Testing the observation-modelling framework to distinguish between hydrological drought and water scarcity in case studies around Europe

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Abstract: Water scarcity and hydrological drought are keywords for river basin managers in water-stressed regions like Australia, California and the Mediterranean Basin. Unfortunately, the underlying processes of hydrological drought and water scarcity are often confused. ‘Hydrological drought’ is defined here as a natural hazard, a (sub-)surface water deficit 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 phenomenon that water managers and policy makers can influence. The interrelationship between hydrological 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 in hydrological time series is water scarcity (human-induced) and which part is hydrological drought (climate-induced). So the urgent question of many water managers is: how to distinguish between water scarcity and hydrological drought? In this paper, we use the observation-modelling framework proposed by Van Loon and Van Lanen (2013) to separate natural (hydrological drought) and human (water scarcity) effects on the hydrological system, which has been developed for Mediterranean conditions (Upper-Guadiana basin in Spain). 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 amount of hydrological 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 (CZ) and the Netherlands (NL). 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 cases showed us that the framework is able to quantify the effect of human influence on anomalies in the hydrological system and to compare these with effects of natural influences (hydrological droughts). In the Svitata catchment (CZ), for example, groundwater abstraction for irrigation resulted in a longer duration of anomalies and a higher deficit volume. In the Bilina catchment (CZ), only some severe multi-year droughts remained after major water transfers into the catchment, which were also much less severe. And in the Poelsbeek catchment (NL), the scenario with a constant groundwater abstraction for drinking water resulted in a non-linear reaction of groundwater anomalies during periods of drought. These results show the general applicability of the observation-modelling framework. We demonstrated the range of methods that can be used and the range of human influences the framework can be applied to. However, the study also illustrated that reliable results only can be obtained with the framework if the model is capable of reproducing the natural situation, which is dependent on the availability of sufficient data, in particular for the undisturbed situation. If applied well, the observation-modelling framework can help water managers in water-stressed regions, like the Mediterranean, to combat water scarcity, and to better adapt to hydrological drought by decreasing their vulnerability.

Key words: Water scarcity, hydrological drought, hydrometeorological observations, hydrological modelling, anomaly analysis, anthropogenic vs. natural effects, case studies

1. INTRODUCTION

Water scarcity and hydrological drought are keywords for water resources managers in water-stressed regions (Wilhite & Buchanan-Smith, 2005; Tsakiris et al., 2013). 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 (Seneviratne et al., 2012). ‘Hydrological drought’ is defined as a natural hazard, i.e. caused by climate variability resulting in a deficiency of water in rivers, lakes, and aquifers (Mishra and Singh, 2010). So hydrological drought is a period of below-normal (sub-)surface water availability with natural causes (also called ‘climate-induced’ drought) and water scarcity is a period of below-normal (sub-)surface water availability with anthropogenic causes (also called ‘human-induced’ drought; Sheffield & Wood, 2011; Van Loon, 2015). Mixing up of the terms ‘water scarcity’ and ‘hydrological drought’ can be misleading and should be avoided, as there is a fundamental difference in how water management can influence these phenomena (Van Loon and Van Lanen, 2013). 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 hydrological 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 (hydrological drought) and anomalies caused by human influence (water scarcity). The proposed observation-modelling framework was developed for Mediterranean conditions (case study catchment in Spain) for analysing the effects of groundwater abstraction (Van Loon and Van Lanen, 2013). It is still an open question whether the applicability of the framework is limited to the circumstances in the Spanish case study (i.e. Mediterranean climate, multiple aquifer system, large groundwater abstractions for irrigation) and with the specific tools suggested for this case study (i.e. a conceptual rainfall–runoff model for naturalisation, variable threshold level method for drought analysis) or whether the framework is more general and other tools can be implemented in the approach for studying the effects of other issues in other catchments. In this paper we investigate 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 study the range of possibilities of the framework. We do not pretend to obtain the most accurate results for the case study regions, but rather are interested in the general usefulness 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; reproduced with permission of publisher Wiley).

