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Hydrology and Earth System Sciences Discussions

Interactive comment on "A process-based typology of hydrological drought" *by* A. F. Van Loon and H. A. J. Van Lanen

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1 General comments

We want to thank Dr. Ross Woods very much for his positive response to our our manuscript and his valuable comments. Please find below our response to the comments regarding content and presentation of the research.

2 Major points

2.1 Point 1

2.1.1 comment Dr. Ross Woods

"Section 4.1: How can the reader have confidence that the simulated state variables generated by the calibrated models are reliable? The models have been calibrated on flow only, using a fixed model structure. There may be other model structures which give equally good simulations, but quite different time series of soil moisture, or groundwater, or snow. This is important, because the conclusions of the paper rest heavily on modelled state variables which have not been independently validated."

2.1.2 reply authors

We agree that this is a very important issue. For drought studies, it would be most desirable to have long (tens of years), complete time series of observed state variables. Unfortunately, these data were not available for this study and are in general very rare, in particular for contrasting catchments. The main purpose of using a model in this research is the simulation of state variables (snow accumulation, soil moisture, groundwater storage) for which no long time series exist. In the manuscript, we only show the performance of the model on discharge. Validations on state variables are not shown but were done as well. A summary of previously published reports is given below. Although, in most cases, catchment average values were compared with point observations, we think that it gives valuable information of the performance of the HBV model on simulating state variables.

For the Narsjø catchment, we used the HBV model with similar settings and calibration procedure and objective function as Hohenrainer (2008). Hohenrainer (2008) performed a validation on observed soil moisture and groundwater levels. Soil moisture had a reasonable fit to observations. Some deviations were found in winter, i.e. decreasing observed values vs. constant simulated values. This is partly because the TDR probes measured available water content which is lower than stored water content due to soil frost, and partly because HBV does not simulate outflow from the soil moisture store when evaporation is zero (see manuscript, Figure 3). Groundwater had a good fit to observations. The coefficient of determination, r^2, was quite high with 0.65 and visual comparison indicated a good ability of the model to reproduce the general dynamics of the groundwater table. Hohenrainer (2008) stated that the onset and duration of drought periods were captured reasonably well by the model, justifying the use of simulated soil moisture and groundwater series for drought analysis.

For the Upper-Metuje catchment, a validation against observed groundwater levels was performed (Rakovec et al. , 2009). The coefficient of determination was high (r^2 = 0.76) for the first period and slightly lower (r^2 = 0.54) for the second period, in which some human influence (i.e. abstraction) was reported. Visual comparison indicated a good ability of the model to reproduce the general dynamics of the groundwater table and extreme high and low levels (Rakovec et al. , 2009).

For the Upper-Sázava catchment, both snow storage and groundwater simulations were validated (Rakovec et al. , 2009). For groundwater, the coefficient of determination was quite low (r^2 = 0.21). This is probably due to the lack of representativeness of the groundwater well for groundwater in the entire catchment. Actually, most of the catchment consists of crystalline rock, whereas the groundwater well is located in sedimentary rocks. Furthermore, some measurement problems were recorded at this well (Rakovec et al. , 2009). The correlation of some sub-periods was higher (up to r^2 = 0.43). For snow, the coefficient of determination was reasonable (r^2 = 0.57). The general pattern of the simulation agrees well with observed values.

For the Nedožery catchment, both snow storage and groundwater simulations were validated (Oosterwijk et al. , 2009). The coefficient of determination was reasonable

(r^2 = 0.42). Visual inspection of the time series of observed and simulated groundwater levels showed that the general dynamics of the groundwater table were reproduced, but extreme high and low levels were not correctly simulated. However, calibration on both discharge (Nash-Sutcliffe efficiency) and groundwater levels (r^2) simultaneously did not improve results for the lower levels. For snow, visual comparison between simulated and observed snow cover showed that the model was able to simulate snow in the correct period and with the correct amount (Oosterwijk et al. , 2009).

For the Upper-Guadiana catchment, a validation against observed groundwater levels was performed in part of the undisturbed period (Veenstra , 2009). In Upper-Guadiana, data of more than one groundwater well were available. Some of the wells showed quite a poor correlation with simulated values, but the three wells with best correlations had r^2 values of 0.6, 0.54 and 0.43. Visual comparison indicated a good ability of the model to reproduce the general dynamics of the groundwater table, although in some cases low groundwater levels were overestimated. This is probably due to the influence of abstractions. However, inter-annual and intra-annual variation in groundwater levels were reproduced by the model (Veenstra , 2009).

Because the catchments used in this study were part of the WATCH project, other models, both conceptual and physically-based, were also applied (Van Loon et al. , 2011; Van Huijgevoort et al. , 2011). These models include ECOMAG (Narsjø), BILAN (Upper-Metuje, Upper-Sázava, Nedožery), FRIER (Narsjø, Upper-Sázava, Nedožery), and PROOST (Upper-Guadiana). The ECOMAG model showed similar behaviour for simulated soil moisture as HBV, but for groundwater ECOMAG was less well able to reproduce the temporal variability of the observations (Hohenrainer , 2008). The PROOST model had a comparable simulation of groundwater levels as HBV, only the low groundwater levels were not overestimated but underestimated (Van Loon et al. , 2011). For the BILAN and FRIER model we only studied discharge. The BILAN model gave in all catchments a very slow reaction to precipitation and therefore very long recessions (Oosterwijk et al. , 2009; Van Huijgevoort et al. , 2011). The FRIER model gave in all catchments a very fast reaction to precipitation and therefore very short recessions (Oosterwijk et al. , 2009; Van Huijgevoort et al. , 2011). We concluded that the selected other models did not have a better performance than HBV.

