HOW TO DISTINGUISH BETWEEN DROUGHT AND WATER SCARCITY?
USE AN OBSERVATION-MODELLING FRAMEWORK!

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EXTENDED ABSTRACT

Water scarcity and drought are keywords for river basin managers in water-stressed regions like Australia, California and the Mediterranean Basin. Unfortunately, these terms are often misused. They refer to quite different phenomena. ‘Drought’ is a natural hazard, which is caused by climatic processes and their intrinsic variability, and cannot be prevented by short-term, local water management. ‘Water scarcity’ refers to the long-term unsustainable use of water resources and is a process that water managers and policy makers can influence.

The interrelationship between drought and water scarcity, however, is complex. In regions with low water availability and high human activity, water scarcity situations are common and can be exacerbated by drought events. The worst situation is a multi-year drought in a (semi-)arid region with high demand for water. In monitoring the hydrological system for water management purposes, it is difficult (but essential) to determine which part of the signal is caused by water scarcity (human induced) and which part by drought (natural). So the urgent question of many water managers is: how to distinguish between water scarcity and drought?

In this paper, we use the observation-modelling framework proposed by Van Loon and Van Lanen (2013) to separate natural (drought) and human (water scarcity) effects on the hydrological system. The basis of the framework is simulation of the situation that would have occurred without human influence, i.e. the ‘naturalised’ situation, using a hydrological model. The resulting time series of naturalised state variables and fluxes can then be compared to observed time series. Additionally, anomalies (i.e. deviations from a threshold) are determined from both time series and compared. This analysis allows for quantification of the relative effect of drought and water scarcity.

To show the wider applicability of the framework, we investigated case study areas with contrasting climate and catchment properties in Czech Republic and the Netherlands. Using these case study areas we could analyse the effect of groundwater abstraction and water transfer on groundwater levels and streamflow, using a lumped conceptual rainfall-runoff model and a distributed physically-based hydrological model, both forced with observations of meteorological variables, and different forms of the threshold level method for anomaly analysis. These various approaches allowed us to quantify the effect of human influence on anomalies in the hydrological system and to compare these with effects of natural influences (droughts).

The results presented in this paper show the general applicability of the observation-modelling framework. We demonstrate the range of methods that can be used and the range of human influences the framework can be applied to. The observation-modelling framework can help water managers in water-stressed regions, like the Mediterranean, to combat water scarcity, and to better adapt to drought by decreasing their vulnerability.

Keywords: water scarcity, drought, hydrometeorological observations, hydrological modelling, anomaly analysis, anthropogenic vs. natural effects, case studies
1. INTRODUCTION

Water scarcity and drought are keywords for water resources managers in water-stressed regions. In this study, we define ‘water scarcity’ as the overexploitation of water resources when demand for water is higher than water availability. So, we focus on the effect that human activities have on the hydrological system. ‘Drought’ is a natural hazard, i.e. caused by climate variability. Here, we define drought as a period of below-normal water availability with natural causes (Van Loon and Van Lanen, 2013). Mixing up of the terms ‘water scarcity’ and ‘drought’ can be misleading and should be avoided, as there is a fundamental difference in how water management can influence these phenomena. Management can combat overexploitation of water resources (water scarcity), whereas it only can adapt to climate variability (drought) by reducing vulnerability through the implementation of pro-active measures. But how to distinguish the interlinked phenomena of water scarcity and drought?

In a previous paper (Van Loon and Van Lanen, 2013), we developed an observation-modelling framework for that purpose. The framework is based on simulation of the ‘naturalised’ situation, i.e. the situation that would have occurred without any human influence in a disturbed period, on the basis of information derived from a relatively undisturbed period (Figure 1). A comparison of the anomalies in both the naturalised (gridded surfaces) and observed time series (vertically-striped surfaces) provides quantitative transient information on anomalies caused by climate variability (drought) and anomalies caused by human influence (water scarcity). The proposed observation-modelling framework was tested on an analysis of the effects of groundwater abstraction in a catchment in Spain (Van Loon and Van Lanen, 2013). In this paper we show the applicability of the framework to a range of other catchments with different human influences. These examples make use of different hydrological model approaches and different drought analysis methods to demonstrate the wide range of possibilities of the framework.

