WATER QUALITY IN IRISH KARST AQUIFERS

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ABSTRACT

This paper provides a review of Irish research on water quality in karst aquifers. Karst regions are particularly vulnerable to pollution due to the occurrence of point recharge, the thin, patchy soil cover found in some karst areas, the presence of epikarst and the occurrence of conduit flow within the aquifer. The main drinking water quality concern is the presence of microbial pathogens including protozoan parasites resistant to chlorination. Ecological quality issues are also significant, involving the transfer of nutrients (phosphorus and nitrogen) through karst aquifers to sensitive ecosystems. Large temporal variations in water quality pose a particular challenge in managing karst water resources. Agricultural best management practices and public education can play an important role in karst groundwater quality management.

INTRODUCTION

Karst water quality is a topic of particular concern here in Ireland because the predominant bedrock aquifer in Ireland is composed of Carboniferous limestone, and much of the limestone is karstified to at least some degree. As seen from Figure 1, regionally important karst aquifers dominated by conduit flow (Rkc) are found extensively west of the River Shannon, while those with a higher proportion of diffuse flow (Rkd) are found particularly in the south of the country.

Awareness of water quality problems in Irish karst aquifers dates back over many years. For example, Naughton (1983) documented the pollution of Teesan Springs in a County Sligo by the disposal of farmyard slurry and silage effluent through a soakpit 500 metres from the springs. Drew (1984) noted that arterial drainage in the Clarinbridge catchment, County Galway, involving channel excavation into the limestone bedrock, resulted in line and point recharge with polluted surface waters, causing a nitrate plume in the karst aquifer. Aldwell *et al*. (1988) reviewed faecal bacterial contamination of Irish karst aquifers by agricultural point sources, with two water quality surveys in karst regions showing more than 50% of groundwater sources to contain *E. coli*. Research on Irish karst water quality has continued up to the present day, as seen from the review below, and this has fed into both outreach material and policy. For example, the vulnerability of karst aquifers to pollution was highlighted in the booklet on the Karst of Ireland (Daly *et al*., 2000) which is available on the Geological Survey of Ireland website, and the vulnerability of karst aquifers has been taken into account in both the Irish groundwater protection scheme (DELG *et al*., 1999) and the groundwater risk assessments for the Water Framework Directive (Working Group on Groundwater, 2005).

Unfortunately, despite this long history of awareness of karst groundwater vulnerability in the Irish hydrogeological community, water quality problems continue to arise, most recently with problems of *Cryptosporidium* in a number of karst springs providing drinking water supplies in Roscommon (Roscommon County Council, 2013). Therefore it is timely to review Irish experience and understanding of karst groundwater contamination and to consider the approaches required to prevent future problems.

