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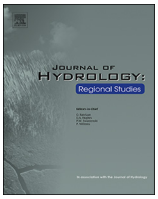

Finding sustainable water futures in data-sparse regions under climate change: Insights from the Turkwel River basin, Kenya

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ABSTRACT

Study region: the Turkwel river basin, Kenya experiences a high level of water scarcity due to its arid climate, high rainfall variability and rapidly growing water demand.

Study focus: Climate change, variability and rapid growth in water demand pose significant challenges to current and future water resources planning and allocation worldwide. In this paper a novel decision-scaling approach was applied to model the response of the Turkwel river basin's water resources system to growing demand and climate stressors. A climate response surface was constructed by combining a water resource system model, climate data, and a range of water demand scenarios.

New hydrological insights: The results show that climate variability and increased water demand are each important drivers of water scarcity in the basin. Increases in water demand due to expanded irrigation strongly influences on the resilience of the basin's water resource system to droughts caused by the global climate variability. The climate response surface offers a visual and flexible tool for decision-makers to understand the ways in which the system responds to climate variability and development scenarios. Policy decisions to accelerate water-dependent development and poverty reduction in arid and semi-arid lands that are characterised by rapid demographic, political and economic change in the short- to medium term have to promote low-regrets approaches that incorporate longer-term climate uncertainty.

1. Introduction

Sustainability of global freshwater is under increasing threats due to changing hydroclimate and abstraction to satisfy rapidly growing water demand (Hall et al., 2014; Wada et al., 2014). Understanding how socio-economic change put additional stress on water resources and translating the scientific evidence into policy decisions are critical steps towards ensuring sustainable water use and allocation (Sadoff and Hall, 2015; Dadson et al., 2017). Regions where development is most acutely needed are often those where data to inform long-term investment decisions is most severely lacking. This paper analyses the drivers of water scarcity in a data-sparse river basin and offers insights that can inform and challenge approaches to water resources planning in data-sparse regions in other basins worldwide.

In East Africa, severe droughts often cause water and food crises affecting millions of people and livelihoods (FEWS NET, 2017). About 3.4 million people in 23 arid and semiarid Kenya counties required food assistance during the second half of 2017(Kenya Food Security Steering Group, 2017). Turkana County was one of the most severely impacted (NDMA, 2017). Highly variable water

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resources and reduced flows in the Turkwel River trigger large human and livestock migration in search of water across country borders to Uganda and Ethiopia (Johannes et al., 2015). Despite the critical importance of water in the basin, the impact of hydroclimatic variability and demand growth on the water resources of the basin remains poorly understood, owing to the lack of scientific studies and limited biophysical data.

The objective of this paper is to identify the main drivers of water scarcity in the data-sparse basin. We estimate the resilience of the basin's water resources system to hydroclimatic changes and growing water demand by modifying the decision-scaling method introduced by Brown et al. (2012) to account for the limited data availability. Using a water resources system model and historical climate data, we construct a climate response surface that shows the ways in which the system responds the climate stressors. Further, we assess the future climate risks using climate projections from Global Circulation Models (GCMs) and investigate the past impacts of the global climate variability using years with strong El Niño/Southern Oscillation (ENSO) events. Finally, we show the impact of growing water demand using various demand scenarios estimated based on different levels of existing or planned agriculture and various population growth rates. Our findings demonstrate the importance of climate risk analysis in development planning and potential climate adaptation measures in regions with limited data to inform long-term decisions.

2. Study area

The Turkwel River basin is located in north-western Kenya (Fig. 1). The river originates in the Uganda side of Mount Elgon and drains into Lake Turkana, the largest desert lake in the world (Avery, 2012), covering a total catchment area of 23,740 km^2. The basin has a complex hydroclimate with highly diverse topography and a marked south-west to north-east rainfall gradient. The southern highlands (SC1 and SC2) receive between 900 and 1749 mm/year; while the arid northern lowland plains (SC4) receive annual rainfall ranging from 99 to 400 mm/year. The basin experiences two rainy seasons: March–June (long-rain) and October–December (short-rain).

The river supplies water to several competing socio-economic sectors. Turkwel Gorge Dam (TGD, 37 km^2 reservoir area, Lehner et al., 2011) produces106 MW, which is the third largest hydroelectric power output of the country (KENGEN, 2017). Several small-scale irrigation projects depend on the river water or shallow boreholes linked to it. The total irrigated area was estimated to be 18 km^2 in 2013 (Maina et al., 2013), but it has continued to expand. The recently proposed Turkwel Multipurpose Project includes an irrigation scheme of 300 km^2 of land for sugar cane and food crop production (KVDA, 2013).

Lodwar town relies on groundwater in alluvial systems for municipal water supply. According to the most recent Kenya's official population and housing census, the population of Lodwar was 45,368 in 2009, and projected to exceed 75,000 in 2017 (CIDP, 2017). The recent discovery of oil in South Lokichar Basin located southeast of Lodwar town (Kuper and Haberer, 2016) and emerging industries could potentially abstract water from the river. In Kenya, environmental flows (EF) are defined as the Q95 (the 5 percentile flow) of the natural flow. The cascade of water abstraction points from the river and water loss (and flow regulation) from the dam can result in unmet EF requirements. This may cause water stress and conflicts among pastoralists who account for 55% of Turkana County population (Johannes et al., 2015).

3. Method

3.1. Climate risk assessment

Climate risk assessment in East Africa is subjected to high uncertainty in the precipitation projections (James et al., 2014; Dosio et al., 2015). Water resources models forced with the precipitation projections aggregates uncertainty by the cascade of models and could lead to a potential climate maladaptation (Wilby and Dessai, 2010). A novel decision support method, known as 'decision scaling' (Brown et al., 2012), was proposed, in which climate projections are used to inform decisions related to risk mitigation rather than being directly used as forcing to water resource models. The method has been applied climate risk assessment on the reliability of municipal water supply (Brown and Wilby, 2012), flood risk analysis (Steinschneider et al., 2015), suspended sediment transport (Bussi et al., 2016), and flood inundation and protection costs (Poff et al., 2016).

