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Hydrology needed to manage droughts: the 2015 European case

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Introduction

It is generally accepted that drought is one of the most costly weather-related natural hazards. In 2015, a long-lasting drought hit Europe, particularly affecting central and eastern Europe. In some regions it was the driest (North Slovakia) and in others (Czech Republic and Poland) it was the second driest summer of the last 50 years (following 2003). Key questions are: (i) how extreme are these events, not only in terms of hydro-meteorological characteristics but also impacts? and (ii) how are these impacts managed?

Droughts often are viewed from a climatic perspective (e.g. Herring *et al.*, 2015; Heim, 2015), with their severity defined by the strength of the anomaly in meteorological conditions (e.g. sea surface temperature, geopotential height, precipitation or temperature). Normalized anomalies in climatic variables, such as the Standardized Precipitation Index (SPI, McKee *et al.*, 1993; WMO, 2006) and the more recently developed Standardized Precipitation–Evapotranspiration Index (SPEI, Vicente-Serrano *et al.*, 2010), have become standard tools to characterize drought. Although the SPI and SPEI have proved their applicability across a wide range of hydro-climatological regimes, there is a pressing need to monitor the impacts of climate and weather events in a more systematic way (Stahl *et al.*, 2016). Many drought-related impacts (e.g. crop yields, water-borne transport, aquatic ecosystems, water supply, energy production) are associated with hydrology rather than solely with weather. Hydrologically oriented drought studies have shown that drought in groundwater or streamflow (hydrological drought) deviates from meteorological drought (precipitation anomalies) (Changnon, 1987; Peters *et al.*, 2003; Vidal *et al.*, 2010; Hannaford *et al.*, 2011; Van Loon and Van Lanen, 2012; Van Dijk *et al.*, 2013). Hydrological drought is a complex phenomenon that integrates many river basin characteristics, such as (but not limited to) land cover, topography, geology and river network structure (Van Lanen *et al.*, 2013; Stoelzle *et al.*, 2014). Minor meteorological droughts may not show up as a hydrological drought, whereas a series of meteorological droughts can merge to form a long-lasting hydrological drought, which usually has a later onset and recovery. Hydrological drought has in most cases a smaller intensity than meteorological drought. The areas that are covered by the different drought types are also varying (Peters *et al.*, 2006; Tallaksen *et al.*, 2009). Additionally, water managers take actions in response to the (forecasted) impacts (e.g. water storage, abstractions, water transfers) in which hydrology plays a key role.

This commentary discusses how drought, from its origin as a meteorological anomaly, manifests itself as a deficiency in soil moisture and subsequently as a hydrological drought. Furthermore, the commentary emphasizes that better understanding and management of drought requires understanding this propagation of water deficits through the hydrological cycle, with consideration of the nature of the resultant impacts on socioeconomic and natural systems also of critical importance. Drought characterization from such a perspective requires concerted multi-disciplinary action from both the climatic and hydrological communities. Although some initiatives (Harding *et al.*, 2011; Schellnhuber *et al.*, 2013) are promising, more widespread and comprehensive action is necessary. We use the 2015 European drought as an example.

The 2015 European Drought

Meteorological conditions

The summer (June – August) of 2015 was characterized by daily maximum temperatures 2 °C higher than the seasonal mean over most of western Europe, and more than 3 °C higher in central Europe (Figure 1a). Large parts of Europe also experienced a severe lack of rainfall and higher evapotranspiration than normal, with negative values of the three-month standardized precipitation–evaporation anomaly (SPEI3) from June onwards across a widespread area. Summer SPEI3 values dropped to as low as −4 in central and eastern Europe (Figure 1b).

Similar to the extreme 2003 summer drought, upper level atmospheric circulation over continental Europe was characterized by a large, positive 500-hPa geopotential height anomaly (Z500; Figure 1c). Positive anomalies first occurred in March, and persisted throughout the summer. This high pressure blocking pattern over Europe prevented the flow of moisture and precipitation across much of Europe. During summer, the positive European anomaly was bordered by a large negative Z500 over the central North Atlantic Ocean, extending to northern Scandinavia. Summer sea surface temperature (SST) was characterized by large negative anomalies in the central North Atlantic Ocean (with the peak difference approximately co-located with the peak Z500 difference), and large positive anomalies in the Mediterranean basin (Figure 1d). The 2015 negative Atlantic SST (JJA) anomaly was within the top 10 coldest summers in this region in the ERSST v4 record extending back to 1854.

