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Hydropower plans in eastern and southern Africa increase risk of concurrent climate related electricity supply disruption.

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Abstract: Hydropower comprises a significant and rapidly expanding proportion of electricity production in eastern and southern Africa. In both regions, hydropower is exposed to high levels of climate variability and regional climate linkages are strong, yet an understanding of spatial interdependencies is lacking. Here we consider river basin configuration and define regions of coherent rainfall variability using cluster analysis to illustrate exposure to the risk of hydropower supply disruption of current (2015) and planned (2030) hydropower sites. Assuming completion of the dams planned, hydropower will become increasingly concentrated in the Nile (from 62% to 82% of total regional capacity) and Zambezi (from 73% to 85%) basins. By 2030, 70% and 59% of total hydropower capacity will be located in one cluster of rainfall variability in eastern and southern Africa, respectively, increasing the risk of concurrent climate-related electricity supply disruption in each region. Linking of nascent regional electricity

sharing mechanisms could mitigate intra-regional risk, although these mechanisms face considerable political and infrastructural challenges.

Hydropower comprises 20.2% of installed electricity production capacity in sub-Saharan Africa (SSA) and is on an upward trajectory (*1*). Hydropower accounts for over 90% of electricity generation in the Democratic Republic of Congo, Ethiopia, Malawi, Mozambique, Namibia and Zambia. Dam building in Africa has recently entered a phase of renewed activity, through a mix of domestic and international collaborations, many with China (Fig. 1; *2*). Rainfall in SSA shows pronounced variability, including: prolonged drying across the Sahel since the early 1970s with some recovery in the last two decades (*3*); relative stability punctuated by extreme wet years in eastern Africa (*4*); and high inter-annual and multi-year variability in southern Africa (*5*). Rainfall variability is responsible for significant fluctuations in lake levels and river flow, creating challenges for effective management of water resources (*4*). The threat to hydropower generation is marked, and, due to the sector's significant and rapidly growing contribution to electricity supply in SSA, climate-induced supply insecurity represents a critical source of economic and societal risk.

The significance of fluctuations in hydropower depends on its contribution to the overall electricity system. If it is complementary to other sources like in the USA and Western Europe (*6*), then this variability may be less of a problem, although still challenging. For example, reduction in India's hydropower of at least 15% in 2016 was associated with low reservoir levels at multiple sites (*7*). Whilst the contribution of hydropower to total capacity in the USA has declined to 7%, the interannual variability of hydropower generation is very high. For example, a fall of 21% (59 million megawatt hours (MWh)) of the USA's total hydropower generation occurred from 2000 to 2001 (*8*). Drought in California directly impacted hydropower generation at multiple sites across the state, with an estimated equivalent of 2.8 million fewer homes powered by hydropower in 2014 as compared to a very wet year in 2011 (*9*). In cases where hydropower dominates the electricity supply mix, like Brazil, Norway and many countries in SSA, climate variability is more of a problem. In Brazil hydropower plants comprise about 80% of electricity generation (*10*) and even though there is significant geographical dispersion of sites and integration through transmission capacity (*6*), reservoir levels at several major sites experienced dramatic decline during drought in 2013-15, negatively affecting production. For example, in 2014 and 2015, generation by the 14-GW Itaipu hydropower plant on the Parana River was around 6 and 3.5 million MWh, respectively, below the most recent five year mean (*11*).

Chronic energy scarcity and episodic supply disruption are widespread in SSA. The economic cost of power outages has been estimated at 5-7% of the gross domestic product (GDP) for Malawi, South Africa and Tanzania (*12*). Studies of specific events highlight major consequences of reductions in electricity production associated with drought; for example, in Kenya a 25% reduction in hydropower in 2000 resulted in an estimated 1.5% reduction in GDP (*13*). Drought associated disruption to hydropower in the Zambezi basin during 1991-92 led to an estimated US$102 million reduction in GDP and a US$36 million reduction in export earnings (*13*).

Recent conditions during the El Niño of 2015-16 highlight the scale of concurrent hydropower disruption associated with widespread drought in SSA. Malawi, Tanzania, Zambia and Zimbabwe all experienced electricity outages (load shedding) due to low rainfall (*14-16*). In May 2015, low water levels at the Lake Kariba reservoir contributed to a reduction in hydropower generation. That month, the country’s national power utility warned that it may cut power supplies by one-third and the Finance Minister reduced the forecast for national GDP growth to 5.8% from more than 7%, in anticipation of power rationing and reduced copper prices (*17*).

The share of hydropower in SSA is likely to grow rapidly as major investments are ongoing and planned. The Programme for Infrastructure Development in Africa (PIDA) energy plan argues for major hydropower developments to keep pace with rising demand, estimating that, from a present total generating capacity of 125GW, capacity needs to increase by 6% per year to 2040 (*18*). Regional power sharing mechanisms and infrastructure for interconnections (Power Pools) are also under development and strongly promoted through the PIDA. They serve in part to manage energy deficits and fluctuations through trade in electricity and may be an important dimension of increasing electricity supply in SSA.