Here we apply the decision scaling approach to assess the resilience of the Turkwel basin water resource system to climate change and variability and to growing water demand. The method consists of three major steps: 1) identifying water-related risks through engagement with local stakeholders, 2) determining climate conditions that can lead to those risks and constructing a climate response surface, and 3) assessing climate risk using data from GCM climate projections.

3.1.1. Water-related risk in the basin

We identified water-related risks in the basin through meetings with local stakeholders and an ongoing engagement through REACH-Improving water security for the poor programme (https://reachwater.org.uk/). The frequent droughts, intensive upstream abstraction from the river, and flow regulation by the dam are perceived to cause water scarcity in the basin. We categorised the risks into four classes (Table 1) to depict the level to which the water demand is met and the degree of reliance on groundwater sources to satisfy the demand. The risk level could increase from low to high as a result of a reduced precipitation amount, a rapid increase in water demand, or a combination thereof. The severe risk level is the most unsustainable since it means that agricultural water demand cannot be met during the growing season potentially leading to crop failure, and that groundwater could severely be depleted.

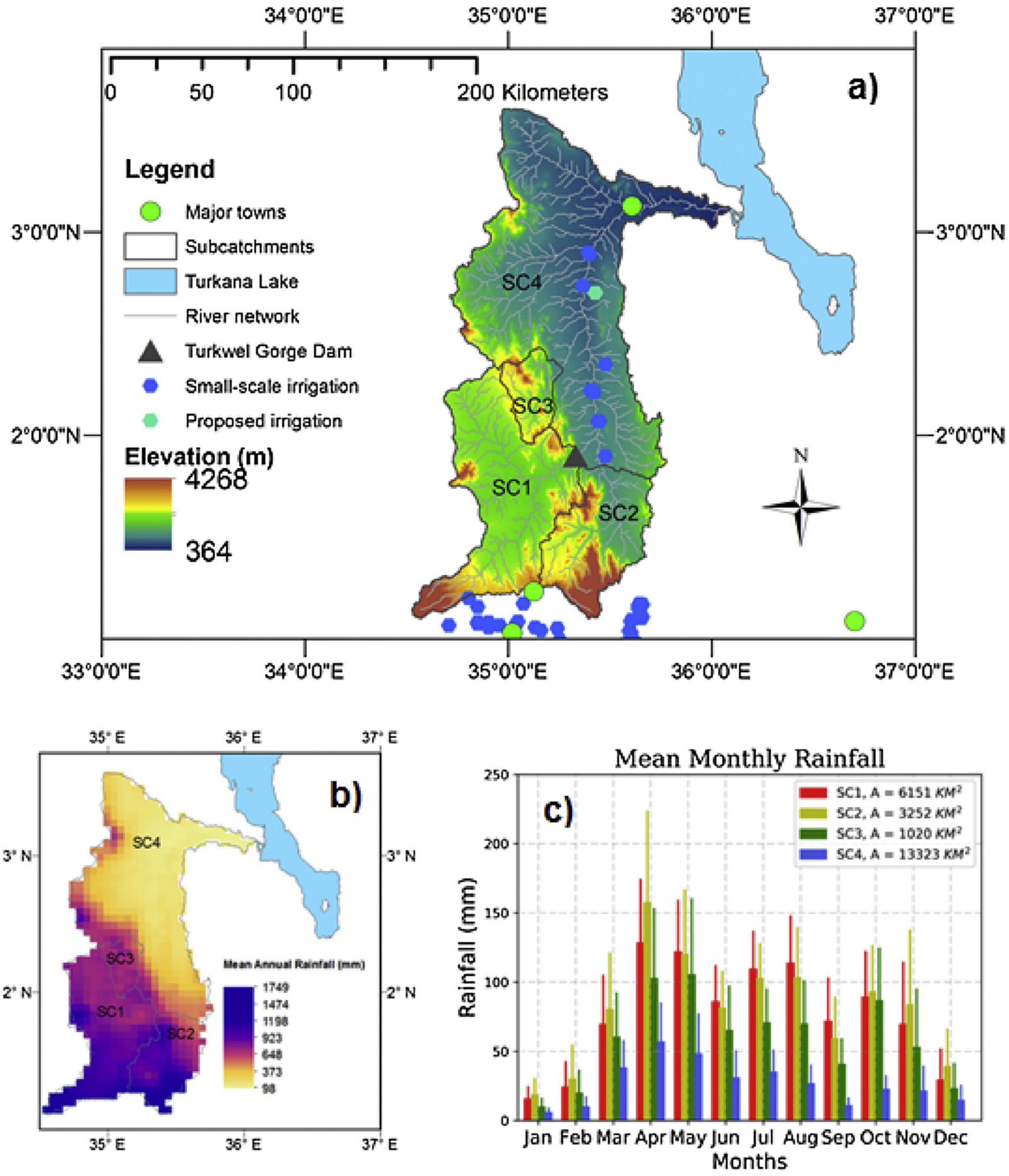


Fig. 1. a) The Turkwel River basin with subcatchment boundaries, topography and water-use sectors. The basin was divided into 4 subcatchments based on topography, climate and land-cover. Lodwar town (green circle) is located on the downstream end of the basin; b) mean annual and c) monthly CHIRPS v2.0 (Funk et al., 2015) rainfall climatology (1981–2016).

Table 1
Risk definition based on meeting the total water demand and risk of groundwater depletion.

Risk level	Water demand	Groundwater depletion
1 (low risk)	Demand fully met for all months	Low level of groundwater depletion.
2 (medium risk)	Demand is met during the growing months (March–September) but may not be the case during the other months. This has an important implication for crops with a long growing season (e.g., sugarcane)	Medium level of groundwater depletion: The total reduction in shallow groundwater storage during the study period (1984–2013) is less than 15%.
3 (high risk)	Same as 2	High level of groundwater depletion: the rate of abstraction is between 15% and 25%.
4 (severe risk)	Demand is not fully met in one or more growing seasons. This could lead to food crop failure.	Severe level of ground water depletion: the total shallow groundwater storage is reduced by more than 25% over the 30-year period.

