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Highway deicing salt dynamic runoff to surface water and subsequent infiltration to groundwater during severe UK winters

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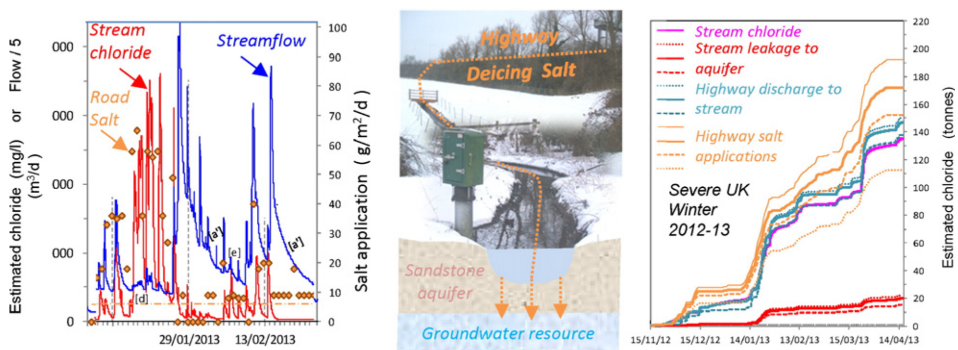
HIGHLIGHTS

- Highway deicing salt dynamic runoff to a stream leaking to groundwater is assessed
- Stream chloride was sensitive to climate control release of applied motorway salt
- >3g/l stream chloride due to low dilution of salt-induced melt of highway snowfall
- Dynamic streambed chloride leakage confirms stream acts as a line-source to aquifer
- Severe winter stream leakage accounts for 54% of 70 t supply well chloride increase

GRAPHICAL ABSTRACT



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ABSTRACT

Dynamic impact to the water environment of deicing salt application at a major highway (motorway) interchange in the UK is quantitatively evaluated for two recent severe UK winters. The contaminant transport pathway studied allowed controls on dynamic highway runoff and storm-sewer discharge to a receiving stream and its subsequent leakage to an underlying sandstone aquifer, including possible contribution to long-term chloride increases in supply wells, to be evaluated. Logged stream electrical-conductivity (EC) to estimate chloride concentrations, stream flow, climate and motorway salt application data were used to assess salt fate. Stream loading was responsive to salt applications and climate variability influencing salt release. Chloride (via EC) was predicted to exceed the stream Environmental Quality Standard (250 mg/l) for 33% and 18% of the two winters. Maximum stream concentrations (3500 mg/l, 15% sea water salinity) were ascribed to salt-induced melting and drainage of highway snowfall without dilution from, still frozen, catchment water. Salt persistance on the highway under dry-cold conditions was inferred from stream observations of delayed salt removal. Streambed and stream-loss data demonstrated chloride infiltration could occur to the underlying aquifer with mild and severe winter stream leakage estimated to account for 21 to 54% respectively of the 70 t of increased chloride (over baseline) annually abstracted by supply wells. Deicing salt infiltration lateral to the highway alongside other urban/natural sources were inferred to contribute the shortfall. Challenges in quantifying chloride mass/fluxes (flow gauge accuracy at high flows, salt loading from other roads, weaker chloride-EC correlation at low

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concentrations), may be largely overcome by modest investment in enhanced data acquisition or minor approach modification. The increased understanding of deicing salt dynamic loading to the water environment obtained is relevant to improved groundwater resource management, highway salt application practice, surface-water - ecosystem management, and decision making on highway drainage to ground.

1. Introduction

Application of highway deicing agents, most commonly sodium chloride salt, is vital to road safety. Most applied salt, however, is ultimately expected to enter the water environment. The legacy of deicing salt gradually accumulating in aquifers is of concern across cold-climate regions (Bester et al., 2006; Foos, 2003; Gedlinske, 2013; Godwin et al., 2003; Harte and Trowbridge, 2010; Howard and Maier, 2007; Kelly, 2008; Lundmark and Jansson, 2008; Meriano et al., 2009; Nystén, 1998; Thungqvist, 2004; Perera et al., 2013; Viklander et al., 2003; Warner and Ayotte, 2014; Williams et al., 1999). Salt application in more temperate areas, although experiencing less snowfall, may still be significant. The Midlands region of the UK studied herein has fairly limited snowfall, yet may often face near-freezing damp or icy conditions that warrant salt application (Andersson and Chapman, 2011). Indeed, such conditions, amongst other factors including the mode of salting and legal requirements to keep roads free of ice and snow, result in the UK having relatively high salt spreading rates compared to similar cold-climate countries (Booth et al., 2011).

