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Drought propagation through the hydrological cycle

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Abstract Time series of simulated recharge, groundwater heads and streamflow were obtained for temperate humid and semiarid climate regions and for quickly and slowly-responding catchments. These were analysed to investigate the propagation of drought through the subsurface, i.e. the change in characteristics (onset, duration and severity) from a meteorological drought to a hydrological drought. In two selected contrasting climate regions (Spain and The Netherlands) the propagation of recharge droughts generally leads to smaller hydrological droughts, except for severe recharge droughts, which might generate very severe hydrological droughts. In quickly-responding catchments more minor droughts will occur, whereas the probability of a very severe drought is higher in slowly-responding catchments. It is anticipated that quantitative knowledge on drought propagation will advance if recharge droughts derived from real instead of synthetic recharge can be better defined, i.e. by use of recharge anomalies.

Key words drought; propagation; subsurface; modelling; threshold approach; humid temperate; semiarid

INTRODUCTION

Drought is a sustained and regionally extensive occurrence of below average natural water availability, and can thus be characterized as a deviation from normal conditions (Tallaksen & van Lanen, 2004). It occurs in all hydroclimatological regions, although frequency and severity vary. A drought starts with a lack of precipitation over a large area and for an extensive period of time (meteorological drought). This water deficit propagates through the subsurface part of the hydrological cycle and gives rise to different types of droughts (Wilhite, 2000). The low precipitation might cause a soil moisture drought to develop. Subsequently, groundwater recharge will be reduced and a hydrological drought (low groundwater heads, groundwater discharge and streamflow) may start.

It is well-known that not all meteorological droughts develop in a hydrological drought and conversely a series of minor meteorological droughts can turn into a severe hydrological drought. Although it is obvious that the characteristics of droughts (e.g. onset, duration) change on its way through the subsurface, it is hard to show the propagation of droughts in reality, i.e. to derive it from simultaneous time series of observed precipitation, soil moisture, groundwater levels and streamflow (Peters, 2003). As a first, explorative step, often simplified hydrological models with generalized input (synthetic recharge: sinusoid function) have been developed to study the propagation of drought. Based upon this very simplified input, it was demonstrated that catchment characteristics, especially the stores (e.g. soil moisture, aquifer storage, glaciers, bogs) determine if and to what extent a meteorological drought turns into a hydrological drought. So far, however, understanding of the propagation of a drought through the subsurface and the role of catchment characteristics is rather limited (e.g. Calow *et al.*, 1999; Peters *et al.*, 2003). Nevertheless, thorough understanding of drought propagation is urgently required for adequate long-term drought forecasting.

This paper explores the propagation of a meteorological drought through the subsurface part of the hydrological cycle. The effect of different catchment characteristics on the propagation is illustrated for contrasting climates.

APPROACH

Different type of droughts was derived from long time series of hydrometeorological variables (e.g. precipitation, soil moisture, groundwater heads, streamflow). Usually not all these data have been monitored over long periods of time. In this study different hydrological models (simple to comprehensive) were applied to generate time series of non-monitored data for temperate humid and semiarid climatic regions, i.e. The Netherlands and Spain. Next the threshold method was used to identify droughts.

Catchments

Data from the Poelsbeek and the Bolscherbeek catchments in the eastern part of The Netherlands (e.g. Tallaksen & van Lanen, 2004) and the Noor catchment (van Lanen & Dijksma, 1999; van Lanen & Dijksma, 2004) on the Dutch–Belgian border were used to characterize catchments with a temperate humid climate. Additionally data were obtained from a catchment in south-central Spain (Upper-Guadiana) with a semiarid climate (Peters, 2003). The average precipitation in the humid temperate catchments varies from 748 to 775 mm year^{-1} and the average potential evapotranspiration is about 450 mm year^{-1}. In the Upper-Guadiana the average precipitation varies from 350 mm year^{-1} in the central part to 580 mm year^{-1} at higher elevations. The potential evapotranspiration is about 960 mm year^{-1}. In the Upper-Guadiana the inter-annual variability in precipitation is higher than in the temperate humid catchments. Time series of precipitation and potential evaporation were used to calculate groundwater recharge with soil water balance models.

