Propagation from meteorological to hydrological drought in the Horn of Africa using both ~~standardized~~standardised and threshold-based indices

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Abstract

There have been numerous drought propagation studies in data-rich countries, but not much has been done for data-poor regions (~~e.g.,~~such as the Horn of Africa (~~[~~HOA)~~]~~). In t~~T~~his study, we characteris~~z~~e~~s~~ meteorological, soil moisture~~,~~ and hydrological droughts and the propagation from one to the other for 318 catchments in the HOA to improve ~~the~~ understanding of the spatial variability of the ~~the~~ drought hazard. We calculate the ~~Standardized~~Standardised Precipitation Index (~~[~~SPI)~~]~~, ~~Standardized~~Standardised Soil Moisture Index (~~[~~SSMI)~~],~~ and ~~Standardized~~Standardised Streamflow Index (~~[~~SSI)~~]~~. ~~Additionally~~In addition, we use the variable threshold method to calculate the ~~drought~~ duration of drought below a predefined percentile threshold for precipitation, soil moisture~~,~~ and discharge. The relationship between meteorological and soil moisture is investigated by finding the SPI accumulation period that has the highest correlation between SPI and SSMI and the relationship between meteorological and hydrological drought is analysed by the SPI accumulation period that has the highest correlation between SPI and SSI time series. Additionally, we calculated these relationships with the ratio between the threshold-based meteorological drought duration and soil moisture drought duration, and the relation between threshold-based meteorological drought duration and streamflow drought duration~~The relationship between meteorological, soil moisture, and hydrological drought is examined by finding the SPI accumulation period that shows the highest correlation between SPI and vs SSMI, and SPI and vs SSI timeseries. A, and , by calculating the ratio between the threshold-based precipitation drought duration and vs soil moisture drought duration, respectively meteorological drought duration vs streamflow drought duration is calculated~~.~~.~~ Finally, we investigate the influence of climate and catchment characteristics on these propagation metrics. The ~~R~~results ~~indicate~~ show that (1) the propagation from SPI to SSMI and the mean drought duration ratio of meteorological ~~precipitation~~ to soil moisture (~~[~~P/SM) ~~] mean duration ratio~~ are mainly influenced by soil properties and vegetation, with the short accumulation periods (1~~-~~ to 4 months) of SPI ~~found~~ in catchments with ~~cropland~~arable land, high mean annual precipitation, and low sand and silt content, while longer accumulations (5 to ~~-~~7 months) are ~~found~~ in catchments with low ~~upstream mean annual precipitation~~mean annual upstream precipitation~~,~~ and shrub vegetation~~ation~~; (2) the propagation from SPI to SSI and precipitation to streamflow duration ratio are highly influenced by the climate and catchment control, i.e., geology, elevation and land~~-~~cover, with the short accumulation times in catchments with high annual precipitation, volcanic permeable geology, and cropland, and the longer accumulations in catchments with low annual precipitation, sedimentary rocks and shrubland; and (3) the influence of ~~upstream mean annual precipitation~~mean annual upstream precipitation is more important for the propagation from SPI to SSI than from SPI to SSMI. Additionally, precipitation accumulation periods of approximately 1 to ~~-~~4 months in wet western areas of HOA, and of approximately 5 to ~~-~~7 months in the more dryland regions are found. This can guide forecasting and management efforts as different drought metrics are thus of importance in different regions. ~~, which is useful information for management because of their more direct relation to impacts.~~

1 Introduction

The~~re are many droughts in the~~ Horn of Africa (~~[~~HOA) experiences recurrent droughts~~]~~ (including the current~~ongoing~~ multi-year drought), which have ~~and these have~~ severe impacts such as crop losses, livestock deaths and diseases, as well as frequent emergencies, food insecurity, infrastructure damage~~s~~ and high economic costs (IGAD & WFP, 2017). This is ~~especially~~particularly devastating for ~~the~~ small~~-scale~~holder farmers whose livelihoods depend~~s~~ on rain~~-~~fed agricultural systems and livestock (IGAD & WFP, 2017).

~~In~~ Over the past decade, studies have been ~~done~~ conducted in the HOA to understand and characteris~~z~~e extreme events such as droughts. Most of these studies use modelled data due to the lack of observational data in ~~this~~the region. The lack of observational data, especially on ~~f streamflow~~river discharge, has led to limited analysis of hydrological drought events. Several of the studies have focused on meteorological and agricultural drought ~~and~~ rather than ~~not~~ hydrological droughts (Agutu et al., 2017, 2020; Anderson et al., 2012; Awange et al., 2016; Belal et al., 2014; Dutra

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et al., 2013; Edossa et al., 2010; Gebrechorkos et al., 2020; Haile et al., 2019, 2020; Kurnik et al., 2011; Lyon, 2014; Nicholson, 2014; Rulinda et al., 2012; Tonini et al., 2012). In ~~T~~ these studies, drought was ~~have~~ assessed ~~drought~~ based on soil moisture (model and reanalysis), precipitation (satellite-~~derived~~based, observed and a combination of both), terrestrial water storage (TWS; through the Gravity Recovery and Climate Experiment) and normalis~~z~~ed difference vegetation index (NDVI).

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Soil moisture and hydrological drought, which ~~greatly~~have a strong impact on agriculture and water use in ecosystems and society~~,~~ respectively, ~~are considered to~~ have devastating ~~impacts~~effects in the HOA (Shukla and Wood, 2008; Van Loon, 2015). Therefore, it is ~~paramount~~ critical for water resource~~s~~ management to understand how the drought signal ~~translates~~transitions from ~~deviating~~aberrant meteorological conditions ~~in~~to soil moisture and ~~finally~~eventually to hydrological drought. This process is ~~referred~~ called ~~to as~~ propagation. Drought propagation is ~~greatly~~strongly influenced by climate and catchment characteristics (Barker et al., 2016; Van Loon and Laaha, 2015; Van Loon and Van Lanen, 2012). Therefore~~Thus~~, ~~there is also a need to assess~~ the combined effects of climate and catchment characteristics on propagation of drought~~s propagation~~ also need to be assessed to better understand~~, for a thorough understanding of~~ the underlying processes of drought development. There are ~~numerous~~many studies on drought propagation studies in data-rich countries (e.g.~~i.e.,~~ USA, China), but not much has been done for the data-poor regions (e.g.~~i.e.,~~ HOA). In this study~~research~~, we define drought as a prolonged period of below-average~~normal~~ water availability. Drought is ~~normally~~usually classified ~~categorized~~ into three types: meteorological (precipitation deficit), agricultural or soil moisture (soil moisture deficit), and hydrological (abnormally low water levels ~~of~~in ~~streamflow in~~ rivers, reservoirs, lakes and groundwater) (He et al., 2013; Huang et al., 2017; Jiang et al., 2019; Van Loon et al., 2016).

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~~The~~ Drought frequency, severity and duration ~~of drought~~ are important characteristics of drought events~~,~~ and can be used to study~~investigate~~ drought propagation. Many studies have quantified these drought characteristics using standardis~~z~~ed indices (i.e., Standardis~~z~~ed Precipitation Index (~~[~~SPI)~~]~~ (Mckee et al., 1993), Standardis~~z~~ed Soil Moisture Index (~~[~~SSMI)~~]~~ (Hao and Aghakouchak, 2014)~~,~~ and Standardis~~z~~ed Streamflow Index (~~[~~SSI)~~]~~ (Huang et al., 2017)). Some studies have also ~~employed~~used threshold-based indices to calculate the ~~drought~~ duration and deficit of drought (as a measure of severity) and to investigate ~~and study~~ drought propagation (Heudorfer and Stahl, 2017; Tallaksen et al., 2009; Van Lanen et al., 2013; Van Loon, 2013; Van Loon et al., 2014; Van Loon and Laaha, 2015). Most of these studies are at the catchment ~~scale~~ level (Apurv et al., 2017; Huang et al., 2017; Tallaksen et al., 2009) and some at the regional level~~scale~~ (Barker et al., 2016; Van Loon, 2013; Van Loon and Laaha, 2015; Xu et al., 2019a). These studies mainly~~mostly~~ focused on the drought characteristics, identifying ~~with~~ some characteristics ~~features associated with~~ related to lagging, attenuation, lengthening and pooling ~~recognized~~. What ~~is still~~remains unclear ~~from~~in these studies is how the propagation of drought from meteorological~~precipitation~~ to soil moisture is~~drought~~ relate~~d~~s to climate and catchment characteristics. ~~Moreover~~Furthermore, the two approaches to ~~characterize~~ drought characterisation differ in that the ~~standardized~~standardised indices do not~~cannot~~ provide information on drought deficit volumes but can be used across different geographical regions, unlike the ~~as opposed to~~ variable threshold-based method which preserves the hydrological values but cannot be used across different geographical regions. These methods ~~may~~ ~~can~~thus provide different information ~~if~~ when used for spatial analysis of drought propagation.

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Many studies have used statistical methods to assess the drought propagation and relate them~~is~~ to climate and catchment characteristics. Some of the studies provide an indication of which variables ~~to~~ should be included in an analysis of drought propagation ~~analysis~~ in the HOA, such as geology, landcover, mean annual ~~mean~~ precipitation and seasonal characteristics. For example, Barker et al. (2016) have characteris~~z~~ed meteorological and hydrological droughts and their propagation in the UK. The relationship between meteorological and hydrological drought was assessed by cross correlating the 1-month SSI (SSI-1) with ~~various~~ different SPI accumulation periods using a Pearson correlation coefficient. They also investigated the influence of climate and catchment ~~properties~~characteristics on hydrological drought characteristics and its propagation using Pearson correlation ~~together~~along with Spearman~~'s~~ correlation. They found that the SPI accumulation periods correlated differently with the ~~1-month SSI~~SSI-1 depending on the region~~s~~ in the UK, which could be due to the differe~~n~~nces~~ce~~ in hydrogeology and mean annual precipitation. Huang et al. (2017) used SPI and SSI to characteris~~z~~e meteorological and hydrological droughts, respectively. They investigated the propagation time and the influence of El Nino Southern Oscillation (~~[~~ENSO)~~]~~, Artic Oscillation (~~[~~AO)~~]~~ and underlying surface ~~characteristics~~ properties on drought propagation in the Wei River Basin in China ~~by~~ using the cross-wavelet analysis. They found that ENSO and AO are strongly correlated with actual evaporation and thus, ~~impacted~~influenced the propagation time from meteorological to hydrological drought (which is influenced by seasonal characteristics). Van Loon and Laaha (2014) used variable threshold level methods to characteris~~z~~e

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meteorological and hydrological drought in 44 Austrian catchments free ~~from~~ of major disturbances. They ~~analyzed~~analysed the combined influence of climate and catchment characteristics of drought propagation using various statistical tools (i.e., bivariate correlation analysis, regression analysis). The~~ir~~ results showed ~~firstly~~ that hydrological drought duration is primarily influenced by storage and release (i.e., base flow index, geology, and land use). ~~Furthermore~~In addition, the duration of meteorological drought is important for hydrological drought duration, and the~~. Finally, the~~ hydrological drought deficit is governed by catchment wetness (mean annual precipitation).