Vegetation response

Vegetation stress in summer 2015 (anomaly of absorbed photosynthetically active radiation; Figure 2) displayed similarities to the SPEI pattern (Figure 1b), but also with obvious differences. At the end of June, only some scattered areas with vegetation stress occurred, mainly in eastern Europe (Ukraine, Romania, Balkan Adriatic

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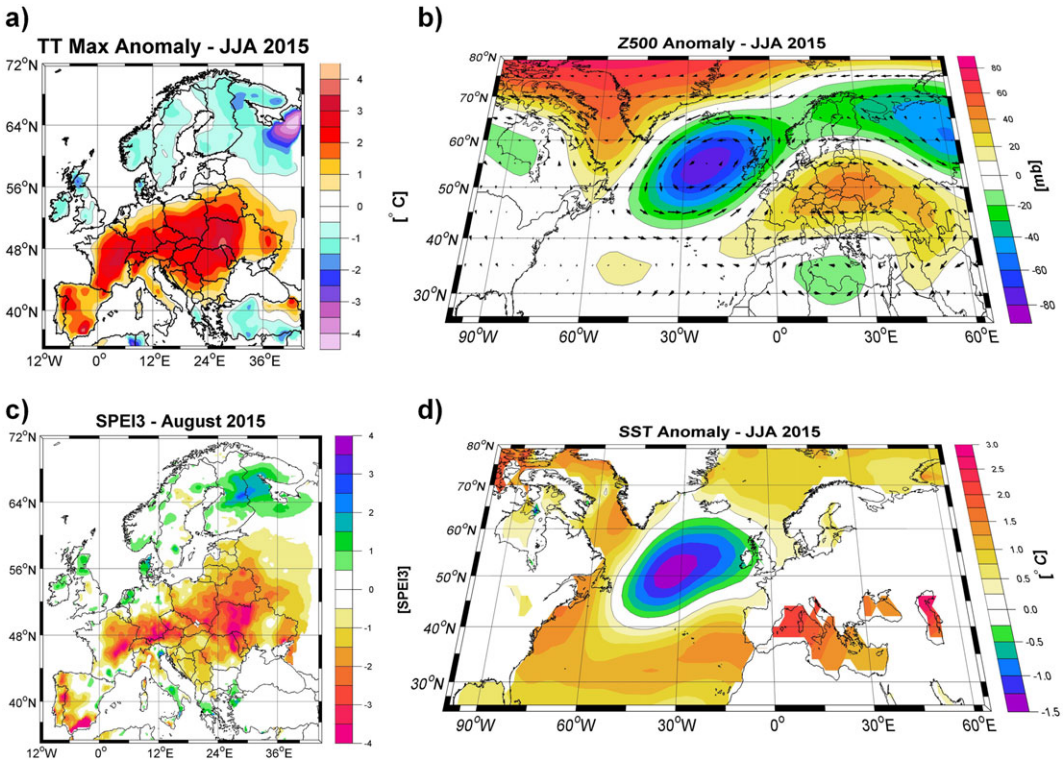


Figure 1. Summer 2015: a) maximum temperature anomalies, E-OBS (Haylock *et al*., 2008), b) precipitation-evaporation anomalies, SPEI3 values; c) 500-hPa geopotential height anomalies, NCEP/NCAR reanalysis (Kalnay *et al*., 1996) and d) SST anomalies, ERSST v4 (Huang *et al*., 2014; Liu *et al*., 2014). The anomalies in panels a, c and d are computed relative to the period 1971 – 2000. The SPEI is calculated following Stagge *et al*. (2015). All variables are averaged over JJA

