Temporal variability of recharge as an indicator for natural groundwater droughts in two climatically contrasting basins

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Abstract Recharge has been simulated in two European basins, i.e. Upper-Guadiana, Spain (semiarid) and Noor, The Netherlands (temperate, humid). Reservoir theory (Sequent Peak Algorithm) is used to derive natural groundwater droughts from long recharge time series. Such droughts are controlled by weather conditions and not by human activities. They are obviously more severe and last longer in semiarid Europe. The severest drought in the Upper-Guadiana lasted three times longer than in the Noor. Moreover, the droughts do not coincide in both climatic regions. In the Noor basin natural droughts agree reasonably with the groundwater droughts derived from groundwater hydrographs due to the low impact of human activities. In the Upper-Guadiana groundwater abstraction leads to substantial differences between natural groundwater droughts and droughts derived from groundwater levels. Simulation modelling (recharge, groundwater hydrographs) can improve understanding of the impact of weather and human activities, including mitigation measures on droughts.

Key words drought; groundwater; recharge; Sequent Peak Algorithm; temporal variability; modelling; Guadiana (Spain); Noor (The Netherlands)

INTRODUCTION

Groundwater droughts develop slowly but can lead to substantial ecological, social and economic impact (Calow et al., 1999; Vogt & Sonninen, 2000). These droughts are hard to identify as compared to meteorological or streamflow droughts. Groundwater droughts are characterized by low groundwater levels that cause reduced abstraction rates or even drying up of wells, decreased groundwater discharge to wetlands and deterioration of groundwater quality if salt water intrudes (van Lanen & Peters, 2000).

A prolonged period with low recharge is the primary reason for groundwater drought. But, heavy exploitation of groundwater resources can exacerbate or even cause groundwater droughts. The term natural groundwater drought has been introduced to define lack of groundwater recharge caused by weather variability. Induced groundwater drought describes the influence of groundwater abstraction or any other human activities affecting natural groundwater recharge or discharge (e.g. land-use change, excessive land drainage). In this study recharge refers to rainfall recharge; recharge from rivers is not included.

The objective of this paper is:
(a) to present a method to determine natural groundwater droughts from the temporal variability of recharge in two European basins with contrasting climates, and
(b) to compare these natural droughts with groundwater droughts derived from well levels which include the impact of heavy groundwater exploitation.

METHODS

Description of basins

Two drainage basins were selected, i.e. the Upper-Guadiana in central Spain and the Noor on the Belgian–Dutch border. The Spanish basin (16 000 km²) has a semiarid climate. Annual average rainfall varies from 230 to 620 mm year⁻¹, whereas average potential evapotranspiration reaches about 960 mm year⁻¹ (Cruces et al., 2000; Peters et al., 2001a). Loamy to clayey soils with deep water tables are dominant in the basin. Land use is mostly dryland cereals and vineyards. Since the 1970s the irrigated area has tripled. Irrigation, which is predominantly from groundwater, has led to drawdowns of over 30 m, rivers have ceased to flow for most of the year and wetlands have disappeared.

The Noor Brook basin is in the southeast of The Netherlands. The Noor basin (10.5 km²) drains eventually into the River Meuse. Average rainfall in this temperate humid region varies from about 515 to 1025 mm year⁻¹ and potential evapotranspiration reaches about 575 mm year⁻¹ (Peters et al., 2001a). Most soils have deep water tables and are silts. Grass is the dominant vegetation in the basin. Groundwater abstractions outside the basin and land-use changes within might cause a reduction of streamflow.

Recharge models

Different recharge models were applied in the Upper-Guadiana and Noor basins because of the data available. In the Upper-Guadiana the SIMPA model (Estrela & Quintas, 1996) was used. SIMPA is a distributed rainfall–runoff model that simulates the monthly water balance for each homogeneous cell (6.25 km²). Land-use data, soil properties and time series of rainfall and temperature (1940–1996) were collated. A calibration procedure is required to estimate the limited number of model parameters (e.g. maximum soil water storage). The results include the time series of monthly groundwater recharge.

In the Noor basin the NUT_DAY model (Peters et al., 2001a) was used. This one-dimensional model is a reservoir model that solves the daily water balance of the root zone for each land unit. In total three units were distinguished. Input parameters for each unit, such as crop rooting depth, thickness and soil moisture retention data of the soil layers, have a physical meaning. Therefore no calibration was performed. Meteorological data from the period 1945–1999 were used to produce time series of daily recharge.

Identification of groundwater droughts

The results of both models were aggregated to time series of monthly recharge for the whole basin. Natural groundwater droughts were derived from these time series through the Sequent Peak Algorithm (SPA). The SPA approach is based upon a semi-
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infinite reservoir with constant outflow. It has been applied successfully by Tallaksen et al. (1997) to derive streamflow droughts from flow data. The SPA is defined as:

$$D_i^* = \begin{cases} D_{i-1}^* + (I_i - I_{i-1}) \Delta t & \text{if } D_i^* > 0 \\ 0 & \text{if } D_i^* \leq 0 \end{cases}$$

(1)

where $D_i^*$ and $D_{i-1}^*$ are recharge deficits in month $t$ and $t-1$ (mm), $I_i$ is recharge in month $t$ (mm month$^{-1}$), $I_x$ is constant outflow (mm month$^{-1}$), and $\Delta t$ is the time step (month). The constant outflow from the reservoir was set to 70% of the long-term average monthly groundwater recharge ($I_{70}$) in this study.

Droughts are characterized by their onset, duration and severity. The severity of a drought is indicated by the maximum deficit ($D_{\text{max}}^*$). Recharge deficits are standardized by the long-term annual groundwater recharge, which allows comparison of droughts in basins in different climate regions. A natural groundwater drought occurs if $D_i^*$ exceeds a pre-defined level, i.e. in this study a $D_i^*$ was chosen that occurs in less than 30% of the months ($R_{30}$). This $R_{30}$ level differs for both basins.

