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Connecting large-scale atmospheric circulation, river flow and groundwater levels in a chalk catchment in southern England

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SUMMARY

Groundwater is an important water resource and globally it represents the largest distributed store of freshwater. In southern England, groundwater is a major source for public water supply, and many aquifers have recently experienced both extreme low and high groundwater levels. In this paper, we use observations of precipitation, river discharge and groundwater levels (1964–2010) and an atmospheric reanalysis to explore the large-scale climate patterns preceding the nine highest and lowest March river discharge and groundwater levels in the chalk catchment of the River Lambourn (Berkshire Downs, southern England). Peak monthly precipitation is shown to occur from October to January, while the highest river discharge and groundwater levels are found from February to April. For high discharge/groundwater levels, composite anomaly patterns of the mean sea level pressure show a stronger than average pressure gradient across the North Atlantic Ocean, with enhanced water vapour transport across southern England. For the lowest discharge/groundwater levels, a blocking high pressure system is found across the British Isles deflecting storms and precipitation to the north. Significantly, the intra-composite variability suggests that different sequences of atmospheric states may lead to high and low discharge/groundwater events.

1. Introduction

Groundwater is an increasingly important water resource: globally groundwater represents the largest distributed store of freshwater (Taylor et al., 2013). Groundwater discharge sustains river base flow (Winter et al., 1998) and supports characteristic groundwater-dependent ecosystems (Boulton, 2005; Boulton and Hancock, 2006). In the context of changes in the frequency and magnitude of hydrological extremes, groundwater abstraction has helped sustain human water security during periods of rapid population increase and provided potable water close to population centres and reliable water for irrigated agriculture (Gleeson et al., 2012). These resources are potentially vulnerable to drought events, and particularly rainfall during those periods that account for the majority of groundwater recharge (Marsh et al., 2007; Bloomfield and Marchant, 2013). Conversely in some river catchments, seasonal increases in groundwater levels may lead to prolonged inundation of low-lying land, and groundwater flooding following high recharge (Hughes et al., 2011; Négrel and Petelet-Giraud, 2005) as experienced in southern England during the winter of 2013/14.

Hence, for multiple practical reasons, it is important that groundwater resources are utilised sustainably and in an integrated manner. This requires long-term rates of groundwater abstraction to be, at least, sustained by current recharge (Gleeson et al., 2012), so as to minimise impact on associated groundwater-dependent ecosystems. However, attribution of 'cause and effect' in understanding the behaviour of many groundwater systems is problematic. Notably, there are difficulties disaggregating anthropogenic impacts on groundwater bodies (i.e. abstraction), from 'natural' variability due to climate drivers (Green et al., 2011). These problems are compounded by the likelihood that anthropogenic effects will induce changes in a groundwater body of a similar magnitude to those that could be anticipated by climate variability. Accordingly, more work is required urgently in catchments that are relatively unaffected by groundwater abstraction, to improve our understanding of the atmospheric controls on groundwater storage (and flux rates), and to provide analogues to