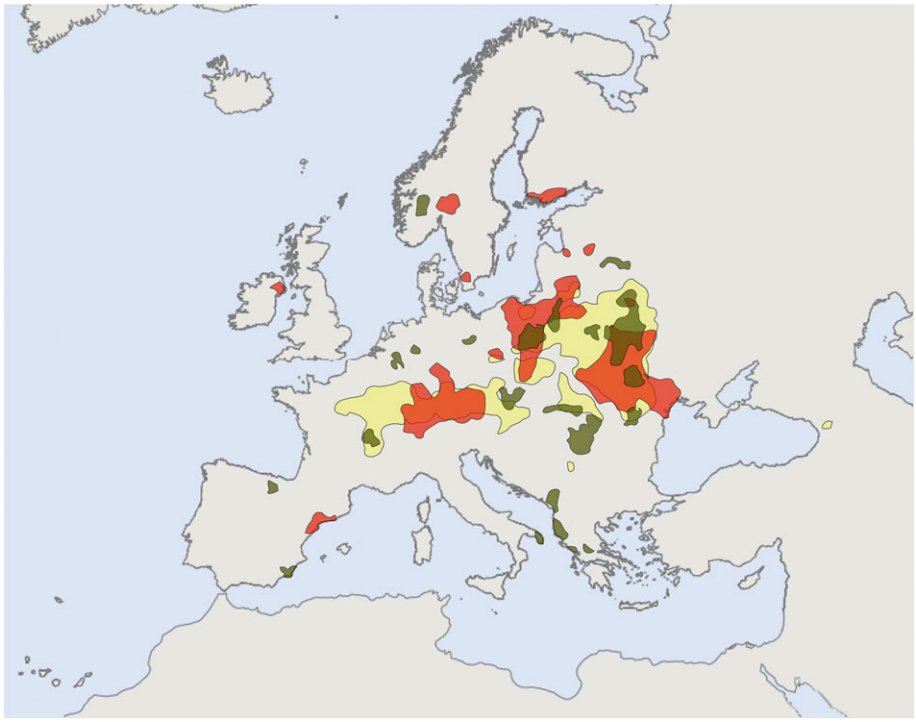


Figure 2. Vegetation stress in the last 10 days of June (green), August (yellow) and October (red). Envelopes were drawn around main areas with pixels classified in an alert phase (derived from the European Drought Observatory; source: http://edo.jrc.ec.europa.eu/edov2/; Sepulcre-Canto *et al*., 2012)

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coast). In August, these areas combined into a west-east zone stretching from central France into Ukraine and Belarus. In October, the west-east zone divided into three core regions: southern Germany, Poland and Ukraine, and some new areas (Latvia, northern Europe) in response to a precipitation deficit that developed in early autumn (not shown). In all cases, the area affected by vegetation stress was substantially smaller than the area experiencing moderate meteorological drought (SPEI < -1, Figure 1b), although they occupied similar regions.

Hydrological response

Low flow and drought characteristics were computed from about 800 daily streamflow time series across Europe (Laaha *et al.*, 2016). The return period of the 7-day minimum flow in 2015 was determined for each month (Figure 3). In June, most gauging stations showed streamflow with return periods <2 years (Figure 3a), with a few exceptions (mostly <5 years). Although SPEI3 ≤ -1 in June occurred in a wide west-east band from the Benelux into Belarus and Ukraine (not shown), low flows remained in the normal range. In August, low flows became more extreme (Figure 3b) in a southwest-northeast zone north of the Alps. Particularly in central Europe (Czech Republic, Poland, southern Germany, northern Austria) and also France, the return period of the 7-day minimum flow increased to more than 50 years. In the Czech Republic and Poland (e.g. Vistula) many rivers recorded the lowest flow on record. Some recovery was seen in the autumn, but low flows were still extreme (return period >20 years) in southern Germany, southwestern Poland and the Czech Republic (Figure 3c).

