bay

These results show the assumption of homogeneity within the bay is not valid. Instead, the freshwater has been observed to sit on top of the saltwater with a distinct interface. This lens of freshwater has been seen to occur up to the midpoint of the bay. However, at this distance from Kinvara, the freshwater-saltwater interface becomes less defined. Spot sampling (with a portable EC meter) also showed the "wedge" to extend further out of the bay in the form of a thin film of freshwater sitting on the top few centimetres of the water column. Considering these factors (as well as the indication of unknown submarine discharges further out in the bay), a method of calculating freshwater entering the bay which does not require the assumption of the bay being well mixed was required.

Based on the concept of the freshwater wedge, another calculation technique was devised. As the tide comes in, the wedge is pushed backwards towards Kinvara and its volume expands due to the continuous discharge of freshwater from the springs. At low tide, this freshwater is then released into the bay, and onwards towards Galway Bay. It has been observed that at low tide, the freshwater discharge at Kinvara is freely draining, similar to a typical surface water spring. Thus, focussing on the CTD located at the spring, the change in volume of the freshwater wedge between the start and end of a low tide period (i.e.

the period in which the CTD is in contact with fresh water) gives an indication of the amount of freshwater lost from the wedge (which should theoretically be similar to freshwater entering the wedge, i.e. spring discharge).

An example of such a low tide period is shown in Figure 12 with a time series plot of depth and salinity for an individual tidal cycle occurring during August 2012. Four specific points in time are chosen and are conceptualised with individual graphs. Time A shows the spring at high tide when the CTD is fully immersed in saltwater. Time B shows the point at which the interface passes across the CTD while the tide goes out. Time C shows the spring at low tide. At this time, it can be seen that the water level at the spring (blue line) does not drop as low as the water level at the outlet (green dotted line), this is due to the constant discharge from the spring. Time D shows the point at which the tide has turned and pushes the interface back across the CTD.

Figure 12: Freshwater wedge calculation, time series plot and conceptual plots.

Using this conceptualisation, the change in wedge volume between times B and D should give an indication to the amount of freshwater lost from the wedge. This method is based on the assumptions that there is no mixing between the freshwater and saltwater zones and that each zone is homogeneous, each of which create uncertainties. However, this estimate should be sufficient to determine whether the outflow prediction is broadly within the range as suggested by the hydrological model (~5 – 15m^3/s). For a more accurate calculation, further transects should be carried out (especially East-West transects across the bay) which would allow for greater confidence in estimating the wedge's shape.

The volume of the wedges was calculated by combining CTD depth data, Kinvara Bay bathymetric survey data (obtained via the Geological Survey of Ireland online database) and an estimated wedge slope. The slope of this wedge was estimated based on the findings of multi-depth spot sampling. The volume of the wedge at times B and D were found to be 693,000 m^3 and 549,000 m^3 - a change in volume over the low tide period of approximately 144,000 m^3. Thus, over the 4.5 hour period between times B and D, it would take an outflow of 8.9 m3/s from the wedge to result in such a volume reduction. Over this same period, the Infoworks model predicts a mean outflow from KW of 8.09 m^3/s. This modelled discharge increases to approximately 9.4 m^3/s with the inclusion of external catchment water (Section 3.1.1) and 10.5 m^3/s with the inclusion of KE discharge (based on KE flow being approximately 11% of KW flow, see Section 3.1.2). Thus, it appears that the salt wedge technique validates the results of the hydrological model. It should be noted however that the salt wedge method does not account for discharges into Kinvara Bay other than those from KW and KE springs.

3.3 Nutrient Loading

A sizeable dataset of monthly nutrient concentrations from springs, turloughs and boreholes was collected between 2010 and 2013. The mean TN concentration for KW was measured as 1.05 mg/l while mean TN for KE was 1.99 mg/l. Little difference was observed for P between KW and KE with concentrations of 22.9 µg/l and 24.2 µg/l respectively (TP). Mean concentrations of N at KW (1.05 mg/l TN) reflect the mean concentrations of the turloughs (1.12 mg/l TN) while the higher mean concentration of KE more closely reflect the higher concentrations of TN found in diffuse-flow dominated regions of the Gort Lowlands as shown via borehole sampling (mean concentration from boreholes: 2.3 mg/l TN). Concentrations of P at the springs were among the lowest mean concentrations found within the Gort Lowlands catchment suggesting the loss of P as water moves through the karst system.

Combining the nutrient concentration dataset for the KW spring with the outflow as predicted by the hydrological model (factored up by 14-18% to account for un-modelled discharge), the nutrient loading entering the bay via KW could be determined. In order to calculate the loading correctly, mean daily flow from KW was determined so that the tidal affect was accounted for. The nutrient loads exiting the system along with the mean daily flow data from KW are shown in Figure 13. The average daily TN load was calculated as approximately 800 kg/day with a measured range of 190-1920 kg/day. For TP, the average daily load was 17.6 kg/day with a measured range of 7.7-25.2 kg/day.

Figure 13: Daily Nutrient Loads exiting the system at KW (based on modelled outflow).

The approximation of nutrient loading into Kinvara can be expanded further with the inclusion of KE. In Section 3.1.2 the diffuse flow per unit area of the modelled sub-catchments was used in combination with an estimated catchment size of KE in order to calculate a rough approximation of discharge from KE (≈ 1.1 m^3/s). Combining this discharge value with nutrient concentrations at KE suggests loading rates of 164 kg N/day and 2.2 kg P/day indicating the total nutrient loads entering Kinvara Bay to be 964 kg N/day and 19.8 kg P/day.

4 DISCUSSION

4.1 Kinvara Spring Discharge

Through a combination of hydrological modelling and hydrochemical analysis, the mean spring discharge at the Kinvara springs has been determined to be approximately 9.75 - 10 m^3/s. This discharge prediction can also be compared to a simple water balance calculation on the catchment area based on annual rainfall quantities versus the total annual discharge from Kinvara (essentially an extremely simplified version of the hydrological model) as follows:

The zone of contribution (ZOC) for both KW and KE (including the additional flow from the Cloonteen and Burren subcatchments) has been estimated as 483 km^2 (Environmental Protection Agency, 2011).

Roughly one third of this ZOC consists of the Slieve Aughty uplands which receive approximately 1400 mm rainfall per annum (based on data from Kilchreest and Francis Gap raingauges). The other two thirds of the catchment consist of the lowlands which receive approximately 1100 mm per annum (based on data from a Met Éireann raingauge located at Ardrahan, (Walsh, 2012)). Thus the entire ZOC could be considered to receive approximately 1200 mm per annum. Annual evapotranspiration within the catchment is approximately 500 mm (based on data from nearby Met Éireann synoptic stations at Shannon and Gurteen). Thus the annual input into the ZOC could be estimated as 1200-500 = 700mm. Combining this input with the ZOC area (483 km^2) suggests an annual input of 3.38 x 10^8 m^3. The annual discharge from both Kinvara springs of between 3.07 x 10^8 m^3 and 3.15 x 10^8 m^3 (based on an average discharge of 9.75 - 10 m^3/s) is similar to this value which again gives credence to the quantification of SGD into the bay.

