

## **Propagation of drought in groundwater in semiarid and sub-humid climatic regimes**

**ELISABETH PETERS & HENNY A. J. VAN LANEN**

*Nieuwe Kanaal 11, 6709 PA, Wageningen, The Netherlands*

[elisabeth.peters@users.wvh.wau.nl](mailto:elisabeth.peters@users.wvh.wau.nl)

**Abstract** It is well known that the groundwater system might significantly affect hydrological droughts. So, to investigate drought in groundwater, recharge was simulated for two climatically contrasting regimes (semiarid: Upper-Guadiana (Spain) and sub-humid: Pang (UK)) and used as data for a linear reservoir model to simulate groundwater discharge. The groundwater system is characterized by a reservoir coefficient. The groundwater discharge was simulated for a range of reservoir coefficients for each of the two recharge regimes. For the semiarid regime multi-year droughts occur more often than for the sub-humid regime because the seasonal component in the recharge is much weaker and more irregular. The effect of the groundwater system is mainly to pool erratically occurring dry months into prolonged groundwater droughts for the semiarid regime.

**Key words** drought; groundwater; low flow; simulation; Spain; UK

### **INTRODUCTION**

It is commonly known that different climatic regimes have different sensitivity to *meteorological drought*. Both drought frequency and severity (deficit) are higher for arid and semiarid regions than for sub-humid regions (Pandey & Ramasastri, 2001). The sensitivity to *hydrological drought* (streamflow and groundwater drought) also depends on the physical characteristics of a basin, as they determine the response to the climatic conditions. For streams with a high proportion of baseflow (high BFI), the vulnerability of a region to hydrological drought is largely determined by its hydrogeology because the flow during drought is often mainly derived from underground storage. However, it is still unclear how droughts are influenced by groundwater systems in detail and how the differences in meteorological droughts between different climatic regimes are propagated through the groundwater system. This propagation is investigated in this paper by simulating recharge and groundwater discharge and by analysing the droughts in the recharge and groundwater discharge for two climate types, namely a semiarid climate (Spain) and a sub-humid climate (UK).

### **DATA AND METHODS**

Recharge was simulated from observed meteorological data for two basins in Europe. These are the Upper-Guadiana basin in Spain (1940–1996) and the Pang basin in the UK (1960–1997). The basins are described in Peters *et al.* (2000). The Upper-Guadiana basin (16 000 km<sup>2</sup>) has a semiarid climate with average annual rainfall

varying from 350 to 580 mm year<sup>-1</sup> and potential evapotranspiration reaching about 1000 mm year<sup>-1</sup>. The Pang basin (160 km<sup>2</sup>) has a sub-humid climate with an average annual rainfall of 700 mm year<sup>-1</sup> and an average annual potential evapo-transpiration of around 600 mm year<sup>-1</sup>. For the Upper-Guadiana the recharge was calculated with the SIMPA model (Estrela & Quintas, 1996; Ruiz, 1998). The distributed recharge was calculated for 500 × 500 m cells. For the Pang basin the recharge was calculated with the SWAP model (van Dam *et al.*, 1997) for a limited number of physiographic units, i.e. different combinations of precipitation, soil and land use. For the Upper-Guadiana and the Pang basin a spatially averaged recharge was calculated (Peters *et al.*, 2000).

The groundwater system was simulated using a linear reservoir. The size and delay of the reservoir were characterized by the reservoir coefficient *j* (days). Although the recharge was calculated for two specific basins, the discharge was not simulated for the Upper-Guadiana or Pang basin itself, but for a range of hypothetical basins with a range of reservoir coefficients from 10 to 10 000 days. This implies that the propagation of droughts through the groundwater system was investigated for a wide range of aquifer characteristics for both climatic regimes. The drought events in both the recharge (recharge droughts) and the groundwater discharge (discharge droughts) were defined using the threshold level approach (Yeveyevich, 1967). Drought duration is defined as the period of time when the recharge or discharge falls below the threshold until the threshold is crossed again. The drought deficit is the integrated area below the threshold. The threshold level was determined using the method described in Peters *et al.* (2003), which uses the total deficit below the threshold to determine the height of the threshold.