![Figure 1. Illustration of the effect of human and natural influences on the hydrological system in the undisturbed and disturbed period (from Van Loon and Van Lanen, 2013).](image)

2. DESCRIPTION OF THE OBSERVATION-MODELLING FRAMEWORK

The observation-modelling framework that Van Loon and Van Lanen (2013) proposed as a tool to make the distinction between drought and water scarcity is depicted in Figure 2. The basic elements in this framework are hydrometeorological data of both the disturbed and undisturbed period, a hydrological model to simulate the naturalised situation, and an anomaly analysis method to extract anomalies from time series of hydrological variables. The undisturbed period is defined as the period in which the human influence on the hydrological system is negligible. This does not mean that there is no human influence at all, only that it is sufficiently minor compared to the effects in the disturbed period.
Figure 2. Illustration of the observation-modelling framework, proposed by Van Loon and Van Lanen (2013) to distinguish drought and water scarcity.

Various model types can be chosen as hydrological model in the framework, e.g. a distributed or lumped model, a physically-based model, a conceptual model, or even a stochastic model (Beven, 2000; Wagener et al., 2004), as long as it is capable of reproducing the natural situation, especially during low flow and drought. The naturalised time series of discharge and/or groundwater (the dashed line in Figure 1) can then be compared to the observed time series of discharge and/or groundwater (the solid line).

Subsequently, anomaly analysis (Figure 2) extracts anomalies from time series of (observed or naturalised) hydrological variables, both state variables and fluxes. In this way, we can investigate deviations from normal conditions (represented by the red line in Figure 1). In the undisturbed period, anomaly analysis on both observed and simulated time series gives drought events. In the disturbed period, anomaly analysis on simulated times series gives drought events (the gridded surfaces in Figure 1), while anomaly analysis on observed times series gives the combined effect of drought and water scarcity (the vertically striped surfaces). The co-called ‘comparison 2’ (Figure 2) then provides information on the effect of human influence on anomalies. Just as for the hydrological model, the specific method used for anomaly analysis within the observation-modelling framework can vary. Some possibilities are the threshold level method (in different forms), the Sequent Peak Algorithm, and other drought indicators (Hisdal et al., 2004; Fleig et al., 2006, Sheffield and Wood, 2011).

3. CASE STUDIES
This study focusses on the comparison of anomalies, comparison 2. We selected three catchments of which the climate and catchment characteristics are different from the Spanish example in Van Loon and Van Lanen (2013). Two catchments are located in Czech Republic (Svitata and Bilina) and one in the Netherlands (Poelsbeek). In this section we provide some information on the catchments and describe the methodology applied to each of the catchments. Further information can be found in Van Lanen et al. (2004) and a summary is given in Table 1.
Table 1. Application of the observation-modelling framework to the selected catchments (Svitata and Bilina in Czech Republic and Poelsbeek in the Netherlands).

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Human influence</th>
<th>Methods</th>
<th>Hydrological model</th>
<th>Anomaly analysis method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Svitata</td>
<td>groundwater abstraction</td>
<td>undisturbed &amp; disturbed period</td>
<td>BILAN</td>
<td>variable threshold Q80</td>
</tr>
<tr>
<td>Bilina</td>
<td>water transfer</td>
<td>undisturbed &amp; disturbed period</td>
<td>BILAN</td>
<td>fixed threshold Q50</td>
</tr>
<tr>
<td>Poelsbeek</td>
<td>groundwater abstraction</td>
<td>scenarios</td>
<td>SIMGRO</td>
<td>variable threshold GW80</td>
</tr>
</tbody>
</table>

3.1. Svitata
The Svitata catchment is located in Czech Republic. After 1975 groundwater abstraction for drinking water supply increased substantially and annual abstraction exceeded 40 million m$^3$. Although minor abstraction was present before 1975, flows were not significantly affected until the late 1970s (Van Lanen et al., 2004). Therefore, the period 1945–1970 was selected as undisturbed period.