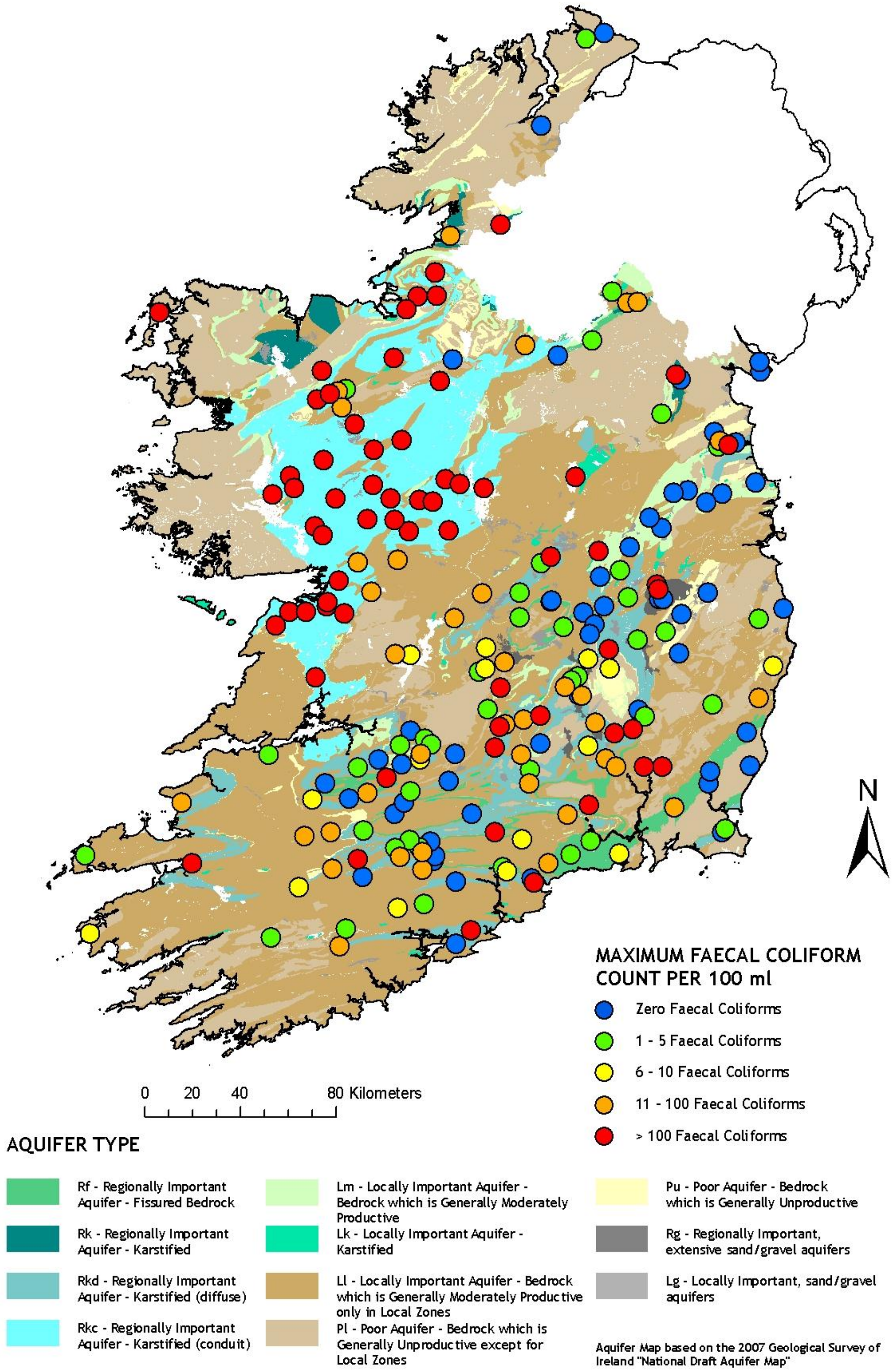

Figure 1: Faecal coliform detections in raw untreated groundwater, 2007-2009 (from Craig *et al*., 2010)
(Note the high occurrence of faecal coliforms in the western Irish regionally important karst conduit aquifers (Rkc).)

RISK ASSESSMENT

Assessing risk of water quality problems involves a consideration of source, pathway and receptor factors (Daly, 2004). Each of these is discussed below in relation to Irish karst water quality:

Potential sources of groundwater contamination in rural Ireland include diffuse agricultural sources (e.g. spreading of fertilizers) and particularly point sources (e.g. farmyards and septic tank systems) (DELG *et al*., 1999). Our karst uplands such as the Burren plateau in Co. Clare and the Geevagh and Bricklieve uplands in Sligo have relatively low intensity agriculture, but are nonetheless prone to localised contamination from point sources. For example, Drew (1996) recorded that silage clamps on bare limestone pavement in the Burren plateau resulted in contamination of karst springs in summer, at times of maximum water demand. Our karst lowlands have greater diffuse pressures due to more intensive agriculture, particularly in the southern dairying region, and although the effects can be mitigated by pathway factors such as thicker subsoils, problematic concentrations of nutrients (nitrogen and phosphorus) have arisen from both diffuse and localised sources. Faecal microbial contamination may arise from both human and animal waste, including effluent from poorly sited, constructed or maintained onsite domestic wastewater treatment systems, farmyard runoff, badly stored manures and slurries, and landspreading of manures and slurries in vulnerable situations; this is discussed further below.