These results cannot be easily generalis~~z~~ed and applied to~~in~~ the HOA ~~due~~ because ~~to~~of the ~~its~~ different climate and hydrogeology. Thus, there is still a need for a deeper understanding of the drought propagation in this region and for ~~the~~ appropriate indicators to ~~be used~~characterise ~~for~~ drought ~~characterization~~. Choosing an appropriate ~~indicator for~~ drought characteris~~z~~ation indicator is key to understanding the ~~linkage~~ relationship between ~~the~~ drought hazard and ~~the~~ drought impacts. Depending ~~Different indices may prove valuable depending~~ on the area of application, different indices may prove useful (Vicente-Serrano & Lopez-Moreno, 2005). The objective of this study is therefor to understand (1) how drought characteristics change as ~~the~~ drought propagates from meteorological to soil moisture and ~~finally~~ to hydrological drought~~s~~ in the HOA,~~;~~ and (2) which climatic and catchment characteristics influence the propagation from meteorological to soil moisture to hydrological drought, using both ~~the~~ ~~standardized~~standardised and threshold-based indices. The study is conducted i~~o~~n ~~a set~~ a number of catchments across Kenya, Somalia and Ethiopia with diverse hydro-climatic and ~~landscape~~ geological~~conditions.~~ characteristics.

2 Case study area

The study was conducted on a selection of catchments based on the ~~level 6~~ boundaries of HydroBASINS level 6, which ~~s covering~~covers Kenya, Somalia and Ethiopia and ~~consisting~~ consists of 338 catchments (Lehner & Grill, 2013). The region has a seasonal climatological regime. It is ~~mostly~~ predominantly semi-arid, but ranges from very humid in the Ethiopian highlands and Mount~~t.~~ Kenya region to very ~~arid~~ dry in parts of Somalia, southern and ~~southeastern~~south-eastern Ethiopia and ~~northeastern~~north-eastern Kenya. The region is mostly ~~made up of~~ shrubland with cropland and forests~~s found~~ in the very humid ~~highly wet~~ Ethiopian highlands, around Lake Victoria and on the high slopes of Mount~~t.~~ Kenya (Figure 1~~Figure 1~~a). The mean annual ~~mean~~ precipitation decreases from ~~the~~ west~~east~~ to ~~the~~ east~~west~~ and from high altitudes (the Ethiopian highlands and the region around Mount~~t.~~ Kenya ~~region~~ receive a~~experiences~~ mean annual ~~mean~~ precipitation ~~over~~of more than 500mm) to low altitudes (~~northeastern~~north-eastern Kenya and Somalia ~~experience~~receive mean annual ~~mean precipitation~~ of ~~below~~ less than 200mm) (Figure 1~~Figure 1~~b and c). P~~The p~~recipitation increases from the ~~the~~ Somalia coast towards the Kenyan coast (Figure 1~~Figure 1~~c), which is also reflected in the forest cover (Figure 1~~Figure 1~~a).

The ~~long~~prolonged rains mostly occur ~~during~~from March to ~~-~~May (~~[~~MAM)~~]~~, while the short rains occur ~~in~~from October~~-~~ to December (~~[~~OND)~~]~~ due to~~following~~ the migration of the inter~~-~~tropical convergence zone (~~[~~ITCZ)~~]~~ from south to north and vice versa (Awange et al., 2016). This is ~~mostly~~ particularly true for Kenya and Somalia, while Ethiopia experiences a single rainy season in June ~~-~~to September (~~[~~JJAS)~~]~~. The region also has a very diverse geology, ranging from rich volcanic soils on~~in~~ the high slopes of Mount~~t.~~ Kenya and in the Ethiopian highlands~~,~~ to sedimentary rocks in the semi-arid areas of southern and ~~southeastern~~south-eastern Ethiopia, Somalia, and eastern and ~~northeastern~~north-eastern Kenya (Figure 1~~Figure 1~~d). The diverse topography, climate seasonality and ~~the~~ large number of catchments and relevant catchment ~~attributes~~ characteristics make ~~the~~ it~~region~~ a suitable region ~~for~~to study ~~region~~.

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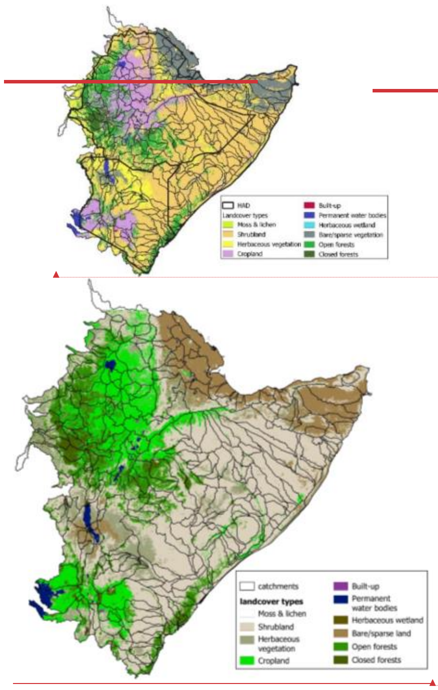

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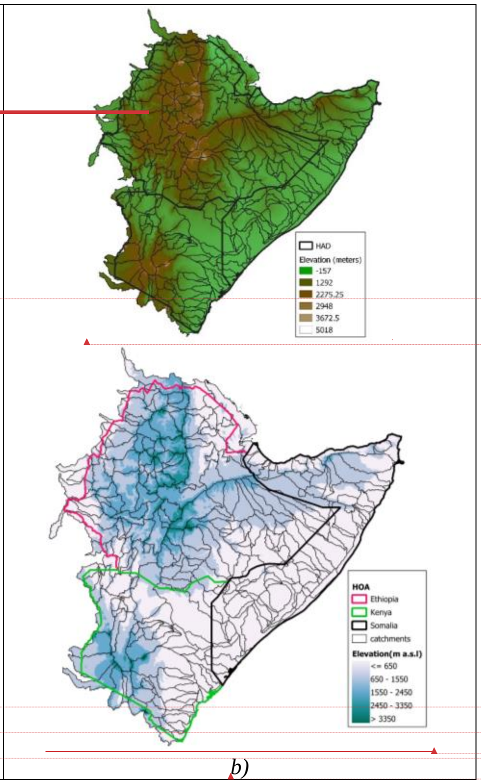

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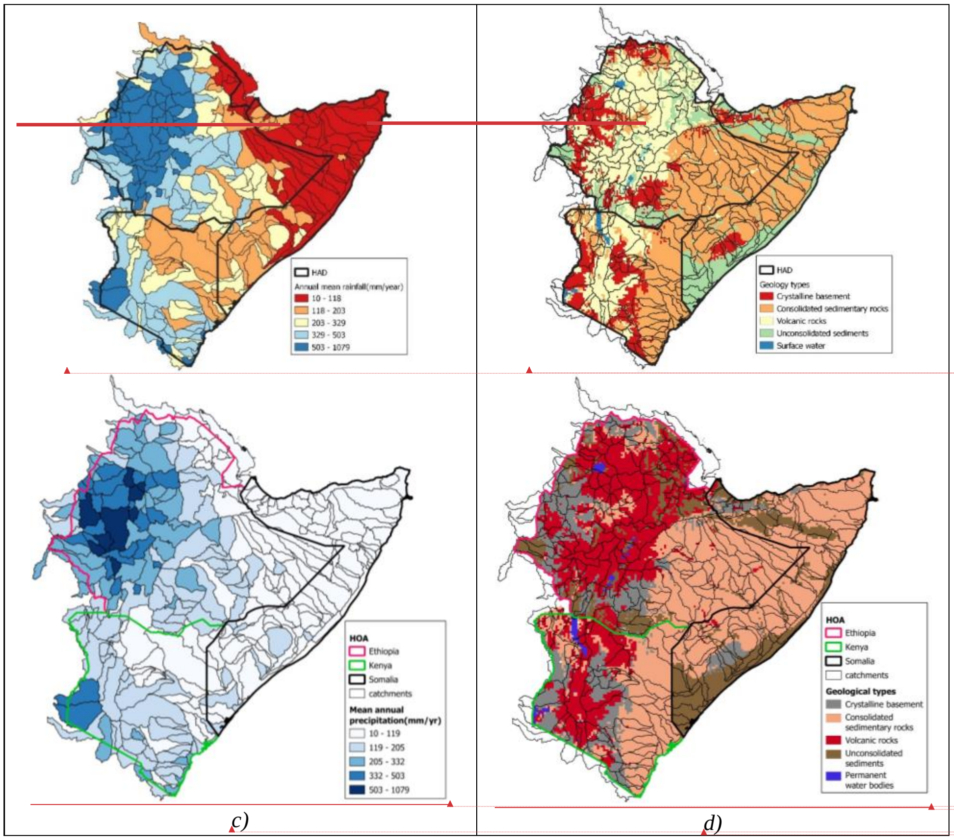

Figure 1~~1~~: Maps showing some characteristics of the study area: a) landcover (Copernicus) (Buchhorn et al., 2020); b) elevation (STRM) (Farr and Kobrick, 2000); c) mean annual precipitation (MSWEP) (Beck et al., 2017)); and d) geology (Africa Groundwater Atlas, 2022).

3 Methodology

The methodology of this study is summaris~~z~~ed in Figure 2. First, the data and their respective sources together with the catchment characteristics are discussed (Section 3.1), followed by calculation of the Standardis~~z~~ed Precipitation Index (~~[~~SPI)~~]~~, Standardis~~z~~ed Soil Moisture Index (~~[~~SSMI)~~] (Ryu and Famiglietti, 2005)~~, and Standardis~~z~~ed Streamflow Index (~~[~~SSI), and the threshold-based indices (Precipitation to Soil moisture mean duration ratio (P/SM ratio) and Precipitation to Streamflow mean duration ratio (P/Q ratio) (Section 3.2). ~~Second~~Then, the drought propagation analysis process is discussed (Section 3.3). Finally, the statistical analysis involving linking of both the standardis~~z~~ed and threshold-based indices with the climate and catchment characteristics, and the comparison of both methods in characterising drought propagation is discussed (Section 3.4).

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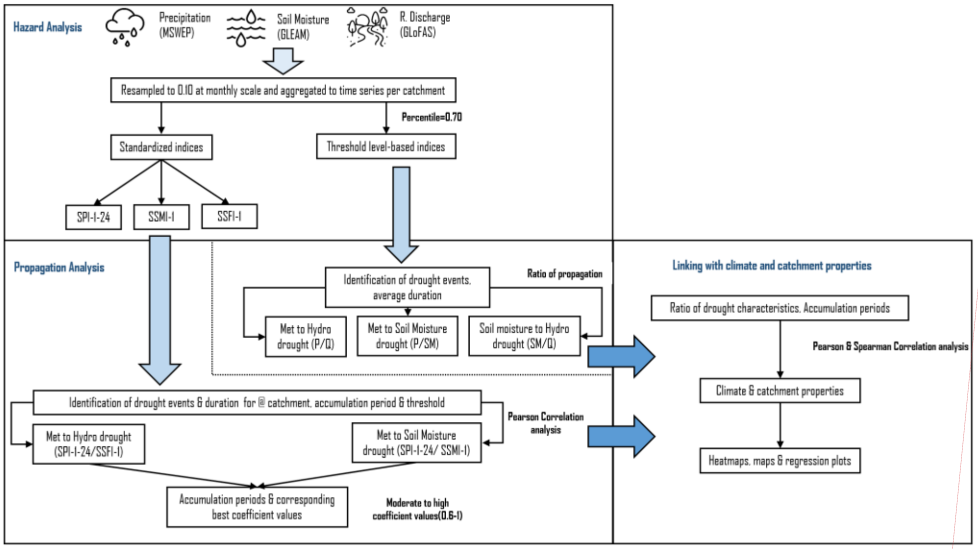

Figure 2~~2~~: Detailed methodology framework showing steps taken from hazard analysis to propagation analysis and finally to linking with climate and catchment characteristics.

