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Propagation of drought in a groundwater fed catchment, the Pang in the UK

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Abstract Regional drought characteristics, such as the area covered by drought and the total deficit over that area, are important measures of the severity of a drought event. Gridded, monthly data from the Pang catchment, UK, are analysed here to study the spatial aspects of the drought as it propagates from a meteorological drought, through a drought in the groundwater system and finally appears as a drought in discharge at the catchment outlet. Drought events are derived separately for each grid cell and variable (rainfall, recharge and hydraulic head) using the threshold level method, and combined to yield regional or catchment-specific drought characteristics. The results demonstrate the catchment control in modifying the drought signal from a series of short duration droughts in rainfall covering large parts of the catchment, through fewer and longer droughts in groundwater recharge, head and discharge. The most severe hydrological droughts in the period 1961–1997 occurred in 1975–1977 and 1991–1992. The average area covered by drought is smaller for groundwater recharge than hydraulic head. Hydraulic head and discharge exhibit similar drought behaviour, which can be expected in a groundwater fed catchment.

Key words regional drought characteristics; hydrological drought; groundwater; rainfall; spatial aspects; Pang catchment, UK

INTRODUCTION

Drought is regional in nature and unlike flood its impacts are not limited to the river network and its direct neighbourhood. Drought affects all components of the water cycle as it develops from its origin as a meteorological drought through a deficit in soil moisture, reduced groundwater recharge and levels, and finally shows up as a low streamflow or dried-up river. Regional characteristics, such as the area covered by the drought and the total deficit over that area, are thus important measures of the severity of the event. An early warning system for drought is seen as an important measure for mitigation or adaptation to the impact of drought. Our ability to forecast seasonal drought depends on the potential to link large-scale climate drivers to the frequency and occurrence of drought in the river basin. This requires knowledge about the temporal and spatial development of drought causing processes both in the climate and the hydrological system. In this study focus is on the hydrological system, namely how the spatial aspects, i.e. regional drought characteristics, of a meteorological drought (deficit in rainfall) is propagated in the hydrological cycle to appear as a drought in groundwater recharge, hydraulic head and discharge. The detailed analysis is done using data from the Pang catchment in the UK.

A general approach for estimating regional drought characteristics is through stochastic modelling of monthly precipitation as reviewed by Rossi *et al.* (1992). An application, adapted to precipitation as well as streamflow, was presented in Hisdal & Tallaksen (2003) in a regional study of drought in Denmark. In their work, a procedure based on the severity-area-frequency (SAF) approach was introduced, which allows the probability of a specific area to be affected by a drought of a given severity to be estimated by the derivation of SAF curves. Subsequently, return periods can be assigned to historical events. Regional drought characteristics were calculated based on drought events selected using the threshold level method with time series of gridded monthly data. The threshold level method, which captures both the duration and the severity of a drought event, has proved to be a flexible approach for characterizing various types of drought (Tallaksen & van Lanen, 2004). Gridded data were obtained from interpolated and simulated long time series derived using a combination of Empirical Orthogonal Functions (EOF), kriging and Monte Carlo simulations.

In this study, gridded time series are obtained using interpolated rainfall and simulated groundwater recharge, head and discharge derived from physically-based soil water and groundwater models. SAF curves are not generated due to the limited number of events in the historical time series. Instead observed frequencies of the area covered by drought and the drought duration and deficit over the area are derived. The approach further differs in terms of the spatial scale of the region of interest and variables analysed. Whereas the whole of Denmark was the basis for the development of the methodology, emphasis is here on the propagation of drought in the hydrological system at the catchment scale. Accordingly, one might refer to these as catchment specific, rather than regional drought characteristics. Finally, the results are compared with the spatial distribution of drought in groundwater as presented by Peters *et al.* (2006) in a similar study of the Pang.

