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The relationship between rainfall and human density and its implications for future water stress in sub-Saharan Africa*David le Blanc and Romain Perez*

Abstract

This paper uses Geographic Information System (GIS) data on population density, rainfall and climate change scenarios in order to identify areas that will be subject to increased water stress due to insufficient precipitation to support their projected population levels in 2050. Density increases across the continent should lead to a significant increase in the extent of water stressed zones, especially around the Sahel belt and in Eastern Africa. Changes in rainfall, the pattern of which remains inherently uncertain today, could mitigate or compound those effects. Consequences of unsustainably high local densities such as migrations are bound to become more prevalent.

JEL Classification: Q25, Q54, Q56

Keywords: climate change, rainfall, climate modeling, demographic growth, migrations, Africa

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The relationship between rainfall and human density and its implications for future water stress in sub-Saharan Africa

*David le Blanc and Romain Perez*¹

Introduction

Water scarcity has been identified as a key constraint to human settlement in much of Africa, most of which is classified as arid or semi arid². Sixty per cent of the African population lives in zones with mean annual runoffs of 300 mm or less, while 40 per cent occupy areas with less than 100 mm of runoff (Vörösmarty and others, 2005; Douglas and others, 2006). Moreover, many Africans live in transition zones between the humid tropics and arid regions such as the Sahel, which suffer from highly irregular rainfall patterns. Therefore, water stress potentially affects the living conditions of most African people. Beyond evident implications in terms of food security and public health, other consequences of water scarcity in Africa have included seasonal and permanent migrations, particularly towards urban areas (Barrios and Bertinelli, 2006), political instability and conflict linked to scarce land and water resources (Wolf and Ross, 1992; Ohlsson, 1999).

In this context, understanding the future impacts of climactic and demographic change on water scarcity in Africa is a crucial matter. Ultimately, changes in water scarcity will be determined by changes in rainfall and human densities, through complex processes and interactions, which will be discussed more fully in Section two. Greenhouse warming is likely to substantially affect the sub-regional and local patterns of rainfall, as observed in the 1960s in the Sahel sub-region.³ Wetter areas would benefit from an increase in their carrying capacity, while drier localities would become more prone to water stress. Most climate models also predict substantial increases in the variability of rainfall patterns over time, leading to more frequent and intense floods and droughts (IPCC, 2007). Because most African countries are still experiencing high or very high population growth rates, demography is likely to increase pressure on water resources. However, local variations stem from the different stages of demographic transition and from the highly differentiated impact of HIV/AIDS in many African countries.⁴ Demographic growth thus could have uneven implications for water stress on the continent.

The objective of this study is two-fold: First, we seek to identify zones in sub-Saharan Africa (SSA) that can be qualified as under water stress, based on the relationship that exists between human densities and average annual rainfalls in the continent. Second, we attempt to estimate the future evolution of the stressed areas, given projected climactic and demographic change. In order to do this, we combine local GIS data on density and rainfall with climate change scenarios. We first estimate the existing empirical relationship

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- 1 We thank David O'Connor and Jean-Michel Chéné for their useful comments. This paper should be attributed to the authors.
 - 2 According to Vorosmarty and others (2005), three quarters of the continent can be classified as is arid or semi-arid.
 - 3 The severe decrease in precipitation in the Sahel during the 1960s and 1970s was the first widely publicized case where climatic changes induced major stress for human settlements on a large scale. Sahel always had been a region of marginal rainfalls shared between farmers and camel herders. In the 1960s, rainfalls suddenly declined, making life difficult for both groups. Herders would experience difficulties to find grass while farmers did not have enough water for their fields. Eventually, the Sahelian drought was deemed to have induced migrations and over-mortality (see e.g. Zeng, 2003).
 - 4 Prevalence of HIV/AIDS is much more pronounced in South East Africa than in the rest of the continent. In countries such as Botswana, Lesotho, and Kenya, the epidemic has already resulted in dramatic falls in life expectancy, and as a consequence in low or even negative projected population growth rates for the next decades (UN, 2004).

between average yearly rainfall and density across sub-Saharan Africa. Zones belonging to the right end of the distribution of densities conditional on rainfall are classified as ‘tense’, or high stress. We then use localized population projections and changes in rainfall predicted by two mainstream climate change scenarios to assess the respective impacts of these two factors on the changes in extent and distribution of tense zones over the continent.