Multi-year climate variability and dependence on hydropower are high throughout SSA, yet an analysis of spatial interdependencies is lacking. Now is a critical juncture for hydropower; electricity production in eastern and southern Africa continues to be disrupted due in part to rainfall deficits, and major new infrastructure planning and investments are underway. Here we analyse spatial coherence in rainfall variability to illustrate concurrent risk to hydropower generation in eastern and southern Africa. We map exposure by rainfall cluster and river basin configuration. We use K-means cluster analysis based on Principal Component Analysis to define areas of shared rainfall variability (clusters) and overlay them with the drainage basins of existing and planned hydropower schemes larger than 50 MW. We calculate the proportion of total regional hydropower capacity in each rainfall cluster and each river basin. Finally, we compare patterns of spatial interdependency with existing (2015) and planned hydropower development (2030) and discuss the implications for electricity security in both regions and more widely in SSA.

Intra-regional clusters

Three clusters were selected for eastern Africa and seven clusters for southern Africa, after comparing results with five and nine clusters, respectively (Fig. 2, Supplementary Figs 1-8 and Supplementary Notes 1-2). With a few exceptions, the clusters are contiguous and show reasonable agreement with expected climate regimes. We considered correlations between the area-average rainfall time series of each cluster and the influence of teleconnections with four indices of large-scale variability: two measuring El Niño Southern Oscillation (ENSO) variability (Nino3.4 and the Southern Oscillation Index, SOI), one measuring Indian Ocean variability, the Indian Ocean Dipole (IOD), and one measuring southern hemisphere extratropical variability, the Southern Annular Mode (SAM).

We examined spatial differences in rainfall by weighting individual grid cells according to their annual rainfall, but we also note that differences in evaporation rates and drainage characteristics mean that areas within a watershed do not contribute equally to river discharge. Hydrological modelling is required to capture fully these factors and their influence on relationships between rainfall and discharge. The results are sensitive to the number of clusters used and whether spatial weighting by rainfall amount is applied, but not sufficiently to affect our overall interpretation of the findings.

We used the period 1956-2011 to define the clusters which reduces sampling variability (by using a relatively long period) and reduces the influence of changing ENSO teleconnection (see Methods and Supplementary Note 3). We also compared the results using a different rainfall dataset (the Global Precipitation Climatology Centre, GPCC, *19*) for the main period of analysis 1956-2011. The results show good agreement – the cluster maps are similar (Supplementary Figs 9 and 10) and the results for concentration of hydropower by cluster also agree well (compare Tables 1 and 2 with Supplementary Tables 1 and 2).

For the three clusters in eastern Africa, annual rainfall shows significant correlations with ENSO and with IOD (Supplementary Tables 3 and 4). The most northwesterly cluster (E3_3, Fig. 2), covering the southeast Sahel and much of the Ethiopian highlands (large parts of the eastern Nile basin, Fig. 1 and 2), shows the weakest correlations with other regions, so it has more independent variability than the others. Cluster E3_2 is not significantly correlated with any of the indices considered here for 1956-2011. Wetter conditions in cluster E3_1 (countries with Indian Ocean coastlines) are associated with positive IOD DMI and with warm (El Niño) ENSO events, consistent with prior studies (*20; 21*). There is an opposite relationship for cluster E3_3, with drier conditions associated with El Niño events consistent with studies of rainfall teleconnections in Ethiopia and flows of the Blue Nile that drains a large part of this cluster area (*22*). As expected due to its lack of proximity, correlations with SAM are weak.

Across the southern African domain, rainfall in nearly all cases is correlated negatively with Nino3.4 and positively with SOI (Supplementary Tables 5 and 6). This consistency agrees with the expectation of drier conditions associated with El Niño events. The weakest correlations are with the northern clusters and the strongest are with the southern and southeastern clusters. Correlations with IOD are weaker because the IOD influence is stronger in eastern African than in southern Africa. For the period over which the clusters were defined, there are no significant correlations with SAM across the southern clusters. This ENSO influence explains why rainfall variability is coherent in these regions, and also between some of the region's pairs.

Rainfall clusters and hydropower

Mapping the rainfall clusters with areas of river basins contributing runoff to hydropower sites allows us to examine the spatial interdependencies in the exposure of hydro-electricity production to climate-related risk. Total installed hydropower capacity is higher in eastern than southern Africa (Tables 1 and 2). Successful completion of the dams identified in (*23*) would put eastern Africa even further ahead of southern Africa in terms of total capacity and lead to considerable shifts in the main sites of production and changes in exposure to climate risk. Hydropower capacity in both regions is concentrated in large schemes and single river basins.

In eastern Africa, dams in the Nile basin dominate current and future hydropower production, increasing from 62% to 82% of the region's total hydropower capacity. Many of these are concentrated on the tributaries of the Nile that rise in Ethiopia (notably the Grand Ethiopian Renaissance Dam on the Blue Nile); the Blue Nile which contributes 53% of overall Nile discharge, the Tekaze (10%) and the Baro (12%) (*24*). Hydropower generation is also concentrated in clusters E3_1 and E3_3, that account for 39% and 60% (in 2015) and 28% and 70% (in 2030) of regional capacity, respectively. The high concentration of generating capacity in the interconnected Nile system, enhanced by the spatial configuration of rainfall clusters, means that the effects of low rainfall and subsequent river flows could lead to concurrent reductions in energy generation across multiple sites. Outside the Nile basin, the Rufiji in Tanzania generates 2% (8% in 2030) and lies almost completely within cluster E3_1. The Omo (25% now, falling to 7% in 2030) lies within clusters E3_1 and E3_3.