CATCHMENT DATA AND METHODOLOGY

The Pang catchment is situated about 25 km south of Oxford and the topographic catchment area is approx. 170 km^2 (Fig. 1). It covers an altitude range from 40 (catchment outlet) to about 230 m a.m.s.l. (surface water divide). The main aquifer supplying water to the Pang is the Chalk aquifer and around two thirds of the discharge is estimated to come from groundwater storage (Peters & van Lanen, 2005). In the south the Chalk is covered by a thick layer of almost impermeable Tertiary deposits with low conductivity, which generates fast shallow subsurface flow. The hydrology of the catchment is simulated using the SWAP model for recharge (Peters, 2003) and the transient MODFLOW model for hydraulic head and groundwater discharge (Peters *et al.*, 2006). The model area is divided into cells with a spatial resolution of 500 m, and the total area (475 km^2) exceeds that of the Pang catchment to allow proper conditions at the boundary of the variable groundwater catchment. In total there are about 1900 cells of which 1089 constitute the Pang catchment. In cells with a low conductivity Tertiary cover, the aquifer recharge is set to a constant low value (~23% of the catchment area). The catchment is separated into five rainfall zones (Peters, 2003), and the models are run for the period 1961–1997 (37 years). The average annual rainfall over the period is about 690 mm and varies little throughout the year. Rainfall is highest in the west (740 mm), where there are slightly higher elevations, and lowest in the northeast (650 mm). Average annual potential evapotranspiration is 520 mm (grassland), and average annual streamflow 120 mm. This rather low streamflow is influenced by groundwater

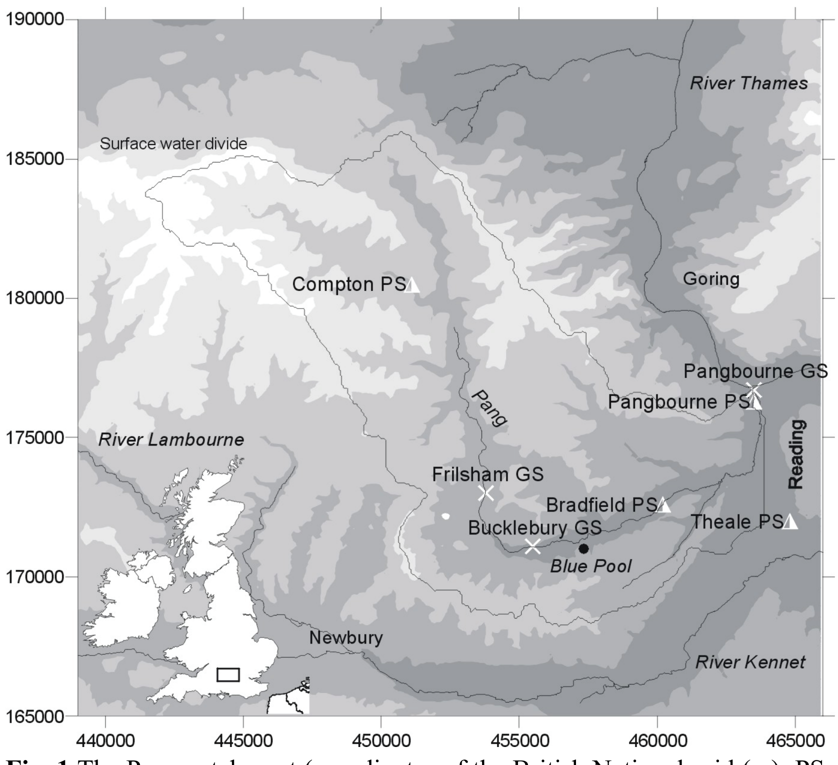

Fig. 1 The Pang catchment (coordinates of the British National grid (m); PS: Pumping station, GS: Gauging station) (from Peters, 2003).

abstractions and water flow to the River Thames during periods of low flow. Simulated groundwater discharge for the Pangbourne gauging station (Fig. 1) is therefore used instead of observed streamflow in the analysis of drought.

Interpolated gridded rainfall is used as input to the SWAP model for simulation of daily recharge. On the basis of catchment characteristics such as soil, land use and rainfall, each cell is assigned to so-called physiographic units. In total 45 combinations are distinguished within the Pang catchment. Daily recharge is calculated for the set of physiographic units (and thus for each cell) for the period 1961–1997 and then aggregated to monthly values. Negative values, representing capillary rise, occur in 119 of the cells. The recharge for each cell is fed into the MODFLOW model (with a time step of three days) to simulate groundwater heads and discharge. These are subsequently aggregated to monthly values.