3.1 Data

In this study we rely on the same types of datasets used in previous studies. Ideally, propagation analysis should be based only on observed data~~,~~ but ~~that~~ this is not always feasible for large-scale analyses~~is~~. In this study, we have therefore ~~prioritized~~ favoured data sources that are as close as possible~~ly~~ to observed~~ational~~ data ~~as possible,~~, while ~~but~~ still covering the entire regional ~~domain~~ range of the HOA. ~~Correspondingly~~Accordingly, we chose ~~opted~~ to use reanalysis data for precipitation and soil moisture, but still used modelled data for streamflow because ~~as~~ no suitable observational dataset in the HOA ~~been~~ was found. These gridded datasets ~~are~~ were aggregated to catchment resolution based on hydrological data and level 6 ~~hydrological data and~~ maps of~~,~~ HydroSHEDS~~,~~ (Lehner and Grill, 2013), ~~for~~ to delineate catchments~~catchment delineation~~.

HydroSHEDS is a global hydrological dataset that provides information on the water drainage systems ~~of the earth~~. It is based on digital elevation models (DEMs) and other geospatial data sources~~s,~~ and ~~is organized~~is divided into several levels of detail, with level 1 being the coarsest and level 12 ~~being~~ the finest. At each level, the dataset provides information on the location and characteristics of water bodies~~,~~ such as rivers, lakes~~,~~ and wetlands, as well as ~~the~~ the topography of the surrounding terrain. Level 6 was ~~selected~~ chosen because it provides ~~a high~~an average level of detail on the water drainage systems. In particular, ~~Specifically, level 6 delineates~~ hydrographic units (HUs) with an average size of ~~around~~ about 10,000 square ~~kilometers~~kilometres are delineated at level 6. ~~HUs are defined as areas that drain to a common outlet point, such as a river mouth or the edge of a lake. HUs are further divided into sub-basins, which are areas that drain to a specific point along a river or other watercourse.~~

For the analysis, we use the upstream contributing area of each catchment. Catchments with an area of 150 square kilometres ~~km^2~~ or more were selected for analysis, reducing the number to catchments to 320. ~~A further two~~Two additional catchments are excluded due to missing values (missing values were due to the resolution of soil moisture and streamflow datasets) after aggregation at the catchment level, leaving only 318 catchments. The remaining catchments provide good spatial coverage of the HOA and its diverse characteristics.

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3.1.1 Hydrometeorological and soil moisture datasets

Precipitation data ~~has been~~were retrieved from the Multi-Source Weighted-Ensemble Precipitation (~~[~~MSWEP)~~]~~ version 2 (Beck et al., 2019)~~1.1~~. This is a global gridded precipitation (P) dataset ~~that covers~~covering the period 1979 to the ~~–~~present. MSWEP has a ~~at three hourly temporal and 0.1 degree spatial resolution~~temporal resolution of 3 hours, daily, and monthly; and a spatial resolution of 0.1 degrees. In this study we sued the daily MSWEP precipitation data. It does not contain pure~~ly~~ observations, but a combination of gauge-, satellite- and reanalysis-based P ~~-~~estimates, depending~~ent~~ on timescale and location (Beck et al., 2017, 2019). This dataset was selected~~chosen~~ for this analysis ~~based on~~due to its spatial and temporal resolution and good performance in capturing spatial and temporal variation of drought conditions (Xu et al., 2019b).

The soil moisture data were ~~has been~~ retrieved from the Global Land Evaporation Amsterdam Model (~~[~~GLEAM)~~]~~ (version 3.5a). The model applies a set of algorithms to estimate land surface evaporation (also known~~referred to~~ as evapotranspiration) and ~~root zone~~root-zone soil moisture from satellite and reanalysis data at the global scale~~,~~ with a spatial resolution of 0.25 degree ~~spatial resolution~~ and a daily temporal resolution (Martens et al., 2017; Miralles et al., 2011). It uses the latest version of MSWEP precipitation~~,~~ (version 2.8)(Beck et al., 2017, 2019), ~~European Space Agency Climate Change Initiative [ESA-CCI] soil moisture (version 5.3),~~satellite observed soil moisture, reanalysis air temperature and radiation and v~~V~~egetation optical depth (~~[~~VOD)(Liu et al., 2011) to produce terrestrial evaporation and root-zone soil moisture~~] (Martens et al., 2017)~~. The root-zone soil moisture is based on the weighted average of the soil surface up to 5 centimetres (top layer), which is more variable, and the root-zone up to a layer of 100 centimetres. ~~–~~The GLEAM model applies the Priestley and Taylor (PT) equation (Priestley and Taylor, 1972) to calculate the Potential Evapotranspiration (PET) based on observations of European Centre for Medium Range Weather Forecasts (ECMWF), ERA-Interim surface net radiation and near surface air temperature (Dee et al., 2011)~~The root zone soil moisture is obtained from a multi-layer water balance model that uses precipitation and soil moisture data as inputs~~. ~~The root zone soil moisture is based on the weighted average of the soil surface of up to 5 cm (topmost layer), which is more variable, and root zone up to 100cm layer.~~ GLEAM datasets have been used in recent studies, including in the H~~orn of Africa~~OA (Javadinejad et al., 2019; Nicolai-Shaw et al., 2017; Peng et al., 2020). For this study, the GLEAM potential evaporation (PET) and ~~root zone~~root-zone soil moisture ~~were used~~ (see http://www.gleam.eu) were used for the period 1981~~2010~~–2020.

Streamflow data were~~has been~~ retrieved from the Global Flood Awareness System (~~[~~GloFAS),~~]~~ which consists of global gridded river streamflow data~~,~~ with a horizontal resolution of 0.1 degrees at a daily time step and at ~~ime~~ period from ~~of~~ 1979 to the ~~–~~present (Harrigan et al., 2020). It combines both the surface~~-~~ and sub-surface runoff from the HTESSEL land surface model used ~~within~~in ECMWF's global atmospheric reanalysis (~~[~~ERA5) (Balsamo et al., 2009; Hersbach et al., 2020)~~]~~ with the LISFLOOD hydrological and channel routing model (Hirpa et al., 2018). LISFLOOD calculates a water balance ~~at~~ with a temporal resolution of six hours~~rly~~ or da~~ily~~y, ~~temporal resolution~~and a spatial resolution of ~~with~~ 0.05 degrees ~~spatial resolution~~ (see http://www.globalfloods.eu/). The GloFAS dataset was selected because there is no observed river discharge data with sufficient spatial coverage and time period in the study region. Unfortunately, GloFAS uses ERA5 Land as precipitation input, which has been found to be less reliable in the HOA region than MSWEP or CHIRPS. Therefore, we tested the GloFAS dataset at the available discharge stations (with discharge values from 1981 onwards; total of 26 stations) in the HOA for bias compared to observed data. We found that while there is a bias in the absolute values, the anomalies are similar between the two datasets *(see for more explanation in section 1 Supplementary Material)*. Since our analysis focuses on relative deviations from normal, we deemed it acceptable to use the GloFAS data to represent discharge anomalies~~The GloFAS dataset was chosen because of the lack of observational streamflow datasets with sufficient spatial coverage and time period. Additionally, we conducted bias test of GloFAS dataset at specific weather discharge stations in the HOA against observational data. We found that whilst there is a bias, the general variation between the two datasets was similar (*see supplementary materials* Fig. S1 and S2)~~.

Catchment characteristics were obtained from ~~multiple~~ a variety of sources. These sources include BasinATLAS (Linke et al., 2019), upstream mean annual~~l mean~~ precipitation from MSWEP (Beck et al., 2017), geolog~~y~~icaly types from Africa ~~g~~Groundwater A~~a~~tlas (Africa Groundwater Atlas, 2022)~~,~~ and landcover types from Copernicus Global Land Cover layers-Collection 2 (Buchhorn et al., 2020). ~~The c~~Catchment characteristics used in this study include soil properties (i.e.~~,~~ percent silt, sand and clay ~~fractions~~, percent mean annual ~~mean~~ soil water content), geolog~~y~~icaly types, land~~-~~cover types, terrain slope, elevation, upstream contributing area, climate zones, ~~upstream annual mean precipitation~~mean annual upstream precipitation , global average aridity index ~~, and average population density~~ (*see Table S1* ~~*further description of these characteristics can be found in*~~ *Supplementary M~~m~~aterial~~s table S1~~*). These

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catchment characteristics were selected because they have been found in previous studies to influence drought propagation in other regions (Barker et al., 2016; Van Loon, 2013; Van Loon and Laaha, 2015). The characteristics were also chosen~~selected~~ because drought intensity~~ tends to ~~ variesy~~ based~~ according~~ on~~ to the topographic location and the time it takes for water to ~~pass~~flow through the catchments.

3.2 Drought Analysis

3.2.1 Standardis~~z~~ed indices

The ~~[~~SPI~~]~~, developed~~ devised~~ by McKee et al. (1993)~~,~~ allows quantification of precipitation deficits or surpluses ~~on~~ over a range of different accumulation periods. In this study, we prefer SPI over other meteorological drought monitoring indices because organizations providing climate services to the Horn of Africa, such as the IGAD Climate Prediction and Application Centre (ICPAC) use SPI specifically for drought monitoring in its East Africa Drought Watch. Several studies in the Horn of Africa have also used SPI (Kalisa et al., 2020; Okal et al., 2020; Dinku et al., 2007; Viste et al., 2013). To represent agricultural drought we selected the Standardised Soil Moisture Index (SSMI) index, and for hydrological drought we selected the Standardised Streamflow Index (SSI).

By the nature of the different indices, different distributions are best suited to fit the different data types. We used the distributions suggested by Stagge et al., (2015) for calculation of SPI, distributions suggested by Ryu and Famiglietti, (2005) for calculation of SSMI and distributions suggested by Vicente-Serrano et al., (2012) for calculation of SSI. We fitted a different distribution for each catchment, which is not a problem in our study because we analyse drought propagation with catchments and do not compare drought characteristics between catchments (*see for more explanation section 2 in Supplementary Material*). The SPI was calculated by summing daily MSWEP precipitation to obtain a monthly temporal resolution. Monthly precipitation values were fitted to a distribution, performed for each catchment, ~~A distribution was fitted through the monthly precipitation values, which was done per watershed~~ to calculate SPI values for~~at~~ accumulation periods ranging from~~of~~ 1 to 24 months. Each ~~watershed~~catchment within the HOA has a specific distribution ~~which~~ that was ~~was~~ either normal, gamma, exponential Weibull or lognormal ~~distributions f~~for SPI calculation (Stagge et al., 2015). The number of zeros in precipitation was considered according to the recommendations of Stagge et al. (2015). In calculation of the~~For [~~SSMI~~] (Ryu and Famiglietti, 2005) ,~~ we used mean monthly GLEAM root~~-~~zone soil moisture content and fitted normal, beta, ~~p~~Pearson3 or ~~fisk~~Fisk distributions (Ryu and Famiglietti, 2005). In the calculation of the ~~For [~~SSI~~,]~~ ~~(Vicente-Serrano et al., 2012)~~ we used mean monthly GloFAS streamflow values and fitted E~~e~~xponential Weibull, L~~l~~ognormal, P~~p~~earson3 or generalized extreme distributions (Vicente-Serrano et al., 2012). The distribution for each catchment and variable was selected based on the Kolmogorov best~~-~~fit method. Each of these distributions ha~~ve~~s been ~~proven~~ shown to fit various indices ~~by~~ in previous studies~~ to work for the different indices. The number of zeros in precipitation was taken into consideration following recommendations from Stagge et al. (2015) for SPI~~.

