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Impact of agronomic practices of an intensive dairy farm on nitrogen concentrations in a karst aquifer in Ireland

M. Huebsch[a,b,*], B. Horan[b], P. Blum[a], K.G. Richards[c], J. Grant[d], O. Fenton[c]

[a] Karlsruhe Institute of Technology (KIT), Institute for Applied Geosciences (AGW), Kaiserstraße 12, 76131 Karlsruhe, Germany
[b] Teagasc, Moorepark, Co. Cork, Ireland
[c] Teagasc, Environmental Research Centre, Johnstown Castle, Co. Wexford, Ireland
[d] Teagasc, Kinsealy Research Centre, Dublin, Ireland

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ABSTRACT

Exploring the relationship between agricultural nitrogen loading on a dairy farm and groundwater reactive nitrogen concentration such as nitrate is particularly challenging in areas underlain by thin soils and karstified limestone aquifers. The objective of this study is to relate changes in detailed agronomic N-loading, local weather conditions, hydrogeological and geological site characteristics with groundwater N occurrence over an 11-year period on an intensive dairy farm with free draining soils and a vulnerable limestone aquifer. In addition, the concept of vertical time lag from source to receptor is considered. Statistical analysis used regression with automatic variable selection. Four scenarios were proposed to describe the relationships between paddock and groundwater wells using topographic and hydrogeological assumptions. Monitored nitrate concentrations in the studied limestone aquifer showed a general decrease in the observed time period (2002–2011). Statistical results showed that a combination of improved agronomic practices and site specific characteristics such as thicknesses of the soil and unsaturated zone together with hydrogeological connections of wells and local weather conditions such as rainfall, sunshine and soil moisture deficit were important explanatory variables for nitrate concentrations. Statistical results suggested that the following agronomic changes improved groundwater quality over the 11-year period: reductions in inorganic fertiliser usage, improvements in timing of slurry application, the movement of a dairy soiled water irrigator to less karstified areas of the farm and the usage of minimum cultivation reseeding on the farm. In many cases the explanatory variables of farm management practices tended to become more important after a 1- or 2-year time lag. Results indicated that the present approach can be used to elucidate the effect of farm management changes to groundwater quality and therefore the assessment of present and future legislation implementations.

1. Introduction

Global population growth is predicted to increase the demand for food by up to 100% by 2050 (Godfray et al., 2010). To meet the growing worldwide need for food, environmentally sustainable, economically viable and productive farming systems are required (Tilman et al., 2002). In Ireland, agriculture is dominated by dairy and beef cattle production from managed grassland (CSO, 2011). The European Union (EU) milk policy is due to change radically in 2015 with the abolition of farm level milk quotas and the ambitious target of a 50% increase in milk production by 2020 has been set in Ireland under the Food Harvest report (DAFF, 2010). Such targets for the agri-food sector must be achieved within current EU environmental legislation and will be further exacerbated by climate change such as an increase in precipitation during the winter time (Brouyère et al., 2004). The EU Water Framework Directive (WFD; OJEC, 2000) is a multi-part and multi-stage piece of legislation that aims, inter alia, to achieve at least "good" water quality status in all water bodies by 2015 with programmes of measures (POM) to achieve such a status implemented by 2012. In Ireland, the Nitrates Directive (EC, 1991) implemented since 2007 is Ireland's agricultural POM. This Directive places restrictions on all potential N inputs into a farming system including: cattle stocking rates with a default of 170 kg N per ha^{-1} or 250 kg N per ha^{-1} on derogation farms (present study site), organic and inorganic fertiliser rates of use, the time of spreading and their storage. Closed periods are in place for spreading of inorganic fertiliser (September–January) and some organic slurry (October–January) and farmyard manure (November–January). Application of dairy soiled water (DSW) may occur provided there is no rain forecast within 48 h of application

* Corresponding author at: Karlsruhe Institute of Technology (KIT), Institute for Applied Geosciences (AGW), Kaiserstraße 12, 76131 Karlsruhe, Germany.
Tel.: +49 721 60845017; fax: +49 721 606279.
E-mail address: manuela.huebsch@kit.edu (M. Huebsch).

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and application rates must not exceed 50 m^3 ha^{-1}. In general, 59% of Ireland's rivers, over 47% of the lakes, 64% of the estuaries and 85% of the groundwater are already at "good" to "high" ecological status (EPA, 2010). For areas where the targets of the WFD will not be achieved by 2015 further legislative steps may be taken in areas of non-compliance and this could reduce farm productivity or at least add to production costs in some circumstances (Dillon and Delaby, 2009).

Leaching of nitrogen (N) fluxes from an agricultural system to groundwater occur from point sources such as farmyard storage or from diffuse chronic sources from soil or through incidental losses during or after application of fertilisers especially when this coincides with an episodic rainfall event (Basu et al., 2011; Brennan et al., 2012). Once anthropogenic reactive N (N_r) is lost it cascades through the environment (Galloway and Cowling, 2002) and occurs in many forms in groundwater such as nitrate (NO_3^-), nitrite (NO_2^-) ammonium (NH_4^+) and organic N through leaching (Murphy et al., 2000). Stuart et al. (2011) indicate that leached losses could increase in future decades due to predicted changes in agricultural land use and precipitation as well as an increase in temperature and evapotranspiration in the UK. The assessment of the effect of weather variation such as rainfall intensity on NO_3^- leaching is complicated by the requirement for long term datasets of groundwater chemistry, farm management practices and meteorology (Randall and Vetsch, 2005). Local weather changes can result in reduced agronomic response to fertiliser application resulting in lower yields and greater nitrogen surpluses on farms (Derby et al., 2005). In addition, it can be assumed that climate change will play an important role to the hydrological cycle with changes to recharge, groundwater levels and flow processes including subsequent changes to groundwater quality (Brouyère et al., 2004).