In southern Africa, there is a growing concentration of hydropower generating capacity in the Zambezi basin – from 73% now to 85% in 2030. Just one rainfall cluster (S7_4) accounts for 52% of existing hydropower generating capacity, and this could increase to 59% by 2030. Cluster S7_3, which encompasses several dams in South Africa, decreases in importance because there are no new large dams planned within its area. Our analysis highlights the current importance of hydropower generation in the Zambezi basin and its potential further concentration in the basin, particularly in the main stem (Table 2). Low runoff and lack of suitable dam sites elsewhere in the region limit the potential to spread risk through developing hydropower in other basins. Risk mitigation could include power sharing with central (Congo basin) and eastern Africa, diversification of electricity generation sources, and improved intra-basin management of reservoir levels and releases for the Zambezi.

Inter-regional risks

Several phases of a mega-project are planned to develop the Grand Inga dam in the Democratic Republic of Congo up to a potential installed capacity of 39,000MW by 2030 (Fig. 1). Recognising this project has been mooted for many years and that it faces numerous challenges, if completed Grand Inga would increase potential for power sharing and regional Power Pools to buffer risk of concurrent electricity outages. Draining much of central Africa, Congo river discharge shows lower interannual variability than other large rivers in SSA (*5; 25*). Good quality long river discharge series are available for the Blue Nile and Lake Victoria (White Nile) in eastern Africa and the upper Zambezi in southern Africa. With the Congo, these four rivers represent the main sources of hydropower in three regions of SSA.

Thirty-year sliding correlations between the four annual river discharge series clearly indicate substantial non-stationary relationships (Fig. 3 and Supplementary Note 4). Correlation is generally very low between the two key rivers in eastern Africa (Blue Nile and Lake Victoria outflows) and between them both and the Zambezi. Correlations are low between Lake Victoria and the Zambezi, and stronger (but highly non-stationary) between the Congo and both Lake Victoria and the Zambezi (Fig. 3b). All three rivers show rising correlation around the beginning of the 1970s, driven by three closely occurring and concurrent very wet years in the three rivers (1961, 1962 and 1964). The low correlation between regions (central, eastern and southern Africa) indicates potential to buffer fluctuations in production between regions, by linking nascent Power Pools.

Discussion

Ambitious expansion plans for hydropower in eastern and southern Africa will increase many countries' already high reliance on hydropower and hence their exposure to the risk of climate-induced electricity disruption. Our results show that hydropower in both regions is dominated by large schemes, in rivers draining the Ethiopian highlands (particularly the Blue Nile) in eastern Africa, and in the Zambezi basin in southern Africa. Interannual rainfall variability in both regions shows strong influences from large scale climate features, particularly the ENSO. Clusters of similar rainfall variability also tend to concentrate risk of concurrent low flows and potential disruption of electricity generation. Further research is recommended to explore the implications for hydropower reliability of the spatial coherence and risk of multi-year drought and of differences in intra-annual variability between seasons in eastern Africa with bi-modal rainfall seasonality.

Our analysis of new dams for 2030 assumes completion of dams at various stages of development. We also assume that spatial patterns of rainfall remain stable for 19 years beyond the end of the 56 year period used to define the clusters. We argue that is a reasonable assumption; whilst there is some temporal instability in cluster areas and teleconnections**,** the recent extensive drought in much of southern Africa, associated with the 2015-16 El Niño is evidence that some spatial coherence and teleconnection with ENSO remains. Nevertheless the potential for non-stationarity of spatial statistics needs to be considered when planning and monitoring the effectiveness of intra- and inter-regional electricity sharing mechanisms. Shifts over time of rainfall correlation would require regular revision of such arrangements. Teleconnections with rainfall in the CMIP5 climate model suite show mixed success (*26*). This suggests that for the moment climate models would not provide a reliable basis for defining clusters in the present climate and for providing a robust simulation of their future evolution.

In terms of rainfall variability, regional Power Pools could mitigate risk of supply disruption, however, they face considerable infrastructural and political challenges.

Whilst both regions have Power Pools, neither has a fully connected electricity grid (*27*). The pace of connection has been slow, but plans are ambitious (*12; 28*). The Power Pools are designed with several objectives – one is to diversify energy sources and as a consequence reduce risk in electricity insecurity. At the moment, energy trade is very limited in the Southern African Power Pool and mainly bi-lateral in eastern Africa, but plans for increased trade are ambitious and hydropower will form a large proportion of new generating capacity.

The trading function of Power Pools requires the existence of coincident surplus and demand; if generation potential is high across the whole Power Pool, prices may decrease, reducing returns on trading; the reverse situation could lead to physical limits to electricity trade, causing energy scarcity and higher prices in countries without alternative supply options. Differences in large-scale influences and patterns of interannual rainfall variability in eastern, southern and central Africa suggest that trading across regional Power Pools (but not within) could offset the tendency at regional scales for coincident surplus supply or demand, due to high reliance on hydropower production in single river basins and/or clusters of shared rainfall variability. Sovereignty issues expressed as concern about national energy security, however, represent an important challenge to energy trading. This is particularly relevant in transboundary basins like the Nile and Zambezi. Such linked systems have potential for much greater operational efficiency and hazard mitigation, but weak cooperation and institutional capacity could severely limit returns on investment and management effectiveness. Past events have highlighted the importance of rainfall variability in causing electricity disruption, other factors like years of under-investment, failures of state monopolies leading to inefficiency, low technological dynamism, and poor service provision are also very important (*29*-*30*).

