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Water and nitrate exchange between a managed river and peri-urban floodplain aquifer: Quantification and management implications

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ABSTRACT

The management of rivers for navigation, hydropower and flood risk reduction involves the installation of in-channel structures. These influence river levels and can affect groundwater flow within hydraulically-connected riparian floodplain aquifers. A comprehensively monitored, peri-urban, lowland river floodplain in the southern United Kingdom was used to explore these dependencies and to examine the implications for the flux exchange of water and nitrate between the river and the floodplain alluvial aquifer. The study demonstrated that rivers maintained at high levels by management structures, result in raised groundwater levels in the adjacent aquifer and complex groundwater flow patterns. Engineered river management structures were shown to promote flow from river to aquifer through the river bed but the majority of the associated nitrate was removed in the hyporheic zone. High-nitrate groundwater recharge to the alluvial aquifer also occurred through overbank flood flows. Across the floodplain, substantial denitrification occurred due to anaerobic conditions resulting from carbon-rich sediments and the shallow water table, the latter linked to the river management structures. An upper limit on the total annual mass of nitrate removed from river water entering the floodplain aquifer was estimated for the study site (2.9×10^4 kg), which was three orders of magnitude lower than the estimate of annual in-channel nitrate flux (1.8×10^7 kg). However, this capacity of lowland floodplains to reduce groundwater nitrate concentrations has local benefits, for example for private and public water supplies sourced from alluvial aquifers. The insights from the study also have relevance for those considering schemes that include the installation, removal or redesign of river management structures, as the resultant change in groundwater levels may have consequences for floodplain meadows and the nutrient status of the aquatic system.

1. Introduction

Floodplains are locations of complex interactions between river water, groundwater and overland flow (Burt et al., 2002). The degree of interaction is dependent on a number of factors, including: the magnitude and direction of the head gradient between river and aquifer; the permeability of the alluvial sediments and the river bed material; and the capacity of the river channel to retain high flows (Sophocleous, 2002). Naganna et al. (2017) provide a comprehensive review of the controls on river bed permeability identifying the importance of the particle size and depth of the bed material, the river channel geometry and upstream sediment supply to the river. Colmation and bioclogging of macropores and associated lower bed permeabilities is more likely to occur in river reaches losing water to adjacent aquifers (Battin and Sengschmitt, 1999; Brunke, 1999; Krause et al., 2007; Younger et al., 1993). Given the range of controlling factors, river bed permeability will be highly spatially variable (Calver, 2001; Irvine et al., 2012). Bed scouring resulting from floods can induce temporal changes in streambed elevation and particle size composition, increasing hydraulic conductivity (Blasch et al., 2007; Doppler et al., 2007; Hatch et al., 2010). Where permeable near surface floodplain sediments occur, Doble et al. (2012) showed overbanking river water can result in substantial groundwater recharge.

The management of rivers for navigation, hydropower and flood risk reduction involves the installation of in-channel structures (Gregory, 2006). These structures are ubiquitous in many countries (Davies and Walker, 1986; Downs and Gregory, 2014). For example, within England and Wales, records from the Government environment regulator, the Environment Agency, accessed in 2014, showed that 17,569 locks, weirs and control gates were located on the 68,755 km of the river network. The operation of engineered river management structures disrupts the natural interaction of surface water and

