# Linking variations in large-scale climatic circulation and high groundwater levels in southern England

**DAVID A. LAVERS[1,2], DAVID M. HANNAH[3] & CHRIS BRADLEY[3]**
*1 Department of Meteorology, University of Reading, Reading, UK*
david-lavers@uiowa.edu
*2 Walker Institute, University of Reading, Reading, UK*
*3 School of Geography, Earth and Environmental Sciences, University of Birmingham, Birmingham, UK*

**Abstract** Groundwater is a crucial water resource, sustaining ecosystems and providing an essential water source during droughts. In certain geological settings, prolonged high rainfall can generate groundwater flooding, as elevated water tables can lead to rapid stormflow runoff. Herein, we quantify the links between chalk groundwater levels in the Lambourn River basin (a sub-basin of the River Thames) in southern England, and the large-scale climatic circulation. Precipitation, river discharge and groundwater levels from 1964 to 2010 are analysed together with monthly large-scale climate data from the Twentieth Century Reanalysis Project. Results show reasonably strong climate–groundwater connections with a lag time of several months, associated with rainfall transit time through the basin. The patterns uncovered improve understanding of drivers of groundwater level dynamics and provide a basis for strategic water resource planning.

**Key words** hydroclimatology; groundwater; precipitation; river flow; climate; River Lambourn; southern England; Twentieth Century Reanalysis

## INTRODUCTION

Groundwater is a crucial water resource in many parts of the World. It can sustain river/wetland ecosystems and human water needs during dry spells and droughts. In certain geological settings, periods of prolonged high rainfall can generate groundwater flooding while elevated water tables increase the proportion of rainfall that forms stormflow. In a changing climate, with projected increases in the frequency and intensity of hydroclimatological extremes, it is inevitable that there will be implications for groundwater systems.

Despite the importance of groundwater, there is a paucity of research on the linkages between groundwater variability and the large-scale atmospheric circulation. Groundwater levels are known to fluctuate with low frequency climate patterns (Holman *et al*., 2011). For three British borehole sites, 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 and the North Atlantic Oscillation (NAO), East Atlantic Pattern and the Scandinavian Pattern. Periods of high and low climate–groundwater coherence were found to relate to variations in the NAO index (Holman *et al*., 2011).

Past studies have used coarse large-scale climate indices, such as the NAO, to investigate climate–groundwater connections. In this study, we consider variables that are of more direct relevance to groundwater levels, namely atmospheric water vapour transport, winds and pressure fields. By employing composite analyses, the large-scale climate conditions that lead to high groundwater levels and river discharge in the Lambourn basin, a sub-basin of the Thames basin in southern England, are identified to advance the process understanding of groundwater response to hydroclimatological drivers. This research has practical implications for (1) forecasting of groundwater flooding in permeable catchments, and (2) advancing the goal of integrated management of water resources.

## DATA AND METHODS

The mean sea level pressure (MSLP), specific humidity $q$ (in kg/kg), and the zonal and meridional ($u$ and $v$) wind fields (in ms$^{-1}$) at a monthly resolution for 1964–2010 were retrieved from the Twentieth Century Reanalysis (20CR) at a 2.0°×2.0° resolution (Compo *et al*., 2011). As atmospheric moisture transport into a region is essential for precipitation generation and resultant

