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Hydrological Response and Complex Impact Pathways of the 2015/2016 El Niño in Eastern and Southern Africa

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Key Points:

- Quantitative and qualitative data provide insights into hydrological impact pathways of precipitation anomalies associated with the El Niño of 2015/2016
- Variable teleconnection patterns, antecedent hydrological conditions and changing socioeconomic boundary conditions led to complex impact pathways of this El Niño event
- Our findings show the need for diverse management responses, with adaptive reservoir management required and diversification of energy and water sources essential

Supporting Information:

- Supporting Information S1
- Supporting Information S2

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Abstract The 2015/2016 El Niño has been classified as one of the three most severe on record. El Niño teleconnections are commonly associated with droughts in southern Africa and high precipitation in eastern Africa. Despite their relatively frequent occurrence, evidence for their hydrological effects and impacts beyond agriculture is limited. We examine the hydrological response and impact pathways of the 2015/2016 El Niño in eastern and southern Africa, focusing on Botswana, Kenya, and Zambia. We use in situ and remotely sensed time series of precipitation, river flow, and lake levels complemented by qualitative insights from interviews with key organizations in each country about awareness, impacts, and responses. Our results show that drought conditions prevailed in large parts of southern Africa, reducing runoff and contributing to unusually low lake levels in Botswana and Zambia. Key informants characterized this El Niño through record high temperatures and water supply disruption in Botswana and through hydroelectric load shedding in Zambia. Warnings of flood risk in Kenya were pronounced, but the El Niño teleconnection did not materialize as expected in 2015/2016. Extreme precipitation was limited and caused localized impacts. The hydrological impacts in southern Africa were severe and complex, strongly exacerbated by dry antecedent conditions, recent changes in exposure and sensitivity and management decisions. Improved understanding of hydrological responses and the complexity of differing impact pathways can support design of more adaptive, region-specific management strategies.

Plain Language Summary The 2015/2016 El Niño was one of the three most severe on record. El Niño is commonly linked to droughts in southern Africa and extreme rainfall in eastern Africa but no two El Niño's are the same. We present an analysis of the impact of the 2015/2016 El Niño in eastern and southern Africa, focusing on Botswana, Kenya, and Zambia. We use field measurements and observations from satellites of rainfall, river flow, and lake levels in combination with insights from experts in each country about awareness, impacts, and responses. Our results show that drought conditions prevailed in large parts of southern Africa, reducing river runoff and contributing to unusually low lake levels in Botswana and Zambia. This led to water supply disruption in Botswana and hydroelectric load shedding in Zambia. Warnings of flood risk in Kenya were pronounced, but the El Niño did not materialize as expected in 2015/2016. Extreme rainfall was limited and caused only localized impacts. Improved understanding of the regional impact of El Niño will help to be better prepared for the next El Niño.

1. Introduction

Sea surface temperatures in the eastern Pacific Ocean following the 2015/2016 El Niño have returned to normal, but the scale of hydrological and socioeconomic impacts of the event have yet to be assessed. El Niño, or the El Niño Southern Oscillation (ENSO) is one of the major and most well-defined drivers of interannual climatic variability in the world. A global phenomenon, El Niño recurs every 2–7 years with varying intensity. The El Niño of 2015/2016 was the strongest on record, on par with the major events of 1982/1983 and 1997/1998 (Parker et al., 2016). El Niño events enhance precipitation variability around the world (Blunden & Arndt, 2016), and are generally associated with drought in southern Africa, and precipitation and floods in eastern Africa (Nicholson & Kim, 1997).

In this paper we focus on three examples of El Niño associated hydrological disruption in urban areas, two looking at drought and one considering flooding. Despite their potential wide-ranging consequences, detailed evaluations of broader socioeconomic impacts of hydrological disruption in Sub-Saharan Africa (SSA) are rare. The impact of droughts in southern Africa during El Niño years has generally been associated with agriculture (Archer et al., 2017; Baudoin et al., 2017; Bennie & Hensley, 2001; Glantz, 2001; Rojas et al., 2014; Stige et al., 2006). With increasing urbanization, however, water supply disruption from chronic and episodic water scarcity has become endemic in SSA. In addition, reliable hydropower production is at risk during prolonged droughts, with many countries relying on a few hydropower dams for a large proportion of their electricity supply (Conway et al., 2015). Electricity infrastructure and consumption has been broadly linked with development, economic growth and increased productivity (Eberhard & Shkaratan, 2012; Geginat & Ramalho, 2015; Kaseke & Hosking, 2013). So too has water infrastructure. The evidence base considering the relationship surrounding the quality of electricity supply and the economy is much sparser, however, and detailed analyses of the role of climate in impact pathways of public water supply disruption are almost nonexistent.

Floods and their impacts in SSA are similarly lacking in attention in the literature, even though the problem is of serious concern (Tarhule, 2005). Floods cause major short-term social and economic disruption in SSA and, through their impact on infrastructure, incur significant long-term financial losses. In Kenya, extensive floods during the 1997/1998 El Niño caused loss of life and livestock and widespread disruption of socioeconomic activities for several months due to extensive damage to property, infrastructure, and communication facilities (Conway, 2002). Most cities in SSA have a large portion of their population living in informal settlements, exacerbating the extent to which people's lives and livelihoods are exposed to flood risk (Bhattacharya-Mis & Lamond, 2011).

The examples given above are illustrative, but the methods and data used to estimate impacts of floods and droughts are often poorly documented. To our knowledge there are no examples for SSA of near real-time assessments with detailed analysis of impact pathways that couple biophysical and management perspectives. Strong El Niño's are relatively rare events that are typically described in studies on global or regional hydrology, that consider temporal correlation with precipitation (Nicholson & Kim, 1997; Nicholson & Selato, 2000; Parhi et al., 2016; Preethi et al., 2015) or a single hydrological characteristic like river flows or water scarcity (Amarasekera et al., 1997; Veldkamp et al., 2015; Ward et al., 2010). Given the importance of El Niño associated anomalies to climate variability in SSA, a better understanding of the hydrological response and impact pathways is crucial for developing effective and adaptive water resources management strategies.

Developing such strategies is complicated by the erratic nature of El Niño. While its drivers and teleconnections are increasingly well understood, El Niño remains elusive. Past decades have seen many false forecasts (Cohen, 2016; McPhaden, 2015; McPhaden et al., 2015) and El Niño's strength and timing varies from event to event. Warm sea surface temperature anomalies in parts of the Pacific are insufficient in themselves to generate an El Niño (McPhaden, 1999). Higher frequency variability, mostly related to westerly winds significantly modulates El Niño events and can even stop its progress (Hu et al., 2014; Levine & McPhaden, 2016; McPhaden, 1999). ENSO is, moreover, just one of the factors governing regional weather variability. Other factors include interactions with different modes of sea surface temperatures variability; the Indian Ocean Dipole (Conway et al., 2007; Saji & Yamagata, 2003), the Subtropical Indian Ocean Dipole (Behera et al., 2000; Behera & Yamagata, 2001; Reason, 2001; Washington & Preston, 2006) and sea surface temperatures in the Atlantic Ocean (Reason & Smart, 2015). This complex system of influences, off-setting or strengthening one another depending on their timing and location of occurrence, leads to profound spatial variation in impacts associated with El Niño in SSA. It also adds considerable randomness to teleconnections and their hydrological consequences.

The 2015/2016 El Niño presents a unique case; it is one of the strongest on record, after a period of relatively mild El Niño events. Advances in data collection, that is, remote sensing, supported by global efforts in consolidating spatially consistent climatic and hydrological databases, mean there is now near real time data and records of sufficient length to trace impact pathways and allow comparison of this El Niño with others, in locations where observations may be very sparse. Forecasts and newly established early warning networks facilitated a management response of which the effectiveness can be evaluated. In this paper we therefore apply a mixed-method approach to examine how precipitation during the 2015/2016 El Niño unfolded and how it propagated through hydrological pathways to generate societal impacts and, secondly, to analyze the role of preparedness and response by resource managers during the events.

2. Methodology

2.1. Methods of Analysis

We adopted a mixed methods research design (Creswell & Clark, 2007; Tashakkori & Teddlie, 1998) that coupled analysis of hydrological data with qualitative data from interviews with key informants. First, we tracked the hydrological response to the 2015/2016 El Niño over a 2-year period, starting in July 2014, to examine the El Niño evolution, that is, to capture the near El Niño year of 2014/2015 and the onset, peak and cessation of the 2015/2016 El Niño. Comparison was made with previous El Niño events classified as "Strong" to "Very Strong," including 1982/1983 and 1997/1998, and with non-El Niño years. Only data series that include the 2015/2016 El Niño, up to June 2016, were used. This composite analysis was supplemented with analyses of precipitation, river flow and lake level time series, to examine the role of antecedent conditions. We traced the hydrological response in four steps:

1. Seasonal precipitation totals were analyzed for locations in, or near, each of the capital areas; Nairobi for Kenya, Gaborone for Botswana and Choma-Batoka, in between Lusaka, the capital of Zambia, and Lake Kariba, the country's major source of hydropower. Annual data were aggregated over the July to June period to capture the complete cycle of precipitation; parts of Kenya experience bimodal seasonality, with precipitation maxima during March to May, known as the long rains, and October to December, known as the short rains, while in the relevant areas of Botswana and Zambia precipitation is unimodal. Cumulative precipitation over the 2-year period was also calculated.
2. Precipitation anomalies over the contributing river basin (in case of the Zambezi) or the whole country (in the cases of Botswana and Kenya) were assessed through the "Weighted Anomaly Standardized Precipitation" (WASP) index (Lyon & Barnston, 2005), based on the monthly CHIRPS precipitation product. WASP gives an estimate of the relative deficit or surplus of precipitation for different time intervals ranging from 1 to 12 months. To compute the index, 3-monthly precipitation departures from the long-term average (here 1986–2015) were obtained and then standardized by dividing by the standard deviation of monthly precipitation. For Kenya a more detailed comparison was made with the notorious 1997/1998 El Niño, using a 6-month WASP for the October to March period.
3. River flows upstream of the main reservoirs integrate precipitation anomalies in the upstream catchment areas and were used to assess the extent of hydrological impacts. Although these observations exclude information on water storage in reservoirs, they are independent of management practices that influence reservoir volumes. Daily river flows were aggregated to monthly sums (for Zambia only).
4. Lake and reservoir levels are an important indicator for hydropower and drinking water shortages. They are influenced by river flows, reservoir management and direct abstractions. Outliers in daily lake levels, shown mostly as sudden drops in the remote sensing derived data, were filtered using a Tukey smoothing (Tukey, 1977) with standard parameterization as provided by the R-package "smooth." Data were then aggregated to monthly values for the analysis (for Botswana and Zambia only).