All drought indices were calculated ~~at a~~with a monthly resolution for the period 1980–2020. The standardised wet and dry periods of each indicator were included in the analysis to characterise changes in anomalies when moving through the hydrological cycle. As such, with this method, we did not define drought events, but aim to identify the anomalies over different accumulation periods. ~~.~~

3.2.2 Threshold level-based indices

The threshold-based approach is a ~~drought analysis method that has been employed~~ widely used method for drought analysis (Heudorfer & Stahl, 2017; Tallaksen et al., 2009; Van Lanen et al., 2013; Van Loon, 2013; Van Loon et al., 2014; Van Loon & Laaha, 2015). In ~~A~~applying this approach, a drought event was defined as any event that falls below the pre-defined threshold. Drought events were identified from the monthly time series of the above~~-mentioned~~ hydrometeorological datasets (precipitation (~~[~~P)~~]~~, soil moisture (~~[~~SM) ~~]~~ and river discharge~~streamflow [~~ (Q)~~] variables~~) using a monthly ~~-~~varying threshold-based approach (without pooling) i.e. an approach that has a different value for each month (this is similar to standardised indices that fit a distribution for each month separately) to account for ~~reflect~~ seasonality, and defined in terms of the duration of drought. This approach has been ~~previously~~ used in numerous studies (e.g.~~,~~ Beyene et al., 2014; Nyabeze, 2004; Van Huijgevoort et al., 2012; Van Huijgevoort, 2014; Van Loon, 2013; Van Loon et al., 2014; Van Loon & Laaha, 2015; Vidal et al., 2010). The 70th percentile was used as threshold. This means that each~~very~~ month of the year has a different threshold ~~level~~ based on the 70th percentile ~~of the duration curve~~ of the values of the hydrometeorological variable ~~values~~ in that month, for all ~~the~~ years in the

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~~timeseries~~time series. P~~In p~~revious studies have used ~~,~~ percentile ranges between the 70th and 90th ~~have been used~~ (Heudorfer & Stahl, 2017; Van Loon, 2013; Van Loon et al., 2014; Van Loon & Laaha, 2015). After testing different percentile values (70th, 80th and 90th percentile~~s~~), we selected the 70th percentile because it ~~was able to~~could clearly capture both moderate and severe droughts. ~~.~~ The other percentiles were eliminated because, with the high precipitation variability experienced in the region, they ~~showed HOA~~had too few droughts, showed a misidentification of less severe droughts, and they ~~missed~~ did not account for most of the ~~most of the m~~major known drought years. This made it difficult to identify patterns and trends *(see section 2 Figure S9, S10 and S11 Supplementary Material)*.

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The duration of the drought event was determined by the total number of consecutive months ~~that the~~in which the value of the variable ~~value~~ was below the threshold ~~value~~. Then ~~Subsequently~~, the average ~~drought~~ duration of drought per catchment ~~was calculated per catchment~~ in the study area was calculated. Finally, the duration ratios were calculated (~~precipitation drought~~meteorological drought duration ~~against~~ in relation to soil moisture drought duration (~~[~~P/SM ratio)~~]~~ and streamflow drought duration (~~[~~P/Q ratio)~~]~~). A ratio closer to 1 indicates that the durations are similar (i.e.~~,~~ there is not so much clustering of ~~precipitation drought~~meteorological droughts into streamflow droughts), wh~~ereas~~ile a ratio closer to 0 ~~indicates~~ means there are ~~substantially~~ many~~more~~ more ~~precipitation drought~~meteorological droughts than streamflow droughts, indicating that they have propagated and clustered into ~~less~~ fewer and longer P/Q droughts.

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3.3 Drought propagation

~~3.3.1 Standardized indices~~

SSMI and SSI integrate processes at the land~~-~~surface and ~~processes and catchment-scale~~ hydrogeological processes in the catchment, respectively. ~~Hence~~Therefore, ~~a comparison~~comparing ~~of~~ SSMI and SSI with ~~the~~ SPI provides an indication of the time it takes~~taken~~ for the drought signal to propagate through the hydrological cycle from precipitation deficits to soil moisture deficits and finally to streamflow deficits. SPI ~~timeseries~~time series with accumulation periods of 1-24 months were cross~~-~~correlated against 1-month SSMI (SSMI-1) and SSI (SSI-1) ~~timeseries~~time series using Pearson correlation per catchment. This cross-correlation method has been used in many similar studies (Barker et al., 2016; Huang et al., 2017; Xu et al., 2019a) and can effectively show the similarity between different drought types. The accumulation period with the highest correlation coefficient with either SSMI-1 or SSI-1 was denoted as SPI-*n* and used as an indication of the propagation of the meteorological drought signal to soil moisture and streamflow respectively. Only correlation values greater than or~~and~~ equal to 0.5 were used ~~retained~~ for the analysis of propagation, ~~because~~ as these were considered ~~as~~ strong signals.

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Propagation times were considered short if~~when~~ the ~~accumulation time of~~ SPI-*n* accumulation time was less than~~below~~ four months. We did not investigate ~~determine~~ whether there was a lag between the SPI and SSI ~~timeseries~~time series, ~~because~~ as other studies have found that the strongest correlations ~~are normally~~usually occur at a lag of zero months (i.e.~~,~~ no lag) (Barker et al., 2016). Finally, the catchments were grouped based on the calculated accumulation periods. To ~~check~~test ~~for~~ the independence of the data between the catchments based on the different groups of accumulation period~~s~~, a one-tailed~~way~~ *t*-test was ~~carried~~performed ~~out~~ to see ~~determine~~ how much ~~statistically different~~ the groups ~~are~~were statistically different from each other.

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~~3.3.2~~ In threshold-based indices, the ~~Threshold based indices~~

~~The~~ drought propagation was ~~investigated~~studied ~~using~~ by the ratio of the drought duration ~~ratios~~ of the hydrometeorological variables. A ratio between the ~~of the~~ duration of ~~precipitation~~ meteorological droughts ~~against~~ and the duration of soil moisture drought (P/SM)~~s~~ was calculated to indicate propagation from ~~precipitation~~ meteorological to soil moisture drought. P/SM mean duration ratio represents the speed with which precipitation deficits affect soil moisture availability, and therefore, how quickly the ability of plants to access water is hampered during drought. A low ratio suggests that soil moisture is more resilient to precipitation deficits (slow soil moisture response to precipitation), which is probably related to catchment properties like soil type. A high ratio indicates that precipitation deficits have a ~~strong~~n faster ~~immediate~~impact on soil moisture availability (faster soil moisture response to precipitation). ~~Furthermore~~We also calculated~~,~~ the ratio of the duration of ~~precipitation drought~~meteorological droughts ~~to~~ and streamflow drought~~s~~ (P/Q) ~~was calculated~~ to show the propagation from meteorological~~precipitation~~ to streamflow drought. P/Q mean duration ratio represents the degree to which precipitation deficits affect streamflow. A low ratio suggests that streamflow is more resilient to precipitation deficits, and meteorological droughts are

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buffered. A high ratio indicates that precipitation deficits have~~s~~ a ~~more immediate~~ quick response in streamflow. Also ~~T~~these~~is measurement~~ P/Q ratios ~~factors in~~ are probably influenced by ~~the effect of meteorological droughts on soil moisture and streamflow droughts leaving only the influence of~~ catchment characteristics like subsurface storage. Overall, we favoured the use of the duration ratios to other conventional indices because these ratios can provide insight into the mechanisms through which drought propagates and the vulnerabilities of different systems to precipitation deficits (Van Loon et al., 2016). These ratios take into account the effect of precipitation deficits on soil moisture and streamflow.

3.4 Influence of possible governing factors of climate and catchment characteristics

The effects of climate and catchment characteristics on propagation were~~as~~ investigated through ~~by~~ statistical analysis. First~~ly~~, we analys~~z~~ed the strength of the relationships using cross-correlation analysis. We calculated the correlation matrix of the pairwise combinations of all variables based on Pearson correlation coefficients. Since ~~As~~ the relationships might not ~~could be non-~~ be linear, we also calculated Spearman correlation coefficients and visually inspected the correlation matrix ~~plotted~~presented as a heatmap ~~to verify~~to verify the results. We created a clustered heatmap of the Pearson correlation matrix to examine~~plore~~ the intercorrelations of the catchment characteristics. We used the Euclidean distance method to ~~order~~rank the coefficients. T~~In t~~he Euclidean distance method orders~~,~~ rows and columns ~~are arranged according to~~by similarity, ~~hence,~~ making it easier to find groups of climate and catchment characteristics that have ~~with~~ a joint effect on drought propagation. We then plotted individual graphs~~plots~~ for each of the key variables against the propagation indices. ~~Additionally~~ In addition, we used raster zonal statistics in QGIS to link variables such as geology, landcover, climate zones, upstream areas and elevation to the indices. Second~~ly~~, we ~~performe~~conducted ~~d~~ a one-tailed~~way~~ *t*-test for ~~on~~ the ~~standardized~~standardised indices of the clustered catchments. The significance test was used to determine whether the clusters of catchments differed~~s~~ per accumulation period.

4 Results and Discussion

In the following sections, drought propagation and the link with catchment characteristics per propagation indicator are discussed in detail. First, the propagation from ~~precipitation~~ meteorological to soil moisture drought is presented, followed by the propagation ~~of~~ from soil moisture to ~~discharge~~ streamflow drought.

4.1 Precipitation to soil moisture

4.1.1 SPI ~~-~~to ~~-~~SSMI

M~~The m~~apping of SPI-*n* for ~~propagation from~~ SPI ~~-~~to ~~-~~SSMI propagation ~~(~~(Figure 3~~a~~) showed high correlation values in all catchments, especially in the south of HOA (Kenya region, average 0.82) (Figure 3a). The high correlation values were found across ~~in~~ the ~~full~~ range of SPI accumulation periods. This ~~may~~ could be due to the strong link between precipitation and soil moisture as~~, since~~ GLEAM uses MSWEP precipitation as one of its inputs. The catchments were ~~split~~ equally divided into ~~between the~~ short and long accumulation periods (1-4 months and 5-9 months with ~~each~~ 159 catchments each (Figure 3b)). The longest accumulation periods (9 and 8 months) were ~~located~~ in the northwest of the HOA, with correlation values greater than 0.7 (Figure 3a). Figure 3b shows that the SPI-*n* of the catchments on the north~~-~~eastern~~ast~~ coast of ~~the~~ HOA ~~HOA~~ were ~~SPI-*n*~~ between 1 and 3 months, while those of catchments at the eastern ~~center~~centre were longer (between 5 and 7 months). *(See section 3.1 Figure S12, S13 and S14 Supplementary Material for spatial plots of the propagation.)*

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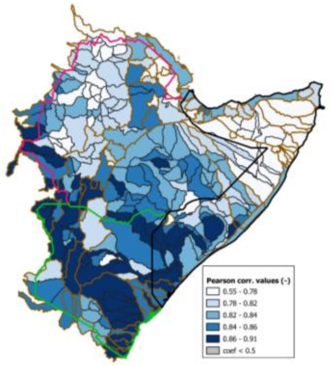

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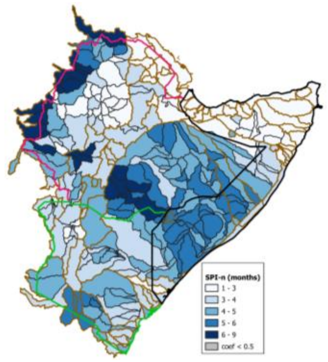