Simple hydrological model

Linear reservoir theory (Tallaksen & van Lanen, 2004) has been applied to calculate time series of groundwater discharge for hypothetical catchments with a temperate humid climate (i.e. Noor catchment) or a semiarid climate (Upper-Guadiana catchment). The following equation was used:

$$q_{gr,t} = q_{gr,t-1} \exp(\frac{-m_t}{j}) + \frac{I_t}{m_t}(1 - \exp(\frac{-m_t}{j})) \qquad (1)$$

where $q_{gr,t}$ is groundwater discharge at month t [L T^{-1}], $q_{gr,t-1}$ is groundwater discharge at month $t-1$ [L T^{-1}], m_t is number of days in month t [–], I_t is groundwater recharge at month t [L T^{-1}] and j is reservoir coefficient [T].

The characteristics of the catchment are represented by the reservoir coefficient j (day):

$$j = \frac{S_y L^2}{\pi^2 kD} \qquad (2)$$

where L is the distance between streams [L], kD is the aquifer transmissivity [L^2 T^{-1}] and S_y is the storage coefficient [–].

The groundwater discharge is not specifically calculated for the Upper-Guadiana or Noor catchments, but for a range of hypothetical groundwater catchments with a range of reservoir coefficients. Thus, the hypothetical groundwater catchments have either the recharge of the temperate, humid climate (Noor) as input or the recharge of the semiarid climate (Upper-Guadiana). A catchment with a small j represents a quickly-responding groundwater system, whereas a catchment with a large j has the opposite response (Peters, 2003; Peters *et al.*, 2003; Tallaksen & van Lanen, 2004).

Comprehensive hydrological model: SIMGRO

SIMGRO is a spatially-distributed physically-based model that simulates regional transient saturated groundwater flow, unsaturated flow, actual evapotranspiration, sprinkler irrigation, streamflow, hydraulic heads and surface water levels as a response to, for example, rainfall, reference evapotranspiration, and groundwater abstraction (Querner, 1997). SIMGRO has been applied to the Poelsbeek and Bolscherbeek catchments to obtain daily time series over the years 1951–1999 (Tallaksen & van Lanen, 2004). The model allows input of spatially-variable catchment properties (e.g. land use, soil type, transmissivity, stream network). SIMGRO simulates for each node and day the actual evapotranspiration, recharge, $I(x,y,t)$, the groundwater hydraulic head, $H(x,y,t)$, and soil moisture storages in the root zone and in the unsaturated subsoil. Additionally, SIMGRO simulates transient streamflow in the longitudinal profile as a response to drainage of the aquifer by ditches and streams, overland flow and water from a sewage treatment plant.

Threshold level approach: NIZOWKA

Drought characteristics (i.e. onset, duration, severity) have been derived from the simulated time series by using the software package NIZOWKA (Tallaksen & van Lanen, 2004). The software is based upon the threshold level approach (Yevjevich, 1967). Time series of daily recharge, groundwater hydraulic heads and streamflow were used in the Poelsbeek and Bolscherbeek catchments with threshold levels of I_{90}, Q_{90} and H_{90} (recharge, streamflow or head that is equalled or exceeded in 90% of the time). The threshold levels apply to the whole year and not to a specific period (e.g. a day or a month). For the recharge a moving average of 30 days was applied to reduce the peaky nature. In the Upper-Guadiana and Noor catchments time series of monthly recharge and groundwater discharge were used with I_{70} and Q_{70} as threshold levels, which hold for the whole year. The monthly recharge was first aggregated to annual values, because otherwise droughts would have occurred in almost all dry seasons.

