Journal of Hydrology 530 (2015) 815–828

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Seasonal forecasting of groundwater levels in principal aquifers of the United Kingdom

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ARTICLE INFO

Article history:
Received 29 April 2015
Received in revised form 16 September 2015
Accepted 5 October 2015
Available online 13 October 2015
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief, with the assistance of Emmanouil N. Anagnostou, Associate Editor

Keywords:
Seasonal forecasting
Ensemble forecasting
Groundwater level forecasting
AquiMod
GloSea5

SUMMARY

To date, the majority of hydrological forecasting studies have focussed on using medium-range (3–15 days) weather forecasts to drive hydrological models and make predictions of future river flows. With recent developments in seasonal (1–3 months) weather forecast skill, such as those from the latest version of the UK Met Office global seasonal forecast system (GloSea5), there is now an opportunity to use similar methodologies to forecast groundwater levels in more slowly responding aquifers on seasonal timescales. This study uses seasonal rainfall forecasts and a lumped groundwater model to simulate groundwater levels at 21 locations in the United Kingdom up to three months into the future. The results indicate that the forecasts have skill; outperforming a persistence forecast and demonstrating reliability, resolution and discrimination. However, there is currently little to gain from using seasonal rainfall forecasts over using site climatology for this type of application. Furthermore, the forecasts are not able to capture extreme groundwater levels, primarily because of inadequacies in the driving rainfall forecasts. The findings also show that the origin of forecast skill, be it from the meteorological input, groundwater model or initial condition, is site specific and related to the groundwater response characteristics to rainfall and antecedent hydro-meteorological conditions.

1. Introduction

Often a cleaner and more reliable source of drinking water than surface reservoirs, groundwater aquifers comprise the world's largest freshwater resource and provide resilience to climate extremes which may increase in frequency with future climate change (Alley et al., 2002; Mishra and Singh, 2010; Sukhija, 2008). Under prolonged dry climatic conditions groundwater drought can develop, often characterised by significantly low groundwater levels which persist for months to years (Lanen and Peters, 2000; Marsh et al., 2007). This may lead to the drying up of significant water-bearing wells and the degradation of ecologically important rivers and springs. Conversely, lasting wet conditions can induce anomalously high groundwater levels resulting in persistent flooding, potentially at large economic cost (Huntingford et al., 2014; Pinault et al., 2005; Upton and Jackson, 2011). Proper management of these resources is vital to ensure their sustainability and to reduce the risk and impacts from groundwater level extremes.

One possible way forward is to forecast future groundwater levels so that management strategies can be employed in advance of likely future events. However, these approaches generally require some insight into future weather patterns and an understanding of site-specific hydrogeological characteristics that control the non-linear groundwater discharge response to changes in groundwater levels (Eltahir and Yeh, 1999; Moore and Bell, 1999). This paper attempts to do this by using state-of-the-art seasonal weather forecasts to drive a series of groundwater models to forecast groundwater levels up to three months into the future.

The majority of groundwater level forecasting studies have been conducted using black-box modelling approaches (Jakeman et al., 2006) whereby an empirical relationship between groundwater level time-series and one or more predictor variables is found using an optimization algorithm (Sahu, 2003). Typically, meteorological covariates, including rainfall and temperature, are used because these perturb groundwater recharge fluxes. Flow through the unsaturated zone and saturated aquifer can slow the response of groundwater level to rainfall events (Alley et al., 2002). Accordingly, a suitable characterisation of this lagged response may be sufficient for forecasting future groundwater levels in aquifers, given up-to-date weather data.

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http://dx.doi.org/10.1016/j.jhydrol.2015.10.018
0022-1694/

The most widely used method to characterise the lagged response of groundwater levels to meteorological predictor variables is the non-parametric Artificial Neural Network (ANN), a flexible tool that is able to implement multiple statistical models to replicate patterns in time-series (Maier and Dandy, 2000). Daliakopoulos et al. (2005) used neural networks to forecast monthly groundwater levels in a highly heterogeneous alluvial aquifer in Crete, Greece. Trichakis et al. (2009) also used ANNs to forecast the change in hydraulic head in a complex karstic limestone aquifer in Greece which proved to be accurate up to a 90-day lead time. Taormina et al. (2012) forecast groundwater levels on an hourly time-step for a flashy shallow coastal aquifer in the Venice lagoon and found that they could accurately reproduce groundwater depths for several months ahead. These, along with other studies that have used ANNs (Nourani et al., 2008; Sreekanth et al., 2009; Ying et al., 2014) all show significant forecasting skill months into the future. However, there are two key limitations with these approaches: (i) not all aquifers exhibit a significant lagged response to antecedent weather; and (ii) to forecast more than one time-step ahead these studies used retrospective observed meteorological predictor variables which would not be available ahead of time.

Tsanis et al. (2008) recognised the second issue and adapted the work of Daliakopoulos et al. (2005) to include a precipitation projection model which, if used in combination with seasonally averaged temperature data, could simulate groundwater levels up to 30 months ahead, achieving a $R^2 > 0.9$. It should be noted, however, that it is likely that this high correlation score largely reflects the model's ability to capture a downward groundwater level trend induced by steady abstractions in the dry season. Even so, it does demonstrate the possibility of using meteorological forecasts to extend the lead time of real-time groundwater level projections.