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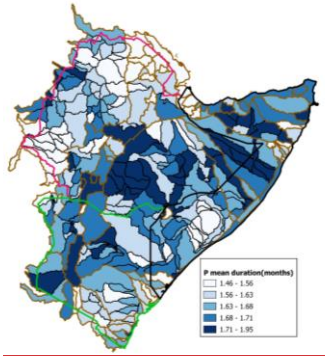

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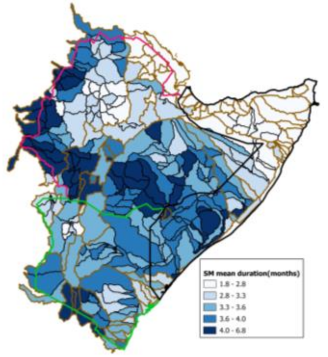

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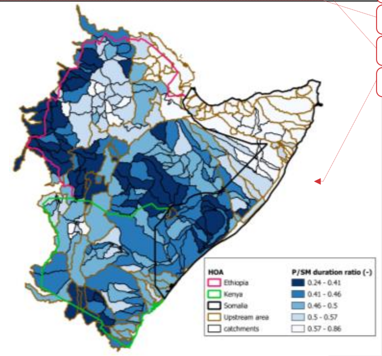

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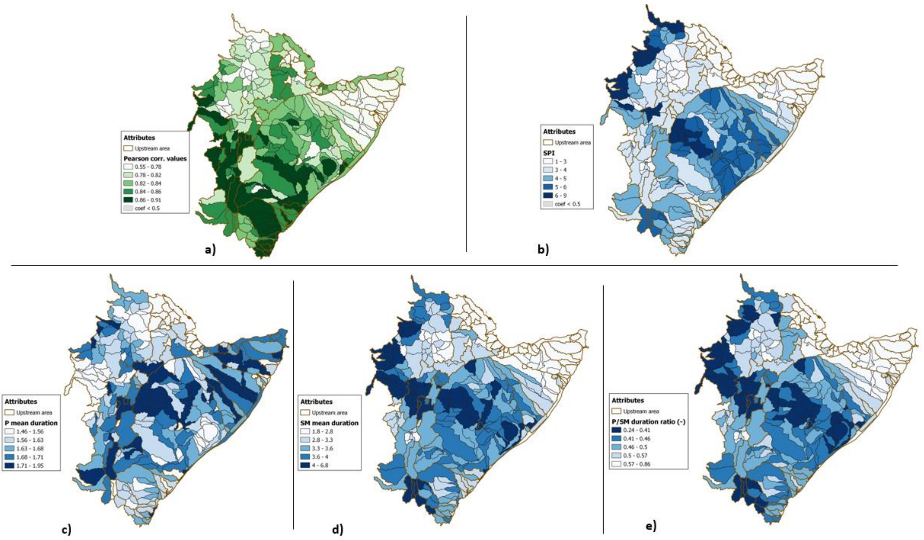

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Figure 3~~3~~: Propagation from precipitation to soil moisture: a) highest coefficient values per catchment (>0.5) from SPI ~~-~~to ~~-~~SSMI; b) corresponding SPI-n (SPI accumulation period having highest correlation with SSMI) per catchment; c) mean ~~precipitation drought~~meteorological drought duration; d) mean soil moisture drought duration; e) ratio of drought mean duration from meteorological to soil moisture (P/SM).

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4.1.2 P/SM duration ratio

The duration of ~~the~~ droughts increases~~s~~ as the drought signal propagates through the hydrological cycle (Figure 3c~~,~~ and d). The duration of soil moisture droughts is ~~greater~~longer than that of ~~precipitation drought~~meteorological droughts, indicating propagation and ~~clustering~~pooling of ~~precipitation drought~~meteorological droughts into soil moisture drought. The map of the threshold-based drought duration ratio~~o map~~ (P/SM) (Figure 3e) ~~-displays~~shows similar processes as the map of the propagation using ~~standardized~~standardised indices ~~propagation map~~ (Figure 3b), i.e.~~,~~ a short ~~-~~precipitation to soil moisture response in the northeast (represented~~shown~~ by short accumulation periods in the ~~standardized~~standardised indices and a high mean duration ratio in the threshold indices (P/SM ratio)).

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The analysis of the P/SM ratio ~~analysis~~ (Figure 3e) shows that the north~~-~~western ~~center~~centre and north~~-~~eastern ~~center~~centre of the HOA have high ratios, which means ~~meaning~~ that ~~in this area~~ soil moisture in this area responds~~acts~~ faster to precipitation (less pooling of ~~the~~ ~~precipitation drought~~meteorological drought events~~s~~). The P/SM ratio decreases ~~moving~~ towards the southeast coast of the HOA (in ~~with~~ some catchments the ~~having~~ ratios is as ~~as~~ low as 0.3), ~~which~~ indicating~~es~~ longer soil moisture droughts towards the southeast coast of the HOA. The~~re~~ ratios are also low ~~ratios~~in ~~on t~~ the catchments ~~located in~~at the north~~-~~western tip and west of the HOA, indicating longer soil moisture droughts and shorter ~~precipitation drought~~meteorological droughts (Figure 3c and d), ~~meaning~~ implying that~~the response of~~ soil moisture in these catchments responds more slowly to ~~to~~ precipitation ~~is slower in these catchments~~ (greater clustering~~more pooling~~ of ~~the~~ ~~precipitation drought~~meteorological droughts).

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4.1.3 Relation of precipitation-to-soil moisture with climate and catchment characteristics

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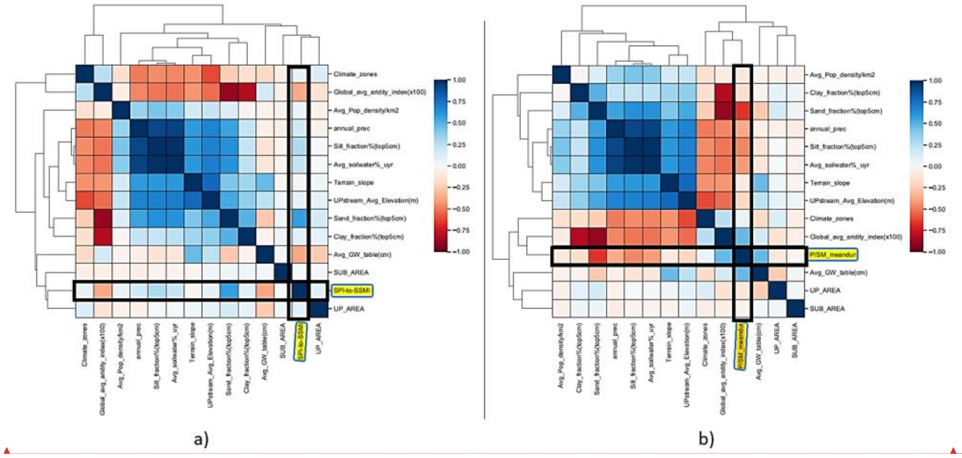

Figure 4~~4~~: Heatmap of Pearson correlations between the propagation indices and catchment characteristics: a) the SPI ~~-~~to ~~-~~SSMI; b) P/SM mean duration ratio.
Note. Euclidean distances used for clustering variables with interchangeable correlations. The heatmap based on the Spearman correlation coefficients (see Figure S15 and S16 S~~s~~upplementary Material ~~Figure S4 and S3~~) showed a similar pattern as Figure 4. Therefore, we assume that linear models (Pearson correlation method) can be used to represent the monotonic relationships even though the relationships are not perfectly linear.*

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SPI ~~-~~to ~~-~~SSMI propagation has longer accumulation times ~~propagation have longer accumulation periods~~ in catchments with low aridity index and higher sand and low silt ~~fraction~~ content (Table 1) and vice versa. These catchments are located in the (semi-)arid eastern ~~center~~centre of the HOA. SPI ~~-~~to ~~-~~SSMI propagation also ~~have~~ significantly related to ~~relationships with~~ percent soil water content~~,~~ and landcover. Similarly, catchments with a low

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P/SM duration ratio have a low aridity index and higher sand ~~fraction~~ content (Figure 5a and b). These catchments have ~~experience~~ low ~~upstream~~ mean annual precipitation~~,~~ and are interspersed ~~riddled~~ with shrubland. They correspond to ~~the~~ catchments with slow propagation from ~~precipitation~~meteorological ~~-~~to soil moisture droughts (~~longer~~prolonged soil moisture droughts; Figure 3d and medium to ~~longer~~prolonged ~~precipitation drought~~meteorological droughts; Figure 3c) due to the slow r~~eaction~~esponse of soil moisture to precipitation. The slow r~~eaction~~esponse ~~occurs because~~ is due to the fact that the soil in these areas tends to be very dry ~~in these areas~~, ~~hence so the process of wetting of~~ the soil surface needs to be wetted before~~occurs first before~~ infiltration can begin. ~~Additionally~~In addition, SPI ~~-~~to ~~-~~SSMI propagation ~~have~~has a longer accumulation in catchments with closed and open forests~~,~~ and herbaceous wetlands and vegetation (Table 1). In these catchments, the interaction between ~~of~~ precipitation and~~with~~ soil moisture is slow, leading to the weaker correlations (Figure 3a). This phenomenon is consistent with the findings of previous studies (e.g.~~,~~ Sehler et al., 2019), which claimed that landcover, soil moisture and precipitation are more strongly ~~have stronger correlations~~correlated in (semi-)arid regions with ~~limited~~low vegetation, while weaker correlations are found in humid regions with forests and dense~~ely~~ vegetation~~ed~~. The propagation of SPI ~~-~~to ~~-~~SSMI has~~propagation have~~ shorter accumulation periods and the P/SM ~~duration ratios~~ ratio ~~are~~ is high in catchments with cropland and bare or sparse vegetation; these catchments are ~~found~~ located in the north-western ~~center~~centre (Ethiopian highlands) and north-eastern tip, respectively.

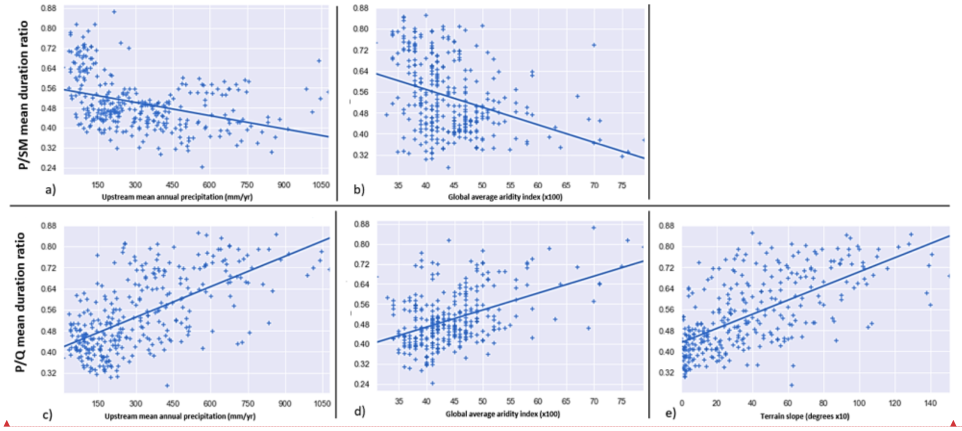

Figure 5~~5~~: Catchment characteristics against P/SM and P/Q mean duration ratios.