The results of hydrological modelling confirmed by manual measurement of flow using salinity across a short time period as well as annual average calculation via a catchment water budget lead to the conclusion that the range of discharges at the Kinvara springs is in fact smaller than had previously been estimated by various studies in the area. For example, previous studies of SGD in Kinvara Bay by Cave and Henry (2011) estimated outflow of fresh water to be between 14 and 31 m^3/s with maximum discharge of up to 96 m^3/s. These flows were estimated using salinity measurements out in the bay making the assumption that the bay is well mixed across every tidal cycle. Equally, Drew (2003) suggested maximum flows of up to 100 m^3/s although this was later revised down to a maximum discharge estimate of 30 m^3/s (Drew, 2008). The most significant factor causing the comparatively low discharge predictions at Kinvara (particularity KW) is the attenuation imparted upon water as it is transmitted through the Gort Lowlands catchment, which previous studies did not have the means to quantify. This attenuation is caused by the retention of water within the turloughs located throughout the catchment as clearly demonstrated in Figure 6. For example, a total river input peak of over 60 m^3/s occurred on the 8th June 2012 and the associated peak at Kinvara occurred eight days later but only reached 11 m^3/s for average daily flow (up to 12 m^3/s during the ebb tide). The recession curve after this peak was damped, with discharge taking ten days to reduce from 11 m^3/s to 10 m^3/s. This extreme attenuation / hydraulic damping caused by the groundwater-surface water interactions (turloughs) in such a lowland karst network has been long known to occur but the quantification of this attenuation has only now been made possible with the development of the hydrological model.

The average high tide in Kinvara Bay is approximately 4.5 mACD (meters above chart datum) which equates to approximately 24.1 $x10^6$ m^3 stored in the bay while the average low tide is approximately 1.1 mACD which equates to 7.2 $x10^6$ m^3. Thus the amount of water which leaves the bay during an average half tidal cycle is 16.1 $x10^6$ m^3, whereas the average amount of discharge from Kinvara springs across a tidal cycle is approximately 0.22 x 0.22 $x10^6$ m^3 ($\approx 10m^3/s$ * 6.2 hours). Thus, of the total amount of water leaving the bay during the average tidal cycle, less than 1.5% of it is fresh water (from Kinvara) which does not return to the bay. It is known however that there are some other freshwater springs discharging further out in the bay, for example at Tarrea Pier on the Eastern shore of the bay (Einsiedl et al., 2009) or Kinvara Harbour. As part of the Gort Flood Studies Report (Southern Water Global, 1998), a deep karst investigation was carried out near Kinvara which found three layers of karst, a shallow layer , 15-25 meters below ground level (mbgl), an intermediate (40-50 mbgl) and a deep layer (70-80 mbgl) (Smyth, 1996). The shallower two layers appeared to transmit rapid through-flow waters and are likely to be linked to the active conduit network and the Kinvara springs. The deeper karst layer appeared to be paleo-karst containing old groundwater and it is quite possible that this water discharges further out into Kinvara Bay or possibly beyond that into Galway Bay. Such submarine springs have already been identified off the coast of county Clare (Drew, 2003), and are believed to reach as far as Inis Meáin, an island over 12km off the coast (Siggins, 2014). However, as the overall water balance in the catchment area has indicated, most of the freshwater SGD into the bay must be coming from the two springs at Kinvara.

Direct comparison of karstic and non-karstic SGD is difficult due to the fundamental difference in discharge mechanism. Globally, SGD in non-karst systems often occurs as a diffuse discharge, and is reported as such (e.g. cm^3 discharge per cm^2 of seafloor per second, cm/s), whereas SGD in well-developed karst systems occurs predominantly as point discharges. Thus discharge at Kinvara is not directly analogous to many non-karst systems, particularly as non-karst SGD tends to be predominantly recirculated seawater rather than terrestrial freshwater. For illustrative purposes only, if SGD in Kinvara Bay was assumed to be diffuse, the discharge would be approximately 1.5 cm/s. In terms of karst SGD, the discharges from karst coastal springs are known to vary significantly, from just tens of l/s to tens of m^3/s and beyond. Most reported springs however lie within a range of between 1-10 m^3/s (Fleury et al., 2007). Kinvara thus provides a good example of a moderately sized and consistently discharging karst submarine spring.

4.2 Nutrient Loading

Nutrient loading from the Kinvara springs into Kinvara bay has been approximated as 964 kg/day N and 19.8 kg/day P. These values have been calculated based on modelled discharge prediction as well as the results of monthly sampling. Again, these values are significantly lower than those predicted by Cave and Henry (2011) and Einsiedl (2012) who suggest average N loading of approximately 5000 kg/day. The mean N and P concentrations in this study were similar to the findings of Cave and Henry (2011) and Smith and Cave (2012). Hence, the higher nutrient loading values of these previous studies are a reflection of the higher discharge estimations upon which the loading rate calculations are based. As Kinvara Bay is host to a number of shellfish aquaculture sites, the lower quantity of nutrient loading from the Kinvara springs into the bay is important to note as it suggests a reduced influence on the bays trophic status from the springs and perhaps a greater influence from the untreated sewage being discharged into the bay at Kinvara.

Smith and Cave (2012) measured both TON (Total Oxidised Nitrogen) and DIP (Dissolved Inorganic Phosphorus) at both springs in Kinvara (KE and KW) with results showing that Kinvara is a strong source of fixed nitrogen into Kinvara Bay. This is important as nitrogen tends to be the limiting nutrient in the marine environment rather than phosphorus (which is generally the limiting nutrient in freshwater systems). TON concentrations from KE were measured up to 1 mg/l while water from KW tended to have approximately half that concentration. Neither spring at Kinvara, however, were considered as significant sources of DIP into the bay. Low concentrations of DIP compared to the DIP concentration in Galway Bay indicated that Kinvara may actually be a sink of DIP rather than a source (Smith and Cave, 2012). The relatively high concentration of N compared to P at the Kinvara springs is a common occurrence in most SGD scenarios as the removal processes of P in groundwater are typically more efficient than those for N (Slomp and Van Cappellen, 2004). The average N:P ratio of rivers discharging into the sea is approximately 18:1 (Smith et al., 2003) whereas SGD N:P ratios tend to be higher. For example, ratios of 18:1 (Swarzenski et al., 2001), 190:1 (Wu et al., 2013) and 660:1 (Kelly and Moran, 2002) have been reported, with higher ratios commonly associated with sewage contamination within the aquifer. The ratios found at the Kinvara springs are moderate in comparison (45:1 for KW, 82:1 for KE), likely due to the relatively high mass flux which occurs within the karst aquifer, and the large component of river water which feeds it. Further out in Kinvara Bay, the N:P ratio is likely to increase due to the contribution of untreated sewage.

5 CONCLUSIONS

The Gort Lowlands karst system has been successfully modelled as a pipe network with a series of tank reservoirs to represent the temporary surface water storage in the turloughs. Using this model the overall spring discharge from the karst network into Galway Bay at Kinvara has been predicted which revealed the damping effect that the network of turloughs creates on the much more variable river and rainfall inputs into the lowland karst catchment. The spring discharges into the sea were found to fluctuate across a fairly narrow band between 5 to 15 m^3/s, with the average flow at KW calculated to be 7.6 m^3/s. These values have been augmented from additional water entering the conduit system between the last turlough on the network (Caherglassaun) and the sea using an alkalinity balance. In addition, the flows from a separate more diffuse epikarst type catchment into Kinvara bay at the KE spring have been estimated to provide an overall average freshwater discharge estimate at the Kinvara springs of 9.75 – 10 m^3/s. The scale of these simulated and estimated discharges were validated up by the findings of a discrete salinity study close to the springs which found the discharge over a specific low tidal period to be 8.9 m^3/s which compared to the simulated value of 10.5 m^3/s across that same time period. This estimated discharge at the springs leads to more realistic estimates of nutrient loading rates into the bay of 964 kg N/day and 19.8 kg P/day. This suggests that the springs may have a lesser influence on the overall trophic status of Kinvara Bay than was previously thought.