Salt application trends over recent decades may remain influential. This is particularly true where aquifers have high storage capacity and correspondingly low turnover of resource. In the US, for example, salt use has increased threefold since the 1970s in the area overlying the Northern glacial aquifer that supplies one-sixth of the nation's population (Nixon, 2013; Warner and Ayotte, 2014). In the UK, significant salt use was triggered by the severe 1962–63 winter with around 1 Mt (million tonnes) of salt being applied that year (Thornes, J.E., *pers. commun.*). Hitherto Thornes indicates grit from power stations had been rather ineffectively used. The 1980 Highways Act was also instrumental in conferring a duty of care on highway authorities to clear snow and ice. This resulted in a step-change in UK operations and the development of a national ice prediction system in the mid-1980s that served as a forerunner to modern route-based forecasting and maintenance decision support systems (Chapman and Thornes, 2006; Handa et al., 2006; Thornes and Chapman, 2008; Nixon, 2013).

Currently, the UK has over 400,000 km of main roads of which 30% are salted via 3500 salting routes (Thornes and Chapman, 2008). The UK applies around <1 Mt of salt during a mild winter, 1–2 Mt for an average winter and 2–3 Mt in a severe winter (Thornes, J.E., *pers. commun.*). This compares to 10 to 20 Mt in the US and 5 Mt in Canada (Environment Canada, 2004). Climate change may additionally influence future applications. Andersson and Chapman (2011) predict declining salt application for the UK (West) Midlands and model 'frost days' in the region to decline from the present 69 to 28 days by 2080. Somewhat contrary to this longer term expectation, our winter field campaigns were conducted during two of the UK's most severe recent winters of recent decades. Public and press interest was notable during 2009–10 as deicing salt supplies dwindled and concerns were expressed over the fate of the vast quantities of salt, indeed record levels, being applied (Hickman, 2010).

Estimating the proportion of salt accumulating in groundwater is challenging. In Toronto, where Howard and Maier (2007) indicate deicing salt has become a potential constraint on urban growth, Perera et al. (2013) estimate that 60% of Toronto's applied road salt drains to surface water and leaves the catchment. The corresponding 40% balance infiltrates to the aquifer. Decreases in baseflow chloride discharges now result in a net aquifer accumulation of 19% of the annual Toronto salt application. In Sweden, Blomqvist and Johansson (1999) estimated 20 to 63% of applied deicing salt was transported by air and deposited on adjacent ground 2 to 40 m from the highway reaching a maximum of 100 m with over 90% deposited within 20 m. Higher percentages were ascribed to greater snowfall, more splash generation and ploughed snow displacement and have been modelled using approaches developed by Lundmark and Jansson (2008). Deposited salt lateral to the highway is likely to infiltrate to groundwater.

Our interest is to investigate the potential for salt infiltration through a leaky streambed that may constitute a significant line-source to the underlying aquifer. This scenario is particularly important where well fields have contributed to an influent stream condition and subsequently prove to be a receptor of the stream contamination present. Our goal was to quantitatively evaluate the impact of winter deicing salt applications at a major highway ('motorway') interchange on the surrounding water environment; in particular, a surface-water reach that receives storm-water discharges from the highway, but leaks to groundwater and may be partly responsible for gradually rising chloride observed in nearby public water supply (PWS) wells (EA, Environment Agency, 2010).

Objectives set were: to understand factors controlling winter season dynamic stream water-quality and the transients of storm-sewer discharges of motorway runoff; to prove surface-water – groundwater connectivity and estimate deicing salt infiltration to the underlying aquifer; and, to consider the potential for the 'pollutant linkage' studied (salt application - highway runoff – storm-sewer discharge – stream transport and infiltration - groundwater advection and abstraction) to account for rising chloride in the supply wells.

Assessing such pollutant linkages, expected to fully develop over years to decades at relevant cross-disciplinary field-scales, is rarely attempted. It is, however, fundamental to assessing the long-term impact of both historic and future deicing activity and integral to the holistic surface-water – groundwater – land use management agenda of the EU Water Framework Directive.

2. Study area setting

2.1. Site scenario

The study located at the Worcestershire – West Midlands border was motivated by Environment Agency interest to better understand gradually rising chloride in PWS wells located close to the national motorway network. Specifically, there was interest to understand the possible influence on the wells of a nearby stream, the Battlefield Brook, that received storm-sewer discharges of motorway runoff (EA, Environment Agency, 2010). The 44 km^2 area Bromsgrove West Groundwater Management Unit is part of the Permo-Triassic Sandstone aquifer, the UK's second most important aquifer (Allen et al., 1997; Tyler-Whittle et al., 2002). This Unit contains seven PWS wells licensed to abstract 73 Ml/d (mega-litres per day) (EA, Environment Agency, 2010). Actual abstraction has been less amounting to 26 Ml/d in 1965 to a maximum of 44 Ml/d in 1991 falling to 35 Ml/d in 2007 (EA, Environment Agency, 2010).

Our focus is on two PWS wells within the Bromsgrove Formation that are situated relatively close to both the motorway network and Battlefield Brook (Fig. 1). The southernmost well, established in 1903, and the other in 1955 are together licensed to abstract 23 Ml/d. Chloride concentrations in the southern well steadily rose from around 25 mg/l in 1974 to stabilise at around 45 mg/l by 1992 followed by a marginal