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 hydrological 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 hydrological drought and water scarcity (reproduced with permission of publisher Wiley).](image)

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 hydrological 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 focuses on the comparison of anomalies, comparison 2 (Figure 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>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 undisturbed &amp; disturbed period</td>
<td>BILAN</td>
<td>variable threshold Q80</td>
</tr>
<tr>
<td>Bilina</td>
<td>water transfer undisturbed &amp; disturbed period scenarios</td>
<td>BILAN</td>
<td>fixed threshold Q50</td>
</tr>
<tr>
<td>Poelsbeek</td>
<td>groundwater abstraction</td>
<td>SIMGRO</td>
<td>variable threshold GW80</td>
</tr>
</tbody>
</table>

3.1 Svitata

The Svitata catchment is located in the eastern part of Czech Republic, in a region with Turonian and Cenomanian sandstone aquifers suitable for the extraction of large quantities of drinking water. The region has an average annual temperature of around 6 degrees Celsius, an average annual precipitation of around 600 mm/year, and an average annual potential evapotranspiration also of around 600 mm/year (Van Lanen et al., 2004). 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 flow duration curve (Figure 3a) shows discrepancies in the region of average flows, but represents low flows (80th percentile and above) better. 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 80th 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. This 80th percentile falls in the range of 70-95 frequently used in drought analysis for perennial streams (Fleig et al., 2006). To exclude minor anomalies we selected events with a minimum duration of 3 months (Fleig et al., 2006).

3.2 Bilina

In the Bilina catchment (also in Czech Republic) large-scale mining activities occurred. After 1960, the natural discharge of the Bilina 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 Bílina catchment is located in the Krušné mountains (elevation: 200–900 m a.m.s.l.) in north-western Czech Republic, in a region with brown coal (lignite) extraction from open-cast mines (Van Lanen et al., 2004). The brown coal mines are in Tertiary deposits, the adjacent mountains consist of crystalline rocks. Average annual temperature, precipitation and potential evapotranspiration are similar to the Svitata catchment (Van Lanen et al., 2004). 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), especially in the low flow domain (80th percentile and above of the flow duration curve; Figure 3b). 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 50th 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 (Fleig et al., 2006). For the Bílina catchment the 80th percentile could not be used because flows increased so much after the water transfers that no droughts would be identified. This is in agreement with suggestions for intermittent streams in Fleig et al. (2006), where also a higher threshold needs to be chosen to identify droughts. Selection of a different percentile threshold in one of the cases of this study also helps to test the robustness of the framework.

### 3.3 Poelsbeek

The Poelsbeek catchment is located in the eastern part of the Netherlands, near the border with Germany. It is a lowland catchment with elevation ranging from 12 to 30 m a.m.s.l. The geology consists on an unconfined Pleistocene sandy aquifer on impermeable Tertiary clay deposits (Querner and Van Lanen, 2001). Average annual precipitation of the Poelsbeek is 775 mm/year, average annual potential evapotranspiration is 440 mm/year, and average annual temperature is around 10 degrees Celsius (Querner and Van Lanen, 2001; www.klimaatatlas.nl). Land use is mainly agricultural (pasture and arable land) 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 (Querner and Van Lanen, 2001; Van Lanen and Querner, 2004). The flow duration curve (Figure 3c) shows large overlap between simulated and observed discharge and also the periods with zero flow are simulated correctly.

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 80th 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 (Fleig et al., 2006).
4. RESULTS

4.1 Svitata

The monthly time series of discharge for the Svitata catchment (Figure 4 – 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 hydrological drought (for example 1981-1984 and 1988-1990). Figure 4 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 limited, 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.

![Graph showing monthly time series of discharge for Svitata](image)

*Figure 4. Monthly time series of simulated and observed discharge (including the monthly variable threshold and anomalies) for the Svitata catchment for the disturbed period (1971-1990).*

<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></td>
<td>mean</td>
<td>max</td>
<td>mean</td>
</tr>
<tr>
<td>Svitata</td>
<td>naturalised Q</td>
<td>10</td>
<td>9</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>observed Q</td>
<td>9</td>
<td>15</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>

*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).*
4.2 Bilina

In the Bilina catchment results are different. In the disturbed period observed discharge (Figure 5, middle panel) was structurally above simulated discharge (Figure 5, 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 hydrological droughts in the 1980s are not reflected in the observations (Figure 5 – 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 a few mm deficit, where more than 200 mm would have occurred without the water transfer.

Figure 5. Monthly time series of simulated and observed discharge (including the fixed threshold, calculated from the undisturbed period, and anomalies) for the Bilina catchment for the disturbed period (1961-1990).