The use of a distributed hydrological model to estimate SGD at Kinvara has allowed for the elucidation of several hydrological details which could not be investigated using other methodologies, such as chemical based techniques or even lumped parameter modelling. The model has shown the temporal variation of discharge at the springs and how this discharge is affected by the tidal cycle. Furthermore, the model is able to quantify the attenuation effect imparted on SGD by the surface water features within the catchment feeding it. Such details have not been previously quantified in Kinvara and are rarely detailed in international SGD studies (which tend to favour chemical based techniques such as radon isotopes). The combination of this hydrological model and the salinity wedge concept allows for the model to be validated (and vice-versa) and offers a potential methodology for estimating SGD at similar intertidal embayments.

In terms of Kinvara, this study has changed the focus of the calculation of SGD from previous studies that have tended to use quantification methods related the water quality in the bay, to the catchment upstream of the springs. Hence, discharge is essentially determined using a complex time varying water balance calculation in the form of a hydrological model, whereby the water entering into the aquifer must come out, but may be severely attenuated. The benefit of this shift in focus to upstream behaviour is that attenuation processes are quantified but also that the effects of heterogeneous mixing within Kinvara Bay are negated.

Finally, the study has also shown that if the catchment area for a karst aquifer is fairly well defined, and its discharge is predominantly composed of terrestrial freshwater, then a simple assessment of mean rainfall recharge across the area will produce a fairly accurate assessment of mean SGD in such situations without needing to go to the effort of a highly complex numerical model or chemical sampling techniques.

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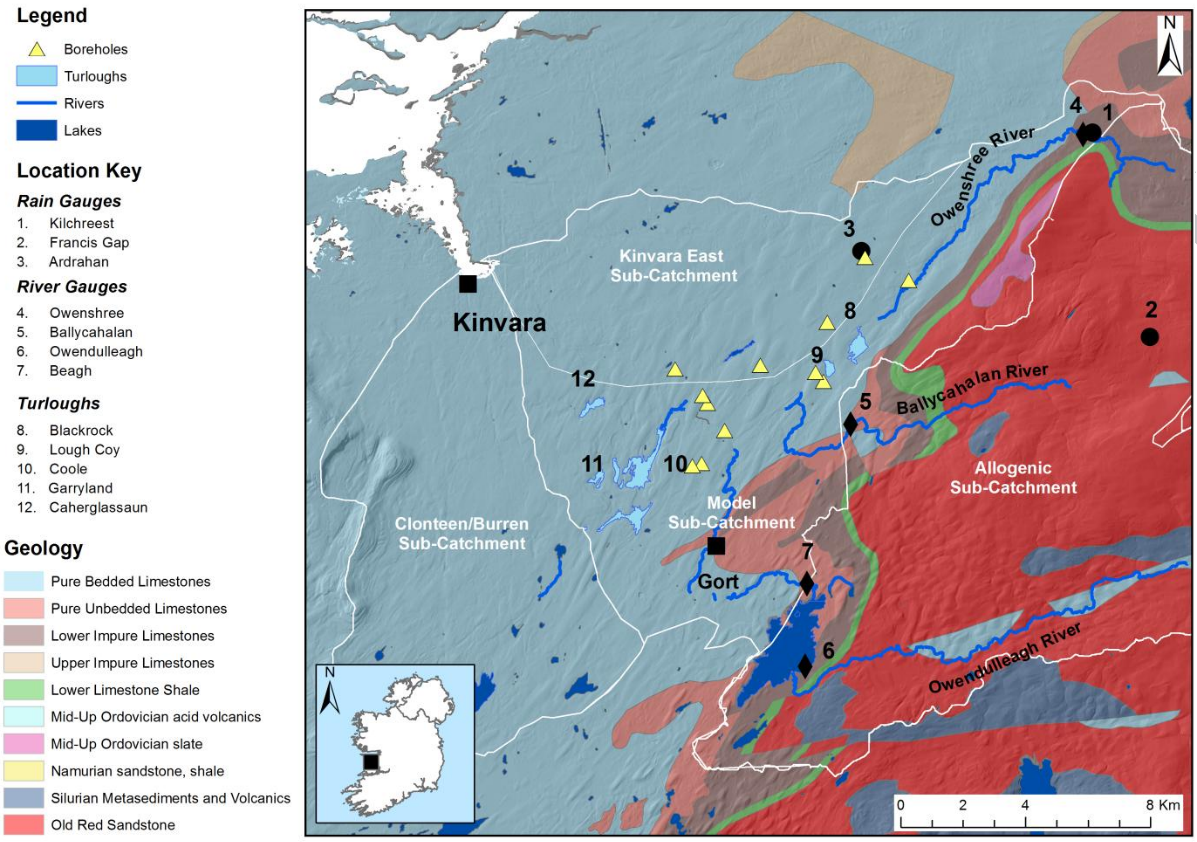
Figure 1


Legend
Boreholes
Turloughs
Rivers
Lakes
Location Key
Rain Gauges
1. Kilchreest
2. Francis Gap
3. Ardrahan
River Gauges
4. Owenshree
5. Ballycahalan
6. Owendulleagh
7. Beagh
Turloughs
8. Blackrock
9. Lough Coy
10. Coole
11. Garryland
12. Caherglassaun
Geology
Pure Bedded Limestones
Pure Unbedded Limestones
Lower Impure Limestones
Upper Impure Limestones
Lower Limestone Shale
Mid-Up Ordovician acid volcanics
Mid-Up Ordovician slate
Namurian sandstone, shale
Silurian Metasediments and Volcanics
Old Red Sandstone
N
Kinvara
Kinvara East Sub-Catchment
Clonteen/Burren Sub-Catchment
Model Sub-Catchment
Allogenic Sub-Catchment
Gort
Owenshree River
Ballycahalan River
Owendulleagh River
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0 2 4 8 Km