Table 2

The El Niño and La Niña years (1950–83) identified using the average December–February MEI values (https://www.esrl.noaa.gov/psd/enso/mei/table.html). The P and T change factors for the Turkwel basin were estimated as the yearly mean relative monthly deviations from the baseline climatology (1984–2013, P and T data source: http://www.cru.uea.ac.uk/).

El Nino years				La Nina years			
Year	DJF MEI	Change factor		Year	DJF MEI	Change factor	
		P (%)	T (°C)			P (%)	T (°C)
1983	2.87	−5.8	0.07	1974	−1.82	−5.0	−6.2
1958	1.42	34.4	−0.26	1971	−1.51	−27.5	−0.93
1973	1.37	9.4	−0.07	1976	−1.40	−21.2	−0.27
1966	1.06	9.5	−0.45	1956	−1.36	−9.1	−0.90
1978	0.88	22.3	−0.67	1950	−1.15	−35.4	−0.91
1980	0.66	−41.6	−0.11	1951	−1.14	10.7	−0.42
				1962	−0.91	−8.2	−0.66
				1955	−0.85	4.8	−0.34
Average		4.7	−0.25			−11.4	−0.63

3.1.2. Climate scenarios

We constructed a climate response surface to identify climate conditions that potentially lead to the identified risk under a specific water demand condition. To do this, we iteratively run a water resources model (Section 3.3) using a range of climate scenarios produced by applying change factors to the observed monthly precipitation and temperature values.

For future climate, we derived climate change information from the fifth phase of Coupled Model Intercomparison Project (CMIP5) multi-model GCM projections (http://cmip-pcmdi.llnl.gov/cmip5/). The precipitation change factor was computed from percentage changes in the mean monthly values between CMIP5 future projections and historical runs. For temperature an additive change factor was estimated. Two future time slices were considered: near-term (2021–2050 or 2030s) and long-term (2071–2100 or 2080s). The period 1981–2005 was selected as the baseline because the CMIP5 historical runs end in 2005. To account for the decadal variability and reduce the related sampling uncertainty we derived the change factors between the two future 30-year time blocks and the baseline period from all continuous pairs of 20-year blocks drawn from the future periods and the baseline (Prudhomme et al., 2010). Then for each month, the median of the change factors calculated from each 20-year block average was considered as climate change factor between the future and the baseline.

In a separate analysis, we used data from historical El Niño/Southern Oscillation (ENSO) years (1950-83) to test if there was a link between global climate variability and the rainfall in the basin and, consequently, show the impact on the water resource system of the basin. Specifically we quantified the monthly precipitation deficit during the most recent severe drought and show the level of risk it posed on the water resources system of the basin. Fourteen years with the strongest ENSO signal from a 1950–83 period were identified based on the Multivariate ENSO Index (MEI) (Wolter and Timlin, 2011) averaged over the winter months (December–February). The DJF months provide the clearest indication for the strength of the ENSO events (https://www.esrl.noaa.gov/psd/enso/past_events.html). Accordingly, there were 6 El Niño and 8 La Niña years (Table 2), while the remaining 20 years were neutral years. For the ENSO years, for consistency with the other climate data described above, we estimated the mean monthly deviation from the baseline period (1984–2013). Note that the El Niño years have a wide range of precipitation anomalies in the basin (34.4% to −41.6% annually, 4.7% average) but the La Niña years have mostly dry anomalies (−35.4% to 10.7% annually, −11.4% average). However, given the large variation in the precipitation anomalies, the ENSO years may not be used as an indication for the wetness or dryness of the basin.

3.2. Water demand scenarios

To investigate the impact of growing demand on the sustainability of the basin's water resources and how it affects the climate risk, we used different water demand scenarios of irrigation and domestic water demand (Table 3). The industrial water demand and environmental flow requirements were unchanged. We considered three scenarios of irrigated areas. The first scenario (A1) corresponds with the existing crop irrigation mainly consisting of maize (75%) and sorghum (24%) (Maina et al., 2013). The second

Table 3

Water demand scenarios.

Demand type	Scenario	Description	Informed by
Irrigated agriculture	A1	18 km^2 of irrigated cropland	FAO 2013 estimate (Maina et al., 2013)
	A2	100 km^2 of irrigated cropland	FAO potential estimate (Maina et al., 2013)
	A3	250 km^2 of irrigated cropland	Expanded agriculture (KVDA, 2013)
Lodwar population	P1	Growth rate of 2.7%	Kenya national average (KNBS, 2012).
	P2	Growth rate of 6.0%	Turkana County's growth rate (Kenya County Fact Sheets, 2013)

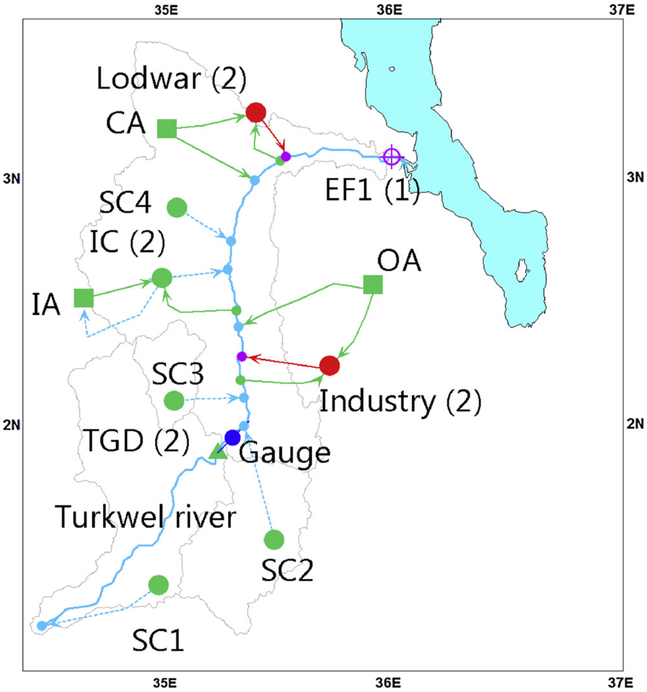


Fig. 2. WEAP model consisting of four subcatchments (SC); irrigation catchment (IC); TGD; demand sites: Lodwar town and industry; alluvial aquifers: CA, IA and OA; and an environmental flow (EF1) requirement. The numbers in the brackets represent the allocation priorities.

irrigation scenario of 100 km^2 (A2) was based on the estimated potential in the basin but with the same crop composition as the scenario A1. The third scenario (A3) also has the same crop composition but a larger area of 250 km^2.

