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Research article

Developing a multi-pollutant conceptual framework for the selection and targeting of interventions in water industry catchment management schemes

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A B S T R A C T

In recent years water companies have started to adopt catchment management to reduce diffuse pollution in drinking water supply areas. The heterogeneity of catchments and the range of pollutants that must be removed to meet the EU Drinking Water Directive (98/83/EC) limits make it difficult to prioritise areas of a catchment for intervention. Thus conceptual frameworks are required that can disaggregate the components of pollutant risk and help water companies make decisions about where to target interventions in their catchments to maximum effect. This paper demonstrates the concept of generalising pollutants in the same framework by reviewing key pollutant processes within a source-mobilisation-delivery context. From this, criteria are developed (with input from water industry professionals involved in catchment management) which highlights the need for a new water industry specific conceptual framework. The new CaRPoW (Catchment Risk to Potable Water) framework uses the Source-Mobilisation-Delivery concept as modular components of risk that work at two scales, source and mobilisation at the field scale and delivery at the catchment scale. Disaggregating pollutant processes permits the main components of risk to be ascertained so that appropriate interventions can be selected. The generic structure also allows for the outputs from different pollutants to be compared so that potential multiple benefits can be identified. CaRPow provides a transferable framework that can be used by water companies to cost-effectively target interventions under current conditions or under scenarios of land use or climate change.

1. Introduction

Variability in catchment water quality is an issue that impacts on many aspects of the environment and society. Improvements to water quality have resulted from the improved regulation of industries that discharge effluent into the water environment from an individual source (e.g. EU Urban Waste Water Directive 91/271/EEC). However the improved control of point sources means that increasing attention is being placed on diffuse sources of pollutants in catchments (Edwards and Withers, 2008). The spatially-diverse nature of diffuse pollution makes it difficult to pinpoint areas for regulation and investment and therefore an integrated catchment based approach has commonly been adopted for its control (Harris, 2013), e.g. the Watershed Approach Framework (USA) (EPA, 1996), Catchment Management Authorities (New South Wales, Australia) (NSW Government, 2003).

In Europe, this integrated approach forms the underlying management structure of the EU Water Framework Directive (WFD) which aims to achieve a 'good' ecological and chemical status for all EU water bodies (2000/60/EC; Holzwarth, 2002). Achieving the required water body status relies on the designated Competent Body (such as the national environmental regulator) outlining a programme of measures, within their river basin management plans, to tackle a range of pollutants which may be implemented by multiple organisations or stakeholders, which may include water companies.

Water companies as recipients of poor water quality and with their own regulatory issues have an increasing interest in controlling pollution at source using catchment management rather than

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relying on increased treatment. At the EU level this is consistent with Article 7 of the WFD which aims at "*avoiding deterioration in their* (Water Companies) *quality to reduce the level of purification treatment required in the production of drinking water*" (2000/60/EC). This, combined with encouragement from the water industry regulatory bodies and the perceived benefits of catchment management within the water industry (such as reducing costs of treatment, promoting sustainability and reducing greenhouse gas emissions) (UKWIR, 2012), have led to all of the major water companies in the UK adopting some form of integrated catchment management (Spiller et al., 2013). However despite national concerns about drinking water limits being breached by multiple pollutants, catchment management investigations have tended to be reactionary and to focus on a single pollutant issue in isolation. This potentially means that companies are not realising the full benefit of an integrated approach to improve raw drinking water quality.

Drinking water catchments often present an inherent mosaic of different land uses, soil types, geology and anthropogenic influences that promote heterogeneity in catchment pollutant processes. For catchment management to be effective and sustainable it is vital that interventions are carefully selected and targeted at Critical Source Areas (CSAs) that pose disproportionately higher risk than others (Strauss et al., 2007; White et al., 2009; Doody et al., 2012). Aside from improved effectiveness and reduced implementation costs, disruption to other catchment stakeholders will be reduced when compared to widespread implementation of interventions (Beharry-Borg et al., 2013).

The selection and targeting of measures has been supported by the development of a number of conceptual frameworks and models to aid stakeholder decisions. However, they have largely been developed with single pollutant issues in mind e.g. the Nutrient Export Risk Matrix (Hewett et al., 2004, 2009) or the CatchIS modelling framework (Brown et al., 2002). Frameworks have also been developed which highlight certain components of pollutant risk such as the SciMap modelling framework which makes an assessment of spatial risk based on hydrological connectivity in a catchment (Lane et al., 2009). Frameworks that concentrate on singular pollutants or risk components however do not always allow for the assessment of the range of pollutants that need to be considered by water companies. Where multiple pollutant frameworks have been produced, they have either been developed for specific land use and soil types (Granger et al., 2010) or tend to focus on a single component of risk (e.g. source comparison in Dawson and Smith, 2010).

The aim of this paper therefore is to develop and demonstrate a generic conceptual framework that allows comparison of the spatial and temporal drinking water quality risks associated with multiple pollutants. This will allow water utilities and their partners to proactively identify critical source areas for multiple pollutants and subsequently better select and target a programme of interventions.

This paper (i) identifies catchment process similarities between different pollutants as a basis for integrating multiple pollutants within a single framework; (ii) proposes a new conceptual framework (CaRPoW – Catchment Risk to Potable Water) to facilitate the selection and targeting of catchment interventions to address multiple pollutants, that meets the needs of water companies based on criteria developed with water company professionals and (iii) discusses the merits and drawbacks of using such a framework to select and target interventions.