The paper is organized as follows. Section two presents the rationale for and limitations of our methodology, and relates our approach to other work. Section three describes the current patterns of population in SSA and the relationship between human densities and rainfalls. Section four presents the implications of future demographic and climactic changes for water stress in the sub-continent, and Section five concludes. Detailed results of the simulations are provided in Appendix one.

Methodology

Review of the literature

Despite human ingenuity and technology, water shortage beyond a certain threshold constrains the density of people that can survive locally. This study focuses on water, with the underlying hypothesis that water scarcity constitutes the most binding constraint to human settlement, at least at low levels of rainfall. This is likely to be the case in Africa, which is the most arid of all continents (Vörösmarty and others, 2005). At the local level, water scarcity appears to be a good proxy for carrying capacity⁵, as it is difficult to overcome through adaptation or water imports. Another important advantage is that data on rainfall are accessible and reliable, and detailed projections of future rainfall patterns are given by mainstream integrated climate models.

Falkenmark, Lundquist and Widstrand (1989) were among the first to propose an indicator to measure water scarcity, introducing the Water Stress Index. Their methodology, which still inspires a large part of research on water scarcity, is based on the calculation of the quantity of renewable water resources available per capita per year at the national level. The authors propose 1,700 m³ as the threshold of water requirements per inhabitant. They consider that a country experiences water scarcity when water supply falls below 1,000 m³. The approach was enriched by Ohlsson (1998), who introduced countries’ “adaptive capacity”, weighting the Water Stress Index with United Nations Development Programme’s (UNDP) Human Development Index. Arnell (2006) uses this simple approach to water scarcity to analyze the impacts of future climate change on water scarcity worldwide, based on predictions by climate change models following scenarios produced by the Intergovernmental Panel on Climate Change (IPCC).

The notion of water stress goes beyond measuring per capita water resources, and aims at incorporating water demand arising from all sectors (agriculture, industry, and households). Shiklomanov (1991)

5 In the sustainable development literature, as well as in the literature concerned with agriculture, the notion of sustainability at the local level has often been introduced through the concept of carrying capacity. Although this concept has received different definitions, for the purpose of this paper carrying capacity could be defined as the maximum productivity of food crops that can be grown on the land (or alternatively, by the number of calories that can be produced per hectare of land) in a sustainable way, that is, without irreversibly depleting local resources (e.g. aquifers or natural landscapes). This notion can be given a more concrete sense in various manners. This productivity in turn is a function of structural attributes (e.g. soil type and quality, proximity to a permanent water source such as lake or river...); climate attributes such as temperature, amount and distribution through the year of rainfall; and, importantly, of the type of technology used. Most of these data are difficult to obtain for the whole of Sub-Saharan Africa. Moreover, the assumption of economic autarky which underlies the concept of carrying capacity obviously does not apply to all zones or even at the country level. Therefore, we chose to focus this study on water, with the underlying hypothesis that lack of water constitutes the most binding constraint to human settlement, at least at low levels of rainfall.

compared renewable water resources and water demand at the national level. This approach led Raskin and others (1997) to propose the first water resources vulnerability index, calculated as the ratio of water demand to total renewable water resources. These authors classify countries as water-stressed if this ratio lies between 20 per cent and 40 per cent, and as severely stressed when the ratio is above 40 per cent. A large number of other indicators have since been devised and utilized in the development literature.⁶

These approaches based on indicators have been considerably enriched through application at sub-national levels.⁷ Vörösmarty and others (2005) used a GIS approach to determine water scarcity through run-off simulations. Enabled by the progress made in GIS systems and databases, this type of approach has been actively pursued in recent years, and has resulted in a much more precise assessment of water scarcity and stress at the local level in Africa (see Vörösmarty and others, 2005; Douglas and others, 2006) and in the world (Arnell, 2006).