The pathway factor is the key issue in relation to karst water quality. Karst aquifers are particularly vulnerable to chemical and microbial contamination (Field, 1989; Smith, 1993). Figure 2 shows a schematic diagram of pollution pathways in karst aquifers. An important factor is the occurrence of point recharge, whereby water can enter the aquifer directly via sinking streams, bypassing the protective cover of soil and subsoil. Dolines (karstic closed depressions) also provide point recharge, with the extent to which the water bypasses the protective layers depending on the type of closed depression (Mellander *et al*., 2013). The potential for contaminant entry via karst features is recognised in the Irish groundwater protection scheme, with a zone within 30 metres of such features being classified as extreme vulnerability (DELG *et al*., 1999). The risk is greatest where point sources of contamination coincide with karst features and point recharge, for example where cattle enter sinking streams or where animal carcasses are dumped into karstic closed depressions. The aquifer is also vulnerable where the soil cover is thin and patchy (for example the karst areas of Clare and south-east Galway with limestone pavement and rendzina soils). Within the aquifer, the presence of a highly weathered epikarstic zone can allow rapid lateral movement of diffuse contaminants to vertical shafts. It also provides temporary storage for contaminants, which may then be released from this zone by flood pulses (Field, 1989). Finally, the presence of conduit flow within the aquifer allows rapid transfer of contaminants with little opportunity for attenuation by adsorption, ion exchange, chemical breakdown or microbial die-off. The short underground residence time also means that very little time is available for remedial action to avoid contamination of water supplies.

The nature of the receptor will determine which water quality parameters are of concern, and at what concentrations. A key concern is drinking water receptors: karst springs and boreholes provide both public and private water supplies, and transfer of contaminants through the aquifer to these supplies may have implications for human health. A more recent concern, particularly with the advent of the EU Water Framework Directive (2000/60/EC) and the emphasis on integrated management of groundwater and surface water resources, is the influence of karst groundwater quality on aquatic ecosystems such as rivers, lakes and groundwater dependent terrestrial ecosystems including turloughs. Nutrient transfer through karst aquifers to such ecosystems is discussed in greater detail below. Ecosystems within the karst aquifer are another type of receptor of which there is growing awareness, on which groundwater contaminants may have a direct impact.

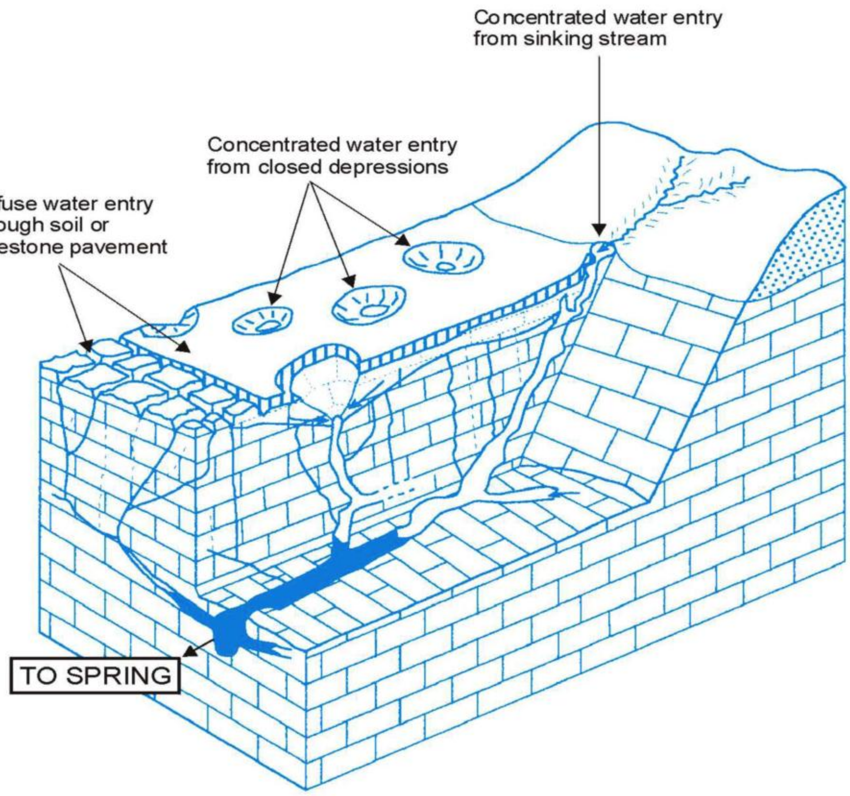

Figure 2: Possible contaminant entry routes to karst groundwater
(From Working Group on Groundwater, 2005, after Gunn)