Drought events are selected from time series of interpolated rainfall and simulated recharge, hydraulic head and groundwater discharge using the threshold level method, which defines drought as periods during which the variable is below a certain threshold level. All events below the threshold are included, i.e. a partial duration series (PDS). Whereas rainfall, recharge and groundwater discharge are fluxes with units [LT^{-1}], hydraulic head is a state variable with unit [L], here mm month^{-1} and metres are used, respectively. The 80 percentile from the duration curve (P80, R80 and H80), is calculated separately for each grid cell and variable (rainfall, recharge and hydraulic head), and then used as a threshold to identify whether a cell is experiencing drought or not. Accordingly, the total area with deficit and the total deficit over that area can be estimated for each variable and month. In this study, the total duration of a drought event (the number of consecutive months where any grid cell is in a drought) and the average area covered by the drought (average over the total duration) are derived for rainfall, recharge and hydraulic head. The (total) deficit volume of a drought event in rainfall and recharge is derived as the sum of the average deficit volume (average deficit over all affected cells) for each month in a drought. The deficit volume in each cell (mm) is standardized with its threshold level (mm month^{-1}) to allow a comparison over the area and between different variables.

Drought in discharge is derived for the time series at the catchment outlet (using Q80 as a threshold level) and standardized similar to rainfall and recharge. This implies that the deficit volumes are given in months for rainfall, recharge and discharge. As hydraulic head is a measure of storage, rather than summing up the deficit in each time step, the average deficit over the grid cells and months (defined as the average deviation from the threshold over the affected area and over the drought period) is calculated. This can also be referred to as the intensity of the drought, which has the unit [L] similar to deficit volume for fluxes. Deficit in hydraulic head is given in metres.

DROUGHT IN THE PANG CATCHMENT

The distribution of *drought duration* is shown in Fig. 2 for rainfall ($\overline{P}_{dur}$ = 1.5 month, N = 77), recharge ($\overline{R}_{dur}$ = 13.8 month, N = 26), hydraulic head ($\overline{H}_{dur}$ = 5.8 month, N = 36) and discharge ($\overline{Q}_{dur}$ = 3.6 month, N = 25). Average values are given in brackets along with the total number of droughts, N. The number of events decreases and the duration correspondingly increases as the drought transforms from a meteorological to a hydrological drought.

For rainfall there are on average two events each year and these are, due to the delay in catchment response, clustered into fewer and longer hydrological droughts. The use of a percentile from the duration curves as a threshold ensures that the same number of days is below the threshold level for all grid cells and variables, but the distribution will be different. The longest duration is found for recharge due to the presence of multi-year events, caused by its cyclic nature. The high seasonality in recharge will normally result in a drought each summer, but during a dry winter it may happen that the recharge does not exceed the threshold and multi-year droughts result. This is clearly seen in the clustering of events for recharge. On the other hand, only the most extreme years show up as multi-year events in hydraulic head (three events) and discharge (one event). For all variables the distribution is skewed to the left with a high number of short duration droughts.