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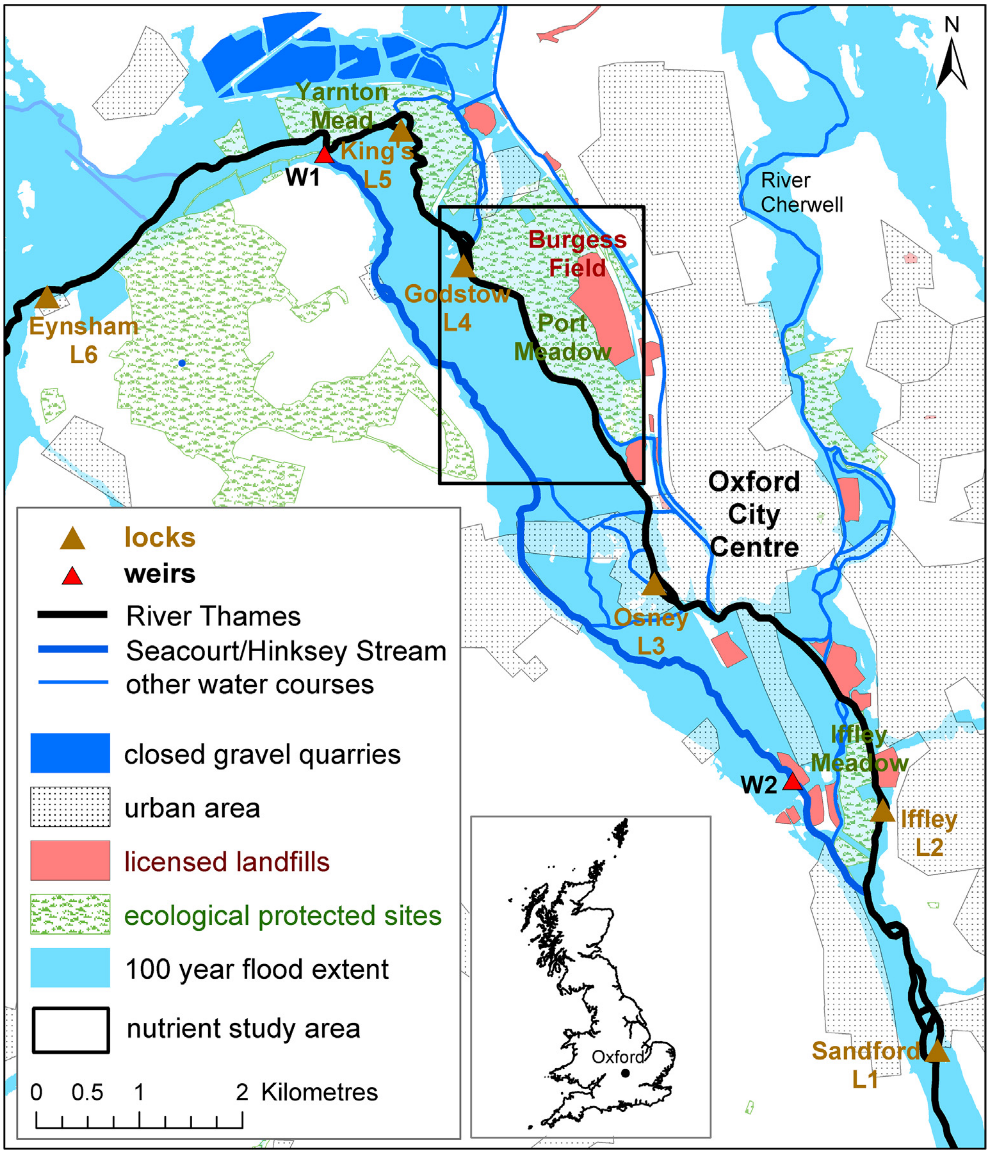

Fig. 1. River Thames floodplain in the vicinity of the city of Oxford, UK. Areas in white are higher ground above the 1-in-100 year flood extent. Contains Ordnance Survey data © Crown copyright and database right (2018).

groundwater. Studies have shown how structures can cause groundwater levels in the associated aquifer to be raised and river reaches to switch from gaining water from the adjacent aquifer to losing water when structures are introduced (Krause et al., 2007; Matula et al., 2014; Lee et al. 2015). The aggregation of fine-grained material associated with lower river velocity upstream of structures and scouring of the river bed downstream, in combination with head gradients that increase and decrease the propensity for colmation, mean bed permeability of rivers under the influence of river structures can be highly variable (Hatch et al., 2010; Naganna et al., 2017). Attempts to address poor river ecology have included the removal of weirs to return the connectivity of river habitats (Gilvear et al., 2013) with likely changes to potentially long-standing groundwater flow patterns and levels.

Groundwater levels are a factor in determining reduction-oxidation (redox) conditions within the subsurface that in turn are a major control on the processing of nutrients (Rivett et al., 2008). Nitrate (NO_3^-), the predominant oxidised form of nitrogen, is readily transported in water and is stable under a range of conditions. However, anaerobic carbon-rich sediments, characteristic of floodplains, have the potential to support large populations of denitrifying bacteria. Shallow water tables help to create these anaerobic conditions, as the aerobic unsaturated zone of the sediments is small (Burt et al., 2002; Kellogg et al., 2005). The rate of denitrification increases with organic matter (OM) content towards the soil surface (Burt et al., 1999) and there is a ready supply of OM to floodplains through inundation by sediment-laden river water. Pinay et al. (2000) found a significant relationship between denitrification rates in floodplain sediments and their texture; highest rates were measured in fine-textured soils with high silt and clay content. These finer-grained floodplain sediments are often found at the surface, as a result of historical clearance of natural vegetation and increased agriculture upstream (Macklin et al., 2010).

The hyporheic zone interface between river and groundwater (Burt et al., 2013) is also a hotspot for nutrient processing (Antiguedad et al., 2016; McClain et al., 2003). Exchanges of water, nutrients, and OM here occur in response to variations in discharge and bed topography and porosity (Boulton et al., 1998). Upwelling groundwater can supply stream organisms with nutrients while downwelling stream water can provide dissolved oxygen and OM to microbes and invertebrates in the hyporheic zone. The improvement to water quality resulting from the actions of the hyporheic zone are the basis of river bank infiltration schemes (Hoehn, 2002) and water sourced from such schemes can provide a large proportion of public groundwater supplies (Ascott et al.,