KARST GROUNDWATER CONTAMINANTS

Nitrate contamination of karst aquifers in rural areas can arise from both diffuse sources (spreading of inorganic and organic fertilizers and release of soil nitrogen due to land use change) and point sources (e.g. badly stored farm wastes and septic tank effluent). The nitrate ion is highly soluble and mobile, so nitrate pollution is found in many free draining hydrogeological situations but karst aquifers are particularly vulnerable. A review of international case studies of nitrate contamination in karst aquifers can be found in Coxon (2011); nitrate in Irish karst aquifers is discussed further below. However, a key aspect of karst groundwater contamination is that it may not be restricted to the more mobile constituents such as nitrate and chloride. Solutionally enlarged joints and sinking streams enable suspended sediment to enter the aquifer. This may cause problems of turbidity in drinking water supplies, but it is particularly important because it can provide a method of entry for a range of adsorbed contaminants including phosphorus, pesticides and viruses. Phosphorus in Irish karst aquifers is reviewed below.

Pesticides occur as contaminants in many aquifer types, but karst aquifers are particularly at risk due to rapid movement through solutionally widened fissures, and also due to the thin soils and subsoils associated with many karst areas. Less mobile pesticides that are readily sorbed to colloidal particles may enter karst aquifers via sinking streams. In Ireland, although pesticides in groundwater have not resulted in any groundwater bodies being placed at poor status, pesticide occurrences have been recorded by the EPA national groundwater quality monitoring programme at a number of locations and data analysis indicated an association with karst aquifers and with springs (McManus *et al*., 2011). Detailed investigations at a karst spring in County Kilkenny (with a catchment including arable land used for winter wheat and spring barley cultivation) detected five pesticide parent products and five pesticide degradation products (McManus, 2012).

Antibiotics are another group of synthetic organic compounds which may occur as contaminants in karst groundwaters, originating both from septic tank effluent and from animal manures, and giving rise to concern about the spread of antibiotic resistance. Dolliver and Gupta (2008) studied leaching and runoff losses of antibiotics from land application of pig and cattle manure in a karst area of Wisconsin, U.S.A.: compounds detected included chlortetracycline, monensin and tylosin, with detections occurring mainly during the non-growing season (November to April) following autumn application of manures. There is a need for similar investigations of antibiotics in Irish karst aquifers.

Finally, a key feature of karst groundwater quality is the high incidence of microbial contamination.

FAECAL MICROBIAL CONTAMINATION

Microbial pathogens are a particular problem of karst aquifers because the lack of filtration within the aquifer and the short underground residence times mean that if organisms manage to pass through or bypass the unconsolidated material overlying the aquifer, they are almost certain to appear in water supplies. The presence of conduit flow within the karst aquifer can allow viable organisms to travel for hundreds of metres or even several kilometers from the point of entry. The microorganisms involved include bacteria, viruses and protozoan parasites. Sources of microbial contaminants include point sources such as badly stored animal manures and slurries, farmyard runoff and septic tank effluent. Diffuse sources, i.e. landspreading of manures and slurries, may also give rise to contamination where the soil cover is thin and karst features are present, as seen for example in the Walkerton pollution incident in Ontario, Canada in 2000, when 2,300 people became ill and seven people died following karst groundwater contamination which appears to have come from landspreading of cattle manure in a vulnerable location (Daly, 2003).