2. Catchment heterogeneity and multiple pollutant processes

The development of this generic framework is based on the presumption that different pollutants sometimes show similarities in either their source, mobilisation or delivery and that this will result in common critical source areas. Building on work by Haygarth et al. (2005) and Granger et al. (2010) we took the key pollutants of concern to drinking water source protection and reviewed their processes within the Source-Mobilisation-Delivery continuum framework that describes the cascade of groupings of pollutant processes that lead to the contamination of drinking water sources (Haygarth et al., 2005). Source processes concern whether a pollutant occurs naturally or as a result of human intervention (Granger et al., 2010). Mobilisation relates to the mechanism(s) by which a pollutant moves from its source either in solution and/or attached to particulate matter. Finally the delivery component refers to the pathway that a mobilised pollutant takes to reach the receptor (water body). Pollutants reviewed include pesticides and nitrate, which have regulated limits under the EU Drinking Water Directive (98/83/EC), and Dissolved Organic Carbon (DOC), sediment and phosphorus which cause issues relating to disinfection by-products, turbidity and reservoir algal blooms, respectively.

2.1. Pesticides

The importance and strength of the source term for most pesticides depends primarily on the agricultural land use, which in turn determines the rate, frequency and timing of active ingredient application. The mobilisation and delivery of the active ingredients are then often primarily determined by hydrological events which can affect runoff, leaching and drain-flow (Leu et al., 2004; Reichenberger et al., 2007). Although less common, spray-drift and overspraying into water bodies can also result from poor pesticide spraying practices (Reichenberger et al., 2007).

Mobilisation can be both in particulate and soluble forms, and is influenced by both soil properties and the sorption strength and solubility of the pesticide (Wauchope et al., 2002; Gavrilescu, 2005). Soil organic matter and clay content determine sorption sites and soil physical properties such as porosity determine the water storage capacity and thus propensity of pesticide sorption (Spark and Swift, 2002; Arias-Estévez et al., 2008). Soil texture and topographical features such as slope, which affect erosion rates, influence mobilisation in particulate forms (Arias-Estévez et al., 2008). Rainfall intensity, duration and timing can influence the onset of soil detachment (particulate mobilisation), the mobilisation of freshly applied pesticides on the soil surface and pesticides in soil solution when soil moisture content is above field capacity (Kladivco et al., 2001; Nolan et al., 2008; Lewan et al., 2009).

Pesticides can be delivered to water bodies by high energy, low energy and non-hydrological delivery pathways. Again pesticide properties are key determinands, with low sorbing and soluble pesticides more likely to be delivered in low energy pathways such as throughflow and leaching (Kördel et al., 2008) and stronger sorbing and less soluble pesticides delivered through higher energy processes such as surface runoff and preferential flow (Riise et al., 2004; Reichenberger et al., 2007). Throughflow and leaching processes are likely to be more prevalent in lighter, sandier soils (Leu et al., 2004) and the higher energy runoff and preferential pathways associated with heavier clay soils that may be subject to artificial drainage (Akay and Fox, 2007; Brown and van Beinum, 2009). Precipitation characteristics, especially the timing and magnitude of the first rainfall event after application (Louchart et al., 2001; Guo et al., 2004), are important in the delivery of pesticides. The significance of non-hydrological processes, such as spray drift and volatilisation, are dependent on the proximity of application to surface water, spraying technique and the properties of the pesticide (Gil and Sinfort, 2005; FOCUS, 2008).

2.2. Nitrogen

Sources of nitrogen on agricultural land include inorganic fertiliser (Domburg et al., 1998), cycled sources such as livestock waste either directly applied by livestock or in the form of manure or slurry applications (Hooda et al., 2000), and internal sources such as nitrate from soil mineralisation (Di and Cameron, 2002). These sources exist in a number of forms including nitrate and ammonium (Hooda et al., 2000; Granger et al., 2010; Jarvie et al., 2010). Agricultural sources are generally diffuse with some point sources associated with farm yards (Edwards et al., 2008) and other non-agricultural sources, such as Waste Water Treatment Works (WWTW) discharges and septic tanks. The main determinands of nitrate sources in a catchment therefore are the type of agriculture (although it varies with cropping and livestock system, and fertiliser and stocking rates) and the presence of any point sources. Nitrate concentrations in rivers can be higher in winter months when plants are not actively taking nitrate from the soil and leaching rates are higher (Jarvie et al., 2010).

Nitrate is mostly mobilised via solubilisation processes (Granger et al., 2010) due to its high solubility (Di and Cameron, 2002). However, the solubilisation of nitrate is closely linked to the soil moisture content which in turn is affected by rainfall and the soil properties such as texture and porosity (Torbert et al., 1999). Incidental mobilisation of ammonium straight after organic fertiliser application can locally occur, although this is dependent on significant rainfall shortly after application (Smith et al., 2001) and reduced soil infiltration capacity (e.g. from livestock poaching) (Butler et al., 2008).