The lumped conceptual rainfall-runoff model BILAN (Kašpárek, 1998) was used. The BILAN model solves the catchment-average water balance on a monthly time scale. The model was calibrated on observed discharge from the undisturbed period and agreed reasonably well with observations (Van Lanen et al., 2004). The calibrated model was used for simulation of monthly flows in the disturbed period 1971–1990. Data on precipitation, air temperature and relative air humidity were used as input.

The threshold level method (Hisdal et al., 2004) was applied to the time series of monthly flow data. A variable threshold based on the 80$^{th}$ percentile of the monthly flow duration curves (Q80) was derived from the undisturbed time series for observed and simulated monthly discharge, separately, and applied to the disturbed period. To exclude minor anomalies we selected events with a minimum duration of 3 months.

3.2. Bilina
In the Bilina catchment (also in Czech Republic) large-scale mining activities occurred. After 1960, the natural discharge of the Bílina was insufficient to cover the demands of the fast growing energy and industrial sectors and the drinking water supply. The Bílina had to be augmented with water transported from an adjacent river basin.

The period prior to 1960 can be regarded as undisturbed and was used to calibrate the lumped conceptual rainfall-runoff model BILAN. Model results agreed reasonably well with observations for the undisturbed period (Van Lanen et al., 2004). The calibrated parameters of the model were subsequently used for simulation of the naturalised discharge for the period 1961–1990 using observed precipitation, air temperature, and relative air humidity as input.

Just as in the Svitata catchment, the threshold level method was applied to the time series of monthly flow data. A fixed threshold based on the 50$^{th}$ percentile of the flow duration curve (Q50) was derived from the undisturbed time series (1932–1960) for observed and simulated monthly discharge, separately, and applied to the disturbed period, excluding events with a minimum duration of 3 months.

3.3. Poelsbeek
The Poelsbeek catchment is located in the eastern part of the Netherlands. Land use is mainly agricultural and shallow water tables are common. In the Poelsbeek catchment a different approach was used than in both Czech catchments. Detailed observations of both hydrometeorological variables and human influences were available and a distributed physically-based hydrological model was set up (Van Lanen and Querner, 2004). This allows for an analysis of the effect of different scenarios. In this paper we focus on one scenario of groundwater abstraction with a constant annual extraction rate.
of 0.75 million m³ and compare the effects of this scenario with a reference scenario without groundwater abstraction.

For this analysis we used the SIMGRO model (Querner, 1997). This distributed physically-based hydrological model simulates transient storages and fluxes based on a system of nodal points within a catchment. This allows the model to deal with spatially-distributed catchment properties and the inclusion of abstraction points at a specific location. The results of the reference scenario simulated by the SIMGRO model adequately reproduced observed groundwater and flow (Van Lanen and Querner, 2004).

To determine anomalies in daily groundwater levels for both the reference (natural situation) and the abstraction scenario (influenced situation) we used the variable threshold level method. In this case we applied a smoothed monthly threshold taken from the 80% percentile of the duration curve (Van Loon and Van Lanen, 2012). To exclude minor anomalies we selected events with a minimum duration of 30 days.

4. RESULTS

4.1. Svitata
The monthly time series of discharge for the Svitata catchment (Figure 3 – middle panel) show that groundwater abstraction resulted in a strong decrease of streamflow in the Svitata after approximately 1975. This caused below-threshold values even in periods without drought (for example 1981-1984 and 1988-1990). Figure 3 can be quantified with the anomaly characteristics duration and deficit (Table 2). The influence of groundwater abstraction on the number of anomalies and their mean duration is negligible, whereas it causes a significant increase in mean deficit volume. The influence on the maximum event is even stronger; the duration is twice as high in the observations as in the naturalised system and the deficit volume is even more than five times as high.

![Figure 3. Monthly time series of simulated and observed discharge (including the monthly variable threshold and anomalies) for the Svitata catchment. Both the undisturbed period (1945-1970) and the disturbed period (1971-1990) are shown.](image-url)
Table 2. General anomaly characteristics for the observed and naturalised discharge of the Svitata and Bilina catchments for the disturbed period, and the Poelsbeek catchment for the entire simulation period (max.difference = maximum deviation from the threshold).