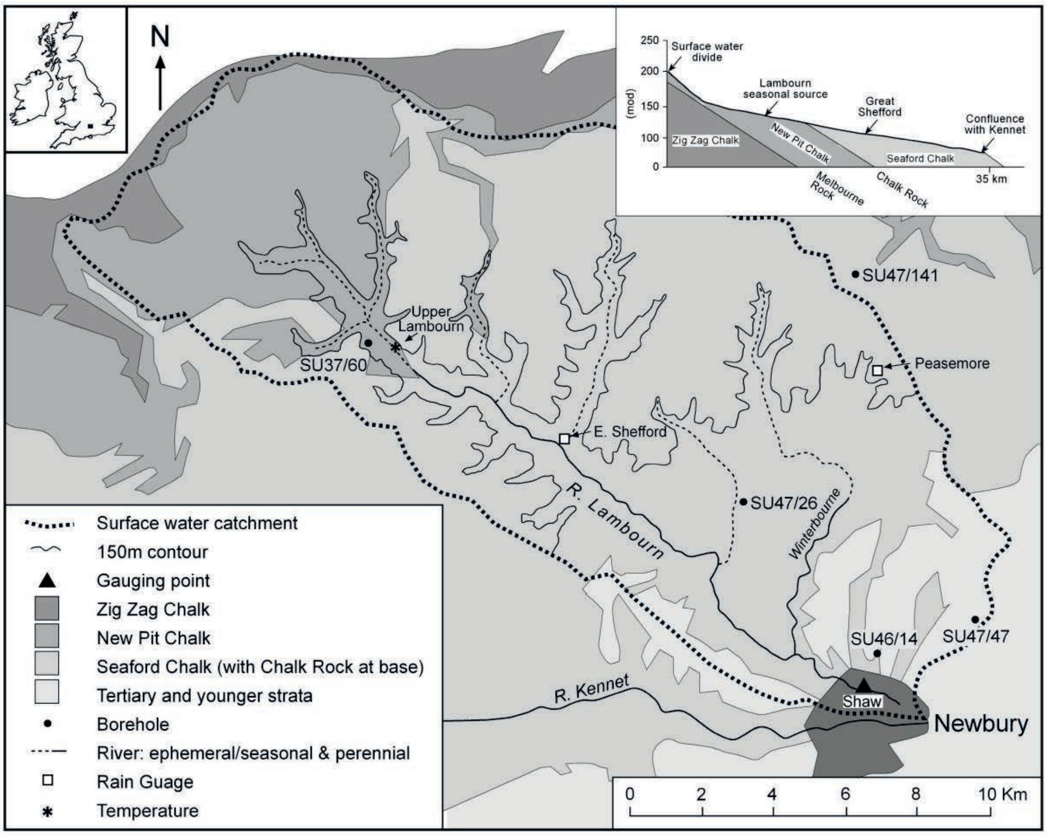


**Fig. 1** A map of the River Lambourn basin (after Grapes *et al*., 2005).

groundwater recharge, we calculated the vertically-integrated horizontal water vapour transport (hereafter IVT) as follows:

$$IVT = \sqrt{\left(\frac{1}{g}\int_{1000}^{300} qu\,dp\right)^2 + \left(\frac{1}{g}\int_{1000}^{300} qv\,dp\right)^2} \quad (1)$$

where $q$, $u$ and $v$ are the layer-averaged variables, $g$ is the acceleration due to gravity and $dp$ is the pressure difference between adjacent pressure levels.

We focused on the River Lambourn, which drains a chalk basin of ~234 km$^2$ in the West Berkshire Downs of southern England (Fig. 1). The basin is largely rural (pasture) with rolling hills that are dissected by a dendritic dry valley network. Mean annual precipitation (at Shaw) is 736 mm, with surface elevations ranging from ~ 250 m above sea level (a.s.l.) in the north and northwest to 70 m a.s.l. in the southeast. The basin is underlain entirely by the Chalk formation, which dips at a shallow angle to the southeast. The Lambourn catchment is relatively unaffected by groundwater abstraction and, as such, is listed as a "benchmark catchment" by the UK National River Flow Archive (NRFA). The basin has been studied intensively during: (1) the Thames Groundwater Scheme (1967–1976), and (2) the UK Lowland Catchment Research (LOCAR) programme (2000–2006) (Grapes *et al*., 2005; Griffiths *et al*. 2006; Butler *et al*., 2012).

A surrogate index of mean basin groundwater levels was generated for 1964–2010 as the mean of groundwater levels observed manually at the five boreholes indicated in Fig. 1. In most years groundwater levels exhibit a strong seasonal cycle reflecting the timing and magnitude of groundwater recharge. Monthly basin-averaged precipitation and daily river flows were retrieved from the NRFA from 1964 to 2010 (46 years); a monthly river flow series was derived from the latter from the gauge at Shaw spanning the period (1964–2010). Herein, we regard the start of the water year as September (following Bower *et al*., 2004), since significant precipitation in September may eradicate soil moisture deficits that develop during the summer.

As extreme events are of most socio-economic interest, the focus herein is on the highest river flows/groundwater levels. The top nine years for a particular month for both river discharge and groundwater levels were selected relating to approximately the 80th percentile (Kingston *et al.*, 2007). The monthly atmospheric fields corresponding to these high years were used in a composite analysis. The composite analysis has the benefit of considering nonlinear associations, as well as being easy to interpret. An anomaly composite analysis was undertaken, which entailed subtracting each of the nine atmospheric fields from the long-term average (1964–2010), and then averaging the anomaly fields. These anomalies highlighted those departures from the climatological average that led to the extreme events.