Figure2

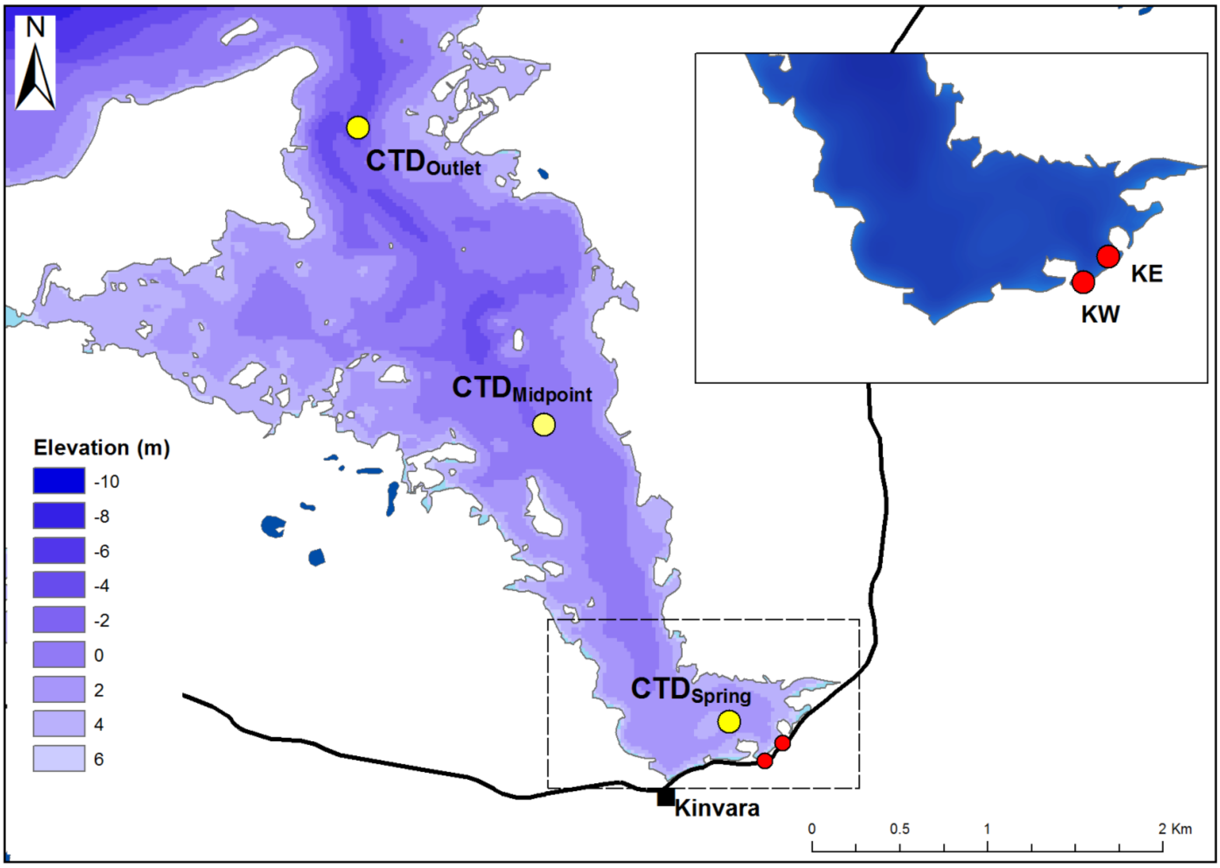

N
CTD_Outlet
CTD_Midpoint
CTD_Spring
Elevation (m)
-10
-8
-6
-4
-2
0
2
4
6
Kinvara
KE
KW
0
0.5
1
2 Km

Figure3

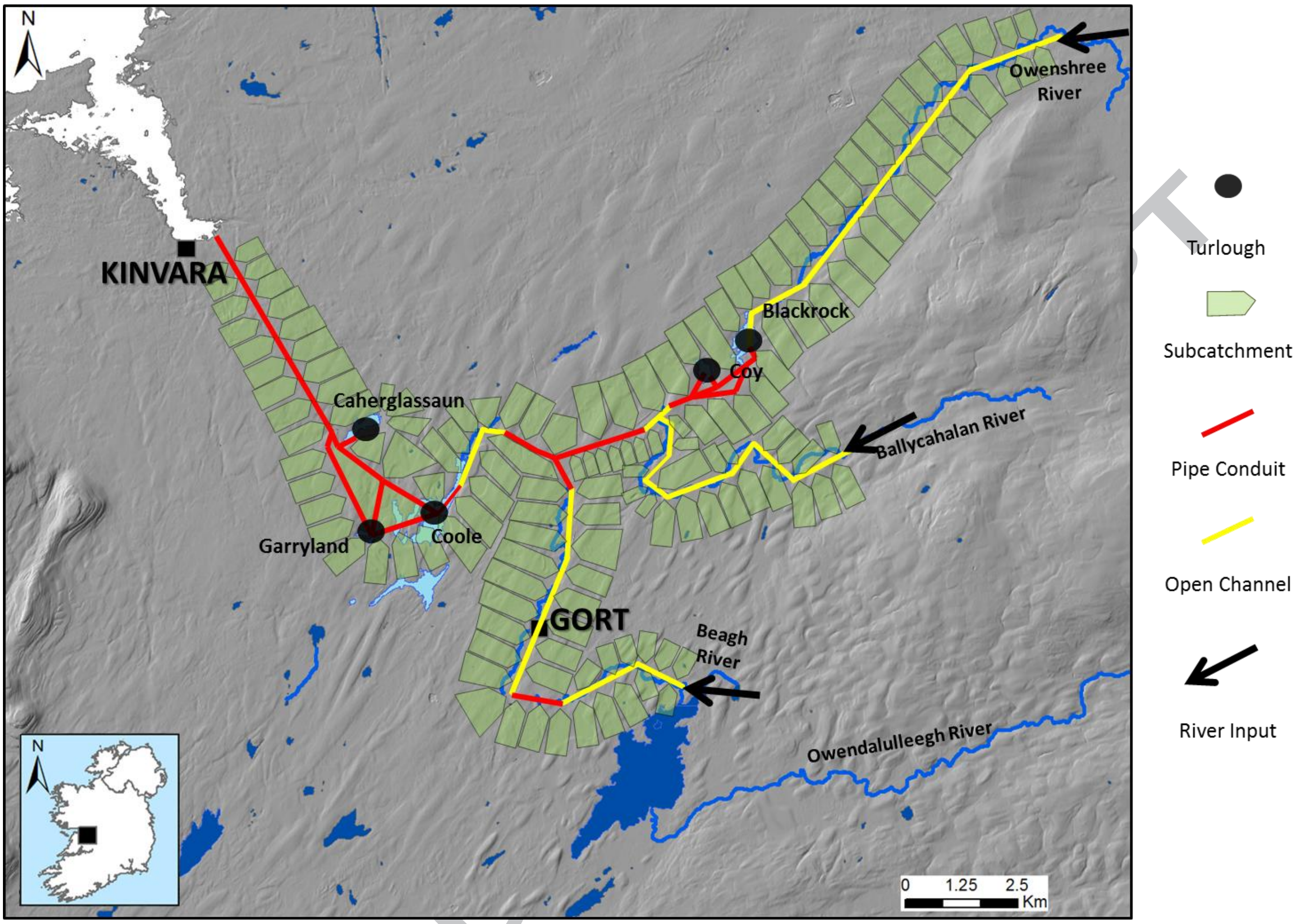

N
KINVARA
Caherglassaun
Garryland
Coole
GORT
Beagh
River
Blackrock
Coy
Ballycahalan River
Owenshree
River
Owendalulleegh River
N
0
1.25
2.5
Km
Turlough
Subcatchment
Pipe Conduit
Open Channel
River Input

Figure4

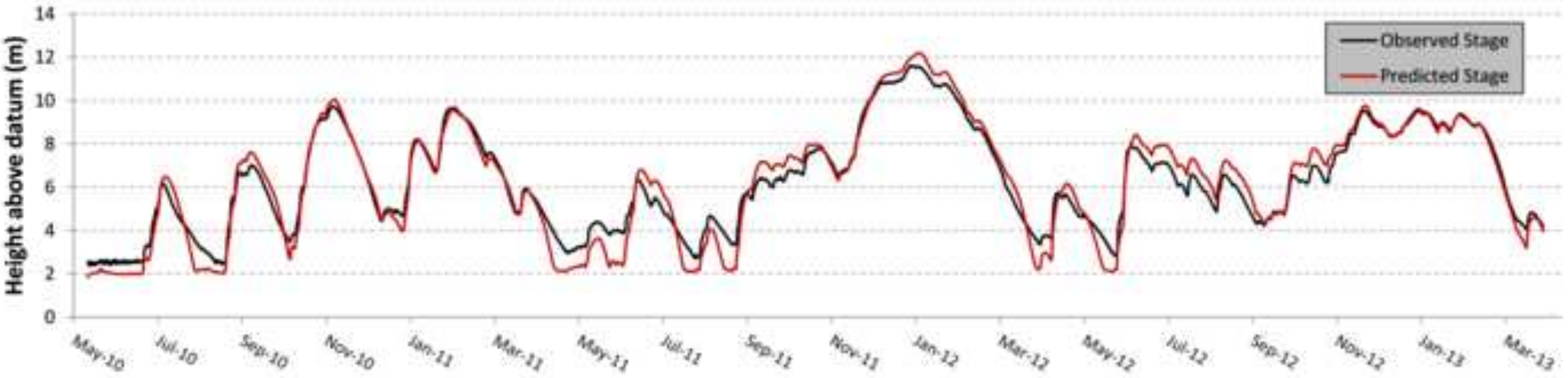

Height above datum (m)
0
2
4
6
8
10
12
14
May-10
Jul-10
Sep-10
Nov-10
Jan-11
Mar-11
May-11
Jul-11
Sep-11
Nov-11
Jan-12
Mar-12
May-12
Jul-12
Sep-12
Nov-12
Jan-13
Mar-13
Observed Stage
Predicted Stage