Alternative black box methods such as support vector machines (Behzad et al., 2010; Suryanarayana et al., 2014; Vapnik, 1999; Yoon et al., 2011) and wavelet decompositions (Adamowski and Chan, 2011; Maheswaran and Khosa, 2013; Partal and Kişi, 2007) have also been used for groundwater level forecasting in the past with promising levels of skill. Mendicino et al. (2008) took a different approach by using a simple conceptual distributed water balance model to derive average groundwater storage over the most southern peninsular of Italy, the outputs of which were used to derive a groundwater drought index. They found that due to the persistence of low groundwater levels in the summer months, droughts could be forecast months prior to their occurrence based on model simulations of the current groundwater storage.

While these studies have shown some skill, the relative infancy of groundwater level forecasting science becomes apparent when compared to the abundance of studies focussed on forecasting other hydrological variables such as river discharge for flood forecasting (see Cloke and Pappenberger (2009) and Cuo et al. (2011) for two comprehensive reviews of these applications). Here, forecasters are not afforded the luxury of long response times to prior weather patterns. At the catchment scale, river flow response time to rainfall is typically of the order of minutes to hours. As such, forecasters drive their hydrological models with medium-range weather forecast products from numerical weather prediction (NWP) centres, which typically offer lead times of 3–15 days. These extended lead times may allow water resource managers and contingency planners to implement mitigation strategies in advance of extreme events. Of course, the benefit of increased lead time comes at a cost; namely that these meteorological products are inherently uncertain due to the non-linear, chaotic nature of the atmosphere (Lorenz, 1963). In response, river flow forecasters now adopt probabilistic methodologies that incorporate this uncertainty rather than relying on a single deterministic forecast. A popular approach that couples probability with determinism is ensemble forecasting (Lewis, 2005) whereby a number of deterministic weather forecasts with differing initial conditions are used to drive the hydrological model. If these realisations are assumed independent and of the same random process, it is possible to assign probabilities to the occurrence or exceedance of given flow thresholds. This probabilistic, ensemble-based approach provides more consistent and skilful outlooks from which users can manage risks more effectively (Addor et al., 2011; Buizza, 2008). One may also cascade other uncertainties, such as those associated with the hydrological model parameterisation, through the forecasting system (Beven, 2006; Pappenberger et al., 2005; Zappa et al., 2010, 2011). A well established approach for this is the Generalised Likelihood Uncertainty Estimation (GLUE) method (Beven and Binley, 1992, 2013), whereby an informal likelihood function is used to weight an ensemble of behavioural models. It should be noted, however, that due to the computational burden, such approaches for real-time hydrological forecasting applications are still not widely used today.

The response of groundwater levels to rainfall generally operate on longer time scales (days to months) than river flows. As such, strategies to mitigate an imposing groundwater drought, for example, can only be properly formulated with a good understanding of the likely future groundwater levels over a similar time scale. Here, longer-range weather forecasts on the scale of months would be required, like those produced by the latest version of the Met Office global seasonal forecast system (GloSea5) which are now showing increased skill up to a three month lead time (Scaife et al., 2014). To date, however, the majority of seasonal forecasting studies have been undertaken by the river flow forecasting community. Yossef et al. (2012) investigated the potential for forecasting monthly and seasonal river flow extremes in 20 large river basins around the world by driving the global hydrological model, PCR-GLOBWB (Sperna Weiland et al., 2010) with observed meteorological forcing data. They found that they could capture observed flood and drought events given skilful meteorological inputs. More recently, Svensson et al. (2015) used GloSea5 seasonal rainfall forecasts to drive a 1 km resolution water balance model (Bell et al., 2013) and forecast winter (December–January–February) river flows across the UK. The forecasts correlated with observed winter river flows with a median correlation score of 0.45. They also found a clear geographical contrast in the source of predictability whereby the initial condition was the strongest source of predictability in the more permeable, baseflow-dominated catchments of south-east England, and the skill was much more dependent on the meteorological forcing data for the flashy catchments in the north-west of Great Britain. The role of river flow response characteristics on seasonal forecast skill was also found to be important for global seasonal river flow forecasting by Yossef et al. (2013). Indeed, contrasting response characteristics to rainfall can also be found in groundwater level time-series (e.g. see the work of Bloomfield and Marchant, 2013), and these are likely to influence the sensitivity of groundwater level forecasts to the meteorological forcing data.

To summarise, skilful forecasts of groundwater levels would provide useful information to water resource managers and contingency planners which could help to mitigate hazards such as groundwater flooding and drought, both of which can lead to social, economic and environmental degradation. Experience gained from the river flow forecasting community shows that skilful ensemble hydrological forecasts can be generated using driving data from medium-range NWP models. However, because aquifers generally respond to prevailing weather patterns over a number of months, the insight gained over a 15-day lead time may be small. This has led most studies to rely on the lagged response of groundwater levels to past weather patterns to make forecasts. However, it may be possible to extend the skilful forecast lead time using