Traditional water scarcity and water stress indicators have some limitations, some of which are recalled by Rijsberman (2004). Indices are often based on uniform thresholds that do not reflect variations in demand resulting from local agricultural specialization or climatic specificities. They also tend not to reflect differentiated capacities of societies to cope with water stress, especially through improved methods of collection of both surface and underground water. Lastly, they also tend to simplify the complexity of water scarcity issues, by failing to give an indication of the quality of fresh water available for human use.

At a more conceptual level, the approach to water scarcity by indices relies on the implicit assumption that water needs are a linear function of human densities. For example, the most well-known indicator of scarcity, the Falkenmark indicator, is calculated by averaging total water resources available locally over the population living in a given area. If the average falls below a certain threshold, e.g. 1,000 m³, the area is considered water stressed. This implicitly assumes that two zones, one of which has both density and water availability twice as high as the other, are in the same situation in terms of water scarcity. Whether this is the case, however, is not clear. For example, water is likely to be a more binding constraint for human settlements at low levels of precipitation or runoff (e.g. because of lower accumulation and retention of water through dry periods of the year), but less so at high levels of precipitation or runoff where other elements may become critical. At any rate, the nature of this relationship should be investigated, and not posited from the beginning.

Furthermore, the computation of these indexes often necessitates recourse to models linking rainfall, which is the most easily observed variable, to intermediate quantities like runoff or water discharge. This intermediary step introduces sources of noise, as the models typically need to be calibrated. Thus, values utilized for the computation of local indices (e.g. for runoff) are those produced by the model and do not necessarily match observed values well, at least for certain locations. By contrast, our approach does not necessitate the use of intermediary models.

6 The 2003 edition of the World Water Development Report mentions more of 150 indicators (UNESCO, 2003). Some of the indicators try to combine multiple dimensions of water as an input to human activities. For example, Sullivan and others (2003) introduces the Water Poverty Index, which combines five components: access to water, water quantity, quality and variability, water uses for domestic, food and productive purposes, capacity for water management and environmental aspects. A drawback of complex indicators such as this, though, is that the statistical data needed to compute them are often difficult to gather.

7 National approaches, by averaging water resources and population over large areas, tended to systematically underestimate water stress, and were also often too broad in scale to be translated into concrete operational policies for water management, which by nature tend to be local.

This study is based on an alternative, yet simple, approach to water scarcity. Areas likely to suffer from tension over water resources are identified through the statistical analysis of population distributions conditional on average rainfall. At a given average precipitation level, tense zones correspond to areas where human density is the highest. Thus, our approach to water scarcity or stress (referred to as water tension hereafter) is based on distributions, and not on averages.

There are many *a priori* reasons to suppose that the relationship between rainfall and density is not linear, and maybe not even monotonic. First and foremost, runoff water, on which most rural communities have to rely for most of their water use, is a non-linear function of rainfall. In their study of the rainfall-runoff relationship in Africa, de Wit and Stankiewicz (2006) show that below a certain threshold, which they indicate is around 400 mm of yearly rainfall, runoff is virtually nil. Thus, except at immediate proximity to permanent streams, communities cannot survive. Between 400 mm and 1000 mm, the relationship between rainfall and runoff is approximately linear. Beyond the 1000 mm threshold, there ceases to be a clear relationship between the two variables. It can be expected that the relationship between rainfall and density should follow the same general pattern, especially for low rainfall.⁸

It can also be expected that at the scale of a continent, at any given level of yearly rainfall, a very high dispersion of human densities will be observed. Local availability of water is only one of multiple factors which condition the possibility of permanent settlement and production. Other reasons for this dispersion would include various climatic, geographic and technological factors. All these elements combine to define the frontier within which human settlements can be sustained locally.

Furthermore, human existence is dependent on water in many ways, and not in a unique, well identified manner. Availability of drinking water is perhaps the most obvious and critical prerequisite for sustained human presence. Water for other human purposes also conditions, through its impacts on health, the demographic conditions that will prevail locally. Water for agriculture is another critical requirement for autarkic or semi-autarkic communities that do not benefit from water carrying infrastructure. The preponderance of one of these factors over the others will vary depending on the type of agriculture practiced, and thus is likely to differ markedly between regions.