<table>
<thead>
<tr>
<th></th>
<th>no. of anomalies</th>
<th>duration [months]</th>
<th>deficit [mm]</th>
<th>max.difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mean</td>
<td>max</td>
<td>mean</td>
<td>max</td>
</tr>
<tr>
<td>Svitata</td>
<td>naturalised Q</td>
<td>15</td>
<td>10</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>observed Q</td>
<td>16</td>
<td>10</td>
<td>58</td>
</tr>
<tr>
<td>Bilina</td>
<td>naturalised Q</td>
<td>20</td>
<td>9</td>
<td>31</td>
</tr>
<tr>
<td></td>
<td>observed Q</td>
<td>3</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Poelsbeek</td>
<td>reference GW</td>
<td>26</td>
<td>3</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>scenario GW</td>
<td>32</td>
<td>14</td>
<td>67</td>
</tr>
</tbody>
</table>

4.2. Bilina

In the Bilina catchment results are different. In the disturbed period observed discharge (Figure 4 – middle panel) was structurally above simulated discharge (Figure 4 – upper panel) due to the water transfer. Clearly, the water transfer was irregular resulting in differences between high flow periods and low flow periods. The use of a fixed threshold shows that the multi-year dry periods in the 1960s and 1970s did result in anomalies in observed discharge, whereas the yearly recurring droughts in the 1980s are not reflected in the observations (Figure 4 – lower panel). This leads to a very low number of anomalies in observed discharge (3 events in the observations vs. 20 events in the simulations; Table 2). The deficit volume changed dramatically, especially for the maximum event leaving only 6 mm deficit, where 215 mm would have occurred without the water transfer.

Figure 4. Monthly time series of simulated and observed discharge (including the fixed threshold, calculated from the undisturbed period, and anomalies) for the Bilina catchment. Only the disturbed period (1961-1990) is shown.
4.3. Poelsbeek
Because the Poelsbeek catchment could be modelled with a distributed physically-based model, allowing for more comprehensive scenario analyses, long time series of groundwater levels and anomalies in groundwater levels could be derived (Figure 5). This is advantageous for drought analysis because droughts are extreme events that typically have return periods of years to decades. In the Poelsbeek catchment the threshold level is not transferred from the undisturbed period to the disturbed period, but from the reference scenario to the abstraction scenario. The effect of the abstraction on groundwater levels (on a location close to the projected abstraction point) is clearly visible in Figure 5 – middle panel and seems to be highly non-linear. Especially in relatively dry years (for example 1971-1974 and 1989-1992; Figure 5 – upper panel), the groundwater levels decrease far below the threshold. This is reflected in the anomaly characteristics in Table 2, where the duration of anomalies in the scenario with abstraction is five time as long as in the reference scenario. Abstraction would cause an extra lowering of the groundwater table during anomalies from 36 cm on average to more than 1 meter in the most extreme case. This is significant as water depths in the Poelsbeek catchment normally are 0 to 1.5 meter below the surface.

![Figure 5](image)

**Figure 5.** Daily time series of simulated groundwater levels for the reference scenario and the abstraction scenario (including the monthly variable threshold, calculated from the reference scenario, and anomalies) for the Poelsbeek catchment.

5. CONCLUSIONS
This study shows that the observation-modelling framework developed by Van Loon and Van Lanen (2013) and tested to quantify the effect of groundwater abstraction on anomalies in discharge and groundwater storage in a catchment in Spain can also be applied:
1. In other catchments, with different climate and catchment properties;
2. For other human influences than groundwater abstraction, e.g. also water transfer;
3. Using different hydrological model types, i.e. a distributed physically-based model vs. a lumped conceptual rainfall-runoff model;
4. Calibrating the hydrological model on an undisturbed period and extrapolating to a disturbed period or simulating both a reference scenario and a human-influenced scenario (using observations for calibration and or validation);
5. Using a different anomaly analysis method, i.e. a fixed vs. a variable threshold level.

In all cases the human influence on anomalies in the hydrological system could be quantified and compared with the influence of climate variability leading to droughts. This, again, demonstrates the usefulness of the observation-modelling framework in making the distinction between drought and water scarcity.

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