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 6). 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 6 – middle panel and seems to be highly non-linear. Especially in relatively dry years (for example 1971-1974 and 1989-1992; Figure 6 – 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 times 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 m in the most extreme case. This is significant as water depths in the Poelsbeek catchment normally are 0 to 1.5 m below the surface.

Figure 6. 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. DISCUSSION

The aim of this study was to test the observation-modelling framework proposed by Van Loon and Van Lanen (2013) on different cases and using different tools. In this section we discuss the outcomes, both in terms of case study characteristics, like climate, and the methods used (models, drought analysis method).

5.1 Case study characteristics

The climate of the chosen case studies contrasts with the Mediterranean environment used in Van Loon and Van Lanen (2013). The climate in the Netherlands and Czech Republic is in general colder, wetter and has a less pronounced seasonality. Seasonality in climate is important for hydrological drought development (Van Loon et al., 2014), but also for the human activities leading to water scarcity. Water use has a pronounced seasonal cycle in many regions around the world (e.g. Griffin and Chang, 1991; Wada et al., 2011), that may or may not agree with the season of highest water availability, leading to seasonal water scarcity (Van Oel et al., 2010; Wada et al., 2011; Hoekstra et al., 2012). To cope with seasonality in drought analysis we recommend a variable threshold instead of a fixed threshold (Van Loon, 2015) for use in this framework. Figure 5 shows how a drought analysis that does not include seasonality identifies a drought every dry season. Especially in semi-arid climates this is not useful in water management, because recharge in the wet season is of crucial importance to water availability in the dry season (e.g. Van Loon and Van...
We also tested different human influences on the water cycle, both positive (supply through water transfer in Bilina catchment) and negative (groundwater abstraction for drinking water in Svitata and Poelsbeek catchments). In the case of the water transfer we might question the use (in this framework) of the same threshold for the undisturbed and disturbed period. The river has shifted to a completely different regime and both society and the ecosystem might have adapted to this new regime, so that a drought is experienced in comparison to the new regime instead of to the old regime and the threshold should also be adapted (Wanders et al., 2015).

The groundwater abstraction as tested in this paper is different from that in the original case study of Van Loon and Van Lanen (2013). Here, the abstraction is used for drinking water which has a far more constant abstraction rate than abstraction for irrigation (studied in the Spanish case study in Van Loon and Van Lanen, 2013), which is more seasonal and more dependent on cropping patterns (again dependent on weather predictions, market prices, etc.). Despite this constant abstraction, we did see a non-linear response of the groundwater levels during anomalies, resulting in very long and severe groundwater deficits. Including a transient distributed saturated groundwater model in the framework is a prerequisite to identify such response, which affects the anomalies.

5.2 Modelling

We also tested two different modelling strategies, a lumped conceptual rainfall-runoff model (BILAN) and a distributed physically-based hydrological model (SIMGRO). We see that the SIMGRO model applied to the Poelsbeek catchment performed better than the BILAN model applied to the Czech catchments (Figure 3). The lower performance of the BILAN model casts some doubt on the reliability of the naturalised time series in the disturbed period. For real world application we recommend working towards a higher model performance by using the best performing model that can be applied given data availability. Additionally we recommend performing an uncertainty analysis like in Van Loon and Van Lanen (2013) to determine whether the signal is stronger than the noise. In this paper, we succeeded in our aim to show that the observation-modelling framework can be used with different hydrological models. Van Dijk et al. (2013) did a similar analysis to compare anthropogenic and natural influences on the “Millenium Drought” (2001–2009) in southeast Australia. They used two modelling approaches, a black-box statistical model and a process-based time series model, to explain the amplification from rainfall deficit to streamflow deficit. They concluded that the time series model was needed to take into account seasonality in climate and catchment storage processes. The application of these more complex models in the framework is, however, restricted by the availability of sufficient data, in particular for the undisturbed situation. If more information is available on the human decision-making in the catchment under study a Multi-Agent Simulation approach can be applied (Van Oel et al., 2010). Such a model is often used in water management applications, but can also be used to distinguish hydrological drought and water scarcity.

6. 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 the Upper-Guadiana 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 hydrological droughts. This, again, demonstrates the usefulness of the observation-modelling framework in making the distinction between hydrological drought and water scarcity, although reliability of the results could have been higher if more data would have been available to apply models that would be better at reproducing the natural situation.

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