Climate extremes represent an episodic problem set against perennial critical energy challenges in SSA. The storage capacity and management flexibility of most reservoir systems are designed for historical patterns of hydrologic variability and contingency measures should mean individual dry years are manageable without disrupting power generation and resorting to load shedding. Improvements in scientific ability to adapt hydropower production to low flows lies in the growing potential of drought monitoring and forecast systems (*31*) and increasingly sophisticated optimization of the water that is available to produce power (*8*). However, success through technical advances is conditional on effective management and wider energy system governance, areas which have a poor record in much of SSA. And yet there are reasons for optimism, as examples of successes are emerging from breakthroughs in market penetration of renewables, the increasing importance of independent power projects (*32*) and growing recognition of the need for resilient systems with multiple options across multiple grids (smart, mini, hybrid and cross-border power pools; *33*).

Existing management challenges and ongoing and planned major hydropower expansion programmes also face the problems of a changing climate. Worldwide infrastructure performance is already being tested by new combinations of intensity and duration of extreme weather and assessing resilience is a matter of strategic importance. However, there are no detailed studies of causal linkages between climate and electricity supply and the economic impacts of supply disruption. Future climate change impacts on hydropower generation have been modelled globally (e.g. *34*) and for transboundary river basins in SSA (*23*). River flow in the Zambezi basin is highly sensitive to changes in rainfall (*35*). Climate projections that include wetting and drying lead to impacts on hydropower ranging from marginal increases to decreases of 10 to 20% in output (*36*). Guidelines to incorporate climate risks into infrastructure planning are emerging but are not widely used in practice (*37*) and few studies consider spatial interdependencies.

Changing spatial interdependencies need to be incorporated into dam design to reduce financial risk and problems of under- or over-design. Increasing importance of hydropower, increasing concentrations of dams in linked river basins, and the potential for increasing levels of rainfall variability under climate change, underscore the need for effective planning of hydropower in Africa.

Methods

Defining rainfall clusters

We defined regional windows to encompass major river basins and general definitions of the geographical extent of eastern and southern Africa: southern Africa is defined as 11° East to 41° East and 36° South to 8° South; eastern Africa is defined as 20° East to 50° East and 12° South to 12° North.

We used gridded, half-degree resolution rainfall data from CRU TS3.23 observations (updated from *38*) for the 32-year period from 1956 to 2011 for the main analysis. Rainfall in eastern and southern Africa shows contrasting seasonal patterns (Supplementary Fig 11) and temporal variability. Parts of eastern Africa experience bimodal seasonality, with maxima in transition seasons (March to May, known as long rains, and October to December, known as short rains), following movement of the Inter-Tropical Convergence Zone. In more northerly (Ethiopia/Sudan) and southerly areas, rainfall is unimodal. To capture the wide seasonal variation in rainfall, we use a calendar year for eastern Africa (this may obscure differences that exist between rainfall variability in the long and short rains in areas of eastern Africa with bi-modal rainfall seasonality) and 12 months from July to June for southern Africa.

The CRU dataset is a global station-based gridded data set which has been widely used for climate and hydrological studies globally and in SSA. Sparsity of observations and declining station coverage in much of SSA may compromise the reliability of the CRU data. However, comparison with other gridded rainfall sets from the Global Precipitation Climatology Centre (GPCC, station-based) and the Global Precipitation Climatology Project (GPCP, land and ocean) shows overall very good temporal correlation with some problems over equatorial Congo and Angola (*39*). In a comparison for all Africa the CRU dataset was found in agreement with satellite-based estimates and to give confidence in its estimation of variability and long-term changes in rainfall (*40*).

In order to define areas in which gridded rainfall values are grouped together according to similarities in their inter-annual variability (clusters), we applied principal component analysis (PCA) and K-means clustering. PCA transforms the large number of gridded rainfall time series (which are inter-correlated) into a reduced number of uncorrelated series called principal components (Supplementary Fig 12, Supplementary Table 13 and Supplementary Note 5). We first standardized the rainfall data across the rows or grid-points. The PCA was in the T mode, rather than the more common S mode (*41*). The resulting principal component time scores were subsequently used in the K-means clustering programme using Euclidian distances (MATLAB software). We calculated Euclidian distances using the unstandardized major principal components' scores (we used the first ten, following ref. *42*). The cluster analysis simply groups together grid-points with similar characteristics (i.e. in this case, with correlated interannual variability).

Although the cluster analysis groups grid cells with similar correlations and excludes grid cells with dissimilar correlation, it is nevertheless the case that there will be intra-cluster variation and there will be correlated behaviour between clusters. The choice of how many clusters to define is, therefore, somewhat arbitrary. We explored this in several ways (see Supplementary Notes 1-3 and Supplementary Tables 7-12 for full results). By using knowledge of different regional climate regimes and calculating correlations between cluster average rainfall time series and four indices describing modes of climate variability: two measuring El Niño-Southern Oscillation (ENSO) variability (Nino3.4 and the Southern Oscillation Index, SOI), one measuring Indian Ocean variability, the Indian Ocean Dipole (IOD), and one measuring southern hemisphere extratropical variability, the Southern Annular Mode (SAM). We also gave preference for spatially contiguous clusters and examined the sensitivity of our results to the use of different numbers of clusters. Choosing fewer clusters might overstate the coherent variability (and thus exposure to concurrent climate risk) by combining grid cells with increasing amounts of independent variability into single clusters, whereas choosing more clusters might understate the coherent variability because separate clusters may in fact be significantly correlated with each other. A further issue is that the strength of spatial correlations may vary over time (due to random sampling variability, changing strength of common external drivers, or dataset artefacts), making the results sensitive to the period of analysis.