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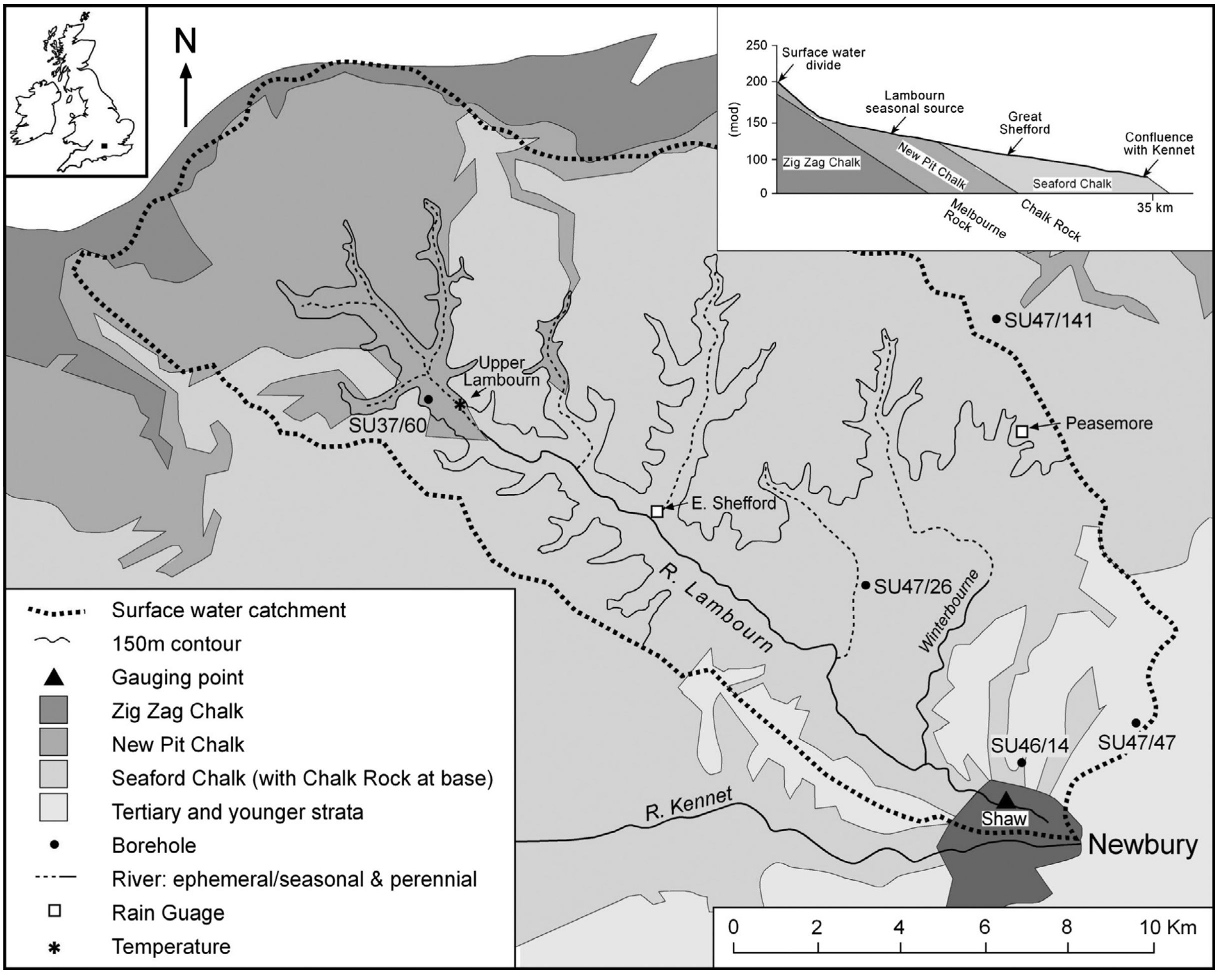

Fig. 1. A map of the River Lambourn basin (after Grapes et al., 2005).

benchmark the 'natural' response in systems where human impacts are significant.

One of the key difficulties when seeking to quantify climate – riverflow – groundwater relationships is accurate estimation of groundwater recharge. Woldeamlak et al. (2007) highlight the sensitivity of groundwater levels in a catchment in North Belgium to recharge, and the implications for increased flood risk. However, recent studies indicate considerable uncertainty in projected estimates for groundwater recharge. Herrera-Pantoja and Hiscock (2008) suggest the likelihood of lower groundwater recharge in England and Scotland, whilst Jackson et al. (2011) project significant variability in future groundwater recharge in southern England (ranging very widely between −26% and +31% of current levels). The significance of this is spatially variable, depending upon the characteristics of individual catchments, as demonstrated by work on the chalk catchment of the River Pang in southern England (Peters et al., 2006; Tallaksen et al., 2009). This research has demonstrated the degree to which drought events can be attenuated and delayed in permeable catchments, and emphasises the importance of catchment properties in determining the variability in drought severity across a catchment.

These uncertainties in estimating UK groundwater recharge are matched elsewhere (e.g. Africa: Kingston and Taylor, 2010; Australia: Crosbie et al., 2011; N. America: Kurylyk and MacQuarrie, 2013) reflecting problems that include the difficulty in quantifying any changes in the seasonality of precipitation, and more particularly in the composition (e.g., duration, intensity, and precipitation type; rain or snow) of individual rain events. In this respect, the simulation of groundwater recharge associated with extreme precipitation is critical; Green et al. (2011) suggest that global climate models currently predict too many days with (1) weak precipitation, and (2) too little precipitation and they conclude that more research quantifying the links between groundwater resources and atmospheric moisture transport is required. For groundwater, the uncertainty of projections is complicated and propagated by translation of the climate signal through the river basin- aquifer system to groundwater levels.

Despite the importance of groundwater, relatively few studies have investigated the linkage between groundwater systems and the large-scale atmospheric circulation (e.g. Anderson and Emanuel, 2008). Commonly river baseflow has been used as a groundwater proxy, although in some catchments fluctuations in groundwater levels have been successfully correlated with low frequency climate patterns (Holman et al., 2011; El Janyani et al., 2012). For example, Holman et al. (2011) employed wavelet analysis to show statistically significant wavelet coherence on multi-annual to decadal time scales between monthly groundwater-level time series (in three boreholes along a northeast to southwest transect across England) and the North Atlantic Oscillation (NAO), East Atlantic Pattern and the Scandinavian Pattern. Periods of high and low climate-groundwater coherence were found to be related to variations in the NAO index (Holman et al., 2011). These studies have used coarse large-scale climate indices, such as the NAO, to investigate climate-groundwater connections. However, studies of European precipitation and river flow have shown climate diagnostics with fixed centres-of-actions are unable to