As noted in the introduction, faecal bacteria have been reported from Irish karst aquifers for several decades. Very considerable improvements in water treatment in recent years have greatly decreased the detection rate of faecal bacteria in treated groundwaters used for public supply, with Hayes *et al*. (2013) reporting a 92% reduction in *E. coli* exceedances in public water supplies and an 89% reduction in exceedances in private group scheme supplies since 2005. However, problems remain particularly in small private supplies, with 11% of these supplies having *E.coli* detections in 2012. Raw water quality remains relevant both because of the large number of private drinking water supplies receiving no treatment or inadequate treatment, and also because of concerns that chlorination does not remove all microbial contaminants, as discussed below. Faecal coliform counts in untreated waters in the national groundwater quality monitoring network are shown in Figure 1, and it can be seen that high counts of >100 faecal coliforms per 100 ml are particularly common in the western Irish Rkc aquifers. As noted by Thorn & Coxon (1992), peak bacterial numbers often coincide with flow peaks, and international karst research (e.g. Pronk *et al*., 2007) has also demonstrated a relationship with turbidity and sediment peaks.

A growing concern with faecal coliform contamination is the presence of verotoxin-producing *E. coli* (VTEC) such as *E. coli* O157 and O26; these can cause dysentery and haemolytic uraemic syndrome, which can be fatal. The Walkerton incident in Canada mentioned above involved *E coli* 0157:H7, combined with *Campylobacter jejuni*. Ireland has the highest reported incidence rate of VTEC in the EU, and exposure to private well water was a risk factor in 47% of cases in 2012 (HPSC, 2013). Viruses are another potential concern: many viruses are retained in soils by adsorption to soil particles, but they may gain entry to karst aquifers while adsorbed to such particles and further work on these contaminants is needed here in Ireland.

Finally, a major concern in karst aquifers is contamination by protozoan parasites, particularly *Cryptosporidium parvum*, which causes acute gastroenteritis, and persistent and potentially fatal disease in immunocompromised individuals. This organism has caused disease outbreaks even where water supplies are treated by chlorination, because it forms an oocyst which is resistant to chlorination; successful removal requires physical barrier treatment e.g. flocculation and filtration, or ozonation. *Cryptosporidium* has been detected in karst groundwater supplies in several countries in the last decade, and here in Ireland it has given rise to problems in the karst springs which provide the water supply for the town of Ennis, County Clare (Page *et al*., 2006, p.64). Within the last year, outbreaks of cryptosporidiosis were traced to several karst springs in County Roscommon used for public water supply, with the Boyle / Ardcarne, Castlerea, Roscommon Central (Ballinagard) and Killeglan water supply schemes all requiring boil water notices (Roscommon County Council, 2013).

CONTAMINATION BY NUTRIENTS

NITRATE

As noted above, nitrate is a common contaminant in many free draining hydrogeological situations, but the characteristics of karst regions make them particularly vulnerable, and passage of this highly soluble and mobile anion to the saturated zone can be very rapid. Because the Carboniferous Limestone has negligible primary porosity, nitrate from diffuse agricultural sources passes rapidly through the fracture network: Richards *et al*. (2005) recorded a vertical travel time of only 34 days through 23 metres of unsaturated zone (0.8m of soil over fractured limestone) at a site in north Cork, while nitrate entering via sinking streams can pass through some karst aquifers by conduit flow in a matter of hours or days.

The synclinal Carboniferous limestone valleys in the south of the country have intensive dairying agriculture, and as a result there are significant nitrogen inputs from both diffuse and point sources. Nitrate in karst aquifers in this region can sometimes exceed the 50 mg/l NO_3 (11.3 mg/l NO_3-N) limit from the Drinking Water Directive (98/83/EC). For example, Bartley & Johnston (2006) investigated nitrate in a karst aquifer beneath a dairy farm in north Cork and found concentrations above the drinking water limit, reaching three times the limit in the groundwater beneath where dairy soiled water irrigation was being carried out in an extremely vulnerable zone. Further research at the same north Cork site by Huebsch *et al*. (2013) investigated factors influencing nitrate concentration over an eleven year period. A decrease in nitrate over the period to below the drinking water limit was attributed to changes in farm management practices (see the concluding section below).