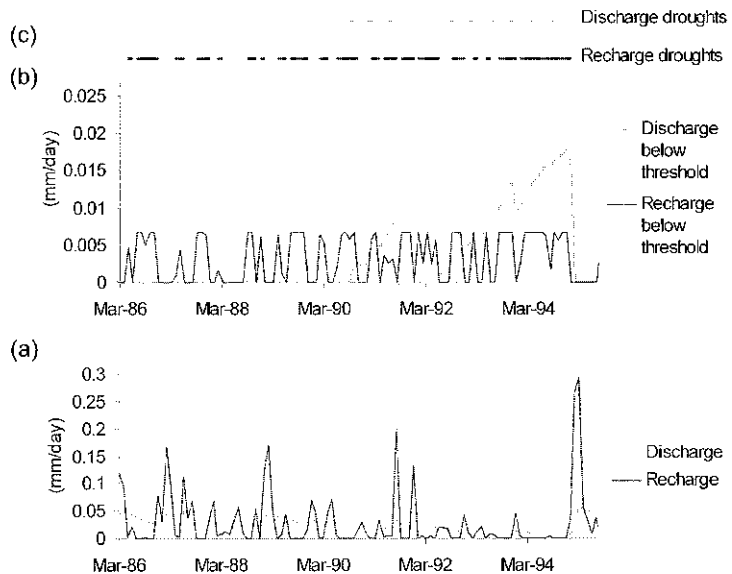


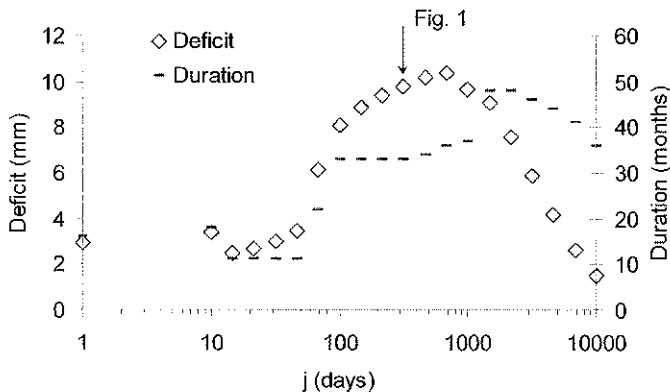
Fig. 1 Recharge, groundwater discharge and droughts in a semiarid region: (a) simulated recharge for the Upper-Guadiana basin and discharge for an aquifer with *j* = 316 days, (b) deviation below the threshold for the recharge and groundwater discharge, and (c) duration of droughts.

## RESULTS

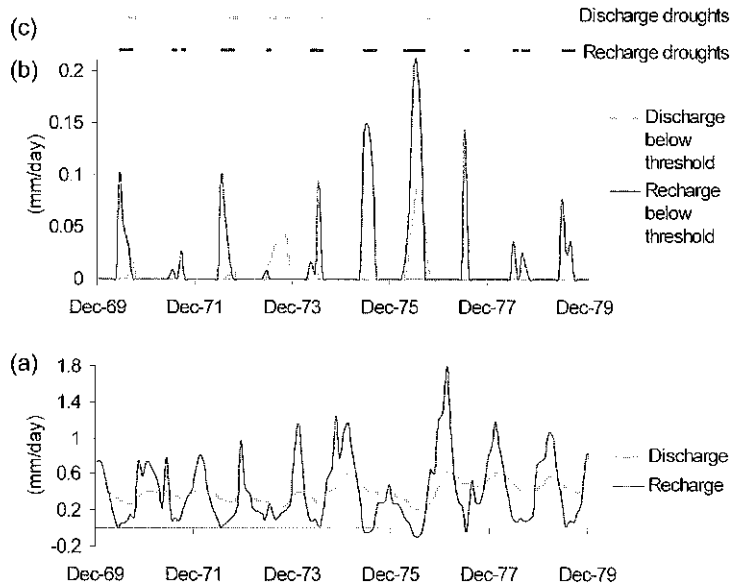
The key to understanding the effect of a groundwater system on droughts is to understand how the delay and attenuation caused by the storage in an aquifer affect the discharge droughts. Figure 1(a) shows the simulated recharge for the Upper-Guadiana basin and the discharge for an aquifer with  $j = 316$  days for 1987 to 1995. As expected the discharge is smoothed and delayed compared to the recharge. Figure 1(b) shows the deviation below the threshold, i.e. when the recharge c. q. discharge is lower than the threshold. For recharge and discharge the threshold was calculated to be  $0.0066$  and  $0.022 \text{ mm day}^{-1}$ , respectively. The recharge below the threshold is bound at the upper end, because the recharge in the SIMPA model concept cannot be smaller than zero. Figure 1(c) shows the duration of the droughts. These figures show a very important additional effect of the propagation through the groundwater system, namely an increased pooling of the droughts. The period from 1988 to 1994 is characterized by a series of years with below average recharge with only one clear recharge drought at the end of 1994. However, it resulted in an extremely severe and prolonged discharge drought.

Figure 2 shows the drought deficit for the major drought in Fig. 1 (1992–1994) for a range of reservoir coefficients. This shows how a range of aquifers with different storage would respond to the same recharge drought. For  $j = 1$  day the deficit of the recharge drought is plotted. The arrow indicates the aquifer with  $j = 316$  days presented in Fig. 1. From the duration it is clear for which values of  $j$  droughts are merged, namely the jumps around  $j = 70$  and  $1000$  days. Thus generally, the amount of pooling increases with increasing reservoir coefficient. For very large  $j$  the discharge drought deficit is smaller because of the attenuation (Peters *et al.*, 2003).