Second, we sought qualitative insights through interviews with key informants about awareness, impacts and responses to the event. Key informants were selected to provide coverage of actors including relevant local and national government departments and nongovernmental organizations (NGOs) in each country (Table 1). Qualitative data are valuable for capturing the depth and complexities of socioenvironmental issues (Mason, 2006; Moran-Ellis et al., 2006; Vaccaro et al., 2010). The interviews were used to reveal the role of management (including social and political influences) in the hydrological impact pathways.

Coding was undertaken in both an inductive and a deductive manner, with the coding scheme developed first based on the theory and ideas that were central to the research question and evolving iteratively in response to the data. The coding scheme comprised five main categories that include hydrological and management dimensions (impacts, responses, warnings and climate information, confounding and compounding factors, and references to other extreme/El Niño events, see Table 2). Each of these five main

Table 1.
Number and Organizations of Key Informants Interviewed Per Country

	N	Organizations
Gaborone, Botswana	13	Dept. of Meteorological Services Botswana (DMS); Dept. of Water Affairs (DWA); National Disaster Management Office (NDMO); Water Utilities Corporation (WUC); Stephenson Associates, Econsult; Centre for Applied Research Botswana (CAR); University of Botswana (UB); Dept. of Town and Regional Planning (DTRP)
Lusaka, Zambia	13	Zambia Red Cross Society; Dept. of Energy in the Ministry of Mines, Energy and Water Development; Disaster Management and Mitigation Unit (DMMU); Zambia Meteorological Dept. (ZMD).; Ministry of Lands, Natural Resources and Environmental Protection (MLNREP); Zambia Water Resources Management Authority (WARMA); Zambia Climate Change Network;
Nairobi, Kenya	14	Ministry of Water and Irrigation; National Environment Management Authority (NEMA); KenGen; Kenya Meteorological Dept. (KMD).; National Disaster Operations Centre (NDOC); IGAD Climate Prediction and Application Centre (ICPAC); State Dept. of Special Programmes under the Ministry of Devolution and Planning; Climate Change Directorate; Kenya Red Cross; National Drought Management Authority (NDMA); Kenya Association of Manufacturers (KAM); National Environment Management Authority (NEMA); Nairobi City Water and Sewerage Company (NCWSC)
All countries	40	

categories contained a range of subcodes designed to capture detail to support the analysis. The coding sought to identify key points within each of the case studies and was used to triangulate and augment the secondary/quantitative data (*Bryman*, 2006). The coding was done using NVivo software (*Wong*, 2008).

Finally, to complement this analysis we tracked Regional Internet Search Frequencies (RISF) (Carneiro & Mylonakis, 2009; Choi & Varian, 2012) of the words "El Niño" in each of the three countries, to highlight when "El Niño" caught the attention of the wider public. RISF provides a weekly index of the relative volume of Google Search queries in a particular geographic region compared to the total search volume. It has been used for different purposes, such as health surveillance (Carneiro & Mylonakis, 2009; Chae et al., 2015; Ginsberg et al., 2009) and forecasting economic indicators (Choi & Varian, 2012; Wu & Brynjolfsson, 2014).

2.2. Data

The Oceanic Niño Index (ONI), a 3-month running mean of sea surface temperature anomalies in the Niño 3.4 region (5°N–5°S, 120–170°W), has become the standard for identifying El Niño (warm) and La Niña (cool) events in the tropical Pacific. This region is strongly coupled with the overlying atmosphere (Barnston et al., 1997) and to global teleconnections (e.g., L'Heureux et al., 2016). Events are defined as five consecutive overlapping 3-month periods at, or above, the +0.5°C anomaly for warm (El Niño) events and at, or below, the −0.5°C anomaly for cold (La Niña) events. An El Niño year is categorized as "Strong" when anomalies are above +1°C, or "Very Strong" when above +1.5°. Data were downloaded from the Unites States National Weather Service Climate Prediction Center (www.cpc.ncep.noaa.gov).

Recent precipitation data for indicator stations in each country were obtained directly from the national meteorological office in the case of Kenya (Wilson airport station) or downloaded from the Climate Data Online (CDO) portal (www.ncdc.noaa.gov/cdo-web/datasets) in the case of Botswana (Gaborone station) and Zambia (Choma-Batoka station). Longer time series were generated using monthly station data (Harris et al., 2014). For better spatial coverage, the "Climate Hazards Group InfraRed Precipitation with Station" data (CHIRPS) were used. CHIRPS is a 30+ year quasi-global precipitation dataset, spanning 50°S–50°N, available from 1981 to the near-present. CHIRPS incorporates 0.05° resolution satellite imagery of infrared Cold Cloud Duration observations, with in situ station data to create gridded precipitation time series (Funk et al., 2015).

River discharge data for the Zambezi, flowing into Lake Kariba, were derived from the Zambezi Water Resources Management system of the Zambezi River Commission (zamwis.zambezicommission.org) for

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Table 2.
Coding Scheme (in Gray Shading Codes Predominantly Used for This Paper)

Main category	Subcode
Impacts	Hazard or nature of disruption
	Sector Impacts (agriculture, energy, health, manufacturing, mining, service, tourism, water)
	Spatial and temporal variations
	Hydrological observations
	Sociopolitical consequences
	Economic consequences
	Positive impacts and beneficiaries
Responses	Sector adaptations (agriculture, energy, health, manufacturing, mining, service, tourism, water)
	Cultural and social adaptations
	External support
	Ex-ante responses (adaptation responses to warnings)
	Ex-post responses
	Successful adaptation
	Opportunities and learning
	Barriers
Warnings and climate information	Climate and El Niño information generation
	Sources of El Niño information
	Timings and warnings
	Accuracy of warnings
	Accessibility and meaningfulness of warnings
	Trust in warnings
	Awareness and understanding of El Niño
Confounding and compounding factors	Sociopolitical confounding factors
	Economic confounding factors
	Environmental confounding factors
Other events	Other El Niño events and experiences
	La Nina and future climate expectations

the Victoria Falls Big Tree station, which has a record of almost 50 years of daily flows. After excluding years with missing data a 45-year time series remained.

Lake level variations for many large lakes around the world are observed using satellite radar altimeters. In Zambia, Kariba lake levels are routinely monitored as part of the G-REALM lake level project by the U.S. Department of Agriculture's Foreign Agricultural Service in cooperation with the National Aeronautics and Space Administration, and the University of Maryland (Birkett et al., 2011). The Gaborone reservoir in Botswana is not included in this dataset and hence reservoir levels were obtained from the Botswana Department of Water Affairs.

Data on perceptions of impacts and management responses were derived from interviews with key informants, relevant ministries and focal agencies, such as the national weather services. A total of 39 respondents were consulted across the three case studies through interviews lasting between 45 min and 2 h (Botswana $n = 13$, Kenya $n = 13$, Zambia $n = 14$; Table 1). Each interview was captured through an audio recording and/or written notes. Audio recordings were transcribed and the data were coded using the scheme illustrated in Table 2.

RISF data on the El Niño event were obtained from the Google trend website (www.google.co.uk/trends), using the search term "El Niño" for each of the three countries.

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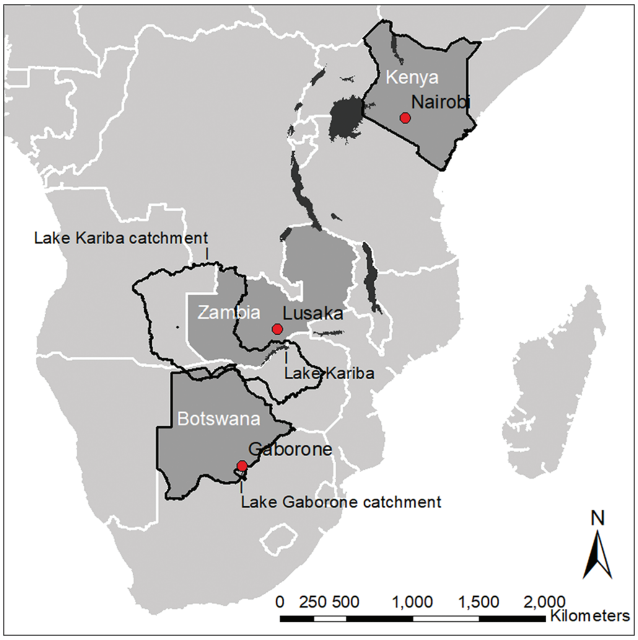

Figure 1. Map of the study areas, with capital cities in red, countries in dark gray and the black polygons delineating the areas used for the WASP precipitation analysis.