We assess the robustness of our results by using different numbers of clusters and time periods. The results demonstrate robustness to the number of clusters chosen (7 or 9 clusters southern Africa, 3 or 5 eastern Africa), and to analysis with an alternative rainfall dataset. The cluster patterns show some instability over time associated with shifting ENSO teleconnections in southern Africa during the 1950s (*20*). We therefore use the period 1956-2011 to define the clusters which reduces sampling variability (by using a relatively long period) and reduces the influence of the changing ENSO teleconnection. Correlations with driving modes of variability are generally stable over this period and contribute to explaining why there is spatial coherence in rainfall variability within clusters and between some clusters.

We also considered the robustness of the results using an alternative rainfall dataset, the Global Precipitation Climatology Centre (*19)*.

Hydropower sites and upstream basin areas

For information on existing and proposed hydropower sites, our primary source of data was a recent World Bank study (*23*) based on key documents and reports prepared by governments and other agencies (Supplementary Note 6). Some hydropower sites and related information not mentioned in (*23*) were collected from an online interactive free database of the Global Energy Observatory (GEO, *43*). Location and coordinate information was also collected from the GEO database. Only sites with more than 50 MW installed capacity were included in the study (Fig. 1 shows location and capacity, Tables 1 and 2 list summary information and Supplementary Tables 14-17 list full details). Three pumped power storage schemes in South Africa, which together provide 28.6% of the region's hydropower capacity, were not included in our main analysis as they recycle water and are less vulnerable to rainfall variability. We used official values of installed capacity for hydropower generation, but we note that operational production is often much lower. For example, the two largest plants in the Democratic Republic of Congo (Inga I 354 MW and Inga II 1,424 MW) are both currently producing at well below capacity due to insufficient maintenance and lack of funding for refurbishment (*44*). The completion dates of dams under construction and proposed are uncertain; some (like Stiegler's gorge and Grand Inga) have been discussed for decades, and others have been proposed and completed quite rapidly. Our estimates for 2030 are drawn from (*23*).

To delineate upstream catchment areas for each mapped dam (with manual adjustment of geo-localization to match Flow Accumulation river line) in the list of hydropower dams in southern and eastern Africa, the upstream basin was obtained with the ArcGIS10 'watershed' tool. The inputs for this calculation were: Digital Elevation Model (DEM) at 30sec resolution from USGS: GTOPO30, and the Flow Direction and Flow Accumulation derived from this DEM on the African continent with ArcGIS 10. As rainfall clusters were only defined up to 12° North, for river basins with dams located northwards of this point (Fig.1, where evapotranspiration exceeds rainfall and runoff contributions are negligible) we scaled to the total basin area (i.e. 100%) using the cluster area proportions calculated for areas southwards of 12° North.

Rivers and lake centerlines in Fig. 1 and 2 are used for visualization only and were obtained from *45*. For the intersection of river basin and PCA cluster areas we used the 'intersect' tool from ArcGIS to obtain the area of overlap between a basin w and each PCA cluster area c (A_w,c). Then we obtained a relative overlap area (relative to the total area of the watershed A_w) for each (basin, cluster) pair by dividing A_w,c by A_w. For the intersection of river basin and PCA cluster weighted by rainfall we used the 'intersect' tool from ArcGIS to calculate (i) the total rainfall in the basin ($PA_w = P \times A_w$) and (ii) the rainfall occurring on the area of overlap between the basin and each PCA cluster area c (PA_w,c=P×A_w,c). Then we obtain a rainfall-weighted relative overlap area (relative to the total rainfall in the basin) for each (cluster, basin) pair by dividing PA_w,c by PA_w. Rainfall data were resampled to a cell size of 0.08 degree to match the resolution of basin and PCA map.

To estimate the proportion of regional hydropower by basin and by cluster, we took the total installed hydropower capacity for each region (for sites > 50 MW) and calculated the proportion by river basin and sub-basin (to capture the physical linkages between sites on the same channel or linked tributaries) and by rainfall cluster.

Data Availability

We use two widely available rainfall datasets (19 and 38) for our analysis. The basin outlines are calculated from Digital Elevation Model (DEM) at 30sec resolution from USGS: GTOPO30. The river flow data are available from the Global Runoff Data Centre (http://www.bafg.de/GRDC/EN/Home/homepage_node.html) with some updates from relevant National Hydrological Agencies (only available from the agencies directly). The sources used to develop information on current and planned dams are listed in Supplementary Table 14 and the information used in our calculations (results in Tables 1 and 2) is presented in Supplementary Tables 15-18 and Supplementary Note 6. The authors are happy to provide further information upon request.

Author Contributions

DC conceived the study and wrote the first draft, CD did the basin areas and overlaps and prepared figures 1 and 2, WAL defined the rainfall clusters, TO did the rainfall-climate indicator analysis and wrote the related text, all authors contributed to subsequent versions of the paper.