RESULTS

First, the propagation of droughts was analyzed in detail by using simulated data with SIMGRO for a catchment with in a humid temperate climate (Poelsbeek and Bolscherbeek catchments; Verwij, 2005). Table 1 gives some drought characteristics for the three major droughts in the second part of the twentieth century. Obviously, droughts in recharge start first. Droughts in the groundwater heads and streamflow are observed later, 10–61 and 10–38 days, respectively. In this catchment, streamflow usually responds earlier than the groundwater head (except 1996). Verwij (2005) illustrates that, of course, the onset and duration depend on the selected threshold level. The duration of all three major droughts is substantially smaller for the recharge drought than for the hydrological droughts (heads and streamflow). The 1996 drought clearly reflects this. A minor drought in the recharge has been observed, whereas droughts over 100 days occur in the groundwater heads and the streamflow. This clearly reflects the antecedent conditions, i.e. low aquifer storage at the start of 1996 due to dry conditions before.

The detailed study above shows that propagation of droughts is complex and dependent on catchment characteristics and a specific year. Subsequently, a more simple approach was adopted using soil water balance models to compute groundwater recharge and linear reservoir models to simulate groundwater discharge to explore the propagation in a more general way. Compared to Peters *et al.* (2003) the simplified approach in this study uses more realistic estimates for the recharge for two contrasting climate regions, i.e. Noor and Upper-Guadiana catchments.

Table 1 Onset and duration of the different types of drought for three major droughts in the Poelsbeek and Bolscherbeek catchments.

Year	Drought in	Onset	Duration (days)
1959	recharge	1 May	62
	groundwater heads	1 July	174
	streamflow	8 June	154
1976	recharge	10 April	50
	groundwater heads	30 May	189
	streamflow	15 May	162
1996	recharge	27 April	5
	groundwater heads	7 May	181
	streamflow(1)	7 May	19
	streamflow	2 June	123

(1) Two separate droughts occurred in the streamflow.

The maximum annual recharge in temperate humid climate (Noor catchment, 1945–2001) and the semiarid climate (Upper-Guadiana catchment, 1940–1996) was 481 and 192 mm year^{-1}. In 30% of the years the recharge is smaller than 202 and 19 mm year^{-1}, respectively. Figure 1 gives a flow duration curve of the simulated monthly groundwater discharge using the simple hydrological model. Clearly the discharge is high for the temperate humid climate and the discharge varies more for the quickly-responding catchment (j = 100 day). In extremely dry years the stream runs dry in flashy catchments, irrespective of the climate region.

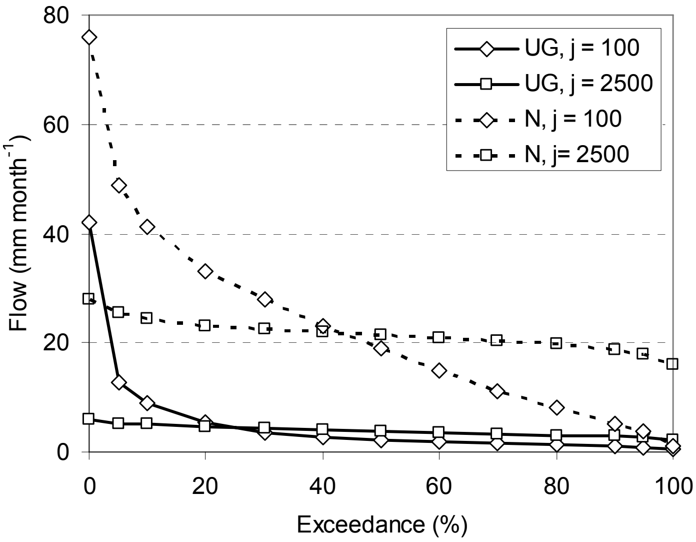

Fig. 1 Flow duration curves for quickly (j = 100 days) and slowly (j = 2500 days) responding catchments with a semiarid (UG) and a temperate humid climate (N).