Groundwater droughts can also be derived from groundwater levels or groundwater discharge (Peters et al., 2001b). These might include human effects, for example, groundwater abstractions. In this study only groundwater levels were used. The cumulative departure of the groundwater level at a representative location from a particular threshold level is used to identify these droughts.

$$CD_i = \begin{cases} CD_{i-1} + (q_i - q_{i-1}) \Delta t & \text{if } q_i < q_x \\ 0 & \text{if } q_i \geq q_x \end{cases}$$

(2)

where $CD_i$ and $CD_{i-1}$ are cumulative departures at day $t$ and $t-1$ (m day), $q_i$ is groundwater level at day $t$ (m), $q_x$ is threshold groundwater level (m), and $\Delta t$ is the time step (day). The threshold level was set at $q_{70}$, which implies that this level is equalled or exceeded 70% of the time.

RESULTS

Temporal variability of groundwater recharge and natural groundwater droughts

Obviously the annual groundwater recharge in a semiarid climate is lower than in a temperate humid climate (Fig. 1). The standardized annual recharge (annual recharge divided by long-term annual recharge) shows that the variation in the recharge in the Upper-Guadiana is higher than in the Noor (Fig. 1). This means that especially in drought-prone years the recharge in the Upper-Guadiana deviates more from the average annual recharge than in northwest Europe.

Natural groundwater droughts were derived from monthly recharge data by the SPA approach (equation (1)) to both climatic regions (Fig. 2). The most severe drought in the Upper-Guadiana was in the 1990s (Table 1). In the Spanish basin more multi-year droughts occur than in the Noor basin. In the Noor basin no prolonged droughts occur and they are more equally distributed over time than in semiarid circumstances.
The severest drought occurred in the late 1940s (Table 1). The temporal distribution of natural droughts in the two basins (Fig. 2) also shows that groundwater droughts do not coincide in northwest and southwest Europe.

**Natural and induced groundwater droughts**

Induced groundwater droughts can be derived from groundwater hydrographs by computing the cumulative deviation (equation (2)). This procedure has been applied to a representative observation well in both basins (Fig. 3). Unfortunately no observations are available before the late 1950s (Upper-Guadiana) and early 1960s (Noor). The CD
in the Noor basin agrees reasonably with the deficit $D^*$ derived from the recharge (Fig. 2). The $CD$ shows some delay and is more pooled than the $D^*$. The natural droughts derived from the recharge that occurred in the 1970s and 1990s can also be recognized in the $CD$ derived from the groundwater levels. This means that the impact of human activities, such as abstractions and land drainage, are small in the Noor basin. Groundwater levels the Upper-Guadiana, however, show a clear downward trend in the period 1970–1995 due to abstractions for irrigation (Cruces et al., 2000). The $CD$ for the historical situation (Fig. 3, UG; current) has increased spectacularly since the 1970s. So, heavy groundwater exploitation leads to induced groundwater droughts that cannot be directly related to the natural droughts (Fig. 2).

A numerical groundwater model was used to simulate groundwater hydrographs with reduced abstractions in the Upper-Guadiana (Cruces et al., 2000; Peters et al., 2001b). The $CD$ derived from the simulated hydrographs for wells in the heavily exploited central part of the Spanish basin provides information about the risk of groundwater droughts for different abstraction scenarios. In Fig. 3, for example, the $CD$ is given for the representative well in the central part of Upper-Guadiana for the scenario that the abstractions are reduced to the pre-1970 rate with the meteorological conditions for 1960–1995 (UG; no abstraction). The significant reduction of groundwater abstraction would have resulted in hardly any groundwater droughts in the Upper-Guadiana, except in the early and the mid 1990s. This groundwater drought coincides with the severe natural groundwater droughts induced by a lack of recharge (Table 1).

### Table 1 Characteristics of the severest natural groundwater droughts in the Upper-Guadiana and Noor basins.

<table>
<thead>
<tr>
<th>Basin</th>
<th>Onset</th>
<th>Duration (month)</th>
<th>Deficit (mm)</th>
<th>Standardized deficit (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper-Guadiana</td>
<td>February 1990</td>
<td>63</td>
<td>38</td>
<td>2.3</td>
</tr>
<tr>
<td>Noor</td>
<td>March 1947</td>
<td>19</td>
<td>211</td>
<td>0.8</td>
</tr>
</tbody>
</table>
CONCLUSIONS

Applying transient recharge models and reservoir theory (Sequent Peak Algorithm) can identify natural groundwater droughts. These methods compute recharge deficits that determine the onset, duration and severity of droughts. The methodology shows that the drought characteristics significantly differ for a semiarid basin (Upper-Guadiana) as compared to a temperate humid basin (Noor). Obviously, groundwater droughts in semiarid Europe are more severe in terms of duration and severity. Moreover, the droughts do not coincide.

Groundwater droughts based upon the cumulative deviation of groundwater levels from a threshold approximately correspond to the natural droughts if the groundwater system is not affected too much by human activities (e.g. Noor). However, if groundwater is heavily exploited (e.g. Upper-Guadiana) natural groundwater droughts are significantly more frequent and severe.

The methodology proposed in this study can be used re-actively to reconsider current activities (e.g. intensive groundwater abstraction) that have a negative impact on droughts. This may also include mitigation measures (e.g. Vogt & Somma, 2000; Querner & van Lanen, 2001). The methodology can also be applied pro-actively to quantify the risk of groundwater droughts with future changes. For instance, the recharge models can be applied to quantify effects of land use or climate change (e.g. Peters et al., 2001a).

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REFERENCES