Nitrate is generally delivered via lower energy leaching and throughflow, with approximately 5 times higher losses of nitrate via leaching than surface runoff in both intensive and extensive agriculture (Parn et al. 2012). Nitrate losses via leaching and throughflow are increased by a soil moisture content high enough to drive vertical and lateral throughflow; soils with a high hydraulic conductivity (Bergström and Johansson, 1991); land management activities such as artificial drainage (Singleton et al., 2001) and the lack of cover crops (MacDonald et al., 2005). Although these processes dominate, ammoniacal-N mobilised incidentally can also be delivered in high energy surface runoff and preferential flow processes (e.g. Ming-kui et al., 2007).

2.3. Phosphorus

Similar to nitrogen, phosphorus can be supplied from external sources such as the application of inorganic fertilisers; cycled sources from the direct and indirect application of livestock waste; and internal sources from the P surplus in many soils (Edwards and Withers, 1998; Withers et al., 2003; Hodgkinson and Withers, 2007). Diffuse sources occur from fields receiving fertiliser and slurry whereas point sources can either be losses from livestock waste in farmyards or effluent discharges from waste water treatment works and septic tanks (Macintosh et al., 2011). The strength of the source depends on the type of livestock (Smith et al., 1998), stocking rate (Withers et al., 2001), fertiliser application rate which can be related to crop type and the P status of the soil, and the presence of non-agricultural point sources in the catchment (Macintosh et al., 2011).

P mobilisation has been demonstrated to occur in particulate form, in solution and incidentally (Granger et al., 2010). Due to the high sorption capabilities of P, particulate detachment processes are generally considered the dominant P mobilisation mechanism (Kleinman et al., 2011). Detachment is dependent on significant erosional rainfall inputs, but can be exacerbated by other factors such as soil texture, tillage, soil compaction and livestock poaching. Solubilisation of P is also possible via the dissolution of P compounds or via desorption when the P sorption equilibrium of the soil is exceeded (Styles et al., 2006). Variables influencing the likelihood of P solubilisation include the soil type (sandy soils have low P sorption coefficients), the organic matter content and the soil moisture content of the soil (Hooda et al., 2000; McDowell et al., 2001; Djodjic et al., 2004). Incidental mobilisation occurs when a slurry or fertiliser application precedes or coincides with a hydrologically effective rainfall event, with inorganic fertilisers generally causing the highest stream P concentrations after incidental mobilisation (Preedy et al., 2001). This can locally be the dominant mobilisation form at the field scale but effects are diluted at the catchment scale (Withers et al., 2003).

High particle associated and soluble P loads can be delivered via surface runoff in both arable and grassland catchments (McDowell et al., 2001; Haygarth et al., 2006; Bilotta et al., 2008). Factors controlling the likelihood of surface runoff P delivery are again related to effective rainfall inputs (Shigaki et al., 2007), topography, soil properties such as texture, and land management activities such as cultivation and soil compaction (Silgram et al., 2010). The presence of preferential delivery pathways (macropores and drainflow) have also been shown to deliver P in both soluble and particulate formats (Heathwaite and Dils, 2000; Gächter et al., 2004). The likelihood of preferential flow pathways as a P delivery mechanism is increased by the presence of artificial drainage (Hodgkinson et al., 2002) and clay soils (due to the presence of macropores) (Van Es et al., 2004). Although the dominant delivery pathways for P are generally thought to be high energy processes such as surface runoff and preferential flow, P in a soluble form can be delivered via lower energy pathways, especially in soils with a low P sorption coefficient, a porous structure and a shallow water table (Börling, 2003).

2.4. Sediment

The water industry considers sediment to be an important pollutant as it causes turbidity (regulated under the Drinking Water Directive (98/83/EC)) and it provides a conduit for other pollutants such as pesticides and phosphorus (Bilotta and Brazier, 2008). ‘Naturally’ derived sediment is produced from erosive processes on the land and from bank and bed erosion in streams and rivers (Walling, 2005). Vegetation cover plays an important role in controlling erosion and sediment loss from land, and thus arable rotations that include periods of minimal vegetation cover often have a high disproportional sediment load contribution (Collins et al., 2009). In lowland river systems inputs from both urban areas and sewage treatment effluent can also provide a significant source of sediment, for example Carter et al. (2003) report annual percentage sediment load values of 19–22% from roads and 14–18% from sewage effluent.

The mobilisation of sediment sources depends on significant energy inputs that enable detachment processes (Granger et al., 2010). The detachment of land based sources is usually via rain drop action or hydraulic detachment from runoff processes (Morgan, 2005). Where livestock is present, poaching can also detach sediment both from land based and river bank sources (Skinner et al., 1997).

The dominant form of sediment delivery is associated with high energy runoff processes. The proportion of mobilised sediment delivered to surface waters is therefore reliant upon runoff processes having enough energy to maintain sediment suspension or saltation. Since energy along runoff pathways is often not maintained, sediment can be deposited before reaching surface waters (Morgan, 2005). Therefore a disproportionate amount of sediment is delivered in the highest energy storm events. Although runoff is the dominant delivery process, studies such as Deasy et al. (2009), have demonstrated that significant macro-pore connections in the soil subsurface can result in fine sediment delivery in sub-surface drains.

2.5. DOC/colour

The majority of DOC (Dissolved Organic Carbon) in surface waters is sourced from the dissolution of organic matter in soils, with some inputs from atmospherically deposited carbon (Dawson and Smith, 2007). Hence, there is a relationship between the organic carbon content of a soil and the DOC concentration/load in the surface waters that drain the soil (Clark et al., 2004; Holden, 2005; Buckingham et al., 2008). The largest source of DOC in British surface waters is from catchments with a high fraction of peat soils (Holden et al., 2007; Billet et al., 2010).