The propagation time from precipitation to soil moisture is also influenced by spatial variability in precipitation within the catchments~~precipitation variability~~, ~~however~~but this influence is not pronounced for ~~in~~ both SPI-to-SSMI propagation and P/SM ~~mean duration~~ ratio. This is ~~seen~~reflected in the low positive correlation value between ~~upstream mean annual precipitation~~mean annual upstream precipitation and SPI-*n* for SPI~~-~~ to~~-~~ SSMI (Figure 4), the average distribution of ~~the~~ accumulation periods per equal interval (quantile) ~~grouping~~ of ~~the upstream mean annual precipitation~~mean annual upstream precipitation grouping (Table 1), and the less steep slope (highest value 0.56) in P/SM ~~mean duration~~ ratio ~~against~~ versus ~~upstream mean annual precipitation~~mean annual upstream precipitation (Figure 5a). This weak correlation can be explained by the fact that ~~because b~~both the short and long accumulation periods (Figure 3b) and the low and high P/SM ~~mean duration~~ ratios (Figure 3e) ~~can be~~are found in the catchments ~~located~~ in the wetter western part of HOA (Figure 1c). The P/SM ratio decreases with increasing ~~upstream mean annual precipitation~~mean annual upstream precipitation, meaning most catchments with high P/SM ratios ~~located~~ in the wetter western part of the HOA ~~were~~respond quickly ~~fast responding~~, while those ~~whereas ones~~ with ~~high~~ low P/SM ratios ~~found~~ in the eastern of the HOA respond slowly ~~responding~~, they are less affected by precipitation deficits. SPI ~~-~~to~~-~~ SSMI propagation and P/SM ~~mean duration~~ ratio are not~~have no~~ dependent~~ce~~ on ~~the~~ upstream area, elevation, and geology ~~type~~ (equal distribution of ~~the~~ mean values in Table 1) (*see Table S2 and S3 S~~s~~upplementary M~~m~~aterial* *~~Table S2 and S3~~*).

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Table ~~11~~: Mean ~~average~~ accumulation period per catchment characteristics: ~~upstream mean annual precipitation~~mean annual upstream precipitation, upstream elevation, upstream area, geological~~y~~ type, and landcover type (≤4 months are considered short accumulation periods and ≥5 long accumulation periods).

	~~*Precipitation (mm)*~~	**SPI-to-SSMI (months)**	**SPI-to-SSI (months)**
	Precipitation (mm)		
~~Upstream mean annual precipitation~~Mean annual upstream precipitation	**10-118**	6.0	3.4
	118-203	5.9	2.7
	203-329	4.9	2.0
	329-503	4.8	1.4
	503-1079	3.1	1.0
	Area (km^2)		
Upstream Area ~~(km^2)~~	**152-3935**	4.3	5.6
	3935-7259	4.1	5.5
	7259-15257	5.0	5.4
	15257-47890	4.3	4.4
	47890-745375	4.7	4.2
	Sand fraction (%)		
Percent sand fraction ~~(%)~~	**11-26**	3.1	5.5
	26-29	4.4	5.6
	29-32	4.8	5.1
	32-35	5.1	4.0
	35-40	5.8	4.6
	Elevation (m)		
Upstream elevation	**3-402**	3.9	6.0
	402-731	4.4	6.0
	732-1043	4.7	4.9
	1044-1544	5.1	4.8
	1545-2493	4.3	3.1
	Geology type		
Geology	**Crystalline basement**	5.0	3.8
	Consolidated sedimentary rocks	4.4	5.0
	Volcanic rocks	4.3	3.1
	Unconsolidated sediments	4.4	4.4
	Surface water	4.0	1.7
	Landcover types		
Landcover	**Shrubland**	4.8	4.8
	Herbaceous vegetation	4.6	4.2
	Cropland	4.4	2.8
	Built-up	4.6	3.5
	Herbaceous wetland	4.8	2.9
	Bare/sparse vegetation	2.3	4.9
	Open forests	5.3	3.8
	Closed forests	5.0	2.7

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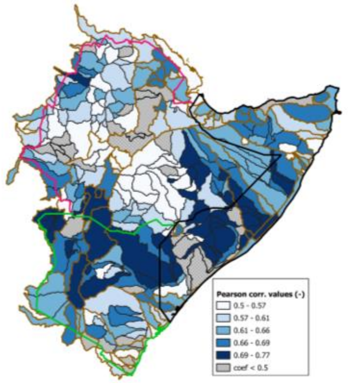
In ~~conclusion~~summary, the propagation of SPI ~~-~~to ~~-~~SSMI ~~propagation~~ and the P/SM mean duration ratio ~~is more~~ ~~d~~depend more~~ent~~ on the soil properties, landcover and ~~when~~the time of the ~~it~~ last rain~~ed~~. All these variables are linked to the storage capacity of the catchment. We see that catchments with a high percentage of sandy soils and shrubland have longer re~~action~~sponse times and ~~long~~ duration~~s~~, while catchments with a low percentage of sandy soils and cropland have short response~~action~~ times and ~~shorter~~ duration~~s~~. This link with soil properties is in line with the findings ~~from~~ of Van Loon and Laaha (2014), who showed that factors such as storage in soils, aquifers, and lakes influence drought duration with longer durations in larger storage and shorter durations in smaller storage.

4.2 Precipitation to streamflow

4.2.1 SPI ~~-~~to ~~-~~SSI

The analysis of SPI ~~-~~to~~-~~ SSI ~~analysis~~ (Figure 6a) shows that the catchments with the low correlation values were m~~ostly~~ainly found in the north~~-~~western ~~at the center~~ centre around the Ethiopian highlands. These areas in the north~~-~~western ~~center~~centre also have short accumulation ~~periods~~times (Figure 6c). A few catchments in the north~~-~~western tip have longer accumulation ~~periods~~periods (5 to 7 months). The majority of ~~the~~ catchments in the HOA have long accumulation periods (≤5 months; 212 catchments)~~,~~ and ~~with~~ 106 catchments hav~~ing~~e short accumulation periods (≥ 4 months). ~~The s~~Signal strength decreases as ~~the further~~ it moves down the hydrological cycle, with the highest correlation value being 0.91 for~~in~~ SPI~~-~~ to~~-S~~ SSMI and ~~being 0.91 and~~ 0.77 for SPI~~-~~ to~~-~~ SSI (Figure 3a and Figure 6a, respectively). This is evident in ~~becomes~~ the ~~clear by the~~ number of catchments where the strength of ~~the~~ correlation value is less than 0.5 (grey sub-catchments in Figure 6a and c). This results in a smaller number of ~~leads to fewer~~ catchments with correlation values above~~higher than~~ 0.5, as the drought propagates from meteorological drought to soil moisture ~~and~~to ~~finally to~~ streamflow drought.



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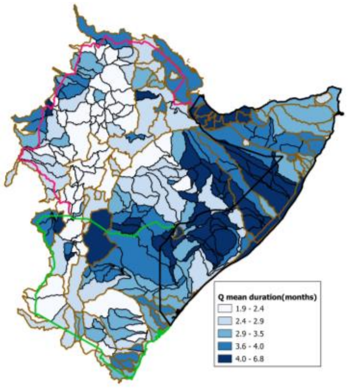

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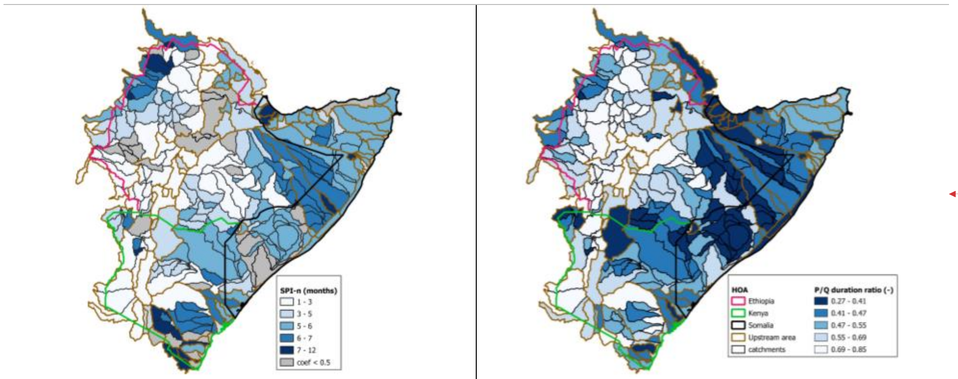

c) d)

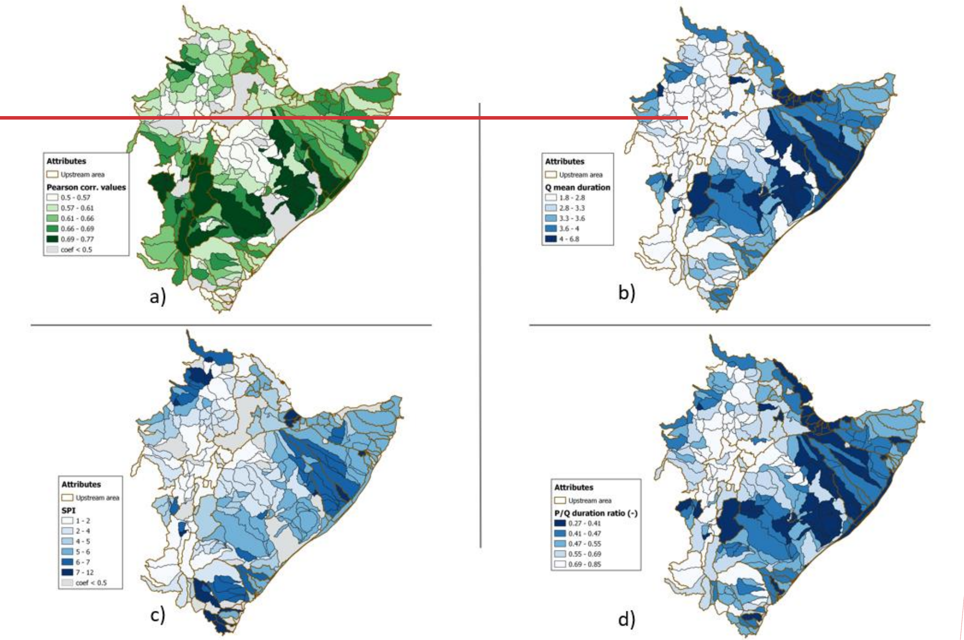

Figure 6~~6~~: Propagation from precipitation to streamflow: a) Highest coefficient values per catchment (>0.5) from SPI~~-~~ to~~-~~ SSI; b) mean streamflow drought duration; c) corresponding SPI-n (SPI accumulation period having highest correlation with SSI) per catchment; d) ratio of mean drought ~~mean~~ duration from meteorological to streamflow (P/Q ratio).