Figure5

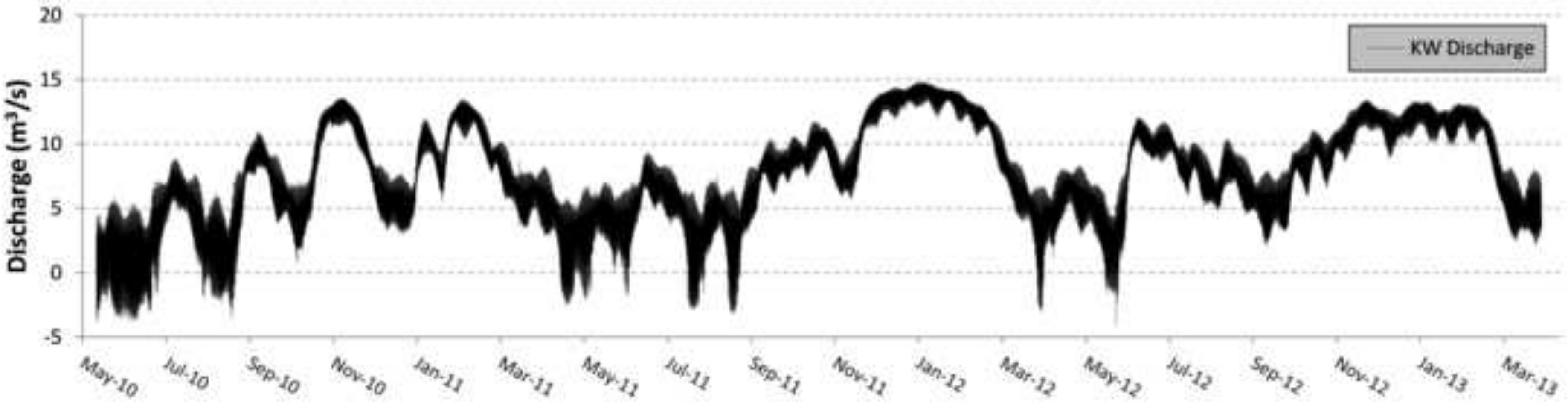

Discharge (m³/s)
20
15
10
5
0
-5
KW Discharge
May-10
Jul-10
Sep-10
Nov-10
Jan-11
Mar-11
May-11
Jul-11
Sep-11
Nov-11
Jan-12
Mar-12
May-12
Jul-12
Sep-12
Nov-12
Jan-13
Mar-13

Figure6

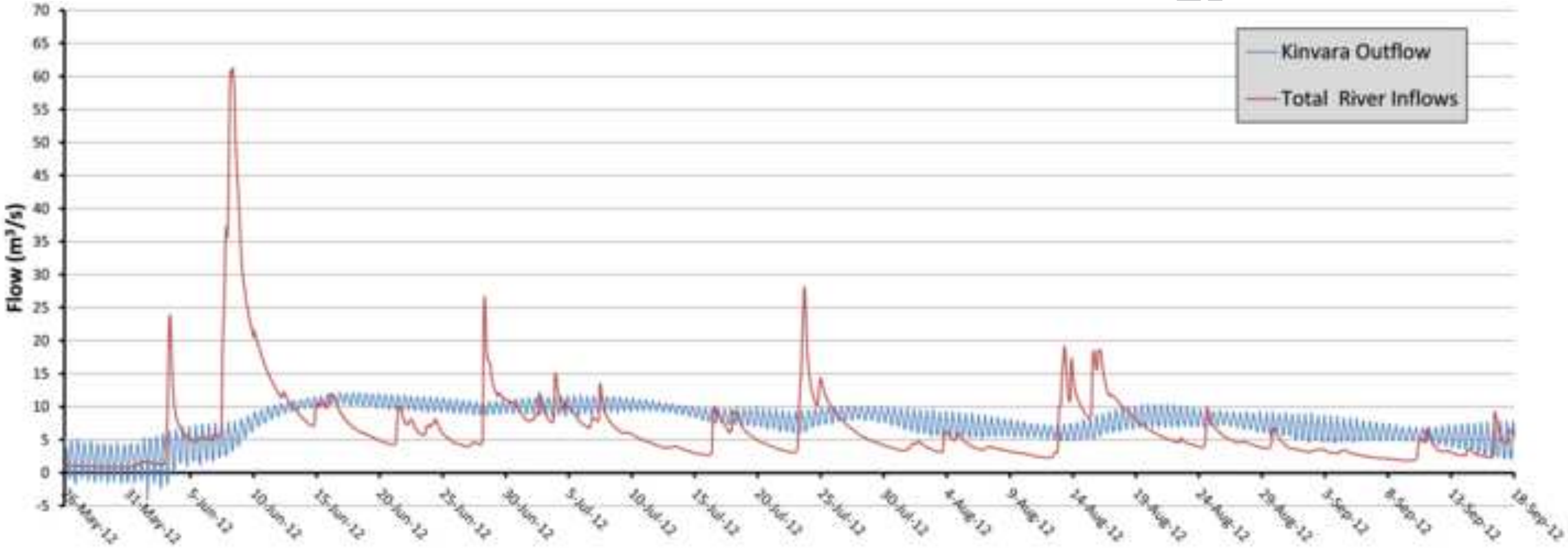
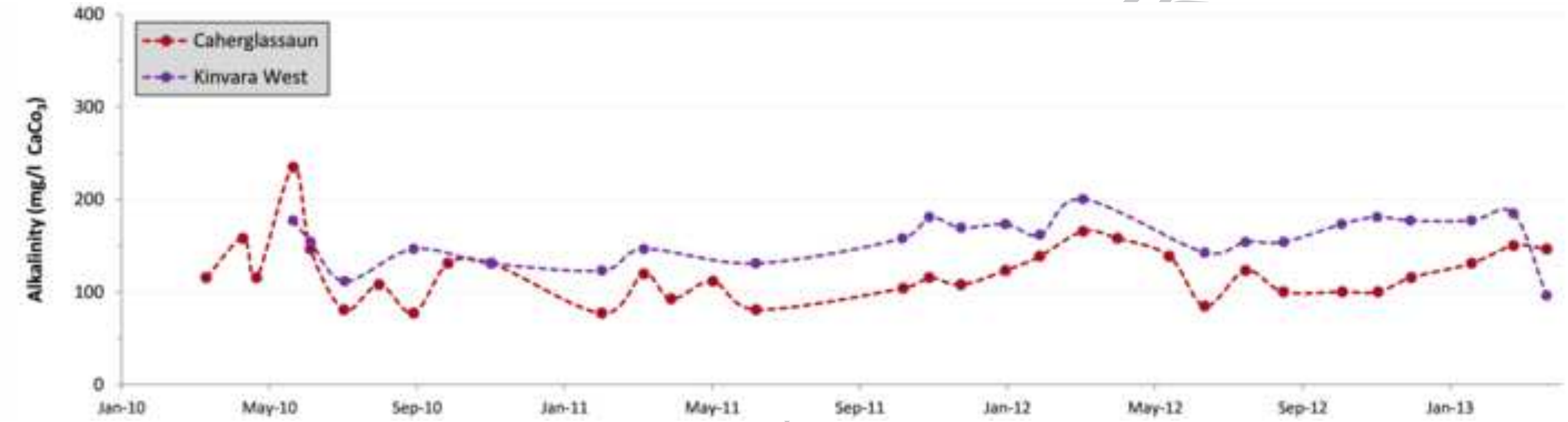

