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The effect of reservoir networks on drought propagation

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Abstract: Human interventions in response to drought can both alleviate and enhance drought. Developments of infrastructure for freshwater storage, groundwater abstraction and irrigation have proved to be effective in overcoming meteorological and agricultural drought in many locations worldwide. At the same time such developments may exacerbate hydrological drought, especially during and following extended periods of (meteorological) drought. In order to effectively manage drought, there is an urgent need to better understand and evaluate the drivers of such events. This means that we need to separate between human and natural factors that affect hydrological processes in basins. In this paper, we demonstrate how the Downstreamness concept can be used for Drought Diagnosis. This is done for a subcatchment of the Jaguaribe basin in Northeast Brazil. Our diagnosis focuses on the propagation of three severe multi-year droughts that have developed during the period 1979-2016. Our study shows how a network of surface water storage reservoirs has affected the propagation of drought. Applying the proposed approach is helpful for the spatiotemporally-explicit assessments of droughts and their propagation. Strategic and operational water (and drought-risk) management relies on valuations of trade-offs between commitments of upstream and downstream uses and technical implementations of upstream and downstream measures. Our study offers valuable insights through the inclusion of sub-basin points of view as an integral part of a river basin perspective. In this way, the effects of anthropogenic processes affecting drought propagation can be better understood.

Key words: Drought propagation, Downstreamness, Jaguaribe basin, Brazil

1. INTRODUCTION

Drought refers to a below-average anomaly of selected variables and occurs when a deficiency of precipitation over some period of time results in a water shortage for human and natural purposes. Determining the magnitude and duration (from onset to demise) of droughts is not straightforward. Different types of drought include meteorological, soil moisture, hydrological, socioeconomic and ecological drought (NDMC, 2017). Hydrological drought may materialize by low levels of streamflow and stored volumes. Hydrological drought typically follows meteorological drought, and there can be a time-lag between them (NDMC, 2017). Water can be stored in surface water storage reservoirs, ranging from large public dams (WCD, 2000) to a multitude of small privately owned dams, often designed to overcome periods of water deficit. The use of reservoirs may lead to smoothed hydrographs, with lower peak flows and higher low flows. Thus, to some extent, the effect of increased water use can be compensated by river regulation using reservoirs (Wanders and Wada, 2015). To improve our understanding of the effects of human activities on the development and propagation of drought (either positively or negatively) new statistical and modelling tools are needed (Van Loon et al., 2016).

In this paper we assess the influence of a network of surface water storage reservoirs on the propagation from meteorological to hydrological drought for a subcatchment of the Jaguaribe basin in Brazil. This is done by using the Downstreamness concept (Van Oel et al., 2011).

2. METHODS

A common indicator of meteorological drought is the Standardized Precipitation Index (SPI;

McKee et al., 1993). For analysing hydrological drought the Standardized Streamflow Index (SSFI) can be used. For the definition drought we have adopted the definition proposed by McKee et al. (1993) for both SPI and SSFI. This means that a period in which the SPI (or SSFI) is continuously negative and the SPI reaches below a value of -1. The drought begins when the SPI first falls below zero and ends with the positive value following a value of -1 or less (McKee et al., 1993). Drought magnitude (DM) is defined as the negative summation of SPI (or SSFI) for all months of the drought (McKee et al., 1993). To account for the effect of seasonal variations a 'running' 12-month SPI and SSFI values are used.

Our approach comprises three steps, as described below. The case study that is used to illustrate our approach is first introduced.

2.1 Case study description

The semi-arid Northeast of Brazil has a history of recurrent water stress (Gaiser et al., 2003; Guerra and Guerra, 1980), which is related to both rainfall variability and human intervention. Annual precipitation is characterized by high levels of temporal and spatial variability (FUNCEME) and is concentrated from January to June. In the area reservoirs of various sizes are so numerous (thousands), that their effect on basin hydrology is significant (de Araújo and Piedra, 2009; Van Oel et al., 2008). High reservoir densities (exceeding three times average annual runoff) in the area have led to reduced hydrologic sustainability (Malveira et al., 2011; Mamede et al., 2012). The largest reservoirs are monitored by Water Agencies, such that changes in volumes over time can be analysed. For this study the catchment of the streamflow gauging station in Morada Nova (sub-catchment of the Jaguaribe basin in Ceará) was selected (Figure 1). For this study all data (precipitation, streamflow and reservoir storage) were obtained from FUNCEME, the Organization for Meteorology and Water Resources for the State of Ceará (Fundação Cearense de Meteorologia e Recursos Hídricos).