We considered two scenarios for Lodwar population growth rates. The first scenario (P1) is equal to Kenya national average population growth rate (2.7%). The second scenario (P2) is approximately the same as the estimated population growth rate for Turkana County (6.0%). Considering the recent decentralisation and the associated population growth in the town, the P2 scenario is likely a more realistic estimate for the rapidly growing population in the town than the P1 scenario. For each scenario, domestic water consumption is set at 50 litres per day per capita, a value that is consistent with the water poverty index for developing countries (Gleick, 1996) but which is less than the estimated per capita consumption in Nairobi (Otieno, 2005).

3.3. Model and data

We used the Water Evaluation and Planning Version 21 (WEAP21) model (http://www.weap21.org/; Yates et al., 2005) for hydrological process modelling and water allocation (see Appendix S1). We set up the model for the Turkwel River basin with three demand sites (Lodwar town, irrigated agriculture and oil industry), a hydropower reservoir and in-stream flow requirement (Fig. 2). Each demand site is supplied with water from the river and shallow groundwater. We assigned the highest demand priority to the in-stream environmental flow (to match Kenya's regulations) while all other users have the same lower priority. Note that the highest demand priority assigned to the environmental flow may not be in practice in the basin (e.g., due to unregulated abstractions upstream); however, in the current model setup we assume it remains the highest priority. Similarly, it is possible to establish the supply preferences to a given demand site when there are multiple water supply sources; however, we assume here that there is no supply preference between stream and groundwater.

We estimated the required environmental flow (EF) as Q95 of the simulated natural mean monthly flow (Fig. S2). The Q95 flow estimated at the outlet to Lake Turkana is 10 m^3/s. We estimated the water need for each demand site as follows. Water consumptions in Lodwar town and the irrigation water demand scenarios were presented in Section 3.2. We set water demand for industry (oil production) at 10,000 m^3 per day, a value which reflects the initial phase of oil production but this value could vary depending on the production extent. Oil exploration began only recently in 2014 and therefore the time period over which production might run is not clear. In our analysis we have assumed a uniform industrial demand for all years during the study period.

4. Results

4.1. Impact of recent drought on the base flow in the basin

Seventy percent of the months during the severe 2014–2016 drought experienced drier conditions compared to the long-term

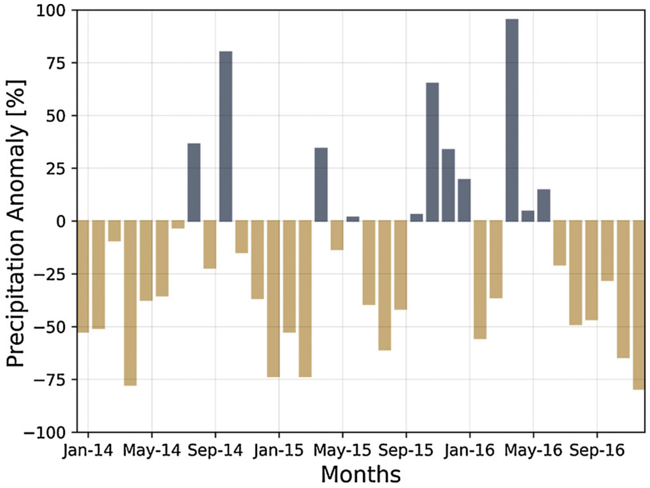


Fig. 3. Precipitation deficit in recent years (2014–2016) compared to climatology (1984–2013) in the Turkwel river basin.

average (1984–2013, Fig. 3). Notably, the start of the growing season (March) received consistently low rainfall for all three years. There was large seasonal variation in the precipitation anomaly during the drought years. In 2014 ten months (except August and October) experienced varying magnitudes of precipitation deficit, with the highest dry anomaly (−78%) observed in April. While 2015 experienced a relatively mild rainfall deficit, the second half of 2016 had an extremely dry anomaly ranging from −20% (July) to −80% (December) with an average (June–December) deficit of −40%. The 2016 rainfall deficit was consistent with what was observed in arid parts of Kenya (and in other countries in the region) and triggered the declaration of national disaster in the country (FEWS NET, 2017).

The normally perennial Turkwel River was completely dry at Lodwar town during the first weeks of March 2017. Fig. 4 illustrates the reduction in baseflow as the result of the low groundwater recharge linked to the extreme drought. Overall, the total rainfall for the month was significantly lower than the long-term average; the lowland plain (SC4) received 40% (16 mm/month) of the long-term average while the estimated basin average was only 34% (25 mm/month). Furthermore, a significant proportion of the total rainfall accumulated in March 2017 (68% for SC4 and 76% for the basin) was recorded over a four-day timespan (March 25–28), suggesting that the rainfall over the remaining days of the month was exceptionally below normal. Fig. 4b shows the flood flow as a response to the four-day rainfall; however, it quickly receded to a near-dry level just one day after the rain stopped (Fig. 4c). The quick flow recession is indicative of the significant baseflow reduction during the extreme drought of 2016/17 in the basin. This emphasizes the impact of long severe drought on groundwater recharge and its destructive effects on water resources of the basin.