Kinvara Outflow
Total River Inflows
Flow (m³/s)
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
-5
26-May-12
31-May-12
5-Jun-12
10-Jun-12
15-Jun-12
20-Jun-12
25-Jun-12
30-Jun-12
5-Jul-12
10-Jul-12
15-Jul-12
20-Jul-12
25-Jul-12
30-Jul-12
4-Aug-12
9-Aug-12
14-Aug-12
19-Aug-12
24-Aug-12
29-Aug-12
3-Sep-12
8-Sep-12
13-Sep-12
18-Sep-12

Figure7



Caherglassaun
Kinvara West
Alkalinity (mg/l CaCo$_3$)
400
300
200
100
0
Jan-10
May-10
Sep-10
Jan-11
May-11
Sep-11
Jan-12
May-12
Sep-12
Jan-13

Figure8

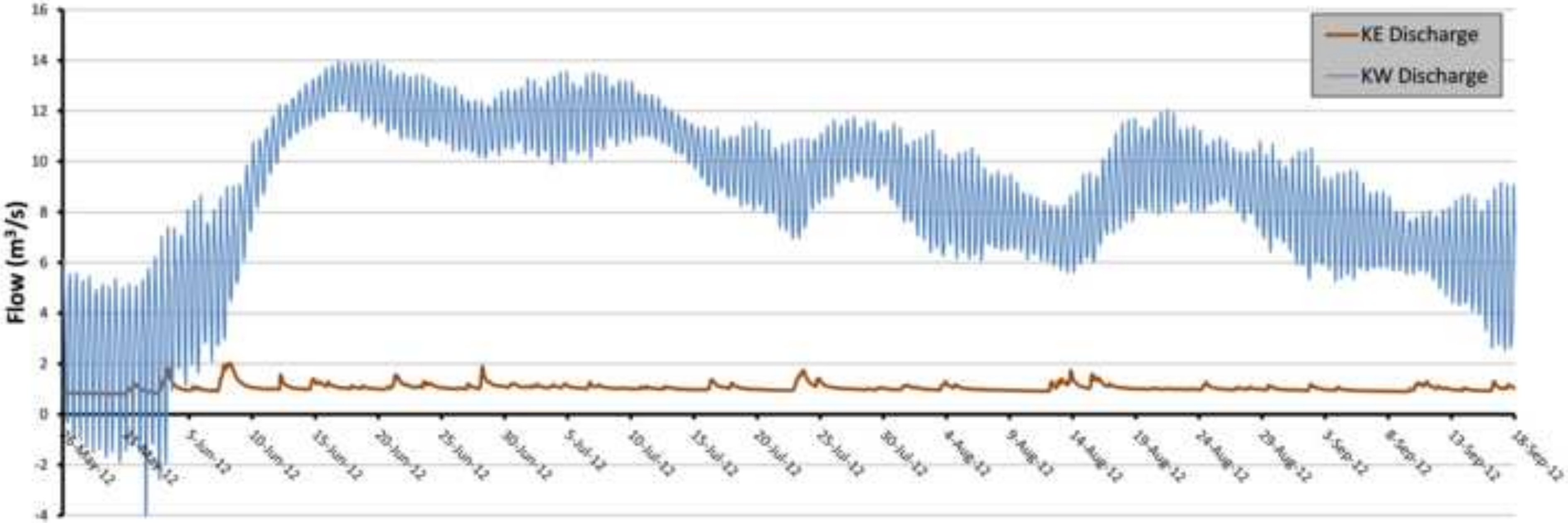
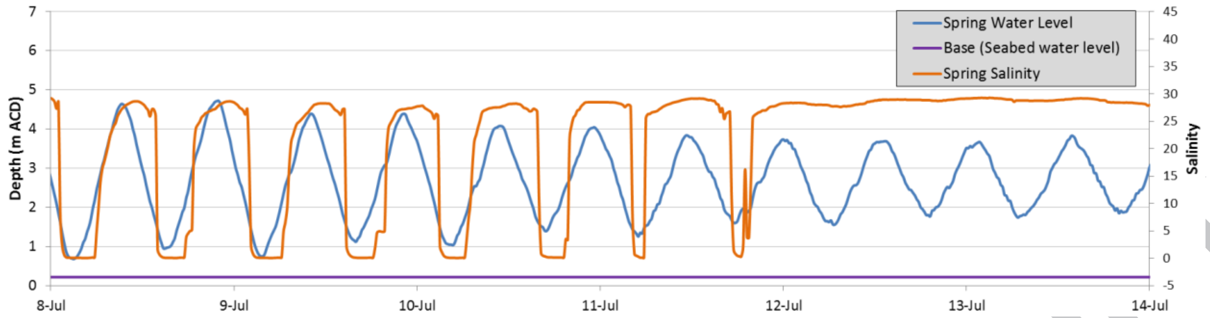
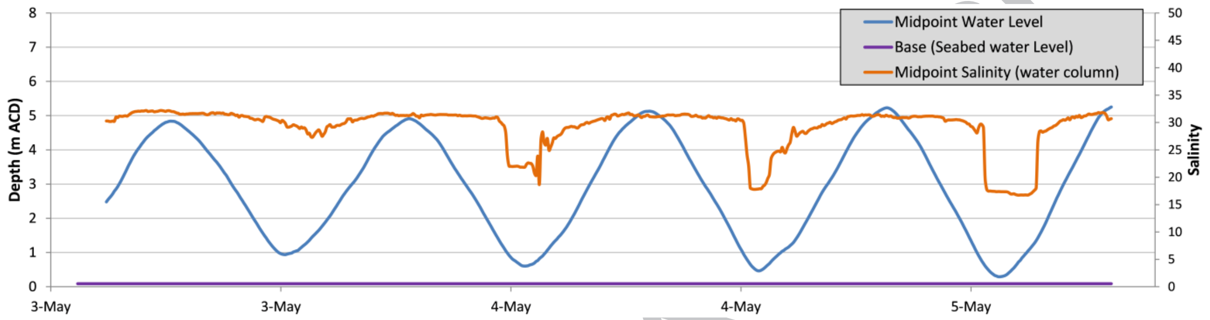

KE Discharge
KW Discharge
Flow (m^3/s)
16
14
12
10
8
6
4
2
0
-2
-4
26-May-12
31-May-12
5-Jun-12
10-Jun-12
15-Jun-12
20-Jun-12
25-Jun-12
30-Jun-12
5-Jul-12
10-Jul-12
15-Jul-12
20-Jul-12
25-Jul-12
30-Jul-12
4-Aug-12
9-Aug-12
14-Aug-12
19-Aug-12
24-Aug-12
29-Aug-12
3-Sep-12
8-Sep-12
13-Sep-12
18-Sep-12