2.3. Case Study Areas

We focused our analysis on the capital cities of Botswana, Kenya, and Zambia. These three countries transect SSA from north to south (Figure 1) and have all experienced severe, but varying, impacts during previous El Niño events. Kenya experienced widespread flooding leading to disruption and loss of life during the El Niño of 1997/1998. While in southern Africa, both Botswana and southern Zambia were affected by large scale drought during the El Niño in 1991/1992, and to a lesser extent in 2009/2010. We examined capital regions where there is a high concentration of business activity (a complementary part of the research considered how business activity was affected by the El Niño event) and high exposure to extreme events. Rapid urbanization, as seen in Nairobi, often leads to high vulnerability to flooding, through settlements encroaching into riverine areas, slow expansion of sewage systems and expansion of impermeable surfaces leading to increased and faster runoff. The impact of drought on water shortages is also often strongly felt in cities, due to a high reliance on water provided by a small number of reservoirs. Following this trend, Gaborone reservoir supplies a large proportion Gaborone's drinking water, while in Zambia, the Lake Kariba hydropower station provides most of Lusaka's electricity.

3. Results

3.1. Evolution of the 2015/2016 El Niño and Early Signals

From as early as March 2015, the Pacific Ocean began to warm rapidly, with an El Niño declared in May, as atmospheric indicators consolidated (Australian Bureau of Meteorology, 2016). Peaking relatively late in November 2015 until January 2016, the ONI index reached values comparable to the strong El Niño events of 1997/1998 and 1982/1983 (Australian Bureau of Meteorology, 2016; Parker et al., 2016), before declining to near normal values by June 2016. Some previous strong El Niño events have been followed by strong La Niña events (the cool phase of ENSO) and early forecasts hinted towards the same (International Research Institute [IRI], 2016). However, the likelihood of a strong La Niña dissipated over the course of 2016 and never occurred.

The preceding year, 2014/2015, sets this El Niño apart from other strong El Niño events. El Niño appeared in El Niño indices early in 2014 (Parker et al., 2016), but in the summer of 2014 an intense easterly wind burst stalled the flow of warm waters to the eastern Pacific Ocean (Hu & Fedorov, 2016; Levine & McPhaden, 2016). Although forecast to be an El Niño year, it therefore never materialized and the Niño-3.4 region was

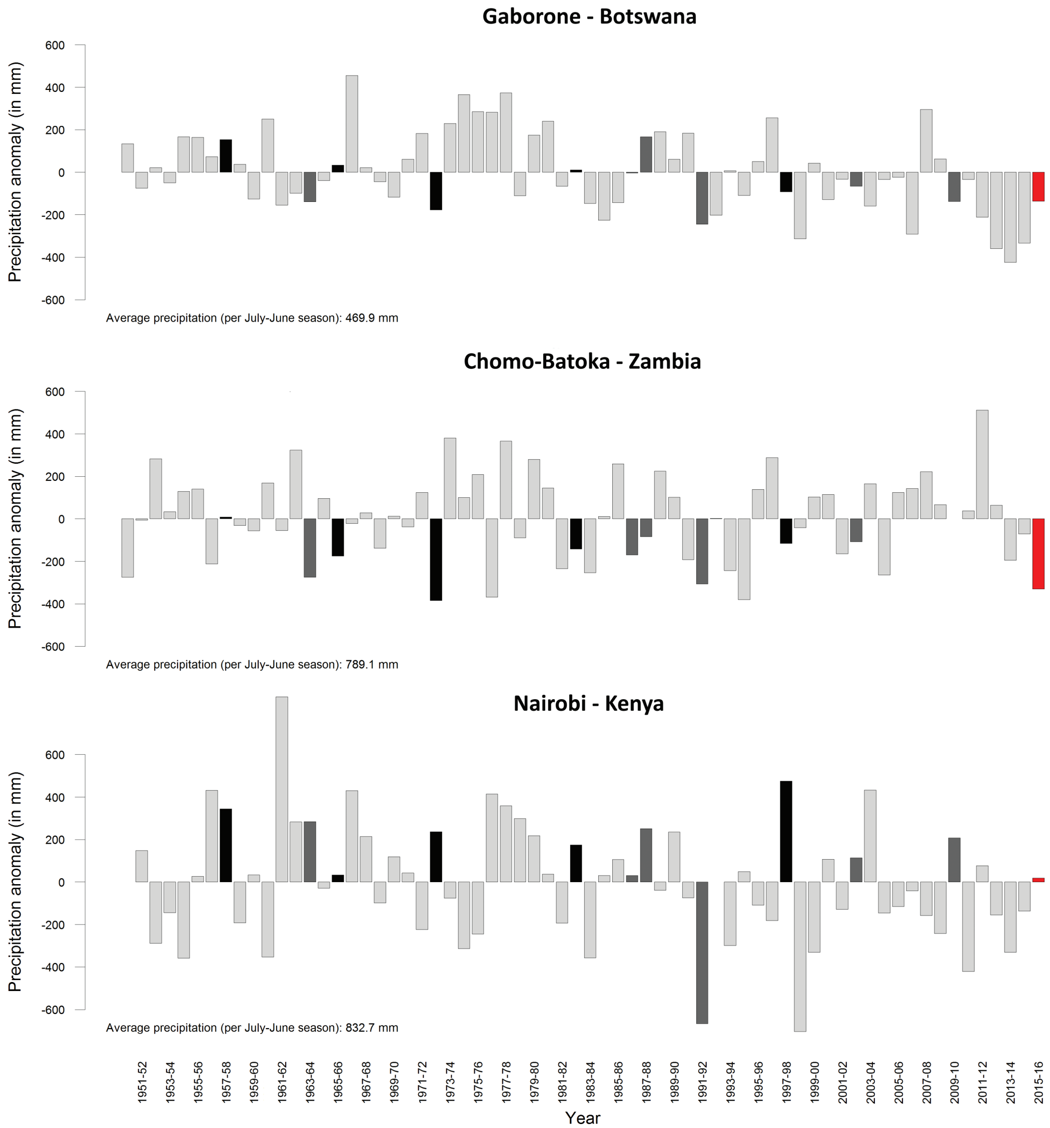

Figure 2. Time series precipitation anomalies for three stations (Gaborone, Botswana; Choma-Batoka, Zambia/Zambezi; Nairobi, Kenya). Previous strong to very strong El Niño events shown in black, moderate Niño events in dark gray, 2015/2016 El Niño is in red. Anomalies are expressed relative to the long-term mean (full period July 1950/1951–2015/2016 June).

neither consistently, nor significantly, warmer than the threshold set for El Niño until early 2015. Despite this "near miss," the ONI index remained considerably higher during the onset period of this 2015/2016 El Niño (Parker et al., 2016).

3.2. Hydrological Response

3.2.1. Precipitation

The 2015/2016 El Niño showed characteristic precipitation anomalies in southern Africa, with Gaborone and Choma-Batoka experiencing lower total precipitation over the July 2015–June 2016 period (Figure 2). In Kenya, where wetter conditions are associated with El Niño, precipitation in Nairobi was near normal during 2015/2016.

The relationship between El Niño and dry conditions is apparent in Chomo-Batoka but not in Gaborone. At the onset of the 2015/2016 El Niño, Gaborone, and Botswana as a whole, was experiencing a multi-year drought which started with the moderate El Niño of 2009, followed by seven consecutive years of below average precipitation. The 2015/2016 El Niño year was comparatively mild compared to previous dry years in that sequence. This multi-year dry spell contributes to a long-term drying trend in Botswana of almost 4 mm per year ($p = 0.002$; Student's t-test of a simple linear regression). Choma-Batoka, meanwhile, shows a strong association between below average precipitation years and El Niño events. In Zambia, situated in the latitudinal centre of southern Africa, droughts often occur in the south of the country, while wetter or normal conditions prevail in the north. Similar to Botswana, prior to El Niño southern Zambia was also experiencing dry conditions, although these were less severe in length and magnitude. The exceptionally dry conditions in Botswana and southern Zambia are further illustrated by the cumulative 2-year precipitation, which includes the pre-El Niño year (Figures 3a and 4a). Cumulative precipitation is below the normal range in the Zambian series but especially dry in Gaborone during the period July 2014 – June 2016. These anomalies are in contrast to previous strong to very strong El Niño's which show a wide spread in precipitation, similar in extent to non-El Niño years. In both cases antecedent precipitation before strong to very strong El Niño years is not consistently wet or dry. No long-term trend is observed in Choma-Batoka.

In Nairobi, all moderate to very strong El Niño's on record have been associated with wet conditions (Figures 2 and 5a), except for the moderate El Niño of 1991/1992, which was the second driest year on record, coinciding with widespread drought conditions to the south. The previous strong El Niño of 1997/1998 saw considerably higher total precipitation, with the 1957/1958 El Niño the most extreme in terms of total precipitation. A long-term drying trend appears visible in the Nairobi precipitation data as well, although is not quite statistically significant (p-value = 0.058).

The spatial extent of precipitation anomalies (three-monthly WASP index), gives a better indication of the catchment scale implications for surface runoff and river discharge than the individual rain gauges (Figures 3b and 4b). In the pre-El Niño year of 2014/2015, Botswana was intermittently dry during the wet season; almost 40% of the country was recorded experiencing dry conditions in October and again in February and March, but almost no areas experienced dry conditions in November, December 2014 and January 2015. In the Upper Zambezi catchment, moderate to extremely dry conditions were experienced during the whole rainy season of 2014/2015, peaking during February and March, which are important months for runoff generation given the catchment's greater potential for saturation. The lack of dry anomalies between June and September is not surprising as this is the dry season, thus even in normal years rainfall is close to zero in both regions. Botswana and the Upper Zambezi showed again large areas of dry conditions during the end of 2015, but from January 2016 the area experiencing these conditions became smaller. In summary, both regions experienced extensive moderately to extremely dry conditions in the latter part of 2014/2015 and early part of 2015/2016 rainy season; that is, the drought was most widespread during the calendar year 2015.