By its nature DOC is mobilised via solubilisation processes with the rate of solubilisation dependent on the rate of organic matter decomposition (Dawson and Smith, 2007). In peatland catchments, decomposition is regulated by temperature, pH and water table depth (Bonnett et al., 2006). The temperature driven nature of DOC production and mobilisation means there is often a distinct observed seasonality with higher loads and concentrations in soil and surface water in the summer-autumn when compared to the winter–spring (Dawson et al., 2011). Whilst these controls explain intra-annual variations in surface water DOC concentrations they do not explain the increase in DOC that has been observed in surface waters over the last 40 years (Evans et al., 2005). Explanations for this include increases in temperature (e.g. Freeman et al., 2001); a reduction in acid deposition due to controls over sulphur emissions (e.g. Evans et al., 2006); CO_2 enrichment from increased emissions (e.g. Freeman et al., 2004); and changes to upland land management such as increases in drainage and moorland burning that influence local hydrology (e.g. Yallop and Clutterbuck, 2009), although no single driver fully explains trends in all catchments.

In peatlands DOC is transported by both low energy throughflow processes and high energy surface runoff and preferential flow (Clark et al., 2008; Holden, 2005) including through macropores or soil pipes in peatlands (Holden et al., 2012). The perceived dominance of each process in the literature is variable but a few studies have quantified the importance of runoff events for intra-annual DOC flux with Clark et al. (2007) showing that 50% of annual DOC exports for a peatland catchment were in the highest 10% of runoff events.

2.6. Pollutant process links

If the same processes within the Source-Mobilisation-Delivery modules control the behaviour of different pollutants then it is reasonable to assume that there is a potential for shared critical source areas. In turn this highlights possibilities for the implementation of interventions within a catchment to have a positive impact on more than one pollutant. Conversely if pollutant processes are different then it acts as a warning for potential pollutant swapping with certain interventions (Stevens and Quinton, 2009). Fig. 1 highlights the dominant process similarities between the different pollutants of direct (or indirect) interest to water companies. Source processes are characterised according to the dominant land uses they are associated with; mobilisation processes to whether pollutants are mobilised in solution, attached to particles and/or incidentally after application; and delivery is characterised by the important pathways to drinking water bodies.

Analysis of Fig. 1 highlights similarities in the dominant process characterisations between pollutants. For example sources of nutrients, pesticides and sediment are likely to be spatially similar as they are dominated by both grassland and arable land uses. Regarding mobilisation of these sources PP, sediment and some pesticides are inherently linked and SRP and N could potentially be mobilised in similar circumstances (mobilisation of soil pore water). Pesticides have the potential to be delivered in the same pathways as any of the other pollutants, whilst sediment and PP are associated with high energy delivery pathways and N and SRP with sub surface delivery pathways.

The process similarities therefore suggest that there is potential for pollutants to be considered within a single generic framework for the purposes of defining catchment risk. Furthermore process similarity could also be used as the conceptual basis for selecting and targeting interventions in an attempt to abate catchment pollutant risk for priority pollutants.

3. A conceptual framework of multiple pollutant processes

Any new framework developed for water company catchment management projects clearly requires input from the end users of the framework within its development. Hence a set of criteria, informed by Graves et al. (2005), were developed in collaboration with water company professionals involved in catchment management, water quality regulation and the delivery of the Water Framework Directive.

The criteria are divided into nine key sub-sections (Table 1). End users were presented with guidance information and the list of sub-sections in Table 1 and asked to each devise criteria. Following further discussion the final criteria were collated (the second column in Table 1) which formed the basis of the conceptual framework development.

3.1. Assessing current modelling frameworks

Models and frameworks previously conceptualised for understanding the linkages of risk between different pollutant processes were selected for assessment against the criteria in Table 1 on the basis that they represented at least one of the key pollutants of concern, accounted for spatial risk, included some form of consideration for interventions (even if just implied) and have been applied to UK or Northern European countries.

Various limitations in the associated pollutants, represented scales and modelling typologies mean that none of the models and frameworks assessed in Table 2 fully matches the criteria. In some respects this is unsurprising as the outline criteria are bespoke to the needs of the water industry which many of the models and frameworks were not developed for, with the exception of SaGIS, CatchIS, Foster and MacDonald (2000) and Grayson et al. (2012). These models that were developed from the viewpoint of a water utility are either focused on single pollutant issues (CatchIS, Grayson et al., 2012) or do not represent the necessary processes within the Source-Mobilisation-Delivery continuum required to select and target specific interventions (SaGIS, Foster and MacDonald, 2000). The Territ'eau framework (Gascuel-Odoux et al., 2009) considers the 'fate' and 'transfer' of phosphorus, nitrates and pesticides to the river network, but has modules for individual pollutants rather than process modules (that are applied to all pollutants) which makes it difficult to compare risks for different pollutants. This limits the identification of potentially appropriate interventions or pollutant swapping.

This review has highlighted the need for a framework that meets the water utility criteria outlined in Table 1, notwithstanding the greater need for generic frameworks at the catchment scale to assess multiple diffuse pollutants for the purposes of risk identification.