Finally, agricultural productivity and local carrying capacity also critically depend on the infra-annual patterns of rainfall.⁹ A last source of variation comes from local differences in access to runoff water and river discharge. Surface water can be complemented by ground water from aquifers. Zones receiving low or even marginal rainfall can benefit from a major river, which can satisfy local water needs at least for some uses, thereby supporting higher densities than would normally be the case. The presence of dams and other hydrological equipment can also allow large areas to sustain higher densities than in the absence of technological improvement.

Our approach is best seen as complementing the studies based on water scarcity indexes of the types mentioned above. As will be elaborated upon in the next sections, our results show strong concordance with those based on more traditional approaches. An additional benefit of our alternative methodology is that

8 In fact, the relation between density and rainfall would exactly mirror that existing between runoff and rainfall, if density were itself a linear function of runoff. As explained above, approaches to water scarcity based on uniform threshold levels for available water per capita implicitly assume exactly this.

9 One critical element here is the length of the growing period (LGP), which in arid zones determines which crops can optimally be grown. Marginal alterations in the patterns of rainfall during the year can have dramatic implications in terms of the types of crops that can be sustainably grown, and therefore in terms of locally sustainable densities.

we are able to shed light on the complicated relationship which exists between rainfall and the distribution of human settlements in sub-Saharan Africa. Yet another contribution of the paper is the comparison of the local impacts of demographic and climate changes, whereas many other papers in the field concentrate solely on climatic impacts.

Methodology

Our approach comprises three main steps. First, the distributions of population densities for a grid map of Africa conditional on mean annual rainfall are analyzed. Specifically, we define 16 rainfall classes (brackets) based on intervals of 100 mm of annual precipitations.¹⁰ Distributions of population densities are then calculated within each class.

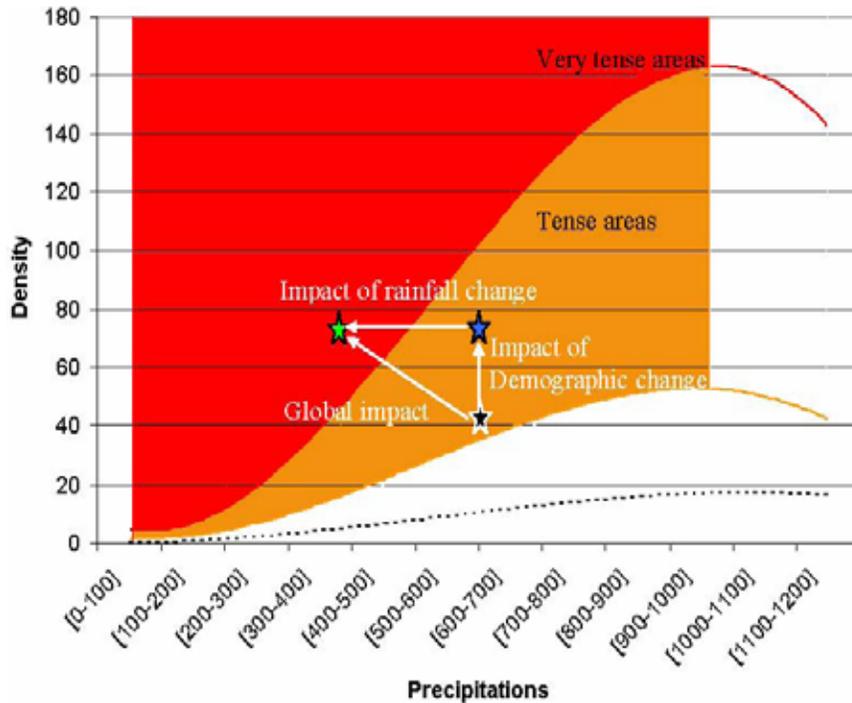
The second step of our analysis consists in identifying and mapping zones likely to be affected by water tension. This is done by examining the conditional distributions of densities, conditional on rainfall. We first identify a limit beyond which rainfall does not appear to constrain densities. Then, for zones receiving less than this threshold quantity of rainfall, we define as 'tense' all the areas whose density is 'too high', given the average rainfall they receive. Specifically, zones located in the highest five per cent of the conditional distribution of densities for each rainfall bracket are labeled 'very tense', whereas zones located in the highest 20 per cent of the distribution are designated as 'tense'. Thus, in our framework, the position of a particular zone in its conditional distribution determines its degree of 'water tension'. Obviously, the positions in the distribution which one chooses as thresholds defining water tension (i.e., five per cent and 20 per cent) are somewhat arbitrary. However, having computed the complete conditional distributions of densities, it is easy to check that our results are not entirely driven by a particular choice of threshold.