Like Fig. 1, Fig. 3 shows recharge and discharge ( $j = 316$  days) and the deviation below the threshold for the recharge and discharge only now for sub-humid conditions (Pang basin recharge) for the period 1969–1979. This period shows only single-year droughts in both recharge and discharge. In fact, in the total period 1960–1997 only one multi-year drought occurs for the sub-humid climate of the Pang. Because of the



**Fig. 2** Deficit and duration of the recharge drought in 1994 for the Upper-Guadiana basin (for  $j = 1$  day) and discharge drought in 1992–1994 for a wide range of aquifer characteristics. The arrow indicates the aquifer conditions of Fig. 1.



**Fig. 3** Recharge, groundwater discharge and droughts in a sub-humid region: (a) simulated recharge for the Pang basin and discharge for an aquifer with  $j = 316$  days, (b) deviation below the threshold for the recharge and groundwater discharge, and (c) duration of droughts.

strong, regular seasonal component of the Pang recharge as compared to the Upper-Guadiana, pooling of the droughts and thus multi-year droughts are much less common.

Figure 4 shows the deficits of three droughts, namely the droughts in 1972 to 1974, for a range of reservoir coefficients (compare Fig. 2). The whole period 1970 to 1974 showed below average recharge (Fig. 3(a)). However, none of the summers in 1972, 1973 or 1974 showed a large recharge deficit (Fig. 3(b)). But in the discharge for an aquifer with  $j = 316$  days, the 1973 drought formed the fifth largest drought in the period 1960–1997. The 1974 drought shows for  $j < 316$  days the typical behaviour of a short, non-severe drought, which means a lower deficit in the groundwater discharge as compared to the recharge. This is caused by the attenuation in the aquifer and thus the larger the attenuation, the lower the deficit in the groundwater discharge. The 1972 drought basically shows the same behaviour, only for aquifers with  $j = 10$  to 100 days the deficit increases slightly going from recharge to discharge. This increase is the result of the delay caused by the aquifer, which can be understood as follows. In this sub-humid climate, the majority of the recharge occurs during winter and spring. A decrease in recharge during this period does not usually cause a drought in the recharge, because the recharge is still over the threshold. However, due to the delay caused by the aquifer, the decrease in recharge spreads over a longer period and thus affects the discharge during the following summer (low-flow period) (Peters *et al.*, 2003). The 1973 drought shows this effect very strongly, as it is a relatively wet summer in recharge (7 mm more than average) following on a dry winter (57 mm less

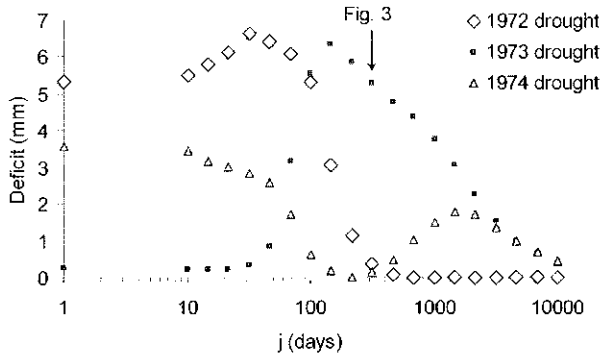


Fig. 4 Deficit of the recharge droughts in 1972–1974 for the Pang basin (for  $j = 1$  day) and discharge droughts in 1972–1974 for a wide range of aquifer characteristics. The arrow indicates the aquifer conditions of Fig. 3.

than average). The relatively large deficit in the discharge drought in 1974 for  $j > 316$  days is also caused by this effect. Because of the less pronounced seasonal cycle in the Upper-Guadiana, this effect is much less clear there.

### CONCLUSIONS

An analysis of droughts in the simulated recharge and groundwater discharge, shows a much stronger tendency for multi-year droughts for the semiarid regime (Upper-Guadiana, Spain) than for the sub-humid regime (Pang, UK). This is caused by the relatively strong, regular seasonal component in the Pang as compared to the Upper-Guadiana. This seasonal cycle has two effects on the discharge droughts. First, it prevents pooling of the droughts and thus the forming of multi-year droughts. Second, it causes a large influence of the recharge in winter (or high flow season) on the discharge drought in the following summer (low flow season), because the effect of the decrease in recharge is delayed. For all cases, the attenuation that results from the storage in an aquifer causes the discharge drought deficits to be small for aquifers with very large reservoir coefficients. So, the major processes influencing the discharge droughts for the semiarid regime is pooling of the droughts and attenuation, and for the sub-humid regime is delay from winter to summer and attenuation.

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