In Kenya, only a fraction of the country experienced very wet to extremely wet conditions (WASP > 2) during 2014 – 2016, with only localized impacts and patterns broadly similar to, or even drier than, non-El Niño years (Figure 5b). Very small peaks occurred in June and November 2015. Analysis of daily precipitation in Nairobi over the period September 2015 – March 2016 revealed a maximum daily precipitation of 51.5 mm on 9 November 2015; an event with a return period of 1.5 years (based on data for 1950 – 2016). Moderately wet areas (WASP > 1) during the 2015/2016 El Niño were mainly confined to small pockets, for example, around Nairobi and in the west of the country, with very wet conditions only in the far west of the country. During the 1997/1998 El Niño, a much higher maximum daily precipitation of 107.4 mm was observed on 14 January 1998, which has a return period of 15 years. Extreme precipitation during the 1997/1998 El Niño was also clearly much more widespread and longer lasting, affecting more than three-quarters of the country (Figures 6a and 6b). Areas with extreme precipitation are not necessarily the most abnormal, as the comparison between total precipitation and WASP for 1997/1998 shows; while in pockets of the central part of the country recorded precipitation amounts of up to 3000 mm, the highest WASP values where recorded in the in the north-east, where precipitation was somewhat lower, but still much more than average and outside the normal variation at those locations.

3.2.2. Runoff

Dry conditions in large parts of the upstream catchment area of Lake Kariba during 2015 reduced peak flows in the Zambezi river just upstream of Lake Kariba in the pre-El Niño year (Figure 4c), leading to a total discharge of approximately 776 m^3/s in 2015, a reduction of 34% compared to the average discharge of 1182 m^3/s. Lake Kariba has an upstream catchment area of 687,535 km^2, draining parts of Angola, Namibia,

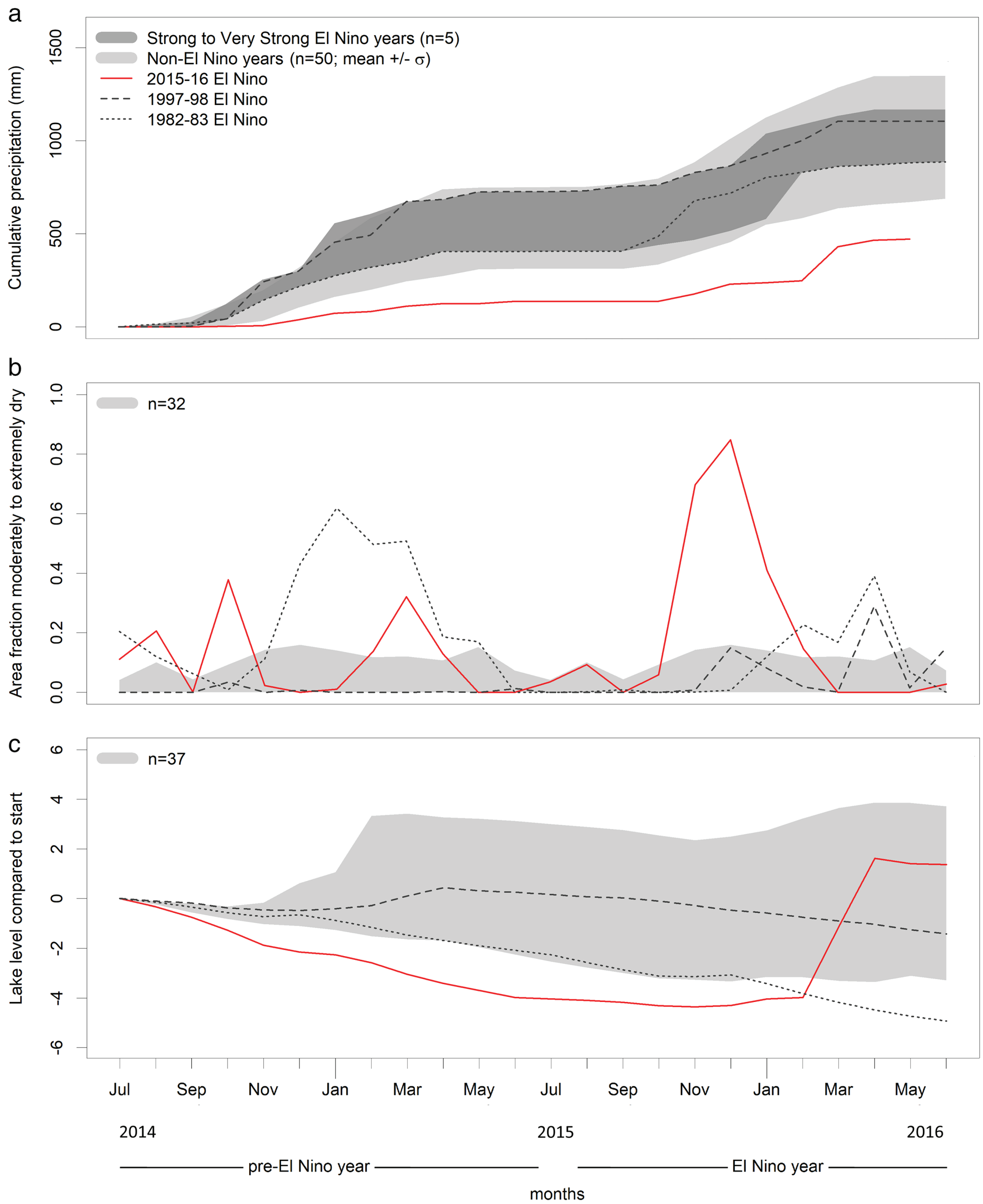

Figure 3. Botswana hydrological impact pathway during 2014–2016. (a) Top cumulative monthly precipitation from July 2014, Gaborone; (b) fraction of country affected by moderately to extremely dry conditions (WASP < -1) and; (c) Gaborone reservoir level compared to July in respective start year. Red line is the 2015/2016 El Niño. The monthly range for non-El Niño years is calculated as the monthly mean $\pm \sigma$.

Botswana, Zambia, and Zimbabwe, and inflows are largely influenced by precipitation in the upper parts of the catchment (Balek, 1971). The Zambezi River is reported to contribute about 86% of the total inflows, with the other 14%, or 200 m^3/s on average, flowing from tributaries in Zimbabwe and Zambia directly into the lake (World Bank, 2010). Flows stayed low until March of 2016, following the pattern of the 1997/1998 El Niño. Low flows equivalent to those recorded in 2015 are not exceptional, though, for the Zambezi; in 8 out of the past 45-years less runoff was recorded (Figure 7). In 40% of years, average annual flows stayed below 1000 m^3/s, with sequences of 4 and 5 years of such low flows occurring in the 1980s and 1990s. Since the 1997/1998 El Niño, flows have generally been above average.