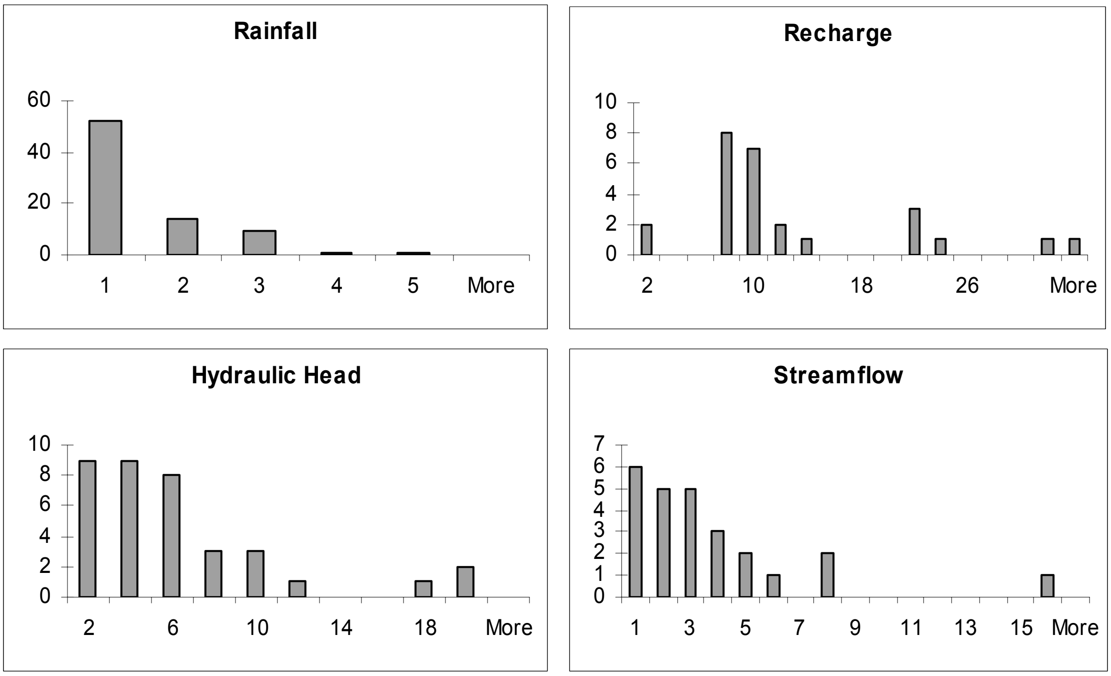

Fig. 2 Drought duration (in *month*) for rainfall, recharge, hydraulic head and discharge (*number of events* is given on the y-axis).

The longest drought lasts from December 1975 to April 1976 for rainfall (5 month, followed by a second drought in the summer of 1976 of 3 months), from May 1988 to April 1994 for recharge (72 month), from June 1991 to December 1992 for hydraulic head (19 month) and from July 1991 to October 1992 for discharge (16 month). The 1975–1976 drought is the second longest drought in discharge (8 month) and recharge (31 month, extending into 1977), whereas for hydraulic head it is less extreme, but a clustering of dry years is found between 1973 and 1977. The severe hydrological drought experienced in 1991–1992 results from a series of smaller rainfall droughts between 1990 and 1991, followed by a major event lasting three months during the winter of 1991–1992. Multiyear events in recharge and head were also reported by Peters *et al.* (2006) for the 1991–1992 drought, although shorter durations in recharge were found, resembling more those of groundwater discharge. The study, which focussed on the spatial distribution of drought duration, did not derive regional or catchment aggregated drought characteristic values.

In Fig. 3 the *average area* covered by drought for rainfall, recharge and hydraulic head is given. Rainfall drought covers, in 43% of the cases, the whole catchment (average area 76%), whereas a maximum coverage of 30 and 75% is observed for recharge and hydraulic head, respectively. The corresponding average values are 16 and 25%. It should be noted that this rather low areal coverage partly stems from the definition of drought duration. As long as one cell is in a drought, the drought continues and consequently, the resultant average area covered can be low, particularly for long duration droughts. For recharge it is further influenced by the proportion of the area (~23%) defined in the model to have a constant low recharge. This area will never experience drought and if left out, an area corrected coverage of 39% (maximum) and 21% (average) results as compared to the original 30 and 16%.

Deficit volume (not shown) has for rainfall a more even distribution over the range of values experienced, but also here a higher frequency of smaller volumes is observed. Recharge, hydraulic head and discharge depict similar patterns in the distribution of deficit volume as compared to duration. Deficit volume averaged over the affected area is for rainfall, $\overline{P}_{vol}$ = 0.43 month (N = 77), recharge, $\overline{R}_{vol}$ = 1.1 month (N = 26) and discharge, $\overline{Q}_{vol}$ = 0.52 month (N = 25). It should be noted that the discharge at the outlet integrates the response over the whole catchment and this value is therefore not directly comparable to the average in recharge deficit (average over the drought affected cells).