4.2. The basin's response to climate variability

The climate response surface for the Turkwel river basin is shown in Fig. 5. The response surface estimated based on historical climate (1984–2013) and the conservative (A1P1) water demand conditions, indicates the combinations of climate conditions that may potentially lead to unsatisfied water demand, a higher risk of groundwater depletion, or both. We represented the range of climate possibilities by increasing or decreasing the monthly precipitation values by a percentage factor ranging from −50% to +50%, and warming temperature up to 6 °C compared to the baseline.

The climate response surface shows a severe risk under historical climate conditions (i.e., no change in precipitation and temperature) and a conservative water demand scenario. This means that the basin has historically been water-stressed, failing to satisfy demand in one or more growing seasons during the 30-year considered, even with high rates of groundwater depletion. An increase in precipitation reduces the risk of water scarcity in the basin. For example, it is estimated that an increase in the monthly precipitation by 5% compared to the baseline, with other conditions remaining unchanged, meets the water demand during the growing season (level 3) for all years during the study period. In other words, if single-season (March-September) irrigation is practiced, then the agricultural water demand can be fully met. A 15% increase in precipitation is estimated to reduce the groundwater abstraction (< 15%), and a 30% increase fully meets the water demand without a significant reduction in groundwater storage.

Conversely, reduced precipitation or warming temperature will increase the risk of water scarcity in the basin. A decrease in precipitation reduces both the surface water availability and the groundwater recharge, while warming temperature increases evapotranspiration which then decreases the available surface water and, thereby, leads to a higher reliance on groundwater supply. It is estimated that a mean monthly precipitation increase of at least 15% (30%) is required to maintain the medium (low risk level without warming temperature. The minimum precipitation required to maintain medium (low) risk levels increases to 20% (35%) at a 1.5 °C warming level (which is expected to occur in the 2030s under the RCP8.5 scenario in the basin) (Moss, 2008). With a warming by 4.2 °C (expected to occur in the 2080s in the basin under the RCP8.5 scenario) a minimum of 30% (45%) precipitation increase is needed to reduce the risk level to a medium (low) level.

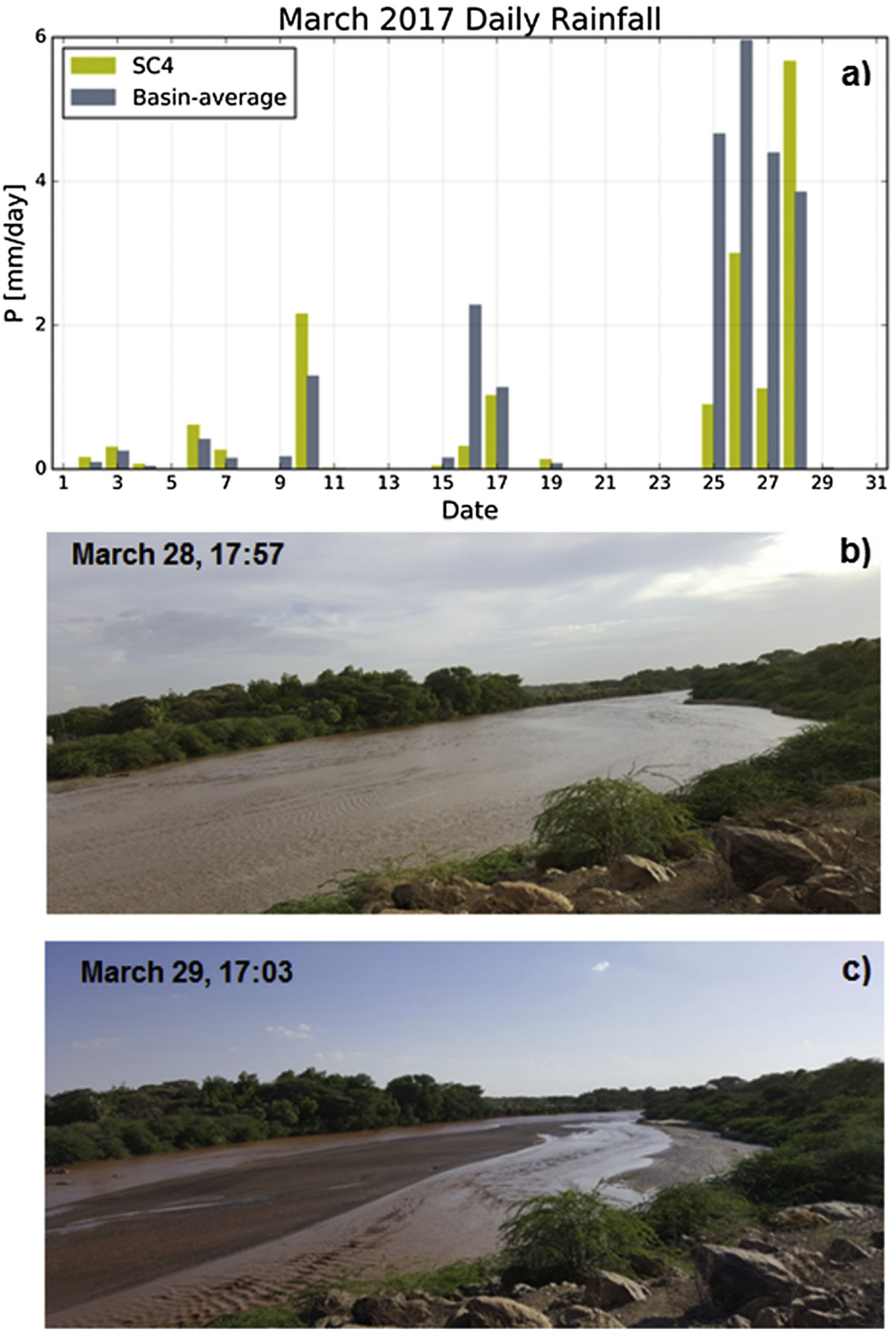


Fig. 4. a) Daily rainfall in March 2017 in the lowland sub-catchment (SC4) and basin-average rainfall over the Turkwel River basin; b) high flow caused by four consecutive days (March 25–28) of rainfall prior to which the river was dry; c) nearly-dry river bed one day after the same rain event at Lodwar bridge (3.114N, 35.605E). The photographs illustrate the substantially decreased baseflow resulting from reduced recharge due to the 2016/2017 drought. The rainfall data were derived from CHIRPS. Photographs (b & c) were taken by the first author.