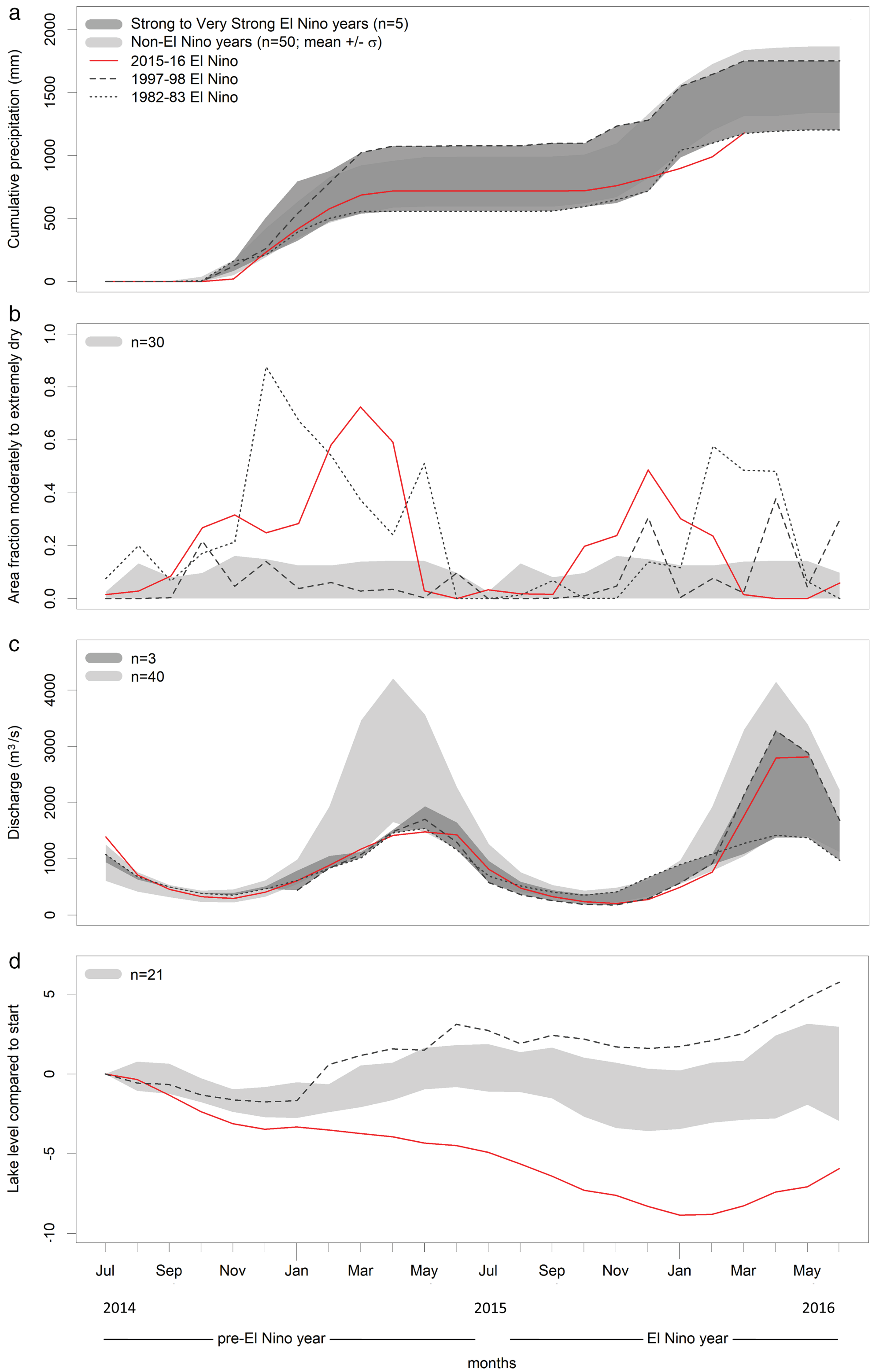

Figure 4. Zambia hydrological impact pathway during 2014–2016. (a) Top cumulative monthly precipitation from July 2014, Choma-Batoka; (b) fraction of the upstream catchment area of Lake Kariba affected by moderately to extremely dry conditions (WASP < -1); (c) monthly discharge of the Zambezi river measured at Victoria Falls Big Tree station, and; *D. kariba* reservoir level compared to July in respective start year. Red line is the 2015/2016 El Niño. The monthly range for non-El Niño years is calculated as the monthly mean $\pm \sigma$.

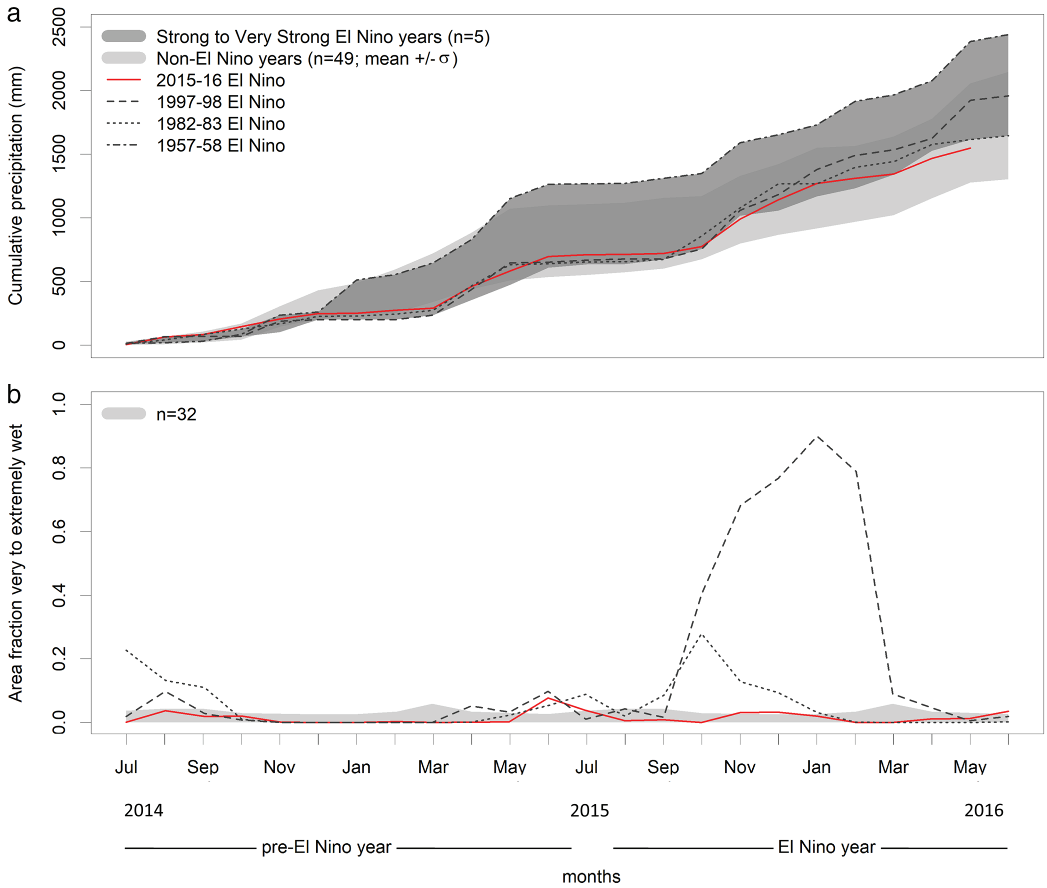

Figure 5. Kenya hydrological impact pathway during 2014–2016. (a) Top cumulative monthly precipitation from July 2014, Nairobi; (b) fraction of country affected by wet to extremely wet conditions (WASP > 2). Red line is the 2015/2016 El Niño. The monthly range for non-El Niño years is calculated as the monthly mean $\pm\sigma$.

Gaborone reservoir inflows are of a totally different dimension. The effective catchment area of Gaborone reservoir covers about 4300 km^2, a fraction of Lake Kariba's. Annual rainfall over the catchment area averages close to 500 mm. With an annual potential evaporation of around 2000 mm, only about 10% of rainfall leads to runoff (Institute of Hydrology, 1980). As a result, rivers draining the catchment area are intermittent, with the reservoir getting water mostly during a few heavy precipitation events in the rainy season. Runoff records for the streams which feed Gaborone reservoir in Botswana are patchy because of this strong seasonality in precipitation and, thus, river flows. In addition, peak flows might be missed as flows are measured manually. Data from the department of water shows that no flows were recorded for the Taung River, one of the major tributaries upstream of Gaborone reservoir, in 2015. On the 16th of March a flash flood led to flow of just 5 m^3/s, which resulted immediately in a rise in lake levels.

3.2.3. Lake Levels

Lake levels in both the Gaborone and Kariba reservoirs integrate the effects of hydrometeorological events and management decisions. Storage capacity adds a much stronger influence from previous years than occurs in most unmanaged river systems. Lake levels dropped to historically low levels during this 2015/2016 El Niño event in both reservoirs (Figures 3c and 4d, respectively, and Figure 8). In the Gaborone reservoir this was the continuation of a lowering trend since 2010. Levels recovered rapidly from February 2016 onwards, though from a very low base which provided some relief. This was in response to local rainfall and fast reduction in the wider area experiencing dry conditions in January and March 2016. In Kariba, previous years showed normal fluctuations and it was only in 2015 that lake levels dropped due to reduced inflows at the time they normally would rise. By the end of the El Niño, around February 2016,

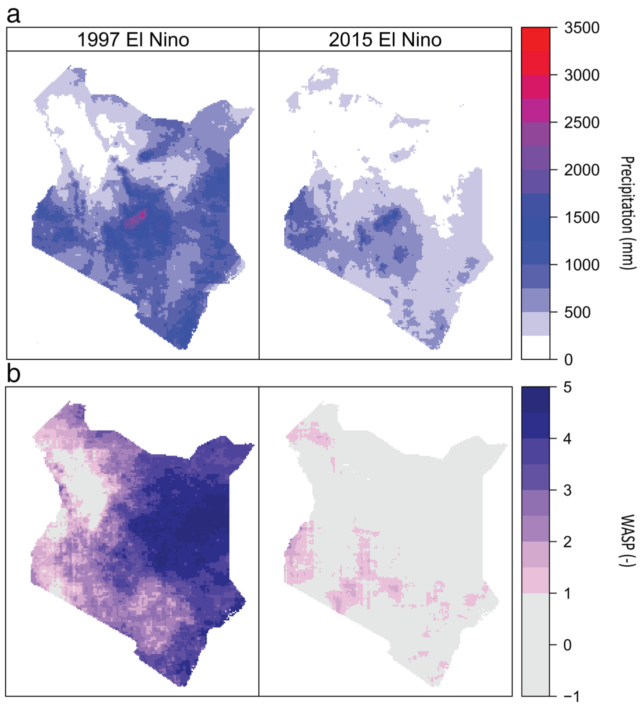

Figure 6. Comparison of seasonal precipitation totals (a, mm) and WASP spatial pattern (b, –) for Kenya between 1997/1998 and 2015/2016, aggregated for the months October–March. WASPs between −1 and 1 represent conditions close to normal. WASP of more than two indicates extremely wet conditions.

Lake Kariba levels recovered a little, most likely associated with the reduction in the extent of dry WASP upstream and in line with the seasonal cycle.

The 2015/2016 El Niño extended, rather than initiated, the adverse hydrological conditions experienced in southern Africa. Because of this ongoing drought (Figure 2), even before the El Niño was in full swing, Gaborone Reservoir levels were 10 m below the long term average water level (Figure 8). Disruption to Gaborone's water supply had intensified since the mid-2000s, with recurring water restrictions enforced by the Water Utilities Corporation (WUC). Despite a total storage of 141 MCM, low inflows in combination with continuous high abstractions of up to 28 MCM a year and high evaporation losses (up to an estimated 22 MCM per year when the reservoir is full with a surface area of 15 km^2) reduced dam capacity to just 1.2%. In June 2014, water abstractions dropped permanently below 2 MCM per month, reducing further to only 0.65 MCM in March 2015. This followed, rather than prevented, the drop in lake level. As shown in Figure 8, a similarly low level was last experienced after the 1981 El Niño, although that drop was less steep as abstractions were lower with Gaborone's population much smaller. The dam level was raised an extra 7 m in 1984 to accommodate demand of an increasing population. The 1997/1998 El Niño had a less severe impact on Gaborone Reservoir.