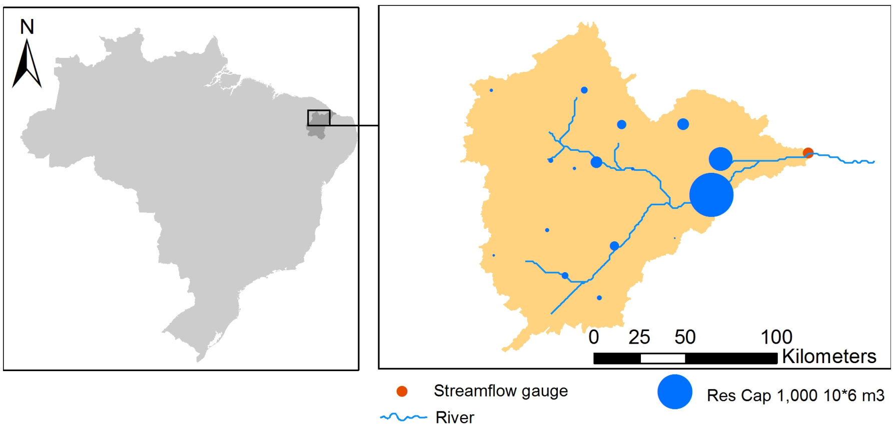

Figure 1. The sub-catchment of the streamflow gauging station Morada Nova, located inside of the Jaguaribe basin in Ceará, Northeast Brazil. Also reservoirs which are monitored by Water Agencies have been indicated.

2.2 Step 1: Calculation of the running 12-month SPI and SSFI

For showing meteorological drought in the catchment area of a streamflow gauging station the 'running'12-month SPI is determined from a time series of precipitation data at the level of the entire catchment area. Thiessen polygons are used for interpolation monthly values of multiple stations for a representative period. To determine the SPI a downloadable program was used (NDMC, 2017). For showing hydrological drought in the catchment of the same streamflow gauging station the 'running'12-month Standardized Streamflow Index (SSFI) was determined using the same program as for SPI (NDMC, 2017).

2.3 Step 2: Evaluation of drought propagation in time

To show how drought propagation behaves over time 12-month SPI and 12-month SSFI for the end of the wet season (the month of June in our case) were compared for selected periods of drought. In this way it was explored how meteorological drought compares to hydrological drought for selected periods of time.

2.4 Step 3: Explanation of drought propagation using information on storage

For the catchment area (upstream of the Morada Nova streamflow gauging station) it is determined how the Downstreamness (Van Oel et al., 2011) of upstream stored volumes and storage capacity have developed over time. The findings of this analysis have been used to explain the propagation of drought. Every location x in a catchment can be characterized by the size of its upstream area. To indicate the relative positioning in the context of the entire catchment area, the upstream area, $A_{up;x}$, is divided by the total catchment area of the river basin, A_{tot}. The fraction determined is called Downstreamness (Van Oel et al., 2011), D_x:

$$D_x = \frac{A_{up,x}}{A_{tot}} \times 100\% \tag{1}$$

The Downstreamness of a function on the basin is defined as the Downstreamness-weighted integral of that function divided by the regular integral of that function. For a function defined on a discrete set of locations in the basin, the Downstreamness is similarly defined as the Downstreamness-weighted sum of the function divided by the regular sum (e.g., Eqs. 2, 3).

In this study, the Downstreamness of storage capacity (D_{SC}) and stored volume (D_{SV}) are defined as in equations 2 and 3, respectively. By comparing the Downstreamness of storage capacity to the Downstreamness of actual stored volumes, one can evaluate how stored volumes are allocated over the storage facilities included in the analysis.

$$D_{SC} = \frac{\sum_{x=1}^{n} SC_x D_x}{\sum_{x=1}^{n} SC_x} \tag{2}$$

$$D_{SV} = \frac{\sum_{x=1}^{n} SV_x D_x}{\sum_{x=1}^{n} SV_x} \tag{3}$$

3. RESULTS

3.1 Meteorological and hydrological drought

Figure 2 shows the development of meteorological drought (running 12-month SPI for the catchment) and hydrological drought (running 12-month SSFI at the Morada Nova streamflow gauging station) for the period December 1979 – June 2016. From Figure 2 it can be seen that SPI and SSFI do not coincide for this area. For certain periods of (meteorological) drought the hydrological drought is mitigated (or even avoided). However, following periods of meteorological drought, extended periods of hydrological drought take place. This is clearly seen for the (meteorological) droughts starting in 1992, 1998 and 2012.