Return periods for drought duration (the period that streamflow is below flow equaled or exceeded 80% of the time over the period 1976–2010) are presented in Figure 3d. Drought characteristics could not be fully established for 2015, because for many gauging stations flow by the end of the autumn was still below the drought threshold. A typical feature of the 2015 drought was its long duration. For instance, one of the major rivers in Europe, the Rhine at the Dutch–German boundary, faced the longest running low flow period since the 1976 benchmark drought. Return periods in drought duration of more than 20 years were mainly seen in central Europe. The flow analysis showed that the drought followed the SPEI3 JJA pattern, but that the hydrological response was delayed through drought propagation and that local differences occurred because of catchment storage processes and antecedent conditions.

Impacts

The impacts of the 2015 drought were manifold across Europe, as derived from various text sources (e.g. reports, websites). The wide range of impacts is not uncommon as illustrated for previous events by the European Drought Impact Inventory, EDII (Stahl *et al.*, 2016). In some central and eastern European regions the impacts continued even into 2016. No drought impacts were reported in Scandinavia and the UK, which matches the drought pattern in Figures 1–3.

The vegetation stress (Figure 2) induced by excessive heat and soil water drought led to lower crop yields. For example, crop losses of up to 50% were reported in the Czech Republic, Germany, Poland and Slovakia for sugar beet and potatoes, while maize was unable to build cobs in some regions. The drought also had a significant

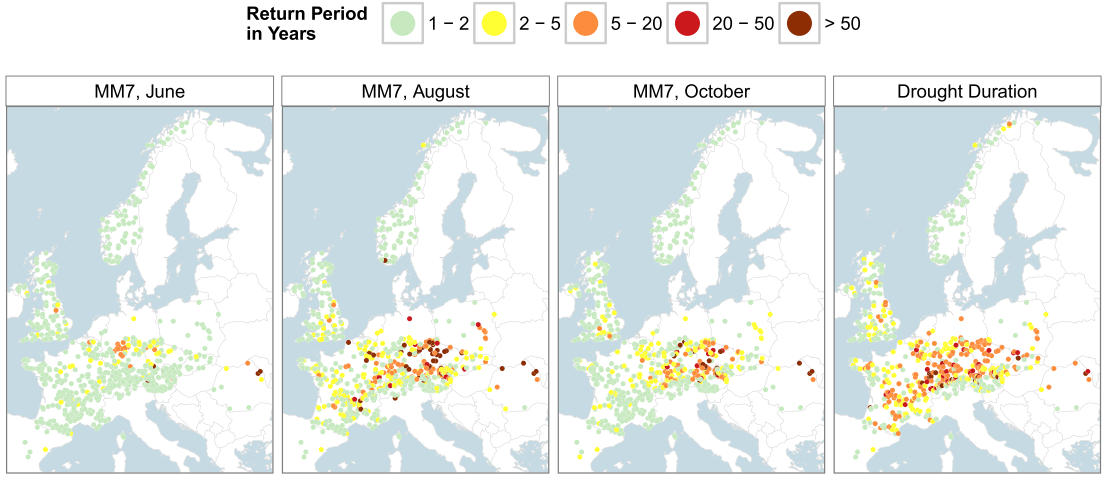


Figure 3. Selected catchments across Europe showing the return period (years) of: a–c) monthly 7-day minimum flow in June, August and October 2015, respectively, and d) drought duration

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impact on livestock farming, with a 50% lower hay harvest (Czech Republic), failing grass cuts (Germany, Slovakia) and substantially lower milk production (Slovakia and Romania). Czech authorities have estimated that the impact of the 2015 drought on agriculture amounts to € 50–100 million. The drought also led to worst summer for Czech firefighters in at least the last ten years, with almost twice as many fires as in 2014. In Austria the drought caused an exceptionally long wildfire season, lasting until the end of 2015.

The hydrological component of the 2015 drought (Figure 3) had an impact on a wide range of sectors, including water supply, energy production, waterborne transportation, freshwater aquaculture and fisheries, water quality, fresh water ecology, tourism and recreation. A summary of these impacts follows. Across central Europe and parts of eastern Europe (e.g. Romania) hundreds of towns and villages faced drinking water supply deficiencies. In southern Germany, boreholes dried up in crystalline rocks leading to water supply shortages for cattle. In eastern Romania record-low groundwater levels were registered and because of groundwater overexploitation water quality deteriorated.