Unlike in the Gaborone Reservoir, the drop in Lake Kariba levels occurred as a single-year extreme event (Figure 8). In January 2016 water levels were as low as 12% of capacity, just 1.75 m above the minimum operating level for hydropower. Through the Kariba North and the newly installed Kariba North Bank Extension, the Zambian electricity company (ZESCO) has recently increased the installed capacity of 1080 MW on Lake Kariba (Energy Regulation Board [ERB], 2015). Another 750 MW provides electricity to Zimbabwe. If operated at full capacity, given their design specifications, these turbines would require over 2300 m^3/s, which is far more than the average inflow, let alone the low inflow during 2015 (see Figure 7, and Supporting Information S1 for calculations). Continuation of high outflows to maintain hydropower production and meet growing demand, despite low inflows as a result of poor precipitation, seems to have led to these low lake levels. Another 300 MW extension is currently being constructed on the Zimbabwe South Bank station, which would require an additional discharge of approximately 400 m^3/s to operate at full potential, bringing the total potential turbine discharge at 2700 m^3/s. Such a large discharge capacity makes it possible to empty the live storage of a full Lake Kariba in a single year of drought and inflows as low as those in 2015 (Supporting Information S1).

3.2.4. Socioeconomic Impact

Key informants in Kenya described spatial patterns of precipitation broadly consistent with the WASP data. Kenya experienced heavy precipitation and episodic flooding during both its short (October–November) and long rains (March–May), but only some areas, particularly in southern and central regions, were severely impacted. Here, precipitation, and associated landslides caused disruption with infrastructure, buildings, crops and livestock destroyed and people displaced. Businesses and schools were forced to close. The most severe impacts, however, were typically felt in areas with existing vulnerabilities, such as

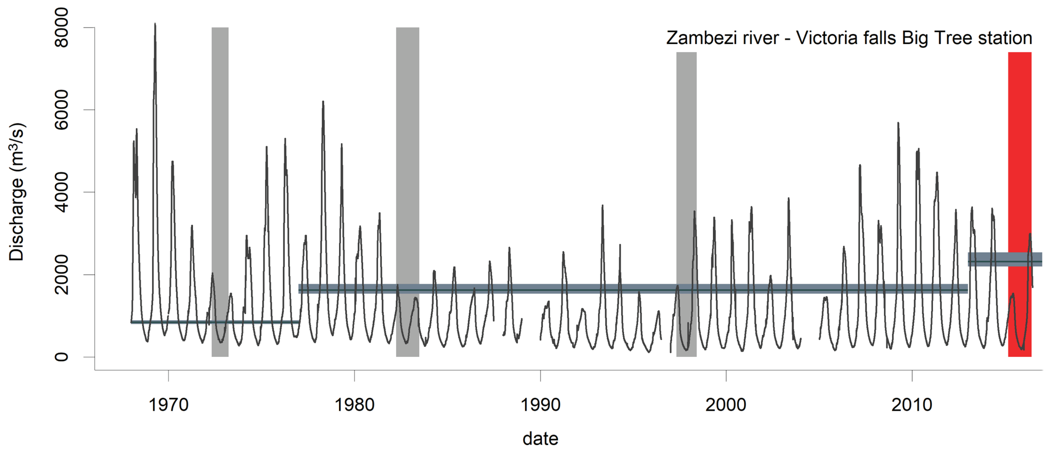

Figure 7. Daily Zambezi discharge (Source: Zambezi River Commission—zamwis.zambezicommission.org), with estimated total design turbine flow capacity at Kariba dam in slate gray (see Supporting Information S1 for calculations). The historic strong to very strong El Niño periods are highlighted in gray and the 2015 El Niño in red.

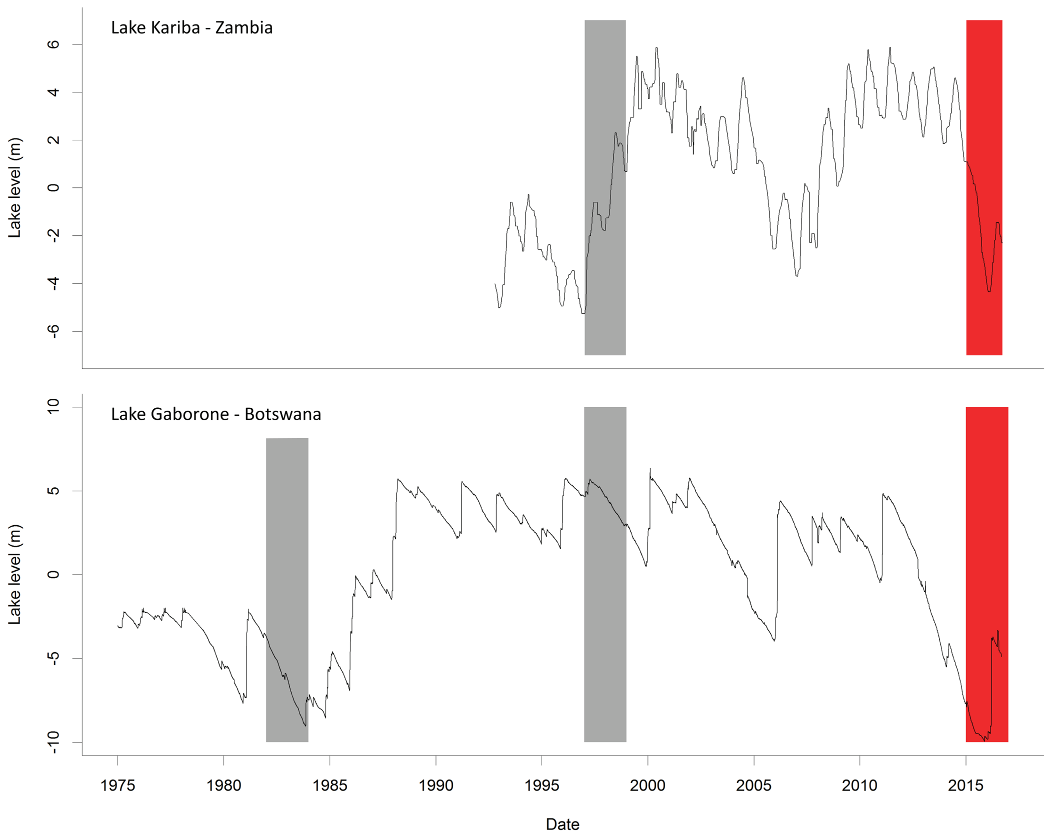

Figure 8. Lake level deviations from the long-term mean for Gaborone reservoir and Lake Kariba, with historic strong to very strong El Niño periods highlighted in gray and the 2015 El Niño in red. The Gaborone dam was raised by 7 m in 1984.

in low-lying and riparian areas, or in urban areas with poorly equipped drainage systems. Some areas of Nairobi were exposed to particularly notable disruption. In December 2015, the International Red Cross reported 113 people killed and 103,000 displaced; similar numbers as during previous recent El Niño's, according to a database of news reports on floods (Dartmouth Flood Observatory, 2016), and with more rains to come. Yet key informants described the extent of disruption as "incomparable" to that experienced during the 1997/1998 El Niño. "In 1997 everybody was a victim" a Kenya Meteorological Department key informant explained. Whereas key informants argued that flooding was generally much less severe and widespread during this El Niño, suggesting some areas and sectors even benefitted from the additional water availability. "It had just isolated impacts in particular zones," an informant from the National Drought Management Authority described.

In Botswana, key informants characterized this El Niño through record high temperatures and water supply disruption, though agriculture was widely affected as well. Gaborone had experienced water usage restrictions since 2013; however the scale of supply disruption was novel. Despite water rationing, demand in the Greater Gaborone Area surpassed supply by 18.2 million liters a day in December 2015 (WUC, 2015). When the rains were delayed again by the onset of El Niño conditions, water supply disruption, including decreased water pressure and complete cut-off of supply, resulted. Occurring most intensely between August and December 2015 (Figure 9), some of the worst affected areas of Gaborone lacked a reliable water supply for several weeks at a time. By September 2015, unreliable water supply had moved to first position in the challenges that businesses reported in the bi-annual Bank of Botswana Business Expectations Survey (Bank of Botswana, 2015); overtaking concerns regarding the availability of skilled labor and domestic demand.

Similar patterns were seen in hydropower disruption in Zambia. Hydropower accounts for >94% of national installed electricity generation capacity, yet in 2015 the Zambian Energy Regulation Board reported a 7% decline in electricity generation from 2014 levels (ERB, 2015). Low water levels left hydropower plants unable to produce enough power and the resulting power deficit, calculated at 985 Megawatts in October 2015 (PwC, 2015), was perceived at its worst between August 2015 and January 2016. At this time, despite steps to purchase expensive conventional energy from neighboring countries, load shedding of 8 h a day was common in Lusaka. "The scale of load-shedding in the year 2015 was unprecedented," the Times of Zambia described (Kabaila, 2015). In 2015 the electricity-supply deficit was estimated at 40–50% of baseload and, alongside a fall in global copper prices and low agricultural output, real economic growth in Zambia dropped to its lowest rate in more than 15 years (Rasmussen et al., 2016).