In the last step of the analysis, changes in precipitation patterns and demography are projected. For each cell of the grid, future projected population and average rainfall in 2050 are computed. The cell is then located in the current distribution of densities for the class of rainfall to which it is supposed to belong in the future. Tense and very tense zones are then identified based on the same thresholds as those used for current population. The principle of the analysis is explained in Figure 1. The figure represents the location of an arbitrary cell of the spatial grid in the rainfall-density space. Actual values of rainfall and density for that cell define the initial position of the cell, denoted by a black star. Simulated changes in 2050 shift the position of the cell on the graph in two ways. First, keeping rainfall constant, demographic growth will shift the initial point upwards or downwards (blue star). This is the demographic impact. Then, changes in annual rainfall will shift the cell leftwards or rightwards (green star). This horizontal shift measures the climate (or rainfall) impact. The sum of the two impacts is the total impact.

It is important to underline the fact that features used to identify tense and very tense zones in the future (i.e. the 80th and 95th percentiles) are extracted from current conditional distributions. In reality, technological change has the potential to allow more people to sustain themselves per unit of land, through increases in productivity, investment, and better water mobilization techniques. It is thus to be expected that distributions of population conditional on rainfall will shift to the right in the future. Local technology improvements however, are only one of the possible responses to increased population pressure; other responses include emigration. Our framework can be understood as a hypothetical scenario in which no technological change takes place, and no local water-related investment is implemented. The future tense zones that emerge from our analysis are precisely those which will need such investments in order to sustain

¹⁰ In the higher range of precipitations (beyond 1400 mm of rainfall), the classes are broader, in order to keep a minimal number of grid cells in each class.

Figure 1:
Basic Principle of Simulations



Source: Authors' elaboration.

their populations locally. Our results can thus be taken as a gap analysis, which aims at mapping the areas where technology improvements will eventually be needed if emigration from them for economic reasons is to be minimized in the future.

The Data

This section briefly describes the datasets used as well as the way they are utilized.

Population data

We use data produced by the Gridded Population of the World (GPW) project of the Center for International Earth Science Information Network (CIESIN) of the Earth Institute at Columbia University.¹¹ Version GPWv3 of the project provides online access to grid data showing population density on a small scale (2.5 minutes of angle).¹² In all the analysis, we use the data for 2000.