Low flows and associated high water temperatures caused reduced energy production along rivers in southern Germany, Czech Republic, Poland and European Russia. Some hydropower stations had to be shut down: in the northeast Czech Republic the majority of small hydropower plants were out of service for four months. In August, 1600 of the biggest companies in Poland suffered from power restrictions. French and Czech hydropower production was 30–50% lower than normal in some summer and autumn months. Similar reductions were reported for one of the main hydropower stations in the downstream part of the Don River (Russia).

The 2015 drought significantly impacted water-borne transportation, notably in France, Germany and European Russia. In Germany, load losses on the Rhine, Danube, Elbe, Oder and Weser Rivers and in Russia on the Don River were up to 50%.

The drought and associated heat triggered oxygen deficits and high temperatures in surface water bodies in Germany, Slovakia and European Russia, which influenced freshwater aquaculture and fisheries (lower fish yields), while causing other water quality issues (blue–green algae blooms and botulism). Dried-up fish breeding grounds and dying fish were reported in several central and eastern European countries. Fresh water ecosystems in the Czech Republic were also impacted by hydropower plants; 25% of the small plants could not comply with the ecological minimum flow standard. Violation of environmental flow requirements in upstream headwaters also happened in Germany.

Tourism and recreation were impacted in several countries because low reservoir and river levels restricted leisure activities in these water bodies. Access to forests was also restricted because of the high fire risk.

The impacts of the 2015 drought were also felt beyond the core region in central and eastern Europe. For example, in Belgium and the Netherlands a 1-in-20 year meteorological drought occurred from April to August. Some early crops (such as potatoes) had yield losses of up to 30%. Low flow in the major Dutch rivers caused salt water intrusion in the river mouths over tens of kilometres, affecting fresh and brackish water ecosystems. Water-borne transport in the Netherlands was strongly impacted. The shallow water depth affected transport until late November (with up to 50% cargo losses in the autumn), mainly because of little river inflow from upstream (Switzerland and southern Germany). Shrinkage of old peat dikes caused cracks leading to increased flood risk in the Netherlands. In the autumn many houseboats were sitting askew on dry stream bottoms because of the unprecedented low water levels.

Drought management

Surface water and reservoirs are particularly important means to manage a drought. For instance, in the Czech Republic, reservoirs were 90% full at the start of the 2015 summer. During the drought event, reservoirs were emptied to provide direct water and to increase low flows downstream. Reservoir storage remained above 30% with a few exceptions, but most reservoirs were still in decline at the end of October 2015, which had not happened since 2003. In the eastern part of Romania, the volume of some large inter-annual regulation reservoirs was also very low (remaining storage: about 30%) at the end of 2015. In northeastern France, reservoirs used for sustaining low flows had their available volume below the 1-in-10 year level in early September. In Germany, record water transfers from the Danube to Main basins were implemented for low flow augmentation. In the Dutch lowlands, surface water levels were raised to conserve water.

Some canals or sections in northeastern France were closed to water-borne transportation for several months, not re-opening until the end of 2015. Transport in Romania also faced restrictions. In the Netherlands, boats had to cope with more costly lock operations. Special measures were implemented in the main river network until the end of the autumn as a response to the low inflow from upstream.

In many European regions crops were irrigated when possible. Record irrigation of corn and tobacco was

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reported in the Upper Rhine Valley in Germany. In contrast, water abstraction restrictions were in place in 70 French departments in early August, which enforced a complete water abstraction ban for all non-priority uses, including irrigation. In early November some crisis orders were still active in Burgundy. In the Netherlands there were bans on abstraction of surface water for irrigation to avoid deterioration of water quality until mid-August when rain caused relief. Locally, in the Czech Republic, Poland, Slovakia and southern Germany tank trucks were ordered to fill reservoirs in municipalities with water supply deficiencies because of low inflow from local springs. Many municipal councils banned water use for watering gardens, swimming pools or washing cars.