Load shedding in Zambia and water supply disruption in Botswana largely occurred in the capital cities of Lusaka and Gaborone, where populations are connected to the electricity and water supply networks. To balance the network, load shedding was concentrated in areas of high demand. In both capitals resource supply was also strategically prioritized, with networks surrounding industrial hubs and key services typically offered greater protection. This resource disruption nevertheless caused major challenges to economic activity. Unless able to source alternative supplies, businesses requiring water or electricity found activities such as manufacturing, processing and refrigeration disrupted. Hospitality businesses such as hotels, restaurants and retail outlets struggled to prepare food, launder clothes and provide customers with flushing toilets. These challenges were exacerbated in both countries by unreliable scheduling of supply disruption. Loss of business assets, reduced productivity, price fluctuations and lay-offs were common consequences of the loss of supply (see Supporting Information S2).

3.3. Management Response

3.3.1. Preparedness

The unprecedented nature of load shedding and the scale of water supply disruption proved an additional challenge in Zambia and Botswana. Steps taken by the Zambian and Botswana government to prepare for El Niño generally targeted agricultural drought, as had been experienced in previous El Niño events. Agricultural extension activities proposed cropping regimes and supplied additional seeds in Zambia. The government of Botswana provided draught power, fencing, subsidized stock feed, and canceled loans. However, disruption to electricity and water supply became a problem during this El Niño, at a scale that it had not previously. Rapid development, urbanization and expansion of industry, as well as extension of water and electricity grid networks, in both countries, has increased demand for water and energy at unprecedented rates. Notably similar low levels in Lake Kariba in 1995 (see Figure 8) did not induce comparable load shedding and traditionally Zambia has had an electricity surplus (Hillig et al., 2016), even selling power to neighboring nations through the Southern African Power Pool (SAPP). As a result, and as described by a representative of the Ministry of Energy and Water Development, "nobody was sitting under the expectation that we are going to have a sudden gap in energy … This country had never prepared for that." Reflecting this dynamic, there was little acknowledgement of load shedding in the Zambia Vulnerability Assessment

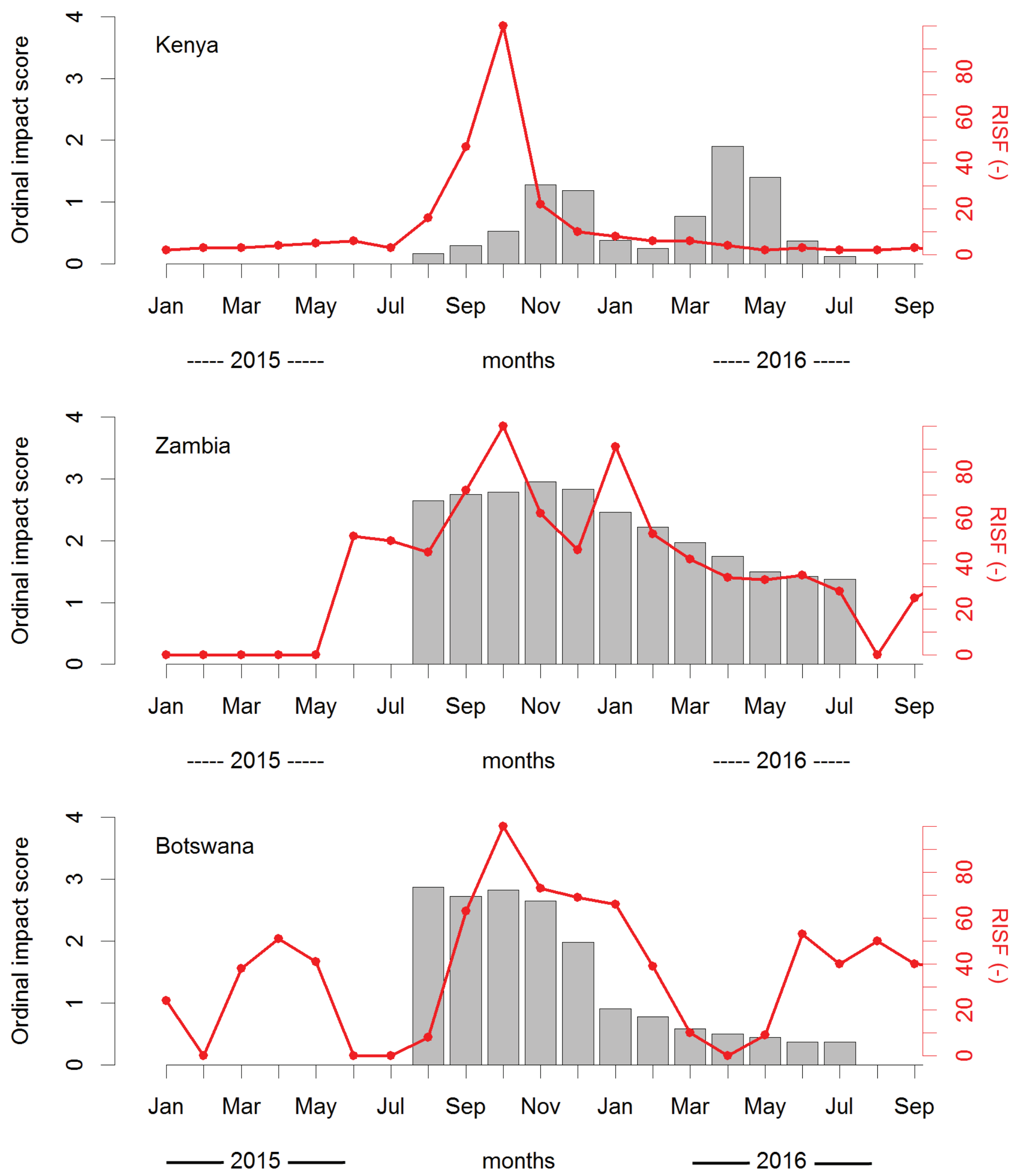

Figure 9. Appearance of El Niño in Google Internet Search Frequencies (scaled as a percentage to the maximum, in red) and perception of El Niño's impact among Small and Medium Enterprises (See Supporting Information S2 for data source and processing, covering the period August 2015–July 2016 only, in gray).

Committee In-Depth Vulnerability and Needs Assessment Report published in June 2015, despite its stated intention "to understand the impact of these prolonged dry spells on selected sectors of the economy" (Zambia Vulnerability Assessment Committee, 2015).

In contrast to Zambia and Botswana, Kenya was generally better prepared to deal with the impacts of El Niño. The legacy of the 1997/1998 event has allowed El Niño to penetrate social discourse in Kenya in a way not seen in Zambia or Botswana. This legacy persists in institutional memory and awareness of flood risk is consequently high. Kenyan key informants perceived a corresponding high level of national preparedness for El Niño among the government, the private sector, communities, and even individuals, who were said to have "learnt from" the 1997/1998 El Niño. In justifying this position, they described the establishment of institutions such as the National Disaster Operations Centre following the 1997/1998 El Niño, as well as mobilized resources and a coordinated El Niño response. Advances in the monitoring and communication of El Niño risks were cited, as were activities such as the allocation of designated contingency funds, sewage drain clearing, improved seed selection and animal vaccination initiatives. Indeed, key informants described Kenya as almost "over-prepared" given the eventual scale of disruption.

3.3.2. Timeliness of Forecast

National seasonal forecasts emerging from August meetings of Greater Horn of Africa and the Southern African Regional Climate Outlook Forums, confirmed the development of a persistent strong El Niño for the first time in late-August/early-September 2015. The majority of key informants reported that awareness of the El Niño climate conditions spread with the release of national seasonal forecasts around August, corresponding with the start of the spikes in RISF (Figure 9). Continued interest in El Niño in Botswana and Zambia, as expressed by the RISF, matches the impact SME managers identified (see Supporting Information S2), with energy disruption dissipating slower than water supply shortages over the course of 2016. The consecutive rise in El Niño RISF in Botswana from June 2016 onwards might have been the result of discussions on the development of a possible subsequent La Niña, although RISF data for Botswana have to be interpreted with care as internet usage is relatively low and the discourse surrounding the impact was framed more in terms of "drought," rather than El Niño. In Kenya, a peak in RISF captures the initial seasonal forecast moment, followed by a sharp reduction in interest as impacts failed to materialize. The incidence of heavy precipitation in April and May in the Nairobi area during the long rains did not lead to increased internet searches (Figure 9).

Key informants disagreed on the helpfulness of the time frame for communicating El Niño forecasts. While the challenges of adaptation in the face of limited advance warning were often highlighted in interviews, meteorological departments described this scheduling as an attempt to balance forecast timeliness with accuracy. Meteorological departments, it emerged, are reluctant to share El Niño climate information at earlier stages in forecast development, for fear of the consequences of being perceived to have delivered a "wrong" forecast. A key informant from the Kenya Meteorological Department explained that the department had experienced legal threats as a result of forecasts, commenting that; "users expect 100% accuracy" and that "[this year] people complained that there was no El Niño, because they did not experience heavy rains like last time." A respondent from the Kenya National Drought Management Authority expressed similar concerns, stating they regretted involvement in disseminating the seasonal forecast. For a future El Niño "we would only facilitate the meteorology people to disseminate the information … it's like we carried the cross … our team was disseminating the information but then, when it happened that it did not rain, they were coming back to us saying that now you need to give us relief because you gave us the wrong information." Concerns regarding forecast accuracy were further warranted by key informants who also suggested that because the 2015/2016 El Niño did not materialize as expected, Kenyans might be less likely to take a future forecast so seriously. Respondents also described political barriers to earlier dissemination of forecasts. For example in Zambia the upcoming election was perceived as a barrier to the timely release of the drought forecast. In this case, key informants emphasized the role of personal contacts, including from within meteorology departments, in obtaining early insight. This allowed them to take timely action on a personal level before the official forecast was released.