The drought duration (month) and the severity, which is expressed as deficit (in mm water depth), are plotted in Fig. 2 for the two contrasting climate regions and quickly and slowly responding catchments. Six multiple-year droughts in the recharge came about in the semiarid climate region (Upper-Guadiana, Fig. 2(a)), whereas not more than four of such droughts occurred in the temperate humid climate (Noor, Fig. 2(c)). Note that the number of recharge droughts is affected by the chosen time resolution (aggregation of monthly recharge to annual values). The duration and severity graphs show that in both climate regions the quickly-responding catchments have a larger number of discharge droughts than the slowly responding ones. For instance, in the semiarid region, 42 discharge droughts were identified in the quickly-responding catchment (Fig. 2(a)), whereas in the slowly-responding catchment the number equals 13 events (Fig. 2(b)). In general the (minor) discharge droughts last longer and are more severe in the quickly-responding catchments as opposed to slowly-responding catchments (Fig. 2, compare left and right columns). A rather small number of very severe discharge droughts would have occurred in the second part of the 20th century. In the semiarid climate one such drought would have been happened in the quickly-responding catchment (early 1990s, Fig. 2(a) and 2(e)) and two in slowly-responding (early 1950s and early 1990s, Fig. 2(b) and 2(f)). In the temperate humid climate no very severe drought would have taken place in the quickly-responding catchment (Fig. 2(c) and 2(g)) and one in the slowly-responding catchment (1950s, Fig. 2(d) and 2(h)).

The graphs for the quickly-responding catchment (Fig. 2, left column) show that substantial droughts in the recharge do not lead to severe discharge droughts, except for the early 1990s drought in the semiarid climate. This effect, i.e. decrease of duration and severity of droughts through subsurface processes, is even stronger in the slowly-responding catchments (Fig. 2, right column). The discharge droughts in the quickly-responding catchments are hard to link to the recharge droughts (propagation) probably due to the aggregation of monthly recharge to annual values. The graphs for the slowly-responding catchments suggest that there might be a better link between the severity of the recharge and discharge droughts (Fig. 2(f) and 2(h)) than with the duration (Fig. 2(b) and 2(d)).

CONCLUSIONS AND DISCUSSION

The analysis shows that there is more clustering of droughts in the recharge in dryer climate regions (higher persistence). Both the complex and the more simple hydrological modelling approach demonstrate that in contrasting climate regions the propagation of recharge droughts through the subsurface generally leads to smaller hydrological droughts (less severe in terms of deficit). However, severe droughts in the recharge (long duration and/or high deficit) may result in