4.3. Impact of climate change and variability

The change factors computed from the CMIP5 high-end (RCP8.5) projections for the near-term (2030s) and long-term (2080s) superimposed on the climate response surface is shown in Fig. 5. A total of 37 (18) GCM models provide combined precipitation and temperature runs for both the 2030s (2080s) and historical (1980–2005) periods. The results indicate that significant majority of GCMs predict a wetter and a warmer future for the Turkwel river basin. However, studies in East Africa have documented that climate models wrongly predict increasing rainfall trends in the coming decades (Rowell et al., 2015). We observed that about one-third of

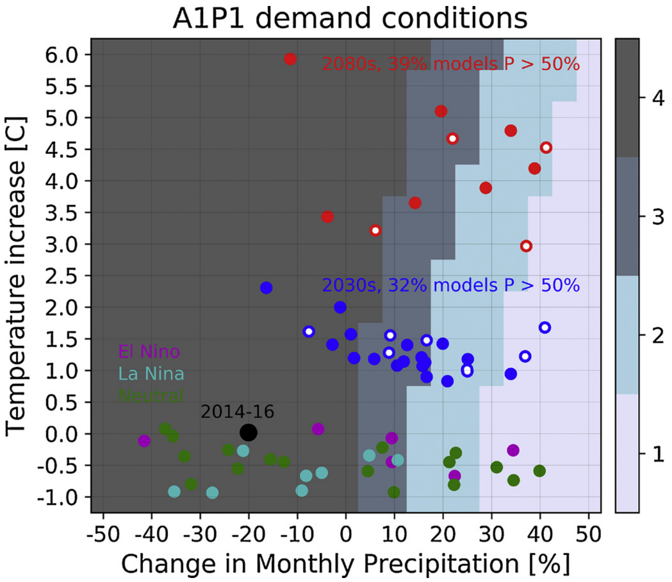


Fig. 5. Climate response surface created based on reference climate (1984–2013) under A1P1 demand conditions. The increasing risk levels (1–4) depict the risk of unmet water demand and groundwater depletion (see Table 1). Projected precipitation and temperature changes for 2030s (blue) and 2080s (red) are indicated for individual GCM RCP8.5 projection. The white markers show climate models with similar historical climatology and trends with CHIRPS precipitation in the region. Each El Niño and La Niña years (1950–83, Table 2) are also shown. See Appendix S2 for the 2014–16 drought.

the models predict more than 50% precipitation increase for both 2030s and 2080s compared to the baseline. They also predict a warmer future with average increases of 1.5 °C and 4.2 °C for the near-term and long-term respectively. The GCMs with relatively better seasonality and trend agreement with the historical climate (white marked in Fig. 5) show similar tendency of wetter and warmer future. The risk of the future climate change alone on the water resources of the Turkwel river basin is therefore inconclusive and may, if taken uncritically as a projection of greater abundance of water resources, create the potential for serious maladaptation (e.g., Magnan et al., 2016). Under the conservative A1P1 water demand conditions, 43% (39%) of the GCMs indicate a low risk of in 2030s (2080s); 11% (28%) a medium risk, 30% (17%) a high risk, and 16% (17%) of the GCMs indicate a severe risk in 2030s (2080s).

To investigate how the climate variability may impact the water resources of the basin we displayed all the historical years (1950–83) including 6 El Niño, 8 La Niña and 20 neutral years as earlier. The ENSO years show large precipitation variability that ranges between −41.5% and 34.4% compared to the baseline period. While the La Niña years were on average drier in the basin, there was clear indication of La Niña leading to positive and El Niño to negative precipitation anomalies and vice versa.

Overall, half of the 34 years had precipitation deficits that could lead to a severe risk of water scarcity under the A1P1 demand condition. The severe risk level means that the water demand was unmet during the growing season and the groundwater abstraction was high. Seven years (20%) resulted in a high risk while 4 years (12%) led to a medium risk. The low risk level of fully meeting water demand with low level of groundwater dependence was achieved for only 6 (18%) years, indicating that the Turkwel river basin has been historically water-stressed. The finding that the water demand is not fully met during the whole year for the majority of the historical years has an important implication in relation to proposals to move to agriculture with a longer growing season (e.g., sugar cane) where water availability is not adequate to satisfy the agricultural needs even during relatively wet years, which suggests that it may not be sustainable to invest in large scale projects that requite year-long irrigation in the basin unless additional water source is sought. In summary, while the validity of the wetting trend in the future climate projections remains doubtful, the negative impacts of climate variability highlight the extent of water scarcity in the Turkwel river basin.

4.4. Impact of increasing water demand

Fig. 6 presents the shift in climate response surface due to the growing water demand. Results reveal that expanding irrigated agriculture from 18 km^2 (A1P1) to 100 km^2 (A2P1) crop significantly increases the water demand and leads to an increased risk of unsatisfied demand and groundwater depletion. The climate risk level rises with a further expansion of irrigated agriculture to 250 km^2 (A3P1). Under historical climate (i.e., no change in precipitation and no warming temperature) the total unmet demand increases from 0.1% (A1P1) to 8.9% (A3P1) of the total demand and groundwater depletion rises from 27% to 61%. The amount of precipitation needed to achieve the lowest risk level (level 1) with no warming, shifts from +30% for the A1P1 to +40% and +50% of the monthly values for the A2P1 and A3P1 scenarios respectively. While the population growth also increases the domestic water consumption, it does not have as much impact on the risk curve as the irrigation expansion in the basin.