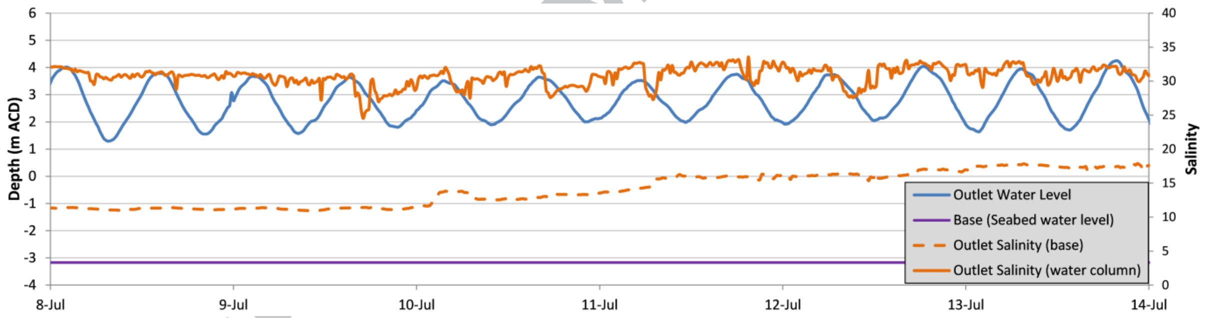
Figure 9



(a) Spring CTD



(b) Midpoint CTD



(c) Outlet CTDs

Figure 10

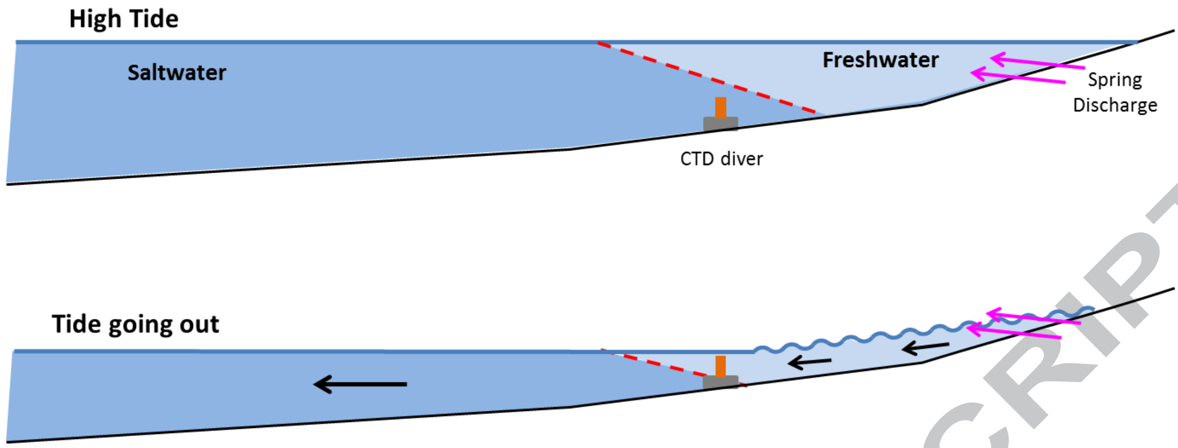
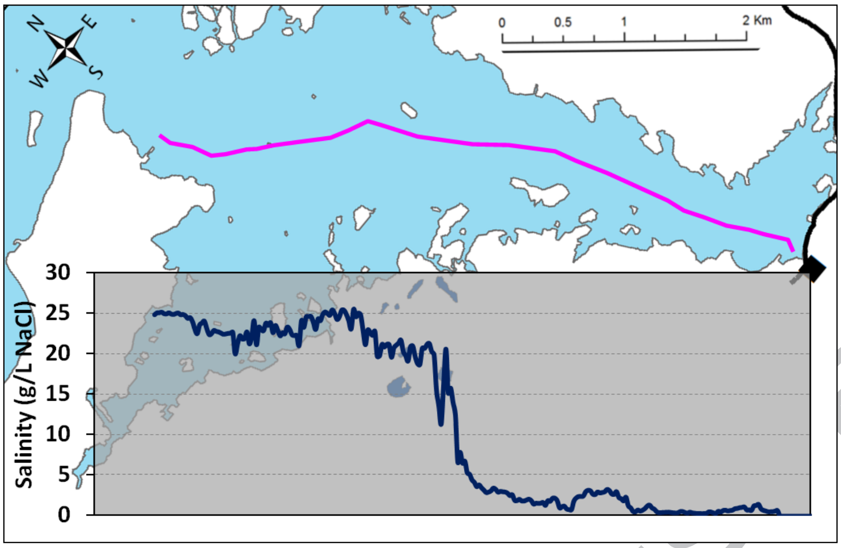
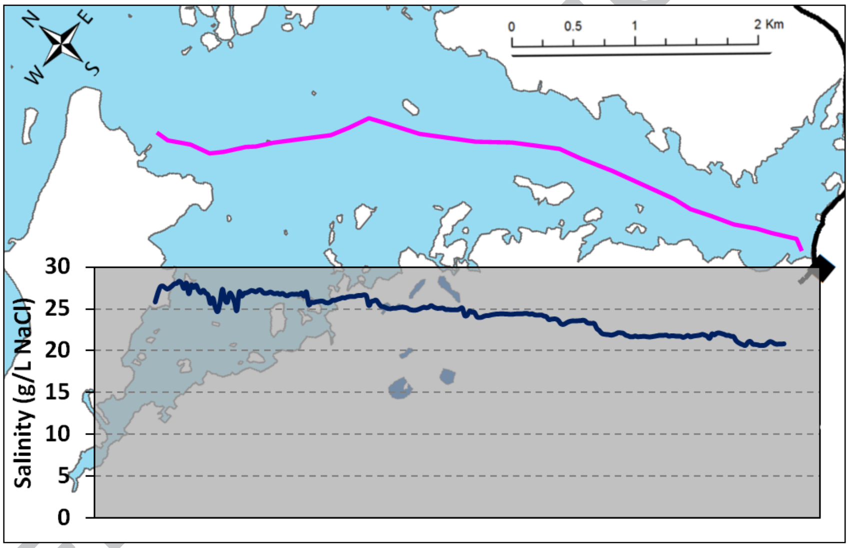

High Tide
Saltwater
Freshwater
Spring
Discharge
CTD diver
Tide going out

Figure 11



(a) at depth 10 cm.



(b) at depth 90 cm.