## RESULTS AND DISCUSSION

### Monthly precipitation, discharge and groundwater level variability

Boxplots of monthly precipitation, discharge and groundwater level are shown in Fig. 2 (a), (b) and (c), respectively. Climatologically, monthly precipitation totals tend to peak in winter, and is followed by the highest discharge and groundwater level in March or April. Although there are likely to be longer residence water stores than 2–3 months in the Lambourn, this time lag generally reflects the time taken for recharge waters to pass through the basin. As the upper-quartile of March discharge and groundwater level exceeds that of April, and because March is typically the end of the recharge season, hereafter, our analysis focuses on March as the target month and the large-scale circulation leading up to this time.

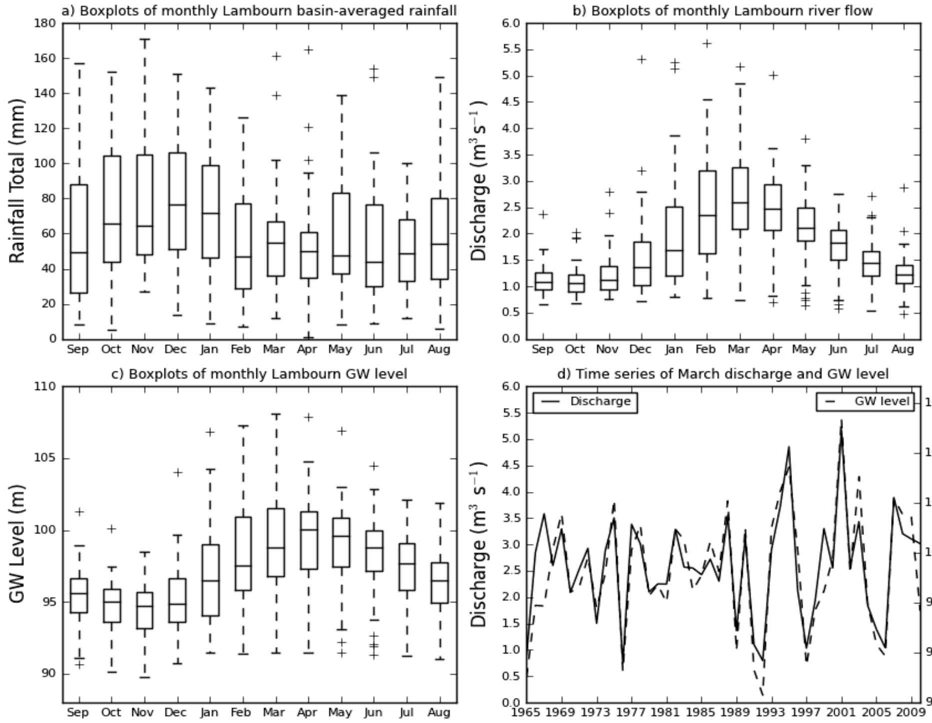


**Fig. 2** Boxplots of monthly (a) rainfall, (b) river flow, (c) groundwater (GW) levels, and (d) time series of March discharge (solid line) and groundwater levels (dashed line) for the river Lambourn basin. (The crosses in panels (a)–(c) represent values outside 1.5 multiplied by the interquartile range.)

### Composite analysis of the top nine March groundwater events

Figure 3 shows the concurrent and lagged composites of the MSLP and IVT anomalies for the top nine March groundwater levels. During September and October (Fig. 3 (f) and (g)) a lower than average pressure was situated near (or over) the British Isles leading to average/above average moisture transport into southern England. From November to March (except February), there was a larger than average pressure gradient across the North Atlantic Ocean, as shown by the MSLP contours, and above average IVT into southern England. The 250 hPa wind anomalies reveal a stronger than average zonally-oriented wind that was located over, or to the south of, the British Isles (not shown). In these regions, extratropical cyclones would have formed and travelled towards Britain along storm tracks, with the poleward transport of heat and moisture on synoptic time-scales taking place within the storms' warm conveyor belt and atmospheric river (Lavers *et al*., 2011, 2012). Broadly speaking, the climate patterns associated with the top nine peak discharges and groundwater levels are similar, indicating a consistent hydroclimatological response.