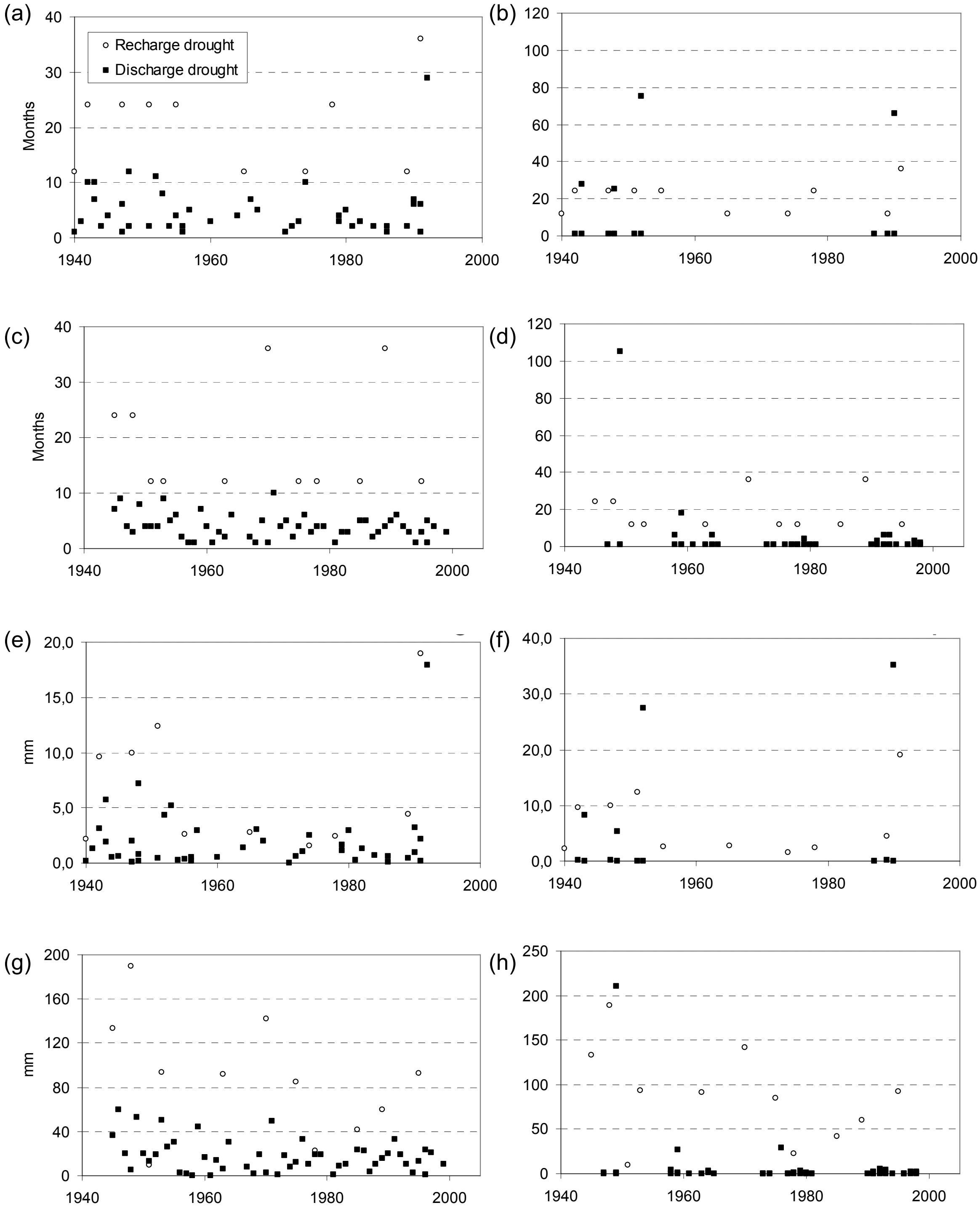

Fig. 2 Duration (month) and severity (deficit in mm) of drought in the recharge and the discharge for different catchment characteristics for a semiarid climate region (UG) and a temperate humid climate region (N): (a) duration, UG and j = 100, (b) duration, UG and j = 2500, (c) duration, N and j = 100, (d) duration, N and j = 2500, (e) deficit, UG and j = 100, (f) deficit, UG and j = 2500, (g) deficit, N and j = 100, (h) deficit, N and j = 2500. In case of multiple year droughts the duration and deficit are plotted at the onset year.

very severe hydrological droughts. Catchment characteristics, such as storage properties (soils, aquifers), aquifer transmissivity and river network determine the propagation of a drought in the subsurface. In quickly-responding catchments more minor droughts will occur, whereas the probability on a very severe drought is higher in slowly-responding catchments.

Peters *et al.* (2003) give quantitative relationships for the propagation of droughts in the subsurface using synthetic recharge as input. The current study shows that it is still hard to give these relationships if more realistic recharge estimates are used. Clearly, a higher time resolution is required to define recharge droughts, especially for the quickly-responding catchments. However, it should be avoided to have a recharge drought every summer due to seasonality because by definition a drought cannot occur every summer. The use of threshold levels for the recharge for specific periods (varying thresholds, e.g. per month) instead of for the whole year to define recharge anomalies might help to advance understanding of propagation of droughts through the subsurface.

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