3.2 Propagation of drought in time

One way of representing human-modified drought is to compare the values of SPI and SSFI for periods of drought directly (Figure 3). It is clear that for the first two periods shown, years with low

SPI values and low SSFI values are followed by years of above-average SPI and low SSFI. The periods of 1990-1996 and 1997-2003 show similar patterns. For the drought period that started around 2010 one would expect to observe a similar pattern, unless a flood event would take place such as happened in 2004.

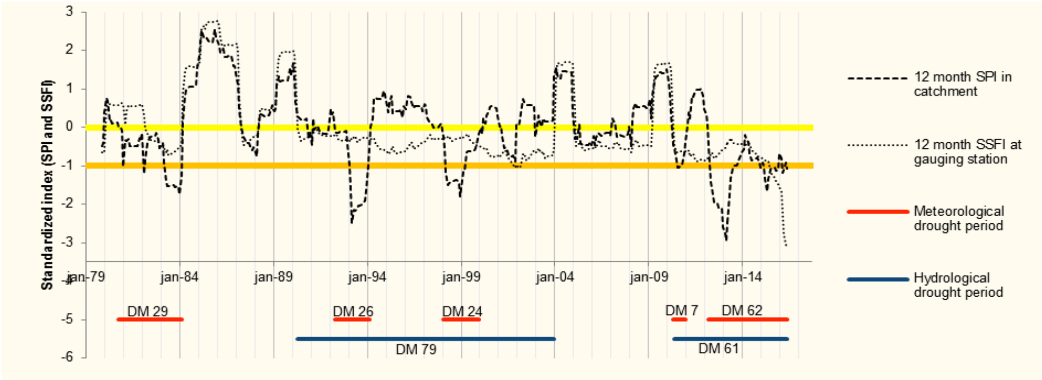

Figure 2. Drought profile for the catchment upstream of the Morada Nova Streamflow gauging station: SPI based on a Thiessen-interpolated time-series of monthly rainfall values for the catchment area; SSFI based on a time-series of streamflow values for monthly values at the Morada Nova Streamflow gauging station; Stored volumes in surface water reservoirs upstream of the gauging station. For periods of hydrological and meteorological drought the Drought Magnitude (DM) is been indicated

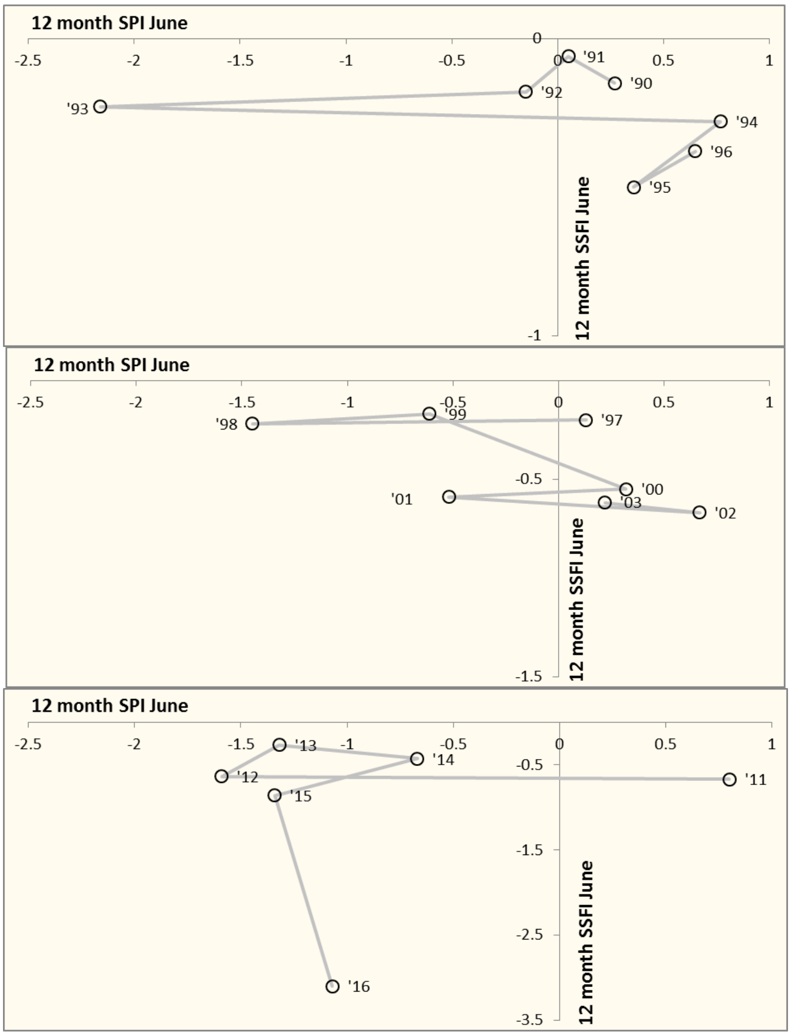

Figure 3. Morada Nova human-modified drought diagram. Periods with low values for both SPI (12 month SPI for June) and SSFI (12 Month SSFI for the month of June) are followed by periods with higher SPI and low SSFI.