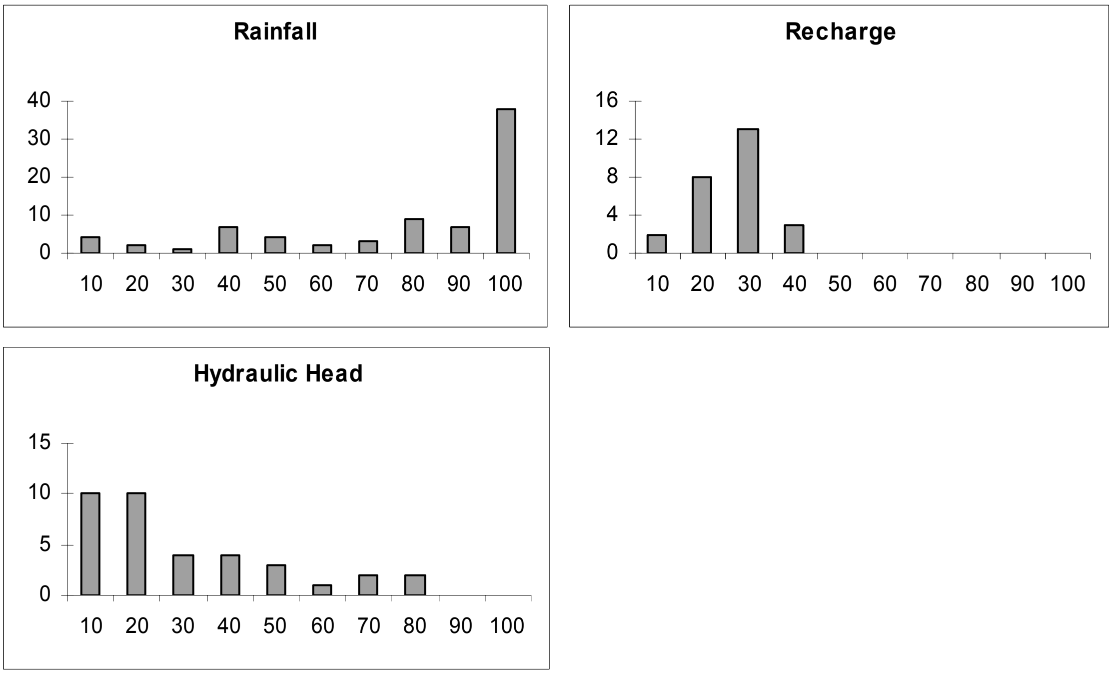

Fig. 3 Average area covered by drought (in *percent*) for rainfall, recharge (area corrected) and hydraulic head (*number of events* is given on the *y*-axis).

DISCUSSION AND CONCLUSIONS

The impact of drought on natural water resources, whether groundwater or streamflow, depends on the climate input as well as the properties of the catchment, as demonstrated in this study. The rather large differences found in drought behaviour (temporal and spatial patterns) as it propagates in the hydrological cycle, stresses the importance of including not only one variable in a study of drought at the regional or catchment scale. Rather the purpose of the study should guide the choice of variables and methods adopted.

This study illustrates the added value of applying regional drought characteristics in analysing the propagation of drought in the hydrological system at the catchment scale. The results clearly demonstrate the catchment's control in modifying the drought signal, from a series of short duration droughts in rainfall covering large parts of the catchment, through fewer and longer droughts in groundwater recharge, head and discharge. The average area covered by drought in groundwater is smaller than for rainfall, and larger in hydraulic head as compared to recharge. The areal coverage is influenced by the way drought duration is defined and, for recharge, also by the size of the area experiencing constant recharge. It is recommended that introducing an additional criterion to the threshold level, namely a critical area, is considered when defining drought events based on a high resolution spatial model (i.e. a drought exists only if a certain percentage of the region or catchment area is in a deficit).

The two most severe historical droughts considering all variables occur in 1975–1977 and 1991–1992, and are most noticeable for hydrological droughts. Multi-year droughts occur more frequently for recharge due to its marked seasonal pattern, but are also observed in hydraulic head and discharge. For recharge, durations of up to six years are observed, and as a result recharge has a markedly longer average duration.

Hydraulic head and groundwater discharge exhibit similar drought behaviour, which can be expected in a groundwater fed catchment like the Pang. Slightly longer durations are obtained for hydraulic head as compared to discharge despite the fact that fewer droughts result for discharge, which partly reflects the higher number of multi-year events for head. Shorter duration droughts in groundwater discharge as compared to hydraulic head were also observed by Peters *et al.* (2006), which used a slightly different approach to the threshold level method, They further found that drought in discharge resembled drought in recharge more than in head and argued that this was a result of the delay and attenuation in the groundwater system. The latter is not confirmed in this study and care should be taken in concluding that the longer durations derived in head is due to the longer response time of the groundwater system as there is an important difference in the type of variables being studied. Hydraulic head represents, similar to reservoir level, a measure of storage. Analogous to the sequent peak method, SPA, which relates the flow below a threshold to the required storage in a period with storage depletion and subsequent filling up (Tallaksen *et al*., 1997), the drought event can be defined to last until the time of maximum depletion, in which case the maximum depletion equals the deficit volume of the event. The SPA method might, however, overlook drought events occurring shortly after a major event, and is therefore not recommended for analysis of PDS (Fleig *et al*., 2006). Definition of drought in a comparative study involving variables of different units will be the topic of a further study, where also long time series will be simulated to derive severity-area-frequency curves. This will allow return periods of historical droughts to be estimated for regional or catchment specific drought characteristics.

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