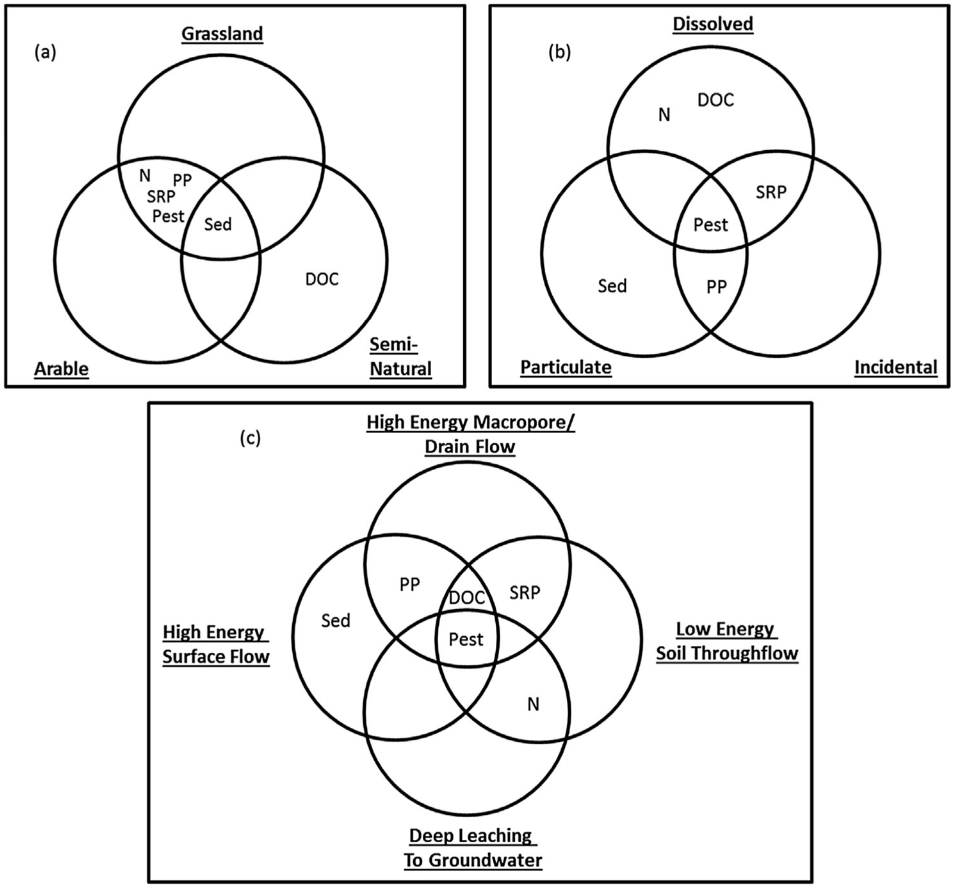

Fig. 1. Process linkages between the water industry priority pollutants framed within the (a) Source, (b) Mobilisation and (c) Delivery continuum (adapted from Granger et al., 2010). Pest – Pesticides, PP – Particulate Phosphorus, SRP – Soluble Reactive Phosphorus, N – Nitrate, Sed – Sediment, DOC – Dissolved Organic Carbon.

3.2. The CaRPoW framework

The Catchment Risk to Potable Water (CaRPoW) Framework (Fig. 2) has therefore been developed in response to the need for a generic framework applicable to key drinking water protection concerns. The core basis of the framework is centred on the Source-Mobilisation-Delivery continuum (Haygarth et al., 2005) which has previously been developed for phosphorus and applied to other

Table 1
Criteria framework used to define conceptual framework with input from water industry professionals (adapted from Graves et al., 2005).

Criteria sub-sections	Water company defined criteria
1. Background – General information on framework/model	1.1 Operate in English
	1.2 Supporting methodology for drinking water source protection decisions
2. Systems Modelled – Components of the system represented by framework/model	2.1 Represents lowland and upland systems; arable, grassland and moorland dominated systems
	2.2 Focus on surface water systems although consideration of groundwater made in some capacity
3. Objectives	3.1 Characterise dominant diffuse pollution processes from source to delivery in drinking water catchments
	3.2 Assess spatial and temporal variation in process characterisations
	3.3 Classify risk of pollutant characterisations
	3.4 Compare risk classifications between different pollutants
	3.5 Select and target interventions according to the high risk areas
4. Viewpoint of analysis – Who the methodology is being developed for	4.1 Modelled from the viewpoint of a water company with a focus on abstracted raw water quality
5. Spatial scale and arrangement	5.1 Field/land unit scale
6. Temporal scale	6.1 Monthly for some model components but output to be seasonal or annual risk
7. Generation and use of data – How the framework/model is used	7.1 GIS methodology with potential to derive information from other models if necessary
	7.2 Potential for framework to be used in a qualitative assessment
8. Platform and interface	8.1 Initial development in spatial modelling platform
9. Inputs and outputs	9.1 Inputs are spatial-temporal datasets and parameters defined by user
	9.2 First output is modular (source, mobilisation and delivery) process risk
	9.3 Second output combined total risk output with all three modules
	9.4 Third output is risk comparison between pollutants
	9.5 Intervention options selected according to process characterisation in post-processing of outputs 9.1–9.3

Table 2
Evaluation of existing frameworks and models against the water company criteria components.