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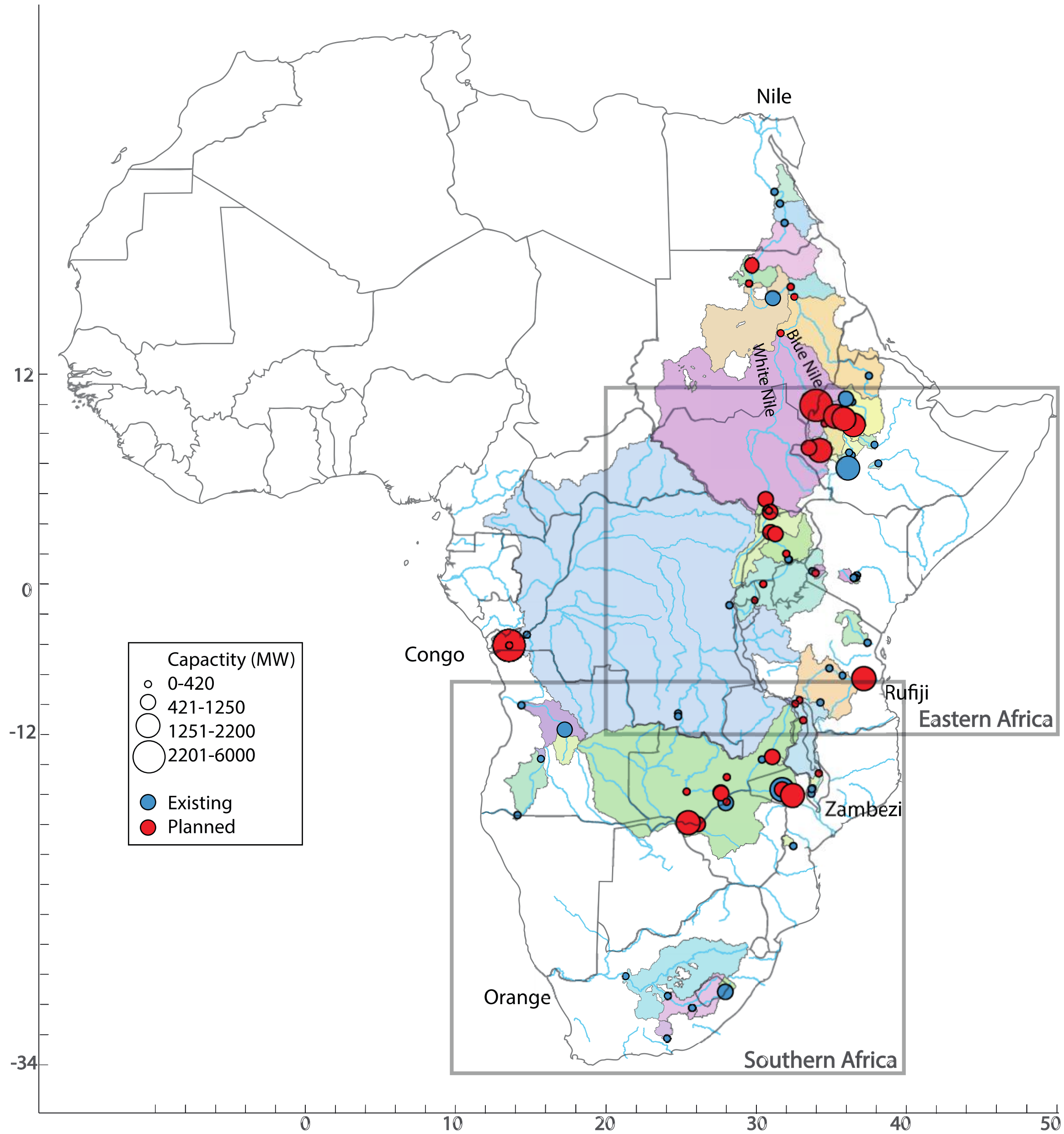
Figures

Fig. 1. Existing and planned hydropower dams and their main river basins in eastern and southern Africa. Existing hydropower dams in blue, planned in red (2030) and only dams >50 MW are considered. Icons are sized according to installed generating capacity (MW). Boxes show boundaries used to calculate rainfall clusters. Randomly shaded areas represent the main basins upstream of the hydropower dams.

Fig. 2. Cluster areas of coherent rainfall variability in eastern Africa and southern Africa. (a) In eastern Africa rainfall is January to December (three clusters, 1956-2011) and (b) in southern Africa rainfall is July to June (seven clusters, 1956/57-2010/11). Icons represent existing (blue) and planned (red) hydropower dams, sized according to installed generating capacity (MW). Black lines show the boundaries of the main river basins.

Fig. 3. 30-year sliding correlations between annual river flow series for four main hydropower generating basins in central, eastern and southern Africa. a; BN = Blue Nile, LVic = White Nile (Lake Victoria outflows) and Congo. b; Zam = Zambezi.