3.3 Downstreamness of storage capacity and stored volume

For the catchment of the Morada Nova streamflow gauging station meteorological drought (e.g. 1998-1999) led to a drop in reservoir volumes. Then, when it started raining (moderately) again (2000, 2001) a stabilization of reservoir volumes took place. However, this situation coincided with a drop in the Downstreamness of stored volumes (Figure 4). This means that the water that was stored in the basin was mostly stored in reservoirs located in relatively upstream locations. In fact, the largest reservoir located furthest downstream almost ran empty. The effect of this imbalance was the human-modified drought (or extended hydrological drought), continuing until 2003. During this period it was not possible to generate streamflow of the same level as during the meteorological drought (1998-1999) because of the relatively low volumes in the reservoir located furthest downstream. In fact, a flood (2004) was required to restore the balance. Between 2004 and 2014 a situation existed in which the Downstreamness of stored volumes and storage capacity were around the same level (Figure 4). However, from 2014 onwards a drop in Downstreamness of stored volume is observed again. This time, even more articulated than the previous one. This makes it very well possible that an extended period of hydrological drought will follow, unless a significant flood event occurs, such as the one in 2004.

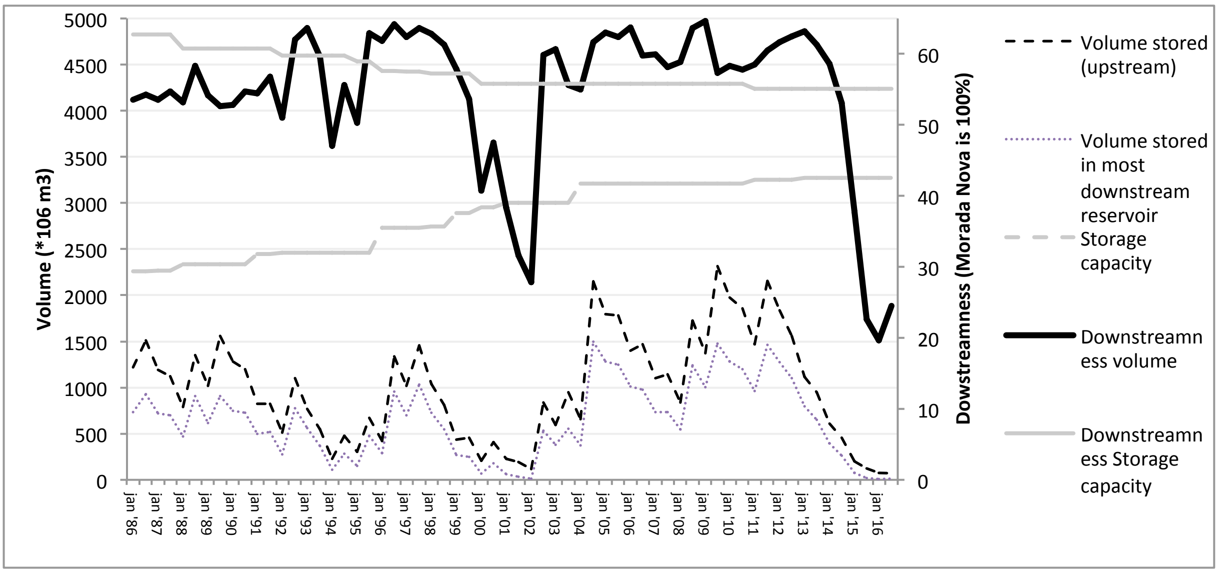

Figure 4. Downstreamness of the surface water storage capacity (solid grey line), stored volume (solid black line) in the catchment of the Morada Nova gauging station as it developed over the period 1986-2016.

4. DISCUSSION

This study provides an approach to investigate the effect of a reservoir network on drought propagation. In human-modified systems there can be enlarged differences between meteorological and hydrological, as shown in this paper. Additional information can be obtained from using the Downstreamness concept. Our results show clear indications that the present ongoing drought could be extended for many years to come. That is, unless a substantial flood will restore the balance in storage and thus ends the hydrological drought.

The datasets used to determine SPI and SSFI do not take into account changes in the anthropogenic influence over time. This can lead to a skewed distribution in which hydrological drought in early years remains undetected because of the severity of the later droughts.