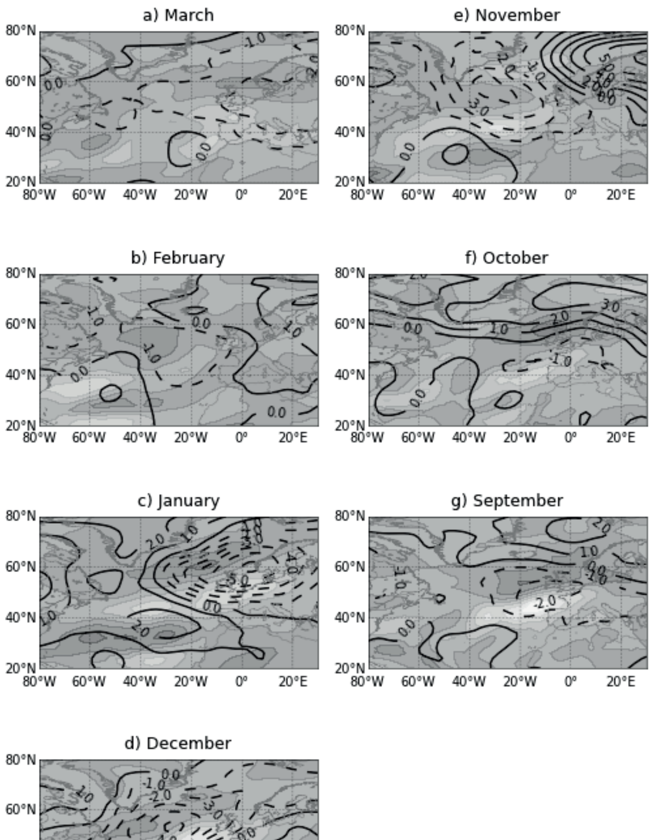


**Fig. 3** Composite monthly mean anomaly fields of the IVT (in kg m$^{-1}$ s$^{-1}$) and MSLP (contours; in hPa) before the top nine March groundwater levels.

## CONCLUSIONS

This study aimed to quantify links between groundwater levels and the large-scale climatic circulation for the Lambourn River basin in southern England. Results show that the highest groundwater levels generally occur in March or April at the end of the winter recharge season. Reasonably strong climate–groundwater connections exist in the Lambourn basin, with a lag of several months due to the time taken for rainfall to pass through the permeable basin. Prior to the top nine March groundwater levels, above average water vapour transport occurred over (or near) the basin in six of the seven prior months. The patterns revealed aid the process understanding of the lagged nature of the links between the large-scale climate and groundwater variability, and provide a basis to inform strategic water resource planning given the future availability of reliable seasonal climate forecasts of the large-scale climate patterns.

## REFERENCES

Bower, D., Hannah, D. M. & McGregor, G. R. (2004) Techniques for assessing the climatic sensitivity of river flow regimes. *Hydrol. Processes* 18, 2515–2543. doi: 10.1002/hyp.1479.

Butler, A. P., Hughes, A. G., Jackson, C. R., Ireson, A. M., Parker, S. J., Wheater, H. S. & Peach, D. W. (2012), Advances in modelling groundwater behaviour in Chalk catchments. *Geol. Soc. Sp. Publ*. 364, 113–127.

Compo, G. P., *et al.* (2011) The Twentieth Century Reanalysis Project. *Quarterly Journal of the Royal Meteorological Society* 137(654), 1–28.

Grapes, T. R., Bradley, C. & Petts, G. E. (2005) Dynamics of river – aquifer Interaction along a chalk stream: the River Lambourn, UK. *Hydrol. Processes* 19, 2035–2053.

Griffiths, J., Binley, A., Crook, N., Nutter, J., Young, A. & Fletcher, S. (2006) Streamflow generation in the Pang and Lambourn catchments, Berkshire, UK. *J. Hydrol.* 330, 71–83.

Holman, I. P., Rivas-Casado, M., Bloomfield, J. P. & Gurdak, J. (2011) Identifying non-stationary groundwater level response to North Atlantic ocean-atmosphere teleconnection patterns using wavelet coherence. *Hydrogeology J.* 19, 1269–1278.

Kingston, D. G., McGregor, G. R., Hannah, D. M. & Lawler, D. M. (2007) Climatic controls on New England streamflow, *Journal of Hydrometeorology* 8, 367–379 doi:10.1175/JHM584.1.

Lavers, D. A., Allan, R. P., Wood, E. F., Villarini, G., Brayshaw, D. J. & Wade A. J. (2011) Winter floods in Britain are connected to atmospheric rivers. *Geophysical Research Letters* 38, L23803, doi:10.1029/2011GL049783.

Lavers, D. A., Villarini, G. Allan, R. P. Wood, E. F. & Wade A. J. (2012) The detection of atmospheric rivers in atmospheric reanalyses and their links to British winter floods and the large-scale climatic circulation. *J. Geophys. Res*. 117, D20106, doi:10.1029/2012JD018027.