The risk level of future climate on the water scarcity rises with water demand. Fig. 7 presents the probability of each of the four

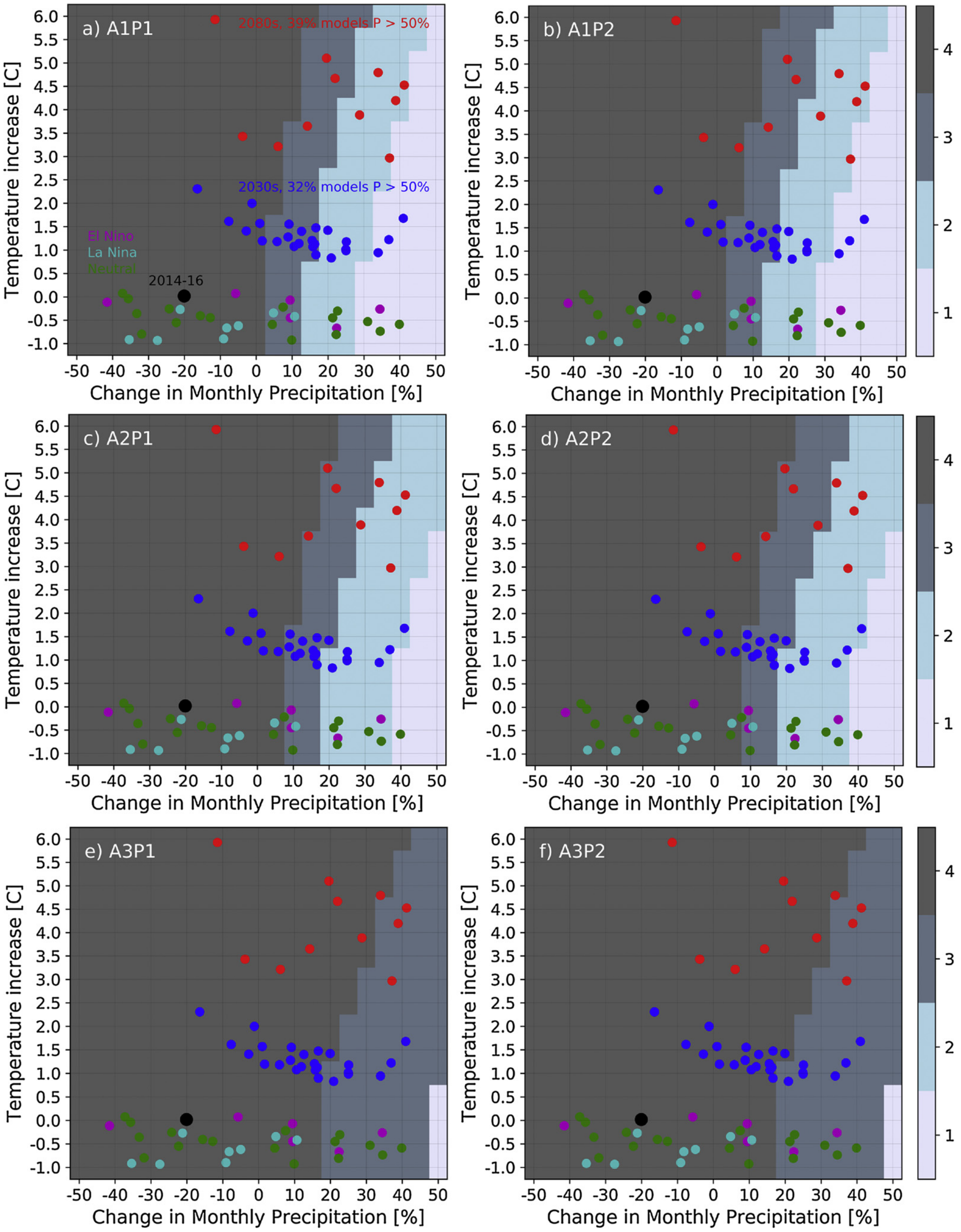
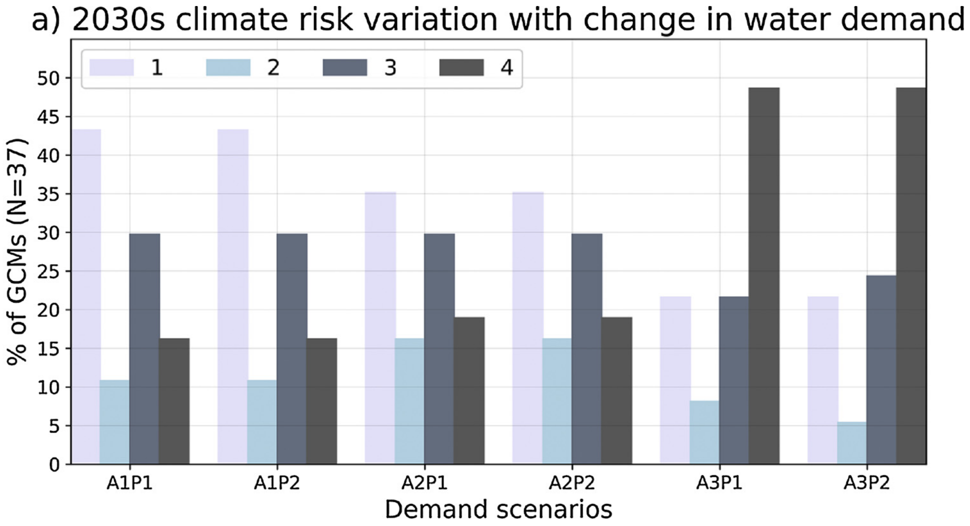


Fig. 6. The impact of demand growth is shown using three scenarios of irrigated area and two Lodwar population growth rates (see Table 3).

risk levels (as the percentages of the GCMs) for each of the six water demand scenarios. In the 2030s, the probability of experiencing severe risk (level 4) which includes the combined case of unmet water demand during the growing season and a very high rate of groundwater depletion grows three times from 16% to 49% as a result of the increase in water demand from A1P1 to A3P2 scenarios. Similarly the probability of the desirable low risk (level 1) decreases from 43% to 22% making it much less likely than the severe risk for the highest demand A3P2 scenario. We also found a comparable increase of the probability of the severe risk level with growing water demand in 2080s: 17% at A1P1 and 44% for A3P2 scenarios.