We agree with Dr. Woods that searching for a better model structure to simulate low flows is certainly one of the most important challenges in drought research. Staudinger et al. (2011) showed that currently it is still difficult to find a model structure that improves low flow simulation. In our research, we have tried several model structures within the HBV model. For example, for all catchments, the DELAY-model structure was tried, which only gave better results in the Upper-Guadiana catchment. Therefore, we have chosen to use the DELAY-model structure only in Upper-Guadiana and the STANDARD-model structure in all other catchments.

2.1.3 proposed action

We will add some sentences about the validation of state variables to the manuscript and refer to the scientific reports, which are available though the WATCH project website.

2.2 Point 2

2.2.1 comment Dr. Ross Woods

"Figure 14: it is not clear to me that all relevant climates can be ordered along the vertical axis, nor that all relevant climates have been included. The vertical axis is predominantly sorted by temperature, but not entirely; the introduction of precipitation to some classes make the axis harder to interpret. I am not clear where on this axis the authors would place the climate described as oceanic or maritime. Perhaps it is too much to hope that all climates can be placed within a single axis?"

2.2.2 reply authors

We agree with Dr. Woods that the vertical axis of Figure 14 is not unambiguous.

2.2.3 proposed action

We will adapt Figure 14, so that the climate types sorted by temperature and precipitation are on a separate axis. We trust that this increases readability of the figure.

3 Minor points

3.1 Point 1

3.1.1 comment Dr. Ross Woods

"Section 2.4 "Other land cover types are agriculture (23%), natural meadow (6%), and urban area (5%) (Oosterwijk et al., 2009). Human influence is very limited in this catchment." It seems unusual that 23% of the land is in agriculture, and yet human influence is very limited."

3.1.2 reply authors

The 23% agriculture mentioned for the Nedožery catchment is not cropland, but extensive grassland.

3.1.3 proposed action

We will use the same phrase as in Upper-Metuje and Upper-Sázava: “Human influence is limited to extensive agriculture."

3.2 Point 2

3.2.1 comment Dr. Ross Woods

“Section 2.5 “This makes it a slowly responding catchment with a relatively high base-flow.” Since the discharge is only 16 mm/y, I would perhaps rephrase this as “This makes it a slowly responding catchment, with most of the runoff discharged as base-flow.””

3.2.2 reply authors

Thanks for the suggestion.

3.2.3 proposed action

The phrasing will be changed.

3.3 Point 3

3.3.1 comment Dr. Ross Woods

“Section 3.2: “We applied a monthly threshold derived from the 80th percentile of the monthly duration curves.” Are the results sensitive to the choice of the 80th percentile? What if you had chosen the 90th?"

3.3.2 reply authors

The choice of a different percentile in the calculation of the threshold level will change the numbers in Table 3. For example, with a 90th percentile threshold, less droughts with shorter durations and lower deficit volumes and max.deviations are expected, and with a 70th percentile threshold the opposite. However, the relation between drought characteristics of the variables is not expected to change. Droughts will still get less and longer when propagating from precipitation, to soil moisture, to groundwater. This is shown, amongst others, by Oosterwijk et al. (2009).

Furthermore, the drought typology that is based on drought analysis will not change when using a different threshold, because the same processes that cause drought using an 80th percentile will be present when using a 90th or a 70th percentile. The distribution over the drought types (as shown in Table 4) might slightly change. When using a 90th percentile threshold, Table 4 might have slightly less droughts types with low deficit volume, e.g. *cold snow season drought*, and more with high deficit volume, e.g. *rain-to-snow-season drought* and *composite drought*. This change is expected to be comparable in direction (but smaller in magnitude) to the difference between Table 4 and 5.

3.3.3 proposed action

We propose no action on this point. Addition of a paragraph on the influence of different percentiles would extend the paper, but would not change the conclusions.

3.4 Point 4

3.4.1 comment Dr. Ross Woods

"Section 3.2 "A inter-event time period of 10 days was used for all catchments," Surely this time should vary with the response time of the catchment? Are the results sensitive to this choice?"

3.4.2 reply authors

The inter-event time period is quite a subjective parameter. A number of studies have been devoted to this choice (e.g. Tallaksen et al. (1997) and Fleig et al. (2006)). Yes, it is catchment-dependent and it should be optimised for each catchment separately. There is three reasons that we did not do this, i.e. i) the pooling method applied should be as simple as possible, ii) time constraints, iii) our results would not be influenced significantly.

Other options for pooling using the inter-event time criterion are the use of the inter-event excess volume and a combined method of inter-event time and inter-event excess volume (Madsen and Rosbjerg , 1995; Tallaksen et al., 1997). These methods are more complex, so we did not choose to use those.

Tallaksen et al. (1997) and Fleig et al. (2006) tested a number of inter-event time options for representative sample of catchments around the world (taken from a global

dataset) and concluded that the sensitivity curves generally start to level out around 5 days, and for most streams the deficit characteristics do not change substantially after 10 to 15 days, implying that a maximum of pooling is obtained. Other studies used a inter-event time period of 2 days (Engeland et al., 2004), 6 days (Tate and Freeman , 2000), and 30 days (Pandey et al., 2008). In this study, we have chosen 10 days, which is quite a conservative number. This minimizes the occurrence of dependent drought events, but should not include too long high peaks in a drought event. In each catchment, we did find one or two events that should have been pooled to previous events, but these are only few in comparison to total numbers of drought events of 27 to 60 (around 5%).

Just as for the previous comment choosing a different inter-event time duration would only slightly change the numbers in Table 3 and 4, and would not change the drought typology.

3.4.3 proposed action

We propose no action on this point, because adding a paragraph would extend the paper, but would not change the conclusions.

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