In karst regions with less intensive agriculture such as the Burren plateau and parts of the western limestone lowlands of Clare and east Galway, the shallow, patchy rendzina soil cover and high degree of karstification increases the risk of leaching. However, this is counterbalanced by the lower agricultural intensity and lower nitrogen inputs in these regions, with the result that nitrate concentrations are significantly lower (see Craig et al., 2010, Map 2.2). Therefore nitrate is not a concern from the perspective of drinking water quality, but it may be of ecological concern at much lower concentrations in some situations. Nitrogen can be the limiting nutrient to eutrophication of freshwater bodies in some circumstances and it is generally the limiting nutrient in estuarine and coastal waters: The Surface Water Regulations, (SI 272 of 2009) set an Environmental Quality Standard (EQS) for good status of coastal water bodies of 2.6 mg N/l (at salinity 0 psu). The entry of nitrogen to Galway Bay from submarine and intertidal groundwater discharge has been studied by Cave & Henry (2011).

PHOSPHORUS

Rivers, lakes and turloughs on the western Irish limestone lowlands have close interactions with karst groundwater (Coxon & Drew, 2000), and phosphorus is generally the limiting nutrient to eutrophication in these ecosystems. Investigations of groundwater phosphorus (P) in this area (Kilroy & Coxon, 2005) showed that mean total phosphorus (TP) concentrations in both springs and boreholes were greater than the 20 μg/l threshold for eutrophic conditions in Irish lakes from the Phosphorus Regulations (SI 258 of 1998), with some sites also exceeding the more recently set groundwater threshold value of 35 μg/l Molybdate Reactive P (from the Groundwater Regulations, SI 9 of 2010), which is based on the Irish EQS for good status of river water bodies (from the Surface Water Regulations, SI 272 of 2009). The combination of ecologically significant groundwater phosphorus concentrations and the high contribution of groundwater flow to surface waters in karst regions resulted in 101 groundwater bodies occupying 13.3% of the area of Ireland being designated as of poor chemical status for the Water Framework Directive (Daly, 2009).

Kilroy & Coxon (2005) found that dissolved reactive phosphorus (DRP) was the dominant P component in karst springs, but particulate P and dissolved unreactive P increased to a greater degree than DRP during periods of high rainfall. Research by Mellander *et al*. (2013) at Cregduff springs, Co. Mayo, showed that in this catchment the soils have an unusually high capacity to retain P and buffer against P leaching, and over 90% of the mapped dolines (karst depressions) are sediment floor dolines, which they classed as low P risk; these factors help to explain why total reactive P concentrations at the spring remain below the groundwater threshold value for most of the time. However, karst aquifers remain at risk from high P loads from point sources such as badly stored farm wastes or from point recharge via sinking streams. Kilroy & Coxon (2005) provided a case example of passage of a contaminant plume attributed to release of silage effluent to a sinking stream, resulting in an increase in TP concentration in the downgradient spring from 42 to 1,814 μg/l within 24 hours. Such localised pollution incidents are of particular concern in the summer months when groundwater constitutes a high proportion of river flow.

POTENTIAL IMPACT ON ECOSYSTEMS WITHIN KARST AQUIFERS

Ecosystems within the karst aquifer, including organisms in caves and within the network of solutionally widened fractures, are currently receiving increased attention (although as noted by Knight & Penk (2010), the first record of Irish groundwater Crustacea dates back to Kinahan in 1863). Knight & Penk's 2010 survey of Irish groundwater Crustacea in Ireland includes the northernmost record in Europe for the genus *Niphargus*, from the Carrowmore cave system in County Sligo. Wood *et al*. (2008) document the effect of organic pollution on cave invertebrates in Derbyshire; it is likely that such ecosystems will need to be taken into account in future groundwater management decisions.