Figure 12

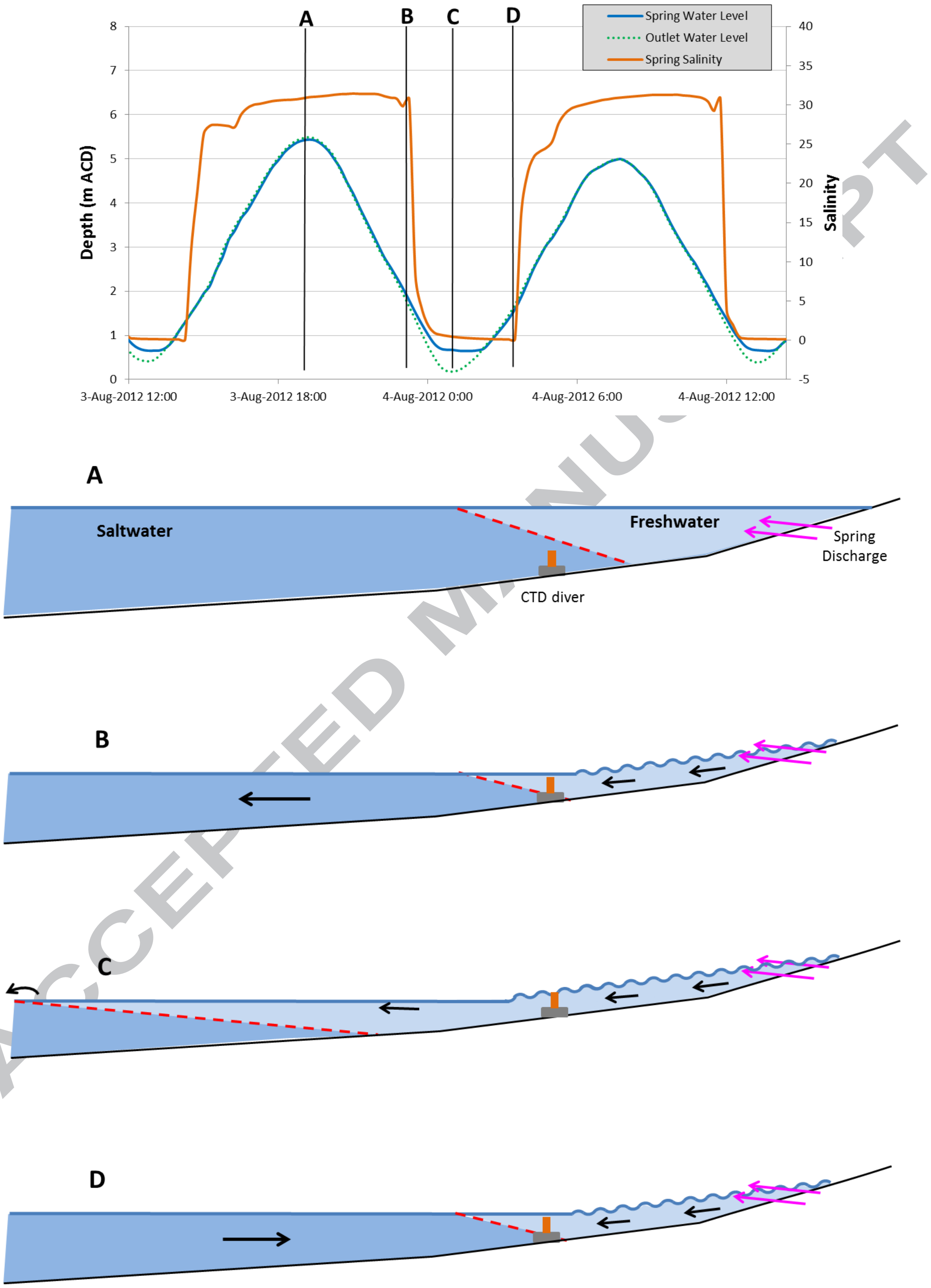
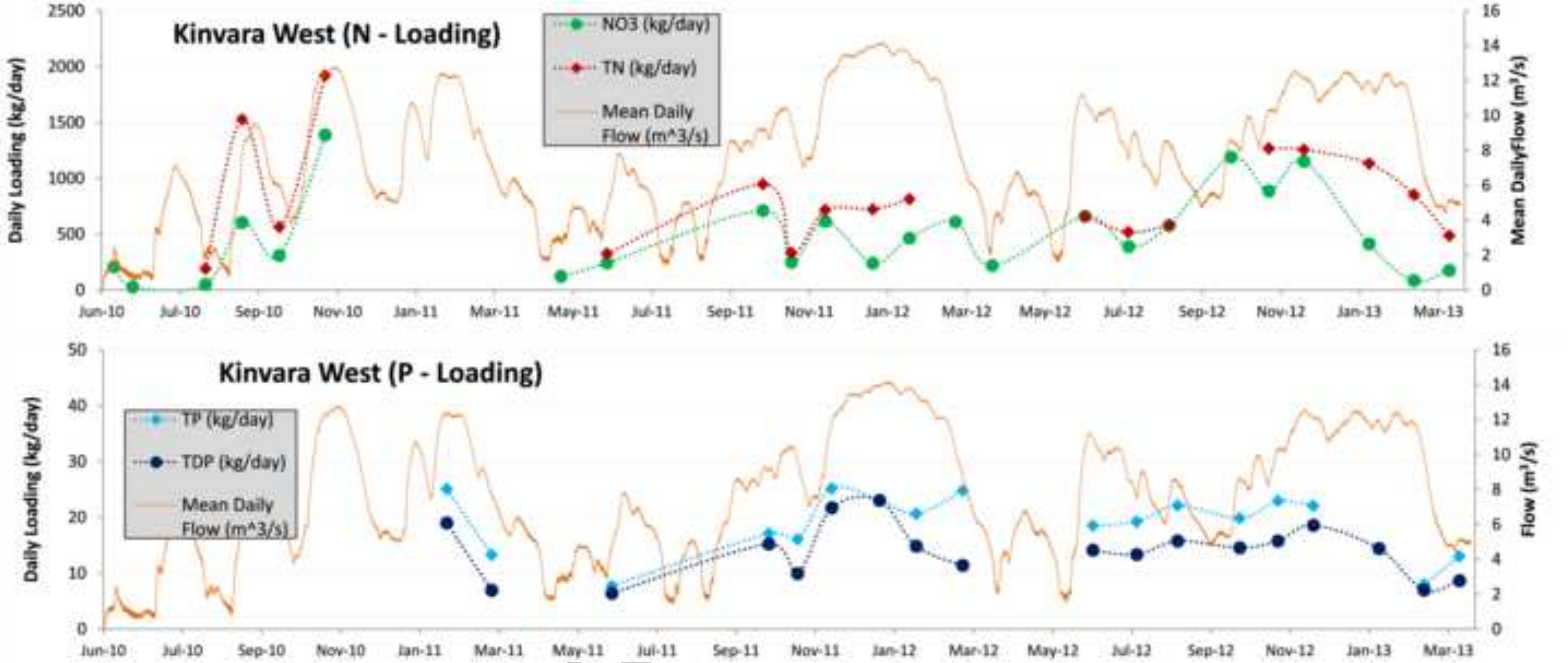

A
B
C
D
Spring Water Level
Outlet Water Level
Spring Salinity
Depth (m ACD)
Salinity
8
7
6
5
4
3
2
1
0
40
35
30
25
20
15
10
5
0
-5
3-Aug-2012 12:00
3-Aug-2012 18:00
4-Aug-2012 0:00
4-Aug-2012 6:00
4-Aug-2012 12:00
A
Saltwater
Freshwater
Spring
Discharge
CTD diver
B
C
D

Figure 13


Kinvara West (N - Loading)
NO3 (kg/day)
TN (kg/day)
Mean Daily Flow (m^3/s)
Daily Loading (kg/day)
Mean DailyFlow (m³/s)
2500
2000
1500
1000
500
0
16
14
12
10
8
6
4
2
0
Jun-10
Jul-10
Sep-10
Nov-10
Jan-11
Mar-11
May-11
Jul-11
Sep-11
Nov-11
Jan-12
Mar-12
May-12
Jul-12
Sep-12
Nov-12
Jan-13
Mar-13
Kinvara West (P - Loading)
TP (kg/day)
TDP (kg/day)
Mean Daily Flow (m^3/s)
Daily Loading (kg/day)
Flow (m³/s)
50
40
30
20
10
0
16
14
12
10
8
6
4
2
0
Jun-10
Jul-10
Sep-10
Nov-10
Jan-11
Mar-11
May-11
Jul-11
Sep-11
Nov-11
Jan-12
Mar-12
May-12
Jul-12
Sep-12
Nov-12
Jan-13
Mar-13

Highlights

- Hydraulic model used to estimate submarine groundwater discharge from intertidal karst springs
- Modelled estimate of Submarine groundwater discharge validated by salinity survey
- Nutrient loading from karst springs estimated via combination of sampling and hydraulic modelling
- Hydrological model has shown submarine groundwater discharge and nutrient loading to be lower than previous estimates