Related criteria sub-sections		1, 4	2	2	2	3	3	3	3	5, 6	7, 8, 9
Framework/ model	Reference	Drinking water specific?	Land uses represented	Pollutants represented	Hydrological systems represented?	Separate source-Mobilisation-Delivery?	Pollutant comparison?	Intervention targeting?	Transferable, generic methodology?	Spatio-temporal scale?	Platform and outputs
Phosphorus Indicators Tool	Heathwaite et al. (2003)	✗	Upland and lowland – grassland, arable, semi-natural,	Soluble and particulate phosphorus	Surface water	S-M-D	✗	✗	✗ (principles could possibly be generic)	1 km^2 – Annual	GIS risk maps – total and component risk
FARMSCOPER	Gooday et al. (2014)	✗	Lowland – grassland and arable	Soluble and particulate phosphorus, nitrate, sediment, pesticides	Surface water and groundwater	S-M-D	✓	✓	✓	Farm scale – annual	Numerical assessment
Granger et al. (2010)	Granger et al. (2010)	✗	Upland and lowland – grassland	Soluble phosphorus, particulate phosphorus, nitrate, nitrite, ammonia, fine sediment	Surface water and groundwater	S-M-D	✓	✗	✓	n/a	Qualitative classification
NERM	Hewett et al. (2004)	✗	Upland and lowland – grassland and arable	Nitrate and phosphorus	Surface water and groundwater	✗	✓ (Potentially Implicit)	✓	✓	Farm scale – n/a	Qualitative classification
SNIFFER – Diffuse Pollution Screening Tool	Sniffer (2006)	✗	Upland and lowland – grassland, arable, semi-natural	Phosphorus, nitrate, sediment, pesticides, metals	Surface water and groundwater	✗	✗	✗	✓	1 km^2 – annual	GIS risk maps
SCiMap	Lane et al. (2009)	✗	Upland and lowland – grassland, arable, semi-natural	Potential for all pollutants	Surface water	D	✗	✗	✓	User defined – n/a	GIS risk maps – total risk
SAGIS	Comber et al. (2013)	✓(but not exclusively)	Upland and lowland – grassland, arable, semi-natural	Phosphorus, nitrate, sediment, metals	Surface water	✗	✗	✗	✓	Catchment scale – Annual	GIS risk maps – total risk
CatchIS	Brown et al. (2002)	✓	Lowland – grassland, arable, semi-natural	Pesticides, nitrate	Surface water and groundwater	✗	✗	✗	✗	Catchment scale – Daily (time series), Annual (spatial risk)	GIS risk maps – total risk
Foster and MacDonald (2000)	Foster and MacDonald (2000)	✓	Upland and lowland – grassland, arable,semi-natural	Cryptospridium, pesticides, oil and grease, colour, trace metals, faecal bacteria, lead, phosphorus, nitrate	Surface water	✗	✗	✗	✓	Catchment scale – annual	GIS risk maps – total risk
Grayson et al. (2012)	Grayson et al. (2012)	✓	Upland – grassland and semi-natural	DOC and water colour	Surface water	✗	✗	✗	✗	Catchment scale – annual	GIS risk maps
PSYCHIC model	Davison et al.(2008)	✗	Upland and lowland – grassland, arable, semi-natural	Soluble phosphorus, particulate phosphorus and sediment	Surface water	S-M-D	✗	✗	✗	1 km^2 grid (Tier 1), farm scale (Tier 2) – monthly	GIS risk maps – total and component risk
The Territ'eau framework	Gascuel-Odoux et al. (2009)	✗	Upland and lowland – grassland, arable, semi-natural	Phosphorus, nitrate, sediment and pesticides	Surface water	✗	✗	✓	✓	Field to catchment scale – annual	GIS risk maps – total risk

agricultural pollutants in heavy soil grassland systems by Granger et al. (2010). The selection of the continuum as the key basis for the framework is centred on the need to disaggregate pollutant processes from how pollutants are derived (Source) to how they reach a water body (Mobilisation and Delivery), so that intervention decisions are informed by the main component of risk.

3.2.1. Defining pollutant risk

The CaRPoW framework takes a novel approach to the spatial application of the three modules of the Source-Mobilisation-Delivery continuum in order to determine pollutant risk. The source and mobilisation modules are both implemented at the 'field scale' as the key scale for agronomic intervention. Within CaRPoW 'field scale' relates to areas of land that share common land use, soil and drainage characteristics i.e. the smallest scale at which differences in substance source strength and mobility might exist using available spatial datasets. However these are also still separated by 'real world' field delineations to give a mosaic of spatial units across the catchment each with a unique source and mobilisation risk.

As with the traditional Source-Mobilisation-Delivery continuum the source module of CaRPoW refers to the mass of pollutant potentially available for mobilisation, as not all of the source may be available for mobilisation (e.g. pesticides bound to the soil, nitrate taken up by crops). This can consist of a single source (e.g. pesticides applied to fields) or multiple sources (e.g. phosphorus from manure, inorganic fertiliser and/or the soil) depending on the pollutant.

The mobilisation module represents the proportion of the available source module output that is mobilised and delivered to the edge of the field. It is therefore dependent on the initiation of runoff and drainflow processes and hence the field's soil water balance. For some pollutants such as pesticides the time factor between source availability and the initialisation of mobilisation processes is also important for source degradation and is therefore considered within the mobilisation module.

