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A conceptual model for the analysis of multi-stressors in linked groundwater–surface water systems

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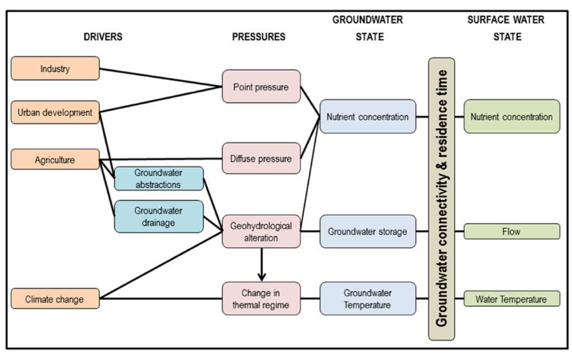
HIGHLIGHTS

- A framework is proposed to analyse stressors in groundwater-surface water systems.
- This is the first application of the DPSIR scheme to groundwater systems.
- Groundwater can act as a medium for the propagation of stressors to surface water.
- Groundwater can buffer the effect of stressors in time and space.
- A need for more ground- and surface water temperature data is identified.

GRAPHICAL ABSTRACT



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ABSTRACT

Groundwater and surface water are often closely coupled and are both under the influence of multiple stressors. Stressed groundwater systems may lead to a poor ecological status of surface waters but to date no conceptual framework to analyse linked multi-stressed groundwater – surface water systems has been developed. In this paper, a framework is proposed showing the effect of groundwater on surface waters in multiple stressed systems. This framework will be illustrated by applying it to four European catchments, the Odense, Denmark, the Regge and Dinkel, Netherlands, and the Thames, UK, and by assessing its utility in analysing the propagation or buffering of multi-stressors through groundwater to surface waters in these catchments. It is shown that groundwater affects surface water flow, nutrients and temperature, and can both propagate stressors towards surface waters and buffer the effect of stressors in space and time. The effect of groundwater on drivers and states depends on catchment characteristics, stressor combinations, scale and management practises. The proposed framework shows how groundwater in lowland catchments acts as a bridge between stressors and their effects within surface waters. It shows water managers how their management areas might be influenced by groundwater, and helps them to include this important, but often overlooked part of the water cycle in their basin management plans. The analysis of the study catchments also revealed a lack of data on the temperature of both groundwater and surface water, while it is an important parameter considering future climate warming.

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1. Introduction

Europe's groundwaters and surface waters are affected by multiple anthropogenic stressors (Hering et al., 2014) which are having an impact on their status. For example, approximately 20% of Europe's groundwater bodies have a poor chemical status, while about 50% of the surface water bodies have failing ecological statuses (European Environmental Agency, 2012). Groundwater and surface water are not separate components of the hydrological system, rather they are linked and interact over a wide range of physiographic and catchment settings (Winter et al., 1998; Woessner, 2000; Sophocleous, 2002; Dahl et al., 2007). Consequently, the use and development of or contamination of one or other resource can have an effect on the other component of the system (Sophocleous, 2002). Many aquatic ecosystems in lowland streams are dependent on a supply of groundwater (Brunke and Gonser, 1997; Hatton and Evans, 1998; Power et al., 1999; Wriedt et al., 2007) and together with specific terrestrial ecosystems are referred to as Groundwater Dependent Ecosystems (GDEs) (Hancock et al., 2005; Kløve et al., 2011). Because groundwater-surface water (GW-SW) systems are often so closely coupled, stressed groundwater systems may lead to a poor ecological status of surface waters (Kløve et al., 2011). Much research has already been undertaken on the effect of stressors on surface waters (e.g. Feld and Hering, 2007; Stendera et al., 2012; Nõges et al., 2015; Piggott et al., 2015; Baattrup-Pedersen et al., 2016; Schülting et al., 2016). And although a significant body of research has been developed over the last 50 years or so related to a wide range of aspects of GW-SW interactions – in particular the implications for ecological functioning of the riparian zone (Fleckenstein et al., 2010), Sophocleous (2002) identified the following, still unresolved, research challenge: how to better understand the environmental impacts of multiple processes that affect both groundwater and surface water across multiple spatio-temporal scales. In the same paper, Sophocleous (2002) cited a conceptual model of Brunke and Gonser (1997) who diagramatically illustrated how human induced pressures from contamination, land-use practices and hydro-engineering impacted on one specific GW-SW interaction, colmation - the clogging of streambed sediments, and the ecological consequences. Despite this intial problem-specific example, to date no comprehensive conceptual framework has been developed to analyse linked stressed GW-SW systems. The objective of this paper is to address that issue by proposing a framework to help analyse the effect of groundwater on surface waters in multiply stressed systems. This will be illustrated by applying it to four European catchments, the Odense, Denmark, the Regge and Dinkel, Netherlands, and the Thames, UK, and by assessing its utility in analysing the propagation or buffering of multi-stressors through groundwater to surface waters in these catchments.