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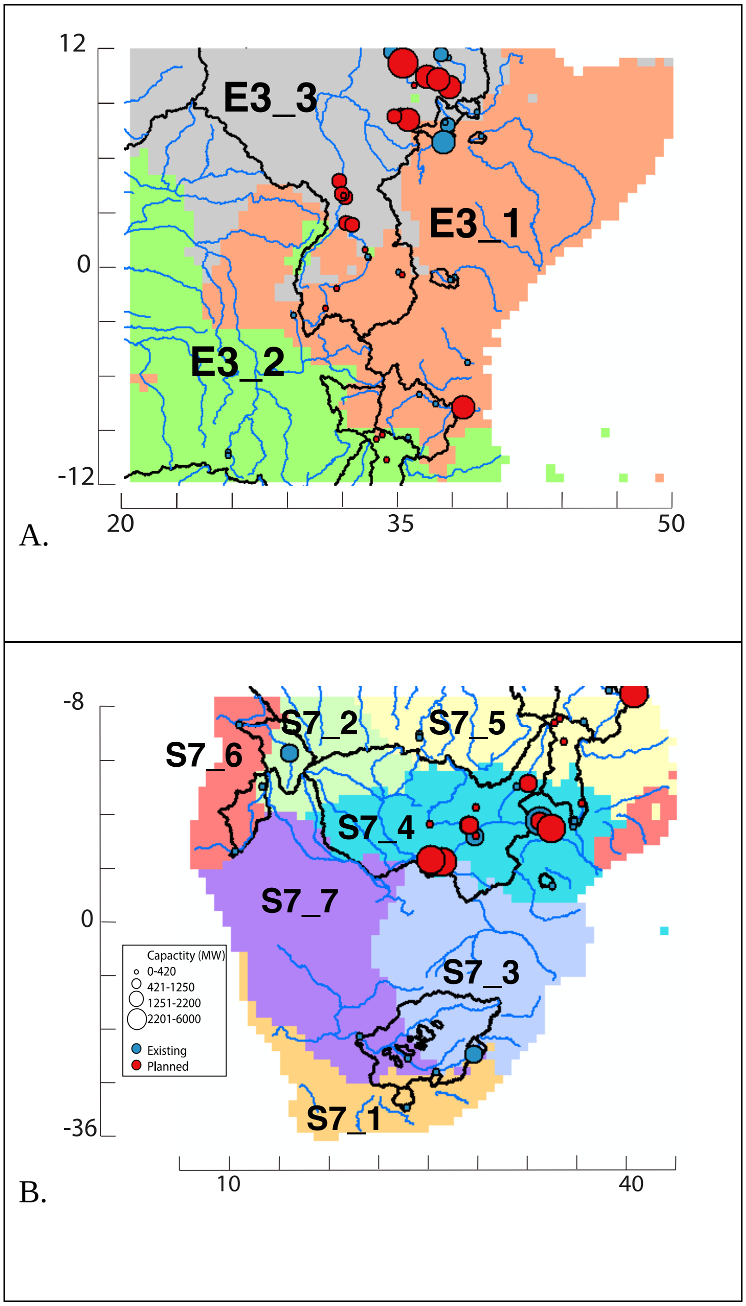

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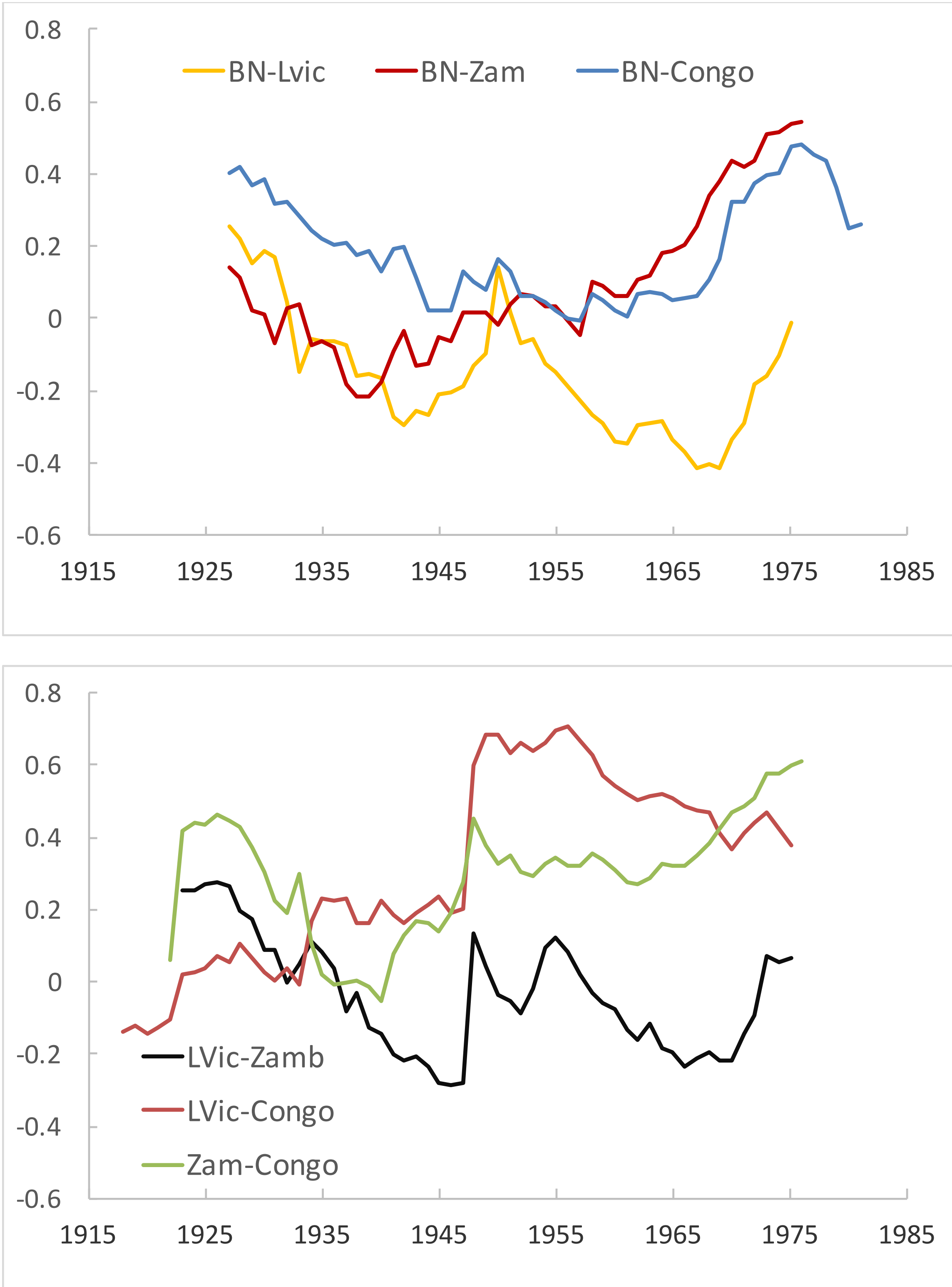