Karst aquifers are an important water resource, which cover about 20% of the earth's dry ice-free surface and provide potable water for approximately 20–25% of the world's population (Ford and Williams, 2007). Although karst aquifers are very vulnerable in terms of water quality, the exploration, understanding and interpretation of karst aquifers is still rather challenging mainly due to fast groundwater flow velocities in the conduit systems (Goldscheider et al., 2007). Classical hydrogeological site investigations such as pumping test analysis and/or determination of groundwater isolines have a high potential for failure as the results often only reflect the specific (i.e. local) area that has been monitored and do not show the flow behaviour of the entire study area (Bakalowicz, 2005). The characterisation of conduit systems has many complications such as spatial distribution of the conduits and temporally variable discharge (Goldscheider et al., 2008). To elucidate the shape and connections of shallow conduits, 2D and 3D geoelectric resistivity surveying (Hamdan et al., 2012) has been used as well as microgravity surveying in karst systems (Hickey, 2010).

Exploratory data analysis applied to groundwater NO_3^- data is an affective means of explaining spatial and temporal trends of NO_3^- in shallow groundwater (<30 m) (Nas, 2009). Maximum likelihood Tobit regression analyses (sets a censored NO_3^- concentration, e.g. background level and builds a model based on the significance of explanatory variables) has been used by many to investigate elevated NO_3^- concentrations in aquifer systems (Fenton et al., 2009a; Yen et al., 1996). Explanatory variables across these studies include but are not limited to: landuse around individual monitoring wells, distance of the monitoring well from potential point sources, saturated hydraulic conductivity (k_s) of screen intervals, screen interval depth, depth to top of aquifer, denitrification potential determined by groundwater di-nitrogen (N_2)/argon (Ar) ratios, redox potential, dissolved oxygen concentration and N_2. Other techniques such as logistic regression can predict the likelihood that a certain groundwater threshold concentration will be breached (Menció et al., 2011). This can also be used to find significant explanatory variables that explain spatial and temporal patterns of groundwater NO_3^- concentrations (e.g. well depth, geology and presence of a fracture network, nitrogen fertiliser loading, soil drainage class percentages, seasonality of water table position) (Nolan, 2001). Furthermore, Oenema et al. (2010) used multiple linear regression to evaluate the significance of different agricultural practices on NO_3^- groundwater occurrences in the Netherlands.

Many studies have been undertaken to help to define, develop and improve best management practices to achieve better groundwater quality worldwide (Thorburn et al., 2003; Zhang et al., 1996). However, exploring relationships between farm management practices and groundwater water quality is further complicated due to time lags from source to receptor via hydrological and hydrogeological pathways (Wang et al., 2012). For Ireland, it is now clear that the achievement of WFD targets by 2015 may not be possible where time lags are too long (Fenton et al., 2011a). Such time lags depend on socio-economic factors such as the delay in implementing measures due to the costs and perception of farmers, soil/subsoil type, bedrock geology/hydrogeology and climatic factors such as rainfall (Stark and Richards, 2008) and should be estimated when attempting to relate agricultural management and groundwater quality (Meals et al., 2010). Farms present in areas of moderate to high recharge, with shallow free draining soils of low effective porosity (n_e), underlain by extremely vulnerable limestone aquifers typically have: (1) optimal conditions for grass growth which is needed for intensive dairy farming and (2) the shortest vertical travel times to groundwater (1–2 years on the current study site, e.g. Fenton et al., 2009b). Therefore, such farms have the capacity to affect groundwater quality quickly through management change, but it is difficult to provide a tool for the prediction of time lag that has to be simple on the one hand and be reflective of a highly complex environment on the other.

To date there has been limited work relating long term farm management and local weather variation with NO_3^- concentrations in groundwater at farm scale, especially in highly vulnerable areas. The objective of this study is to relate changes in detailed agronomic N-loading, local weather conditions, hydrogeological and geological site characteristics with groundwater N occurrence over an 11-year period on an intensive dairy farm with free draining soils and a vulnerable limestone aquifer, whilst also considering time lag.

2. Materials and methods

2.1. Site description and characterisation

The intensive dairy farm study site (48.1 ha) at the Teagasc Dairy Production Centre, Fermoy, Co. Cork (8°15′W, 52°10′N) is located in a lowland limestone area in southern Ireland. The site is up-gradient of the Funshion River, close to a public water supply well and down-gradient of the large River Blackwater (Fig. 1). The perennial grassland farm is located on a limestone plateau with flat topography and negligible runoff. Two inferred groundwater divides are presented in Fig. 1, emanating from the juncture of the two rivers and intersecting the southern boundary of the site (Kelly and Motherway, 2000; Preston and Mills, 2002). The study site consists of 11 boreholes (BH 1–12, note BH 6 collapsed shortly after installation and was not suitable for this study) drilled at different stages since 2001 and are distributed across the entire farm (Fig. 1). Three wells (BH 4, BH 11, BH 12) are 150 mm diameter open boreholes and the remainder consist of a 50 mm diameter piezometer casing. Average drilling depth on site is 40.8 m (minimum depth of 22.0 m at BH 5 and maximum depth of 59.5 m at BH 3).