CONCLUSION: EDUCATION AND MANAGEMENT IMPLICATIONS

While the water quality problems reviewed in this paper are not unique to karst areas, they tend to occur with particular severity because of the distinctive characteristics of karst. In particular, the occurrence of concentrated recharge in closed depressions and swallow holes, combined with the presence of conduit flow and flow in solutionally widened fractures in the aquifer, render karst regions particularly prone to groundwater contamination. As noted in the introduction, this scientific understanding has already been taken on board in Irish environmental policy and management: the national groundwater protection scheme takes special account of karst aquifers, and an awareness of their vulnerability also fed into the Water Framework Directive groundwater body risk assessments. Furthermore, the Good

Agricultural Practice regulations giving effect to the EU Nitrates Directive (SI 31 of 2014 and earlier versions) include a ban on landspreading of manure within 15m of karst features such as swallow holes and collapses, and a ban on manure storage within 50m of such features, while spreading of soiled water is strictly limited in karst regions where the depth to bedrock is less than a metre. Nevertheless, some challenges of education and management remain.

Approaches to preventing karst water pollution may vary in different karst regions. In the Burren karst plateau, the BurrenLIFE project aimed to develop a community based model for sustainable agriculture, providing a model for conservation of distinctive karst flora and fauna and prevention of rural depopulation while minimising any adverse impacts on the environment (BurrenLIFE, 2010). Where karst aquifers are overlain by a thicker mineral soil cover and have more intensive agriculture, particularly in the southern dairying region which is likely to see greater intensification in line with the Harvest 2020 policy, the level of implementation and effectiveness of the current karst-specific Good Agricultural Practice regulations should be evaluated, and development of additional agricultural Best Management Practices specific to karst situations may be needed. On the north Cork dairy farm studied by Huebsch *et al*. (2013), decreases in nitrate in the underlying karst aquifer over an eleven year period were attributed to altered timing of slurry applications, reductions in inorganic nitrogen fertilizer usage, the movement of the dairy soiled water irrigator to a less karstified area of the farm and a change to minimum cultivation rather than ploughing during pasture re-seeding operations, and the authors concluded that implementation of the Nitrates Directive had helped to improve the water quality on the study site. They suggested that mapping of high risk and low risk leaching areas within a farm could be an effective management approach for positioning of the dirty soiled water system and also noted that increased grazing intensity should be strategically positioned on less vulnerable areas.

Improvements to domestic wastewater treatment systems (in terms of siting, construction and operation), and the installation of mains sewerage in urban fringes with high densities of unsewered housing, should bring about a decrease in microbial contamination. The current national programme of septic tank inspections is being made according to an EPA risk assessment which takes karst into account in the determination of pathway susceptibility (EPA, 2013). (It should be noted however that because the risk ranking is also based on unsewered housing density, the areas of low risk from MRP and pathogens in the western Irish karst lowlands in EPA (2013) Figure 14 cannot be taken to mean low risk of faecal contamination of an individual domestic well). Agricultural best management practices can also result in reductions in faecal bacterial numbers, as noted in a U.S. study by Boyer & Pasquarell (1999). However, while improved management of both human and animal waste can improve the microbial quality of karst waters, it is not feasible to eliminate such contamination. Shutting down of raw water intakes at times of maximum risk, during the passage of flood waves at karst springs, may be a useful precaution. However, reliable prediction of contamination incidents can be problematic. Although turbidity is often highly correlated with microbial pathogens, Auckenthaler *et al*. (2002) warn that in some karst systems, microbial numbers may rise several hours before turbidity, so they suggest that spring discharge may be a safer warning parameter. Because of the difficulty of prediction and potentially serious public health consequences, adequate drinking water treatment remains essential.

Finally a renewed and vigorous programme of public education about the vulnerability of karst systems would be beneficial for all Irish karst regions, to increase awareness of the need for adequately constructed and maintained domestic wastewater treatment systems and to prevent problems of poor waste management and illegal waste dumping. A combination of increased public awareness and pollution prevention measures can ensure that the ecological quality of rivers, lakes, turloughs and coastal waters fed by karst groundwater is maintained or improved. From a drinking water perspective, preventative measures to achieve better quality raw water quality need to be combined with adequate investment in water treatment, particularly for protozoan parasites, to ensure consumer safety. Irish hydrogeologists can potentially play an important role in public education and in highlighting the need for prevention measures.

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