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	Installed Capacity	% total	New Capacity	% total	Capacity 2030	% total	Year	Per cent of hydropower capacity in cluster E3_1	E3_2	E3_3	All
Whole region	9841	100	24059	100	33900	100	2015	39.3	0.4	60.3	100.0
							2030	27.6	2.4	70.0	100.0
Nile Basin	6116	62.1	21601	89.8	27717	81.8	2015	14.7	0.4	47.1	62.1
							2030	14.8	0.7	66.2	81.8
Main stem	4092	41.6	1840	7.6	5932	17.5	2015	8.4	0.3	32.8	41.6
							2030	3.5	0.1	13.8	17.5
Tekaze	300	3.0	621	2.6	921	2.7	2015	0.0	0.0	3.0	3.0
							2030	0.0	0.0	1.8	1.8
Blue Nile	1094	11.1	12040	50.0	13134	38.7	2015	0.0	0.0	11.1	11.1
							2030	0.1	0.2	38.5	38.7
Baro	-	-	3487.0	14.5	3487	10.3	2015	-	-	-	-
							2030	0.3	0.2	9.8	10.3
White Nile	630	6.4	1808	7.5	2438	7..2	2015	6.2	0.0	0.2	6.4
							2030	6.5	0.0	0.7	7.2
White Nile BEJ	-	-	2105	8.7	2105	6.2	2015	-	-	-	0.0
							2030	4.5	0.2	1.6	6.2
Omo	2474	25.1	-	-	2474	7.3	2015	12.4	0.0	12.7	25.1
							2030	3.6	0.0	3.7	7.3
Rufiji	460	4.7	2458	10.2	2918	8.6	2015	4.6	0.0	0.0	4.7
							2030	7.0	1.7	0.0	8.6
Tana	527	5.4	-	-	527	1.6	2015	5.4	0.0	0.0	5.4
							2030	1.6	1.7	0.0	1.6
Other basins	264	2.7	-	-	264	0.8	2015	2.2	0.0	0.4	2.7
							2030	0.7	0.0	0.1	0.8

Table 1: Eastern Africa present and planned installed capacity. Sites > 50 MW. Present sites as of 2015; planned sites are for 2030. Per cent of total regional capacity is shown by major river basin (sub-basins in italics) and by area of rainfall cluster (defined for 1956-2011). Rainfall is January to December for eastern Africa (three clusters).

	Installed Capacity	% total	New Capacity	% total	Total capacity 2030	% total	Year	Per cent of hydropower capacity in cluster							
								S7_1	S7_2	S7_3	S7_4	S7_5	S7_6	S7_7	All
Whole region	7196	100	7982	100	15178	100	2015	1.4	26.4	7.1	51.5	5.9	3.4	4.1	100.0
							2030	0.7	22.3	4.1	58.6	9.3	1.6	3.4	100.1
Zambezi basin	5284	73.4	7643	95.8	12927	85.2	2015	0.0	12.5	2.4	50.8	5.9	0.0	1.8	73.4
							2030	0.0	15.7	1.9	56.4	9.0	0.0	2.3	85.2
Kafue	1020	14.1	870	10.9	1890	12.5	2015	0.0	0.0	0.0	13.3	0.9	0.0	0.0	14.2
							2030	0.0	0.0	0.0	11.6	0.9	0.0	0.0	12.5
Zambezi main Stem	3983	55.4	6093	76.3	10076	66.4	2015	0.0	12.5	2.4	36.0	2.6	0.0	1.8	55.4
							2030	0.0	15.7	1.9	43.6	3.0	0.0	2.3	66.4
Shire	281	3.9	680	8.5	961	6.3	2015	0.0	0.0	0.0	1.5	2.4	0.0	0.0	3.9
							2030	0.0	0.0	0.0	1.2	5.1	0.0	0.0	6.3
Orange	600	8.3	-	-	600	4.0	2015	1.4	0.0	4.7	0.0	0.0	0.0	2.2	8.3
							2030	0.7	0.0	2.2	0.0	0.0	0.0	1.0	4.0
Kwanza	700	9.7	-	-	700	4.6	2015	0.0	9.0	0.0	0.0	0.0	0.7	0.0	9.7
							2030	0.0	4.3	0.0	0.0	0.0	0.3	0.0	4.6
Other basins	612	8.5	339	4.2	951	6.3	2015	0.0	5.0	0.0	0.7	0.0	2.7	0.1	8.5
							2030	0.0	2.4	0.0	2.2	0.4	1.3	0.1	6.3

Table 2: Southern Africa present and planned installed capacity. Sites > 50 MW. Present sites as of 2015; planned sites are for 2030. Per cent of total regional capacity is shown by major river basin (sub-basins in italics) and by area of rainfall cluster (defined for 1956/57-2010/11). Rainfall is July to June for southern Africa (three clusters).