The delivery module accounts for the movement of mobilised pollutants from field edge to the water body (such as a river or reservoir) from which drinking water is abstracted, and represents the scale of opportunity for boundary feature and water course management to influence pollutant loads. It therefore incorporates principles of hydrological connectivity, i.e. the better connected a field is to the water body the more likely mobilised pollutants will be delivered. This gives a coefficient of delivery to each field within the catchment i.e. the fraction of mobilised pollutant that is delivered to the water body.

The combination of these three modules provides the overall risk as the mass of pollutant delivered to the water body per annum (Equation (1)).

$$Risk_t \;= Source_t \cdot KMob_t \cdot KDelivery_t \tag{1}$$

where $Risk_t$ is the mass of pollutant delivered to the water body (kg ha yr^{-1}), $Source_t$ is the mass of pollutant potentially available for mobilisation (kg ha yr^{-1}), $KMob_t$ is the coefficient of mobilisation (dimensionless proportion between 0 and 1) and $KDelivery_t$ is the coefficient of delivery (dimensionless proportion between 0 and 1).

CaRPoWs main utility is as a generic modelling framework in which modelling methodologies are implemented in the source and mobilisation components for each pollutant. The delivery component however is based on the same principles of hydrological connectivity for all pollutants. This largely stems from the fact that the movement of different pollutants beyond the field scale is much less understood (Haygarth et al., 2005), along with uncertainties over the accepted processes and complexities of hydrological connectivity within the literature (Bracken et al., 2013). One of the benefits of a generic modular modelling framework such as CaRPoW is that, as understanding of pollutant processes improves and better modelling methodologies are developed, the framework components can be updated.

3.2.2. Pollutant comparison and measure selection

Once risk has been assessed for each of a range of pollutants, comparisons can be made to determine if the risks are spatially concurrent between pollutants. The root cause of risk can be assessed for individual high risk fields by determining which of the three modular components is the most dominant in the high risk classification. Once determined, interventions can be referenced from an inventory (e.g. Newell Price et al., 2011) that is classified by

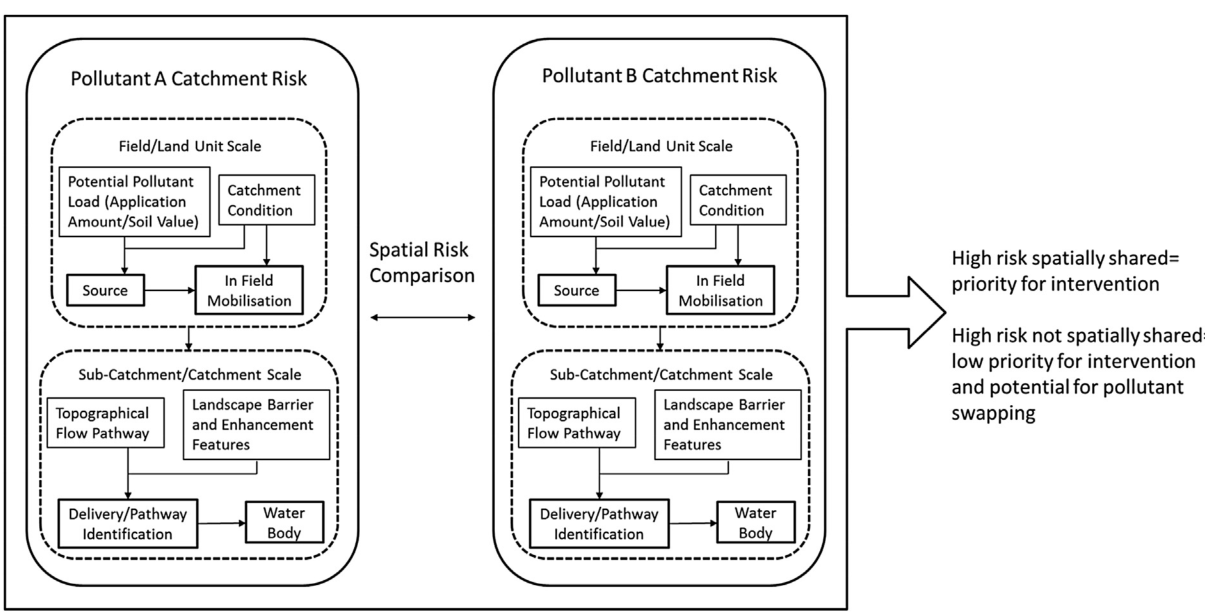

Fig. 2. The CaRPoW Framework. Risk is defined within the three modules for pollutant A and Pollutant B so that risks can be compared overall and between components. Areas that have shared high risk between different pollutants are prioritised for intervention.

risk component and the pollutants mitigated.

It is also important to be aware of pollutants that do not have spatially consistent risk as there may be potential for pollutant swapping. Although CaRPoW does not explicitly incorporate intervention effectiveness i.e. how risk changes after intervention implementation, it is important for the end user to make assessments of where potential pollutant swapping might occur when selecting interventions for one pollutant. For example if a change in land use is the intervention deemed best for a certain field it is important for the end user to judge if this will increase the risk for another pollutant. This is particularly prevalent for pesticides where changing from one crop to another may lead to product substitution. Overall the framework provides the end user information on the potential pre-conditions of multiple pollutant risk, upon which decisions about the most appropriate intervention in a particular area can be made.