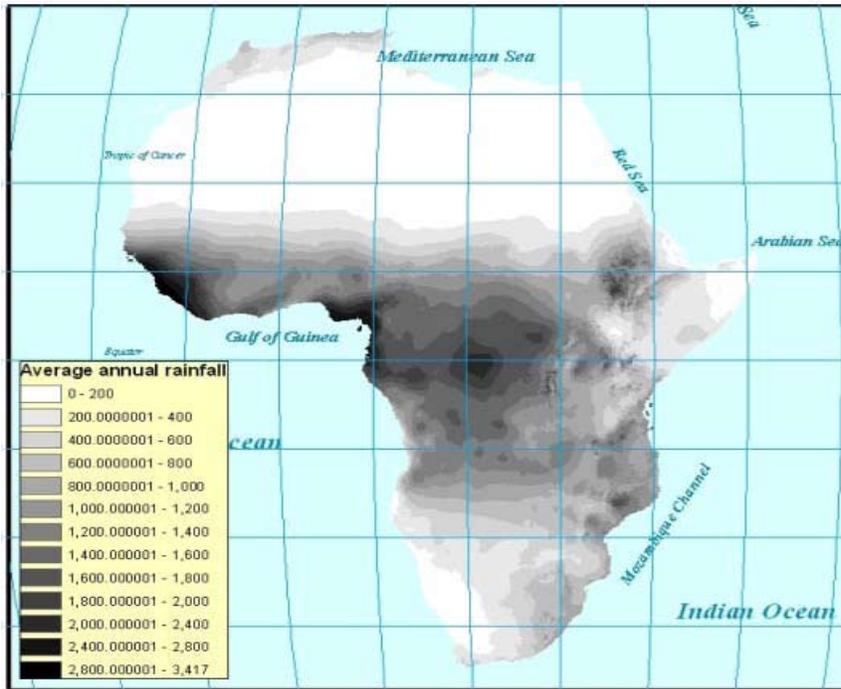
Rainfall data

Data on current rainfall are published by the Food and Agriculture Organization (FAO). In fact, FAO publishes one grid of data for each month of the year, showing average rainfall for this month. We simply add monthly rainfall to obtain average yearly rainfall for the reference period. The corresponding map can be considered as the most accurate source for rainfall in Africa.

11 <http://sedac.ciesin.columbia.edu/gpw/>. The project aims at rendering of human populations in a common geo-referenced framework.

12 This corresponds to squares about 4.6 kilometers wide.

Map 1:

Pattern of Yearly Rainfall for Africa, 2000

Source: Authors' elaboration.

Population projections

Standard population projections at a sub-national level for all Africa do not exist. Hence, we have had to construct projections. Several options were available, which all presented advantages and drawbacks. A first option was to start from population projections included in IPCC scenarios, as is often done in studies trying to assess the impact of climate change globally (see e.g. Arnell, 2006). The problem we face for our regional study is that IPCC projections are global ones, produced with the objective of illustrating possible paths for world population in the next century. However, they are not based on country-level population trends or projections. On the other hand, we need to construct projections that are realistic not only at the global or regional level, but at much finer scales.

Another option was to use GIS population data for 1990 and 2000 and project growth rates obtained from the comparison of the two maps to 2050. While the easiest route, this method fails to reflect demographic transitions that are very likely to occur in African countries in the next fifty years. This approach also does not account for the impact of HIV/AIDS on recent trends in population growth, which has been unequal between African countries. Moreover, using such local level data has the disadvantage of projecting trends where migrations occurring from the tense zones, if any, are already 'built-in'. Since those migrations constitute one of the responses to the problem we want to investigate, it would be better not to incorporate them into population projections in the first place.¹³

The third alternative consisted of using the latest population projections at the country level produced by the United Nations, which incorporate major influences on demographic trends. The drawback of

¹³ There is no perfect solution to this problem. Precise local data on births and deaths would allow one to disentangle the effects of migrations and natural increase in population growth, and to project populations locally with different assumptions about migrations. However, such data do not exist for all countries of Sub-Saharan Africa.

this method is that the information is produced only at the country level. Thus, for example, sub-national differences in population structure, which will affect demographic growth, are not taken into account. However, the advantage of this method is that the latest trends in population growth are taken into account, at least at the country level. Given the weight we put on incorporating the most realistic assumptions into our population projections, we chose this method. Projected population growth rates at the horizon 2050 are extracted from the 2004 population projections produced by the United Nations (UN, 2004) for each country in sub-Saharan Africa. These growth rates are then applied cell-wise to the 2000 GIS population dataset, which results in a GIS dataset containing projected densities for 2050.