3.3.3. Aftermath

Key informants in Botswana and Zambia identified the 2015/2016 El Niño event as an important learning moment; a "wake-up call" for building resilience to future drought and an impetus to act. In particular, it highlighted impacts that had not been foreseen and prepared for. Some felt that the conditions were unprecedented and therefore exceeded the bounds considered in planning previously. However, many interviewees highlighted these issues with planning but felt that El Niño was not the entire problem, rather generally poor planning and management practices were to blame either entirely, or in conjunction with El Niño. Forward planning and better management were seen as an important focus for resilience building in both countries, as was insurance and diversification of national income sources. El Niño was seen as helpful in exposing the weaknesses in the system and increasing political will to address the problems. Referring mostly to structural adaptation to rapidly changing socioeconomic boundary conditions, interviewees notably called for infrastructure development to keep up with population/demographic change. In Zambia, expanding installed hydropower capacity through new reservoirs, and diversifying the national energy mix was regarded as essential.

The international dimension of water supply to Gaborone, project planning horizons falling outside of electoral cycles and financial restrictions, were factors identified to have delayed water infrastructure developments in Botswana, like the extension of the North-South carrier. The impact of a high number of small dams used for agriculture and domestic water use in the Gaborone catchment, and whether these could be managed better, was another issue raised by various respondents—an issue that has been picked up by the national press (e.g., Bosaletswe, 2014) and by international research groups (Helmschrot et al., 2014) as well. Interestingly, however, the number of dams seems not to have changed in 20 years (a number of 200 is often mentioned), when Meigh (1995) showed that the small dams significantly reduce inflows into Gaborone reservoir. It seems unknown whether this effect has changed over the past years or if, and how, a different management approach could help deal with the kind of multi-year drought that hit the catchment. Maintaining and upgrading infrastructure which brings water down from the north of the country, through interbasin water transfers, was seen as a more promising measure. If plans go ahead this north-south carrier will extend up to the Zambezi River in the north of the country, greatly diversifying the country's drinking water supply.

4. Discussion and Conclusions

This study provides three examples of the hydrological response and complex impact pathways in eastern and southern Africa of the 2015/2016 El Niño and preceding years. In eastern Africa, the expected high-intensity precipitation and resultant floods were highly localized and of short duration, closer to normal rather than extreme conditions. Hydrological impacts in southern Africa during the pre-El Niño year (considered a near miss in ENSO terms), were more severe than during the actual El Niño. The extreme effects of drought on drinking water availability and energy production materialized in the second half of 2015 and persisted until the first half of 2016, after which rains alleviated the most immediate problems. From a hydrological impact perspective, this El Niño could be considered a 2-year event. However, to understand the impact pathways on drinking water and energy supply, an even longer window of analysis is needed. This captures the ongoing water supply disruption in Gaborone and load-shedding in Lusaka, associated with rising demand and aging infrastructure. Infrastructure development and maintenance are clearly important social and environmental boundary conditions that shape El Niño responses and impact pathways.

Preparedness for 2015/2016's El Niño was strongly shaped by previous experiences. Zambia's Disaster Management and Mitigation Unit was focused on preparation and response to agricultural drought. As such, the severity of the impacts on reservoir levels, and thus on energy supply, had not been anticipated which reduced the opportunity to mitigate the frequent and prolonged periods of load shedding. Runoff, however, was not unusually low, which suggests that the impacts of El Niño on the energy sector in Zambia were compounded by a diminishing capacity to meet increasing demand over the decades. The 2015/2016 El Niño simply exacerbated—and exposed—the gap.

While Zambia was caught unaware, Kenya was well-aware. Here, the relatively high displacement numbers and casualties despite modest hydrological impacts, raise questions about whether exposure has significantly increased, agencies overreacted, or whether heightened awareness of the El Niño, based on previous experiences, led to unintentional over reporting. The experience of moderate impacts of the 2015/2016 event may challenge effective preparation for the next El Niño.

Complex impact pathways require diverse management responses. Table 3 summarizes factors that shape this complexity as described in this paper. The Kenya case study shows that although forecasts seek to reduce uncertainty, considerable uncertainty inevitably remains. Here, the management response consists mainly of preparedness and coping with the impact once it materializes. The onset of the impact is almost immediate, with little buffer between heavy rainfall and onset of flooding. This makes communicating the uncertainty in forecasts and managing expectations critically important. Greater focus on forecasting skill at different lead times (i.e., the linking of seasonal and shorter forecast timescales), and tailoring of forecasts to specific users through a process of social learning, is essential to make effective use of climate information.

In Zambia there is more time to adjust, as the large catchment area produces a more diverse and slower hydrological response, while the reservoir provides the means to buffer and to manage outflows. But while hydropower turbine capacity has gradually increased in response to increased demand, storage has not,

Table 3.
Factors of Complex Impact Pathways and Management Response

	Type of impact	Hydrological response	Hydrological buffer	Antecedent conditions required[a]	Impact onset	Management response
Kenya	Flooding	Fast	Small	No	Immediate	Coping, general preparedness
Zambia	Energy shortage	Slow	Medium	No	Medium	Adaptive management of reservoir volume before and during event, diversification of energy sources, regional integration of energy supply
Botswana	Drinking water shortage	Medium	Medium	Yes	Slow	Diversification of water supply, limited scope for (adaptive) water demand management during event

[a]For the impact to become severe within the duration of one El Nino year.

thereby gradually increasing Zambia's vulnerability to drought. An estimate of the new storage-turbine relationships shows there is now enough turbine capacity to empty the live storage of a full Kariba reservoir within 1 year of low flows. The impact of this El Niño event therefore raises questions about whether Zambia can cope with a sequence of low flow years under current operational rules. With Zambia and Zimbabwe both depending on Lake Kariba to generate hydropower (which accounts for a high proportion of their overall energy), clear adaptive operating rules and strong joint river basin management is needed to prevent another depletion of the reservoir (encouragingly, moves are afoot to bring together energy regulators in the Zambezi basin, in part to address such challenges). Diversification of sources of electricity is a way forward, as well as an integration across areas of shared climate variability, with the Southern Africa Power Pool approach to integrating energy networks, and even broader integration across regional power pools, important opportunities (Africa Progress Panel, 2017).

In Botswana, the small size of the catchment leads to a more uniform hydrological response to reduced rainfall, with extreme drought conditions building up quickly. The onset of the impact—a lack of piped water supply and drinking water—is, however, still rather slow with antecedent conditions being important. As historic lake level fluctuations and basic storage and demand estimates show, it took about 3 years without significant rainfall to fully empty the Gaborone reservoir, which offered some opportunity to inform people and gradually adjust demand. What complicates water management, though, is the unpredictability of the relief in gradually worsening conditions. The Gaborone catchment is a semi-dry system by default and dependent, even in the best of years, on a few sudden flash floods to fill the reservoirs. Whether a more anticipatory response through reducing demand earlier, in anticipation of shortage, would have mitigated the eventual shortage is questionable, as part of the savings would have been lost to lake evaporation. Operating reservoir levels as low as possible, depending on assurance of supply levels, has been advised in neighboring catchments with similar exceptionally high net evaporation (Swart et al., 2007). Diversification of water supply, by conjunctive use of ground- and surface water and beyond the narrow boundaries of the small catchment filling Gaborone reservoir and the dry southern part of Botswana is currently being explored by the government. This would provide additional water supply as well as reduce the need to assure near 100% reliability from Gaborone reservoir, making it possible to introduce greater flexibility into reservoir operations.

Regional accuracy and timeliness of El Niño forecasts and seasonal forecasts of teleconnection anomalies remain major concerns for resource managers and those involved in translating and packaging climate information for specific sectors and users. This study supports the need for regional metrics of El Niño effects (Jacox et al., 2016) and better understanding of the differences between El Niños (see, e.g., Ashok et al., 2007; Jadhav et al., 2015; Preethi et al., 2015; Ratnam et al., 2014), including what they mean for the development of more nuanced forecasts and guidance. While considered one of the three most severe ENSO events of the past 60 years, the 2015/2016 event teleconnections and impact ranged from severe (Botswana, Zambia) to very modest (in Kenya), a spatial pattern exactly the opposite of the previous very strong El Niño of 1997/1998. This interevent difference increases the time between El Niño events with "expected" impacts, generating confusion about early warnings, reducing social memory, and thereby challenging preparedness efforts and effective response. The 2015/2016 El Niño also showed that intra-event timing of impacts is still poorly captured in early warnings. In Kenya, short rains were delayed, with expected heavy rain only to arrive when preparedness was already waning. This will require attention from agencies such as the Global Framework on Climate Services to help broker improved links between meteorological agencies and intermediary organizations with knowledge brokering roles such as the Red Cross Climate Centre and the Regional Climate Outlook Forums.

The complexity and changing nature of the impact pathways requires adaptive management which incorporates review and adjustment of responses, with more emphasis on planning and contingency than is currently the case. New infrastructure needs to account for both rapidly changing demographics and a potentially broader range of variability in light of climate change. The effect of climate change on El Niño is still under debate with ENSO variability potentially intensifying, weakening, or even undergoing little change, depending on the balance of changes in the underlying processes (Collins et al., 2010). Better understanding of the hydrological impact pathways and ways to respond to extremes such as those caused by El Niño can support a learning process that facilitates better adaptation to future climate change.

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