4. Discussion – Is CaRPoW fit for purpose?

4.1. Benefits and potential uses of CaRPoW

A key advantage of the CaRPoW approach is that it provides the end user (a water company), more insight into their drinking water supply areas. Where catchments are large, heterogeneous and water is abstracted from a river system it is often difficult for water companies to ascertain the catchment processes that dominate pollutant risks (Spiller et al., 2013).

For example Scottish Water is currently implementing an agri-envrionment scheme in the River Ugie catchment in the North East of Scotland in order to reduce pesticide concentrations in abstracted river water. The catchment covers an area of approximately 330 km^2, has a mixture of arable and grassland farming and approximately 400 different farm holdings which poses challenges for water company staff administering the scheme. The catchment size and number of farmers makes it extremely difficult for Scottish Water staff to conduct whole-catchment walkovers to gain the comprehensive spatial understanding of risks needed to prioritise interventions from the many land owners applying for finance from the scheme. This is further highlighted by Spiller et al. (2013) who found that water companies in England and Wales were more likely to implement catchment management schemes if catchments were small, relatively homogenous and the risks are "easy" to identify. By using CaRPoW, water companies can gain a better understanding of how and where catchment management may contribute to reducing water quality risks in the larger more heterogeneous catchments that they previously may have overlooked.

Although CaRPoWs main purpose is to be used as a modelling framework, it can also be used in a purely qualitative manner by industry experts to conceptually frame pollutant risks into the three components when initiating catchment management schemes. The benefits of disaggregating risk into its constituent components in a holistic, systems-based way cannot be gained from other frameworks and models that just define overall risk.

The framework has potential uses in addressing other key catchment management based questions. A big uncertainty in catchment management is where both short to longer term future risks may arise (Pal et al., 2010). This is particularly relevant to pollutants such as pesticides where the location of sources is likely to vary spatially and temporally depending on crop rotations (Balderacci et al., 2008) or changes in crop profitability associated with climate, agronomic or economic change. The framework enables the user to make assumptions, incorporate knowledge gathered from farmers and agronomists, or implement land use/cropping scenarios to predict risk. By having a better understanding of future catchment risks, water companies should be able to plan water abstraction regimes more effectively.

4.2. Potential limitations of CaRPoW

As with any framework or approach, the limitations of CaRPoW should be clearly addressed and communicated. One such limitation is the uncertainty associated with the lack of an accepted and cohesive theory of hydrological connectivity which forms the basis of the delivery component. Bracken et al. (2013) highlight this succinctly in their review of five different approaches to investigating hydrological connectivity (soil moisture connectivity, flow process connectivity, terrain connectivity, connectivity modelling and indices of connectivity), that are all influenced by different conceptual understandings. There is also much to be said about the difference between structural connectivity which is more easily represented in spatial modelling approaches and the more dynamic functional or process-based connectivity which looks at temporal variance in connectivity which is less understood and thus more difficult to model (Bracken and Croke, 2007; Bracken et al., 2013).

The capabilities of CaRPoW to identify where sub-catchment scale interventions should be prioritised in small, homogenous catchments, such as in parts of Scotland and Northern England where drinking water is abstracted from upland reservoir systems with water colour issues, are likely to be limited. Such catchments are often fed by comparatively small hydrologically 'flashy' catchments, with homogenised moorland land uses, peat soils and extensive agricultural drainage ditch networks. Previous modelling studies have demonstrated that these catchments are high risk to water colour as a whole when compared against other catchments (e.g. Aitkenhead-Peterson et al., 2007; Grayson et al., 2012), but there is a dearth of studies that investigate spatial risk within these catchments.

5. Conclusions

In the face of deteriorating raw water quality from a number of diffuse pollution pressures, water companies have started to adopt catchment management interventions for the provision of clean drinking water. Catchment heterogeneity dictates that supply catchments are a mosaic of different land uses, soil typologies and hydrology making it difficult for water companies to ascertain the components and spatial nature of pollutants risks. Thus for interventions to be effectively targeted, conceptual frameworks are required that are able to assess the risks of the multitude of pollutants that must be removed from raw drinking water. We demonstrate that catchment risk from pollutants of concern to the water industry can be split into three constituent components of risk (Source-Mobilisation-Delivery). Highlighted key linkages between different pollutants present opportunities for shared spatial risk and therefore multiple benefits from interventions.

Criteria were developed with water industry catchment management professionals for a new conceptual framework that can uniquely be used to identify pollutant risk, compare risks between different pollutants of water-industry concern and select interventions according to the main components of risk. The Catchment Risk to Potable Water (CaRPoW) framework was specifically created for the water industry to split the components of pollutant catchment risk into Source-Mobilisation-Delivery at field-to-catchment scales. Although modular modelling methodologies are unique for each pollutant their outputs can be compared to assess where spatial risk is shared, under current or future conditions. Once the highest risk fields for multiple pollutants are defined, the dominant components of risk can be ascertained and cross referenced against an inventory of interventions to determine the potentially most suitable intervention. CaRPoW provides a valuable, transferable framework for water utilities to better understand the linkages between a range of pollutant risks in their water supply catchments and hence make more informed decisions on financing interventions.

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