Climate data

Climate data for this study was obtained from the Climate System Analysis Group (CSAG). The CSAG site allows one to download downscaled global climate model projections of a number of climate variables.¹⁴ More precisely, CSAG provides, for the network of climatic stations spread across the African continent, historical data on rainfall during the period 1960-1990, as well as projections for the future, downscaled from five mainstream climate models.¹⁵ Out of the five climate models downscaled by CSAG, we chose two particular datasets corresponding to the CSIRO model and the Hadley Center (HADAm) model. The CSIRO model was selected because it is the only one that covers the period 2046-2065, the closest to present of all models. In addition, the Hadley Center for Climate Change model is widely recognized as one of the most advanced climate change models. The method used to project changes in rainfall for all Africa is detailed in Appendix two.

A word of caution is appropriate at this stage. Predicting rainfall for Africa is hardly an exact science, given the current state of climate models existing in the world. In particular, the main climate models as registered by the IPCC do not all agree on the direction and magnitude of the changes that should affect the Sahel in the next century. While most models predict a wetter Sahel, other recognized models predict still drier conditions in decades to come (Held and Lu, 2005; Held and others, 2006). The impacts of this uncertainty on our results will be further elaborated in Section five.

Human Densities and Rainfall in sub-Saharan Africa in 2000

Densities in Africa exhibit a tremendous dispersion. In our dataset, they range from zero (e.g. in the middle of the Sahara), to more than 10,000 inhabitants per square kilometer in large cities such as Lagos. A closer look at the distribution of densities over the continent, shown in Figure 2, reveals that 30 per cent of the land area in SSA has densities below two people per square kilometer, and another 30 per cent has densities below ten people per square kilometer. On the other hand, the remaining 40 per cent of the territory exhibits highly dispersed densities.

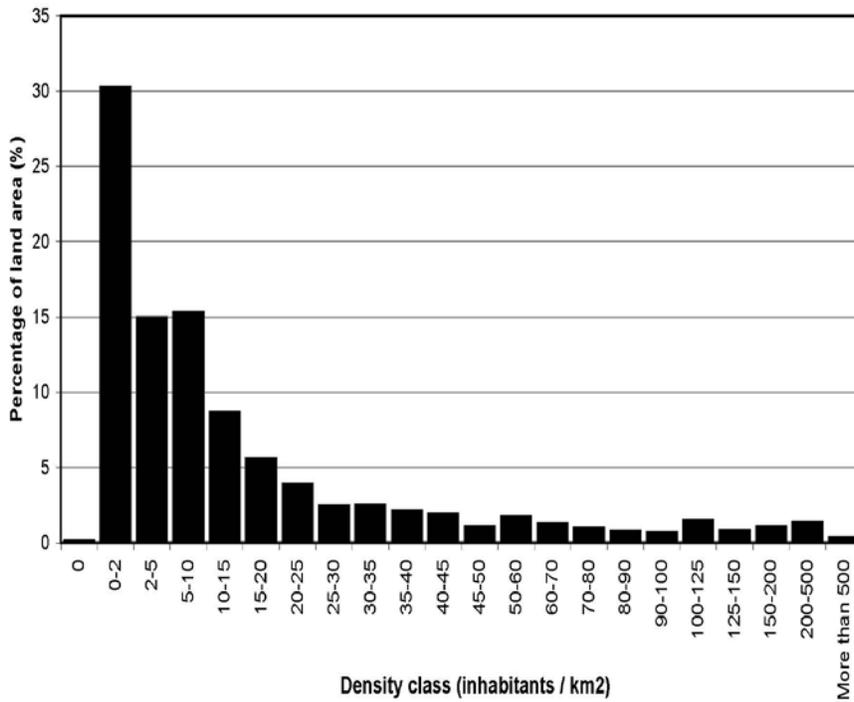
It is tempting to relate the high proportion of African territory having very low density to the large proportion of the territory occupied by deserts or arid zones. However, the idea that densities merely reflect rainfall is too simple. Instead, distributions of densities conditional on the rainfall level also exhibit high dispersions and are skewed to the right. These features are apparent in Figure 3, which represents selected quantiles of these conditional distributions.¹⁶ For example, within the subset of the continent receiving between

14 <http://data.csag.uct.ac.za/>

15 The models covered are CSIRO, HADAm, ECHAM, MIROC, and MRI-CGCM.