4.2.2 P/Q mean duration ratio

Analysis of P/Q mean duration ratio ~~analysis~~(will further be referred to as P/Q ratio) (Figure 6d) shows that the highest duration ratios are found in ~~the~~ catchments to ~~in~~ the west and southwest of the HOA, and low ratios are found to~~in~~ the east of the HOA towards the coast. In the ~~The~~ catchments with ~~the~~ high P/Q ~~mean duration~~r~~r~~atios, ~~experience~~ short streamflow droughts and longer ~~precipitation drought~~meteorological droughts occur, as shown in Figure 6b and Figure 3c, respectively. In these locations, the runoff response ~~of runoff~~ to rainfall is rapid ~~when it rains is fast~~, in contrast ~~as opposed~~ to ~~the~~ catchments ~~having~~ with low duration ratios that ~~and~~ experienc~~e~~ing longer streamflow droughts,

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~~however~~but the streamflow droughts are still longer than ~~precipitation drought~~meteorological droughts. Streamflow droughts are shorter and there is less pooling~~clustering~~ of ~~precipitation drought~~meteorological droughts to soil moisture ~~and finally~~to streamflow droughts in the west and southwest ~~as opposed~~in contrast to the east towards the coast where they become longer and with increased clustering. The catchments in the east of the HOA are also located within the arid and semi-arid areas.~~, t~~ Therefore, whenever it rains, the process of infiltrations has to occur first before any runoff is produced, ~~making~~ resulting in longer ~~the response of s~~streamflow to precipitation ~~longer~~response. The threshold-based drought duration ratio~~o map~~ (P/Q) map (Figure 6d) shows~~displays~~ similar processes to ~~as~~ the ~~standardized~~standardised indices propagation map (Figure 6c), i.e.~~,~~ short precipitation to streamflow response in the west (~~shown~~ represented by short accumulation periods in the ~~standardized~~standardised indices and a high duration ratio in the threshold indices P/Q ratio).

4.2.3 Relation of precipitation to streamflow with climate and catchment characteristics

Propagation ~~from~~ of ~~precipitation~~ meteorological to streamflow drought is influenced by ~~catchment-scale~~ hydrogeological characteristics of the catchment ~~properties~~. In catchments with sedimentary rocks, shrubland, bare or sparse vegetation, low mean annual upstream precipitation, high aridity, low elevation, medium silt content and low sand content, the propagation of SPI~~-~~ to~~-~~ SSI ~~propagation~~ accumulation periods is longer and the ~~-~~P/Q ~~mean duration~~ ratio ~~have~~ ~~longer accumulation periods and longer~~ duration of drought ~~droughts, respectively~~is longer~~, in catchments with sedimentary rock structure, shrubland, bare or spare vegetation, low upstream mean annual precipitation, high aridity, low elevation, medium percent silt fraction and low percent sand fraction~~. These catchments are located ~~in~~ to the east of the HOA towards the coast (Figure 6c and d) and are associated with small to large~~big~~ ~~catchment~~ upstream catchment areas (Table 1). The influence of upstream areas on propagation was not as pronounced as we expected (Table 1 and Figure 7). The lack of influence of upstream areas on the propagation of drought from precipitation to streamflow contradicts the ~~findings~~ findings ~~in~~of previous studies (Haslinger et al., 2014; Van Lanen et al., 2013; Van Loon & Laaha, 2015; Vidal et al., 2010), suggesting that the propagation time from meteorological drought to hydrological drought may be ~~aggravated~~exacerbated by catchment ~~basin~~ size. In these catchments, the mean duration of streamflow droughts ~~mean duration~~ (Figure 6b) ~~shows~~ has ~~-~~longer time scales than the mean duration of meteorological droughts~~precipitation mean duration~~ (Figure 3c), ~~which~~ reflect~~s~~ing the propagation~~,~~ and ~~indicating~~ suggesting that ~~pooling of~~ shorter ~~precipitation drought~~meteorological drought events are pooled into longer and fewer streamflow drought events due to ~~catchment~~ storage processes in the catchment. C~~The c~~atchments~~s~~ streamflow responded more slowly to ~~nse to~~ precipitation ~~was slower~~, ~~hence,~~ resulting in longer accumulation periods~~periods~~ and low P/Q ~~mean~~ ratios. This is due to~~caused by~~ other processes in these areas, such as infiltration and wetting of the soil surface, which have to take place ~~that need to first occur~~ before the ~~process of~~ runoff occurs. Catchments with short accumulation periods and high P/Q ~~mean duration~~ ratios have high ~~upstream mean annual precipitation~~mean annual upstream precipitation, low aridity, volcanic soils, cropland, forests and high elevation (Table 1 and Figure 5). These catchments respond more quickly to precipitation due to ~~streamflow responses to precipitation are faster because of~~ the high saturation of the volcanic soils, which are mostly located in the west of HOA. These ~~findings~~results are ~~in line~~consistent with previous studies (e.g.~~,~~ Li et al. 2019, Laizé & Hannah, 2010)~~, tha t~~which found that the propagation time from meteorological drought to hydrological drought depends on the flow concentration time, which is ~~highly~~strongly influenced ~~affected~~ by elevation, slope, ~~percentage~~proportion of ~~arable~~ crop~~-~~land and ~~bed~~rock permeability.

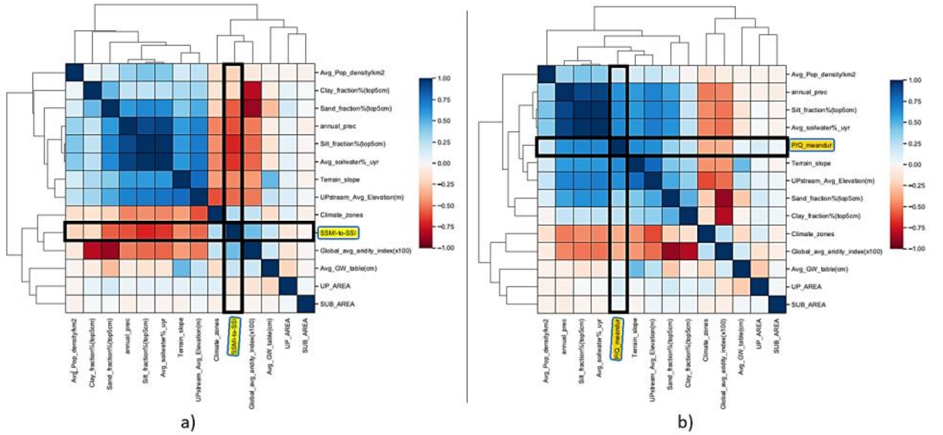

Figure 7~~7~~: Heatmap of Pearson correlations between the propagation indices and catchment characteristics: a) the SPI-to-SSI; b) P/Q mean duration ratio. Euclidean distances used for clustering variables with interchangeable correlations.

C~~The differences in c~~atchment differences~~s~~ in both SPI~~-~~ to~~-~~ SSI propagation and P/Q mean duration ratios ~~has~~ exhibit a spatial pattern that strongly reflects the heterogeneity ~~of the~~in geology (Figure 1d), landcover (Figure 1a), and ~~the~~ precipitation gradient (Figure 1c) from the wetter west to the drier east of the HOA. The overall ~~catchments general~~ precipitation climate of the catchment has a ~~is~~ much ~~more important in~~greater influence on the ~~influencing~~ propagation ~~from~~of ~~SPI-to-SSI and P/Q mean duration~~meteorological to streamflow drought ~~ratio as opposed to~~than on the propagation ~~from precipitation~~of meteorological to soil moisture drought (Table 1 and Figure 5a). The strong link ~~may be~~could be due to ~~a result of~~ the prominent precipitation gradient between the ~~wet~~humid and the (semi-)arid areas. Rainfall in the semi-arid areas is ~~highly~~very erratic and the dry ~~spells~~periods last ~~for~~ longer ~~periods,, leading~~resulting in ~~to~~ very low storage (Vicente-Serrano & Lopez-Moreno, 2006) and longer propagation ~~durations~~times, which translates into longer droughts. This ~~finding~~ result is consistent ~~in accordance~~ with Van Loon et~~.~~ al.~~,~~ (2014) and Barker et~~.~~ al. (2016)~~,~~ who ~~identified~~ found that seasonality ~~in precipitation~~of rainfall is an ~~major~~ important climatic factor ~~affecting~~influencing drought propagation of droughts from meteorological to hydrological droughts.

~~Additionally,~~Moreover, the correlation value of ~~upstream mean annual precipitation~~mean annual upstream precipitation in SPI~~-~~ to~~-~~ SSI propagation was lower ~~when compared~~than the value for ~~to~~ terrain slope, percent silt ~~fraction~~content, upstream average elevation and percent average annual soil water content (Figure 7). This shows that catchment characteristics related to –soil properties, geology and landcover have a greater influence on ~~in~~ the propagation of drought from ~~precipitation~~meteorological to streamflow drought~~, the catchment properties related to soil properties, geology and landcover are more influential~~ than ~~than~~ the ~~upstream annual mean precipitation~~mean annual upstream precipitation ~~in determining the drought propagation~~. This result is ~~in line~~consistent with the findings of Barker et~~.~~ al. (2016), who found that ~~the~~ hydrological drought characteristics of catchments with permeable aquifers ~~outcrops~~ have~~HOA~~ a weak correlation with mean annual precipitation and a strong correlation with catchment storage characteristics such as the Base Flow Index (BFI) or the percentage of highly fractured rock.

5 Discussion

5.1 Implications for research

When we compare~~ing~~ our results with catchment-level~~scale~~ studies (see Section 4), we find comparable processes of drought propagation ~~processes~~ and a similar influence of climate and catchment characteristics on this propagation. As this is a ~~a~~ study specific ~~for~~ to the HOA region, our results have a number of important implications for drought risk analysis in drylands ~~areas~~, but may not be ~~valid~~ transferable ~~for~~to other regions. The HOA region was chosen because of the high~~large~~ variability in climate and catchment characteristics and the large number of catchments.

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~~Within~~In the study region, ~~the ~~precipitation ~~can be found to be~~is related to the elevation (increasing precipitation with increasing~~e in altitude~~ elevation and increasing aridity towards the east, where elevation and precipitation~~ich~~ also~~ has~~ decreasing~~e altitude and precipitation))~~). ~~When c~~Comparing catchments ~~within~~in the (semi)-arid~~-~~ re~~dryland re~~gion of the study area, ~~we ~~it appears that ~~learn that ~~catchment-scale hydrogeological processes, such as geology and landcover, ~~are~~ dominate~~nt in influencing~~ the propagation of drought from ~~precipitation~~meteorological to streamflow, while land surface processes, ~~for example~~such as soil properties, influence the propagation from ~~precipitation~~meteorological to soil moisture drought (Figure 3). This is ~~in accordance~~consistent with previous studies (e.g.~~,~~ Barker et al., 2016; Van Loon, 2013).

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We find that the differences in propagation from ~~precipitation~~meteorological to soil moisture drought~~ to~~ are also ~~be~~ influenced by spatial variability in precipitation~~ variability~~, with the ~~humid ~~wetter western part of HOA having catchments with both short and long propagation timescales, and the drier eastern~~ center~~ having only long propagation timescales. We~~ have learned~~ found that drought ~~periods~~are shorter in~~ the~~ catchments in the humid west of the HOA (with a higher global average aridity index, fertile volcanic soils~~,~~ and~~ cropland)~~ arable land) ~~are shorter ~~than in~~ the~~ catchments in the (semi-)arid east of the HOA. For ~~instance~~example,~~ the~~ catchments in the (semi-)arid east with shrubland, bare or sparse vegetation and ~~underlain with s~~sedimentary rocks (consolidated and unconsolidated) are affected by longer periods of soil moisture drought. In addition, streamflow drought and the time scale for ~~the propagation~~propagation from meteorological~~ drought~~ to soil moisture~~e drought~~ to hydrological drought is also longer (≥5 months). Therefore, for the process of drought propagation from ~~precipitation~~meteorological to streamflow drought, it is important not only to monitor~~ not only~~ precipitation forecasts but ~~–~~information on hydrogeological characteristics, such as geology and landcover, of the catchment is also essential. Incorporating this knowledge into hydrological drought forecasting could significantly increase the predictive value of forecasting systems by making the forecast less dependent on the ~~forecasting~~predictive skill ~~skill ~~of actual precipitation. We have also confirmed that drought duration is influenced by both climate and catchment control processes, similar to Van Loon and Laaha, (2014). There is still a need to further investigate the ~~effect ~~impact on the propagation timescale when we include groundwater.