Additional flushing of the regional surface water system in the Netherlands using water from the main rivers occurred to avoid further salinization. Emergency pumps were installed to reroute surface water and in other places surface water was blocked from flowing into certain streams to avoid further deterioration of water quality. Various water inlets were closed to avoid spreading of blue–green algae. Natural swimming baths were closed (Germany, the Netherlands) due to the deteriorated water quality (blue–green algae bloom and botulism). Resettlement of fish was reported in Germany, Czech Republic and Slovakia. Aquaculture had increased costs for extra oxygenation.

Various measures were also taken for human health and public safety reasons. In German, Dutch Slovak and Romanian cities, additional water was required for watering parks to avoid further development of the urban heat island and to maintain aesthetic value. In Bratislava and Bucharest, water tanks were used to supply tourists and city inhabitants at selected points. The Dutch Water Boards had to frequently inspect 3500 km of drought sensitive peat dikes and to irrigate in case of drought cracks.

Discussion and Conclusions

As shown for the 2015 European event, drought impacts are largely connected to soil water drought (crop yield, wildfires) or to hydrological drought (water supply, energy, transportation, recreation, water quality) rather than directly to the meteorological drought. This implies that knowledge of hydrology, i.e. the propagation of meteorological drought into a hydrological drought, including the role of antecedent water storage, is needed to understand drought impacts. It is also illustrated that stakeholders and water managers respond to impacts by taking measures (e.g. irrigation, water abstractions, use of reservoir storage, rerouting, transfers, conservation) to mitigate impacts, but which can also enhance impacts elsewhere (Van Dijk *et al.*, 2013; Van Loon *et al.*, 2016). Enhancement of impacts typically involves ecological minimum flows that cannot be sustained because of upstream water use. During droughts there is a high pressure on groundwater resources and in several regions more groundwater is abstracted than recharged (e.g. Castle *et al.*, 2014; Panda and Wahr, 2015), leading to undesirable impacts (e.g. reduced groundwater flow to riparian areas and rivers). However, reports on declining groundwater tables are not everywhere available, or no separation is made between impacts due to the drought itself as compared to abstractions due to increased groundwater exploitation, as advised by Van Loon and Van Lanen (2013).

The need for an enhanced hydrological perspective in terms of understanding and managing drought impacts requires urgent action. First, the European water sector should make near-real time hydrological data as readily available as meteorological data (Haylock *et al.*, 2008; Hannah *et al.*, 2011). Currently, large-scale observed flow data become available not earlier than a year after measurement (Global Runoff Data Centre, www.bafg.de/GRDC/EN), which forces experts to resort to simulated flow for pan-European studies (e.g. Gudmundsson and Seneviratne, 2015). Furthermore, drought impacts and response measures (including their success rate) should be archived, for example using the European Drought Impact Inventory (Stahl *et al.*, 2016). Second, multi-monthly and seasonal drought forecasting should be improved beyond the currently available 10 or 14-day forecasted atmospheric indices and soil water anomalies. Some encouraging initiatives at the national scale are ongoing, as reported by the Hydrological Ensemble Prediction Experiment (HEPEX) community. For example, Prudhomme (2015) presented the first operational forecast system for Great Britain that delivers an outlook of 1 to 3 months for river flow and groundwater levels. Promising results on the forecasted 7-day minimum flow for major German waterways were also shown by Meißner *et al.* (2015), which are based upon the seasonal correlation between global oceanic and climatic data, soil moisture and low river flow (Ionita *et al.*, 2008; 2015). Third, drought monitoring and forecasting should be embedded in drought policy. Wilhite (2014) provides a template for action, which in Europe could improve the drought chapter in the River Basin Management Plans.

Managing drought in a pro-active way requires a concerted action of the hydrological and climatic communities. Such action should include pan-European monitoring of hydro-meteorological variables and multi-monthly and seasonal forecasting of both climatic and hydrological variables. Furthermore, impact assessments and exploration of potential promising measures to reduce impacts (considering context specific condi-

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tions at the river basin scale) represent a critical research direction for drought impact mitigation.

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