The process of overbuilding basins, that is to increase reservoir density well-beyond average annual runoff is associated with basin closure (Molle et al., 2010). This process of overbuilding is only for a limited part initiated by organizations involved in planning and management of large-scale infrastructure. In this study we only took into account such large-scale infrastructure (large dams). So our view is limited. In reality the situation could even be much more skewed to upstream, since a huge amount of small reservoirs is installed and managed by farmers acting according to local irrigation needs, particularly during droughts (Mamede et al., 2012), which can be considered to be less sustainable under drought conditions (Krol et al., 2011). A long-term period of human-induced hydrological drought may persist which may only be overcome by extreme anomalies in terms of flooding. Next to physical factors (ground water deficits, dry soils), also perverse incentives may play a role. During periods of scarcity at the basin level, water use may increase (Van Oel et al., 2008) and investments in additional storage capacity may be done. Also investments in modern irrigation technologies often prove to be less effective at a basin scale than on a local scale (Berbel et al., 2014).

5. CONCLUSION

By analysing data on precipitation, streamflow, surface water storage capacity and stored volumes, using the Downstreamness concept the effect of a network of reservoirs on drought propagation was assessed. For our case study area it was found that hydrological drought can continue well beyond meteorological drought due to a skewed distribution pattern of stored volumes towards upstream locations. Explaining the occurrence of this process can be used to inform decision-makers in predicting the severity of an ongoing drought. In this way meteorological predictions can be better interpreted and become more useful for drought risk management and strategic water resources management.

REFERENCES

Berbel, J., Gutiérrez-Martín, C., Rodríguez-Díaz, J. A., Camacho, E., Montesinos, P. (2014). Literature Review on Rebound Effect of Water Saving Measures and Analysis of a Spanish Case Study. Water Resources Management, 29(3), 663-678

de Araújo, J. C., Piedra, J. I. G. (2009). Comparative hydrology: Analysis of a semiarid and a humid tropical watershed. Hydrological Processes, 23(8), 1169-1178

Gaiser, T., Krol, M., Frischkorn, H., Araújo, J. C. (eds.) (2003). Global change and regional impacts: water availability and vulnerability of ecosystems and society in the semi-arid northeast of Brazil. Springer, Berlin, Germany

Guerra, P., Guerra, T. (1980). Seccas contra as seccas. Vol. 29, Mossoro, Brazil

Krol, M. S., De Vries, M. J., Van Oel, P. R., De Araújo, J. C. (2011). Sustainability of Small Reservoirs and Large Scale Water Availability Under Current Conditions and Climate Change. Water Resources Management, 25(12), 3017-3026

Malveira, V. T. C., Araújo, J. C. D., Güntner, A. (2011). Hydrological Impact of a High-Density Reservoir Network in Semiarid Northeastern Brazil. Journal of Hydrologic Engineering, 17(1), 109-117

Mamede, G. L., Araújo, N. A. M., Schneider, C. M., De Araújo, J. C., Herrmann, H. J. (2012). Overspill avalanching in a dense reservoir network. Proceedings of the National Academy of Sciences of the United States of America, 109(19), 7191-7195

McKee, T. B., Doesken, N. J., Kleist, J. (1993). The Relationship of Drought Frequency and Duration to Time Scales. 8th Conference on Applied Climatology, American Meteorological Society, Boston, USA

Molle, F., Wester, P., Hirsch, P. (2010). River basin closure: Processes, implications and responses. Agricultural Water Management, 97(4), 569-577

NDMC (2017). National Drought Mitigation Center. Retrieved from http://drought.unl.edu/Home.aspx

Van Loon, A. F., Gleeson, T., Clark, J., Van Dijk, A. I. J. M., Stahl, K., et al. (2016). Drought in the Anthropocene. Nature Geoscience, 9(2), 89-91

Van Oel, P. R., Krol, M. S., Hoekstra, A. Y. (2011). Downstreamness: A Concept to Analyze Basin Closure. Journal of Water Resources Planning and Management, 137(5), 404-411

Van Oel, P. R., Krol, M. S., Hoekstra, A. Y., de Araujo, J. C. (2008). The impact of upstream water abstractions on reservoir yield: the case of the Oros Reservoir in Brazil. Hydrological Sciences Journal-Journal Des Sciences Hydrologiques, 53(4), 857-867

Wanders, N., Wada, Y. (2015). Human and climate impacts on the 21st century hydrological drought. Journal of Hydrology, 526, 208-220

WCD (2000). Dams and development: A new framework for decision making. Earthscan, London, UK