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The ~~research ~~study also highlights some of the ~~issues~~problems with using SPI, SSMI, SSI~~,~~ and threshold-based duration ratios. ~~The ~~Due to the nature of ~~standardized~~standardised indices, they are~~ makes it~~ unable to identify regions with highly seasonal climates and arid regions (Hayes et al., 1999). Unlike threshold-based indices, it does not ca~~It fails to ca~~pture the water deficits~~ amounts~~ in~~ the~~ different catchments and regions that are more prone to drought than others~~, as opposed to the threshold-based indices~~. ~~Additionally~~Moreover, dry regions with ~~misleading large positive and negative values may occur in the arid regions with ~~the short accumulation periods (1, 2 or 3 months) may have misleadingly high positive and negative values. Although calculating the SPI, SSMI or SSI for any user-defined accumulation periods makes the indicators more flexible, it is still~~remains~~ important to choose~~ that~~ meaningful accumulation periods ~~are chosen ~~to capture ~~the ~~drought conditions and also to select appropriate indicators (Vicente-Serrano & Lopez-Moreno, 2005). ~~Furthermore~~In addition, the results confirm that accumulation periods should be selected based on the impacts of drought~~ impacts~~. The threshold-based indices represent the specific duration of drought event~~ duration~~, thus~~ hereby~~ better representing the link with catchment characteristics and better capturing seasonal ~~precipitation variability~~spatial variability in precipitation within the catchments.

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~~Based on the results presented in this paper, we provide an argument for considering terrestrial processes on the drought propagation in the context of drought risk analysis. We found that drought propagation from meteorological to soil moisture and to hydrological drought cannot be explained by atmospheric processes alone. The propagation process is highly influenced by climate and catchment characteristics, hence, when forecasting droughts it is preferred to use a full hydrological model framework, or at least an indicator-based method which takes (either implicitly or explicitly) such characteristics into consideration, as the results of our study suggests.~~

5.2 Implications for drought monitoring and early warning

Drought mitigation and water resources management require reliable and efficient drought monitoring and early warning systems (M&EW)~~,~~ as they are a critical component of drought preparedness (Barker et al., 2016; Safavi et al., 2018). The efficiency of these systems in ~~analyzing~~analysing extremes is ~~highly ~~largely determined by the choice of indices, which ~~must ~~need to consider and integrate different aspects of information. Drought M&EW systems usually use ~~standardized~~standardised indices such as the SPI, especially ~~since ~~as the SPI is the most widely used index

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to characteris~~z~~e drought (Vicente-Serrano & Lopez-Moreno, 2005). However, the use of ~~standardized~~standardised indices and threshold-based indices for soil moisture and hydrological droughts is not widespread ~~and~~ or~~not~~ well developed ~~for soil moisture and hydrological droughts~~ in the HOA. For example, the National Drought Monitoring Agency (NDMA) in Kenya has a good drought M&EW system, ~~however~~but it ~~this uses~~ only considers precipitation, while impacts are more ~~likely to be~~ associated with soil moisture and hydrological droughts. The SSI and the use of threshold-based indices are less common in the HOA. This may be due to the lack of streamflow data in this region compared to precipitation data, especially for the short time scales required to produce useful drought M&EW products. However, monitoring soil moisture and hydrological variables and incorporating such indices is beneficial for reliable and effective drought planning and water resource management, and it is ~~especially~~ particularly useful for communication purposes if precipitation, soil moisture and streamflow are monitored in a comparable manner.

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~~While~~ Although the use of streamflow and soil moisture data directly in drought M&EW systems is preferred, these systems cannot be used in this region due to the lack of data ~~in this region~~. Therefore, the SPI could be~~provide~~ a surrogate for soil moisture and streamflow impacts, provided suitable propagation times are known. This also ensures the use of ~~standardized~~standardised indices in the HOA and discourages the use of threshold-based indices (which require raw data).~~,~~ Given the uncertainty in modelled ~~and considering the uncertainty in modelled~~ and reanalysis data, it is better to standardis~~z~~e the datasets, as is the case with ~~standardized~~standardised indices ~~do~~ (Van Loon & Laaha, 2014; Van Lanen et al., 2013; Van Loon, 2013). The correlation results (Figure 3b and Figure 6c) showing the spatial variability of SPI-*n* (the accumulation period ~~that is~~ strongly correlated with SSMI-1 and SSI-1, respectively) ~~,~~ ~~provide~~give an indication of accumulation periods that could serve as ~~a~~ proxies~~y~~ for soil moisture drought~~s~~ or streamflow drought~~s~~ in the monthly precipitation data. This allows the use of precipitation data~~, which are~~that is more readily available ~~, for~~to identify~~ing~~ ~~future~~future potential soil moisture and streamflow droughts. ~~Additionally~~In addition, the short soil moisture and streamflow droughts, which are ~~that have been~~ more influential for ~~the d~~drought planning and water resource management, are better captured by the short accumulation periods (Figure 3b and Figure 6c), which are less affected by ~~the~~ decreasing long-term trends in precipitation and streamflow ~~trends~~ in the eastern ~~of the~~ HOA and increasing trends in the western ~~of the~~ HOA (Gebrechorkos et al., 2020). Water managers can use this information on soil moisture and streamflow trends to ~~see~~ identify when to ~~start~~ begin controlling ~~the~~ water users and anticipate drought impacts. The ~~obtained~~ results obtained can~~may also~~ be used to forecast ~~applicable in~~ water resource ~~forecasting~~.

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5.3 Recommendations and further research

Groundwater plays an important role in mitigating the impacts of drought and as a source of water supply in arid and semi-arid areas, ~~particularly~~ especially in the eastern part of the HOA (Adloff et al., 2022). Therefore, to fully understand the process of drought propagation, it is necessary to include the groundwater component in the analysis. ~~Moreover~~Furthermore, while catchment storage ~~in the catchment~~ plays a key role in determining the drought duration ~~of drought an~~and propagation, it is also i~~i~~mportant to ~~take into account~~consider seasonality and autocorrelation of soil moisture, as well as ~~and also~~ streamflow caused by infiltration and evaporation. Therefore, ~~undertaking~~ analysing the propagation ~~analysis~~ of the drought signal through the hydrological cycle and including the groundwater component would provide a more comprehensive picture and assessment of the influence of climate and catchment characteristics on the ~~drought~~ duration, severity and propagation. In addition, the ~~effect~~ impact of seasonal variability (based on ~~the~~ long and ~~the~~ short rains) o~~i~~n drought propagation should be further investigated. Seasonal variability is particularly important for the propagation from ~~precipitation~~meteorological- to- soil moisture drought, especially in the western part of the HOA where the ~~response of~~ soil moisture response to precipitation ~~is~~ depend~~ents~~ on when it last rained. Similarly, the timing of hydrological droughts leading to impacts should be investigated.

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Finally, the availability of ~~for observation-based studies of drought, the availability of hydr~~hydrolo~~l~~ogical records for observation-based studies of drought is a limitation. This is particularly true for the HOA. The period of analysis (1980-2020) does not capture the full range of hydrological variability. We ~~assume~~ anticipate that longer records could affect ~~influence~~ the accumulation periods presented here, although the same regional picture and propagation characteristics would ~~probably~~ likely emerge. ~~Furthermore~~In addition, the use of modelled and reanalysis data has introduced some uncertainty into the analysis. For example, the GloFAS streamflow dataset was developed for a global application and represents streamflow in perennial systems typical of humid regions. ~~Correspondingly~~Accordingly, it does not represent ephemeral flow processes typical ~~of~~ in dry~~land~~ regions. ~~As such~~The~~, the~~ dataset tends to over-/underestimate the streamflow in arid and semi-arid areas~~. As such, the dataset tends to overestimate streamflow in arid and semi-arid areas~~. ~~Hence~~Therefore, a modelling framework ~~that is~~ suitable

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for ~~dryland~~ (semi-)arid areas~~regions~~, where hydrological processes ~~are distinct~~differ from those in humid regions~~, would be preferred~~ is crucial. For example, a model ~~like~~ such as the DRYP hydrological model (Quichimbo et al., 2021) has been ~~designed~~ developed specifically for ~~dryland~~ hydrological processes ~~-~~such as ephemeral flow, surface~~-~~ and groundwater interactions, and high ~~-~~resolution ~~rainfall~~ precipitation in (semi-)arid regions, and therefore ~~– as such h~~has ~~a~~ good potential for further investigation and application. This model has been used to investigate the role of gridded ~~gridded rainfall resolutio~~precipitation resolution ~~n~~ in~~to~~ soci~~etally~~ally~~-~~ relevant water stores (streamflow, soil moisture and groundwater recharge) ~~(Quichimbo et al., submitted)~~ and has been used to ~~generate~~make water balance ~~forecasts~~predictions based on seasonal climate ~~forecasts~~projections in the HOA. ~~(MacLeod et al., in review).~~ A regional version of this model would provide a better alternative for follow-up studies given the GloFAS dataset limitations~~-~~.

6 Conclusion

Drought propagation from meteorological to soil moisture to hydrological drought in 318 catchments in the HOA was ~~analyzed~~analysed using ~~standardized~~standardised indices (over a range of accumulation periods) and threshold-based indices (drought-duration ratios). In addition, the influence of possible governing factors, such as climate and catchment characteristics, was also investigated. The research shows that:

- Precipitation to soil moisture propagation time is longer (5 to ~~-~~7 months) in catchments with shrubland, closed and open forests, herbaceous wetland and vegetation, and high sand and low silt fraction, while being shorter (2-4 months) in catchments with cropland and high ~~upstream mean annual precipitation~~mean annual upstream precipitation.
- Precipitation to streamflow propagation time is longer in catchments with sedimentary rock structure, low mean annual precipitation, and shrubland, while being shorter in catchments with volcanic soils, high annual mean precipitation, cropland and forests.
- In precipitation to streamflow propagation the catchment properties related to soil properties, geology, elevation and landcover are more influential than ~~upstream annual mean precipitation~~mean annual upstream precipitation~~-~~. However, the ~~upstream mean annual precipitation~~mean annual upstream precipitation is ~~more~~ not so important for streamflow drought duration, ~~severity~~ and propagation from precipitation-to-streamflow~~;~~ ~~as opposed~~but ~~to~~ nevertheless mean annual upstream precipitation is even less important in propagation from ~~precipitation to soil moisture~~precipitation to soil moisture .

In summary, precipitation to soil moisture propagation is more dependent on the soil properties as opposed to the hydrogeological characteristics (i.e., elevation) while the precipitation to streamflow propagation experience the combined effect of climate and catchment control properties (i.e., elevation, geology). The results in this study provide an indication of precipitation accumulation periods that could serve as a proxy for soil moisture and streamflow droughts in the HOA. The precipitation accumulation periods of roughly 1~~-~~ to 4 months in wet western areas of HOA, and of roughly 5 to ~~-~~7 months in the more dryland regions are the most suitable for drought analysis. These results can be used as a foundation for future developments in drought monitoring and early warning systems in the HOA, laying foundations for better drought preparedness and increased resilience to drought and its impacts in water resources.

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Competing interests. The authors have no competing interests to declare.

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