a) 2030s climate risk variation with change in water demand

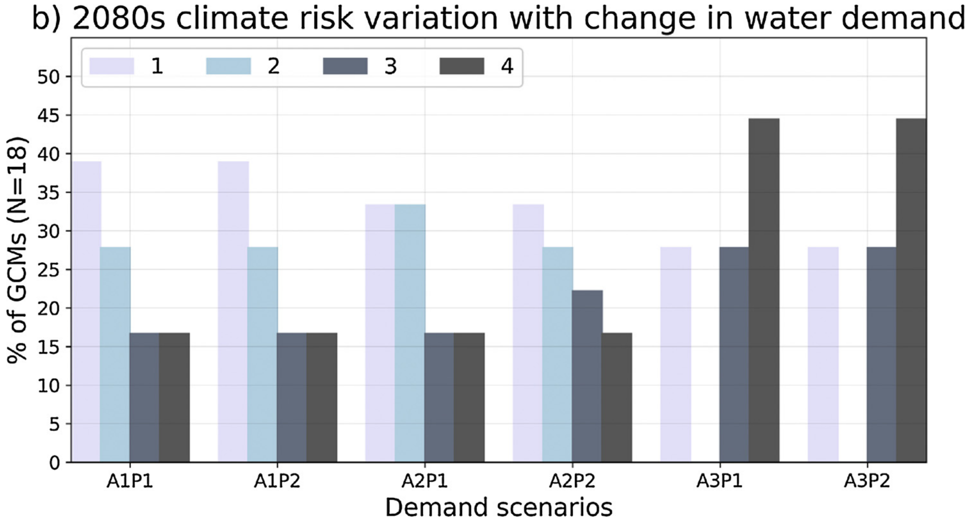

b) 2080s climate risk variation with change in water demand

Fig. 7. Future climate risk level variation with change in water demand in the Turkwel river basin.

5. Discussion

5.1. Limited hydroclimatic data

The limited hydroclimatic data and the large uncertainty in the future climate projections are two important limitations of applying the climate risk analysis in the Turkwel river basin. And yet this is a region in which long-term investment decisions must be made immediately in the presence of limited information. We are therefore explicitly interested in the level of inference that can be sustained based on the information that is available. There is limited or no data accessibility on water abstraction from the river or groundwater sources.

There is an emerging, but so far very limited, understanding of the groundwater resources in the Turkwel basin that requires further investigation. Addressing these issues is not a trivial task, however; it requires a great deal of resources and coordination among stakeholders. It is, of course, vital that additional data be collected to support robust decision-making in the basin. However, the likelihood of long-lived economic investments being made without access to long records over a wide area is high, and we have sought in our analysis to state carefully what inferences can be drawn (about the resilience of the water resource system to future climate, land-use, and development-related stressors). It is, of course, possible that new data will help increase the precision of the statements that we have felt able to make in the course of this work. However, unless there appears a new and substantial water supply source (e.g., groundwater supply or inter-basin water transfer); it is unlikely that new streamflow data will radically alter our assessment of the sustainability of the range of development scenarios being considered.

5.2. Implications for policy makers

Our results show that a potential increase in irrigation water demand combined with high rate of population growth aggravates the impacts of drought such as those caused by global climate variability. While increased food production could alleviate the food crisis, it is also important to consider the additional stress the expanded irrigation puts on the water resources when development projects are planned (KVDA, 2017). There is a recognized link between economic growth and water security in the region (Brown et al., 2011). Achieving sustainable economic development can be challenging without an integrated water resources management that includes managing trade-offs between irrigation, domestic, industrial and environmental water demands, and defining clear priorities among multiple development projects. In the Turkwel basin, this may involve making decisions pertaining to changing irrigation practices (Vision 2030, 2011Vision 2030, 2011) and adapting the dam (which impounds 41% of the precipitation volume of the basin) operation to the downstream water needs in order to release water from the reservoir for the environmental flows and other requirements.

Water resources planning should consider development of groundwater sources. This includes fully characterising the Napuu aquifer system and its interactions with the Turkwel River in order to quantify its sustainable use limits, assess its capacity to buffer climate change impacts, and to protect it from contamination as it directly underlies a rapidly growing Lodwar town. The planners also should also consider the errors in the projected rainfall trends in the region. Climate adaptation and investment planning based on the wrong GCM projections of increasing rainfall trends (Rowell et al., 2015) could lead to a water scarce future.

The implementation of the existing regulations could be achieved through strengthening the institutional capacity of government agencies and local communities and designing effective water policies that take the local water resources and demand conditions into account. To this end, evidence-based policy decisions will have direct implications on the level of progress towards effective climate risk reduction and mitigation efforts in the basin and other regions with limited data.

6. Conclusions

We assessed the resilience of the data-sparse Turkwel river basin's water resources system to climate stressors and growing demand by applying the decision scaling climate risk analysis method. The results reveal that climate variability and rapidly growing water demand are the main drivers of water scarcity in the basin. The frequent occurrence of severe drought due to global climate variability substantially impacted the water availability by reducing runoff and groundwater recharge. In addition, excessive abstraction to satisfy the water demand due to expanded irrigation and population growth in the basin potentially leads to higher risks of unsatisfied water demand and groundwater depletion.

The scenario-based analysis reveals that a potential increase in crop irrigation from 18 km^2 to 250 km^2 in the Turkwel river basin (under historical climate) will increase the unmet water demand from 0.1% to 8.9% of the total demand and the loss in groundwater storage from 27% to 61% over the study period (1984–2013). Furthermore, the probability of experiencing severe risks of unmet water demand and groundwater depletion posed by future climate rises by three times as the result of the potential irrigation expansion. Taken together, our results suggest that policy decisions related to water demand management will have important implications for water scarcity in the basin. While every river basin has its unique set of water-related challenges, the approach used in our analysis can be applied to climate risk analysis of other data-sparse river basins around the world.

Conflict of interest

None.

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Appendix A. Supplementary material

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ejrh.2018.08.005.

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