Here we hypothesise that groundwater affects surface water in a stressed system in two ways: it enables the propagation of stressors spatially and in time through catchments towards surface water, and in addition it acts as a buffer to stressors as they pass through the terrestrial water cycle to surface waters and adds time lags and attenuates stressor signals (in a manner similar, for example, to the attenuation and lagging of naturally occuring droughts in the terrestrial water cycle, Van Loon, 2015). Groundwater functions as a connection between a catchment and connected streams, for example by transmission of time varying heads or by advection and diffusive transport propagating a range of potential stressors towards surface waters. This way, a stressor located somewhere in a GW-SW connected catchment may have an impact on the surface water downstream, even without any direct connection via the surface. However, groundwater may also buffer the effect of stressors as it yields a 'mean' environmental flow and buffers chemistry and temperature in time and space. Streamflow is a mixture of water from different flow routes: overland flow, flow through shallow groundwater including subsurface drains, and deep groundwater flow which have different travel times. The contribution of groundwater to streams and rivers is spatially and temporally heterogeneous, and changes from upstream to downstream (Modica et al., 1997; Gkemitzi et al., 2011). The buffering of stressors by groundwater could mean that groundwater fed surface waters are more resilient to stressors than surface water without a groundwater input.

In order to develop the conceptual framework we focus on three aspects of GW-SW systems, namely the role of groundwater in influencing: streamflow, nutrient chemistry and surface water temperature. Discharge from groundwater is delayed compared to discharge from direct precipitation and overland flow and therefore leads to a more stable streamflow (Smakhtin, 2001). When precipitation infiltrates to groundwater, its temperature quickly equilibrates to around the annual mean when it reaches a depth of generally up to several meters. This is for instance a temperature of 10–11 °C for the Netherlands (Bense and Kooi, 2004) and circa 9 °C for Denmark (Matheswaran et al., 2014). Therefore, as opposed to the seasonally and diurnally fluctuating temperature of surface waters, the direct discharge of groundwater into a stream is characterized by a relatively stable temperature. Seepage of groundwater influences stream temperature though a complex interplay of processes with strong spatial and temporal differences (Conant, 2004; Caissie, 2006). Surface water chemistry is a mixture of the chemistry of all the (groundwater) flow paths it sources from. As such, freshwaters are directly influenced by the quality of groundwater (Rozemeijer and Broers, 2007). Timescales of groundwater flow are important because groundwater with different travel times is characterized by different chemical compositions. The water chemistry is dependent on the flow path and travel time through the subsoil which determine the loading during recharge at source, the chemical interaction with sediments and the time available for chemical reactions.

Following a description of the conceptual framework, the four catchments are briefly described and then each in turn is analysed in the context of the conceptual framework. The framework is then used to compare the drivers, pressures and selected abiotic states between the four catchments. Stressor interactions, propagation and buffering in the groundwater compartment are discussed. Finally, the implications for ecosystem status, management options and needs for future monitoring are considered.

2. Conceptual framework for multi-stressor analysis of GW-SW systems

We propose that the analysis of multi-stressors in linked GW-SW systems and implications for abiotic (and biotic) status of surface waters in lowland catchments can be facilitated by a variant of the Driver-Pressure-State-Impact-Response (DPSIR) model (OECD, 1993; Svarstad et al., 2008). The DPSIR scheme and variants thereof conceptualize and couple natural-social systems and are used for example in European environmental assessments and various large European funded projects (European Environmental Agency, 1999; Kristensen, 2004) as well as extensively in different fields related to: the terrestrial water cycle; marine (Patrício et al., 2016); coastal (Gari et al., 2015); and, onshore systems (Hering et al., 2014; Lange et al., 2017). The models describe a casual cascade of effects from drivers to pressures on the system, which lead to system states, which have an impact which then precipitate a societal response. This response can be linked back to and affect the drivers, pressures, states or impacts. Multiple feedbacks and linkages can be added to the DPSIR scheme, depending on required detail and complexity and it can thus be used to describe for instance connections in a system under multiple-stress (Hering et al., 2014).

For the purposes of the present analysis, and as a first step, we use the framework and focus on the DPS components, where we only consider the abiotic status of groundwater and surface water. The Groundwater DPS framework is presented in Fig. 1 and covers key drivers, pressures and states, which relate groundwater to surface water. Here we take the abiotic states of surface water as proxies for the ecological status (as described in Grizzetti et al., 2015). The groundwater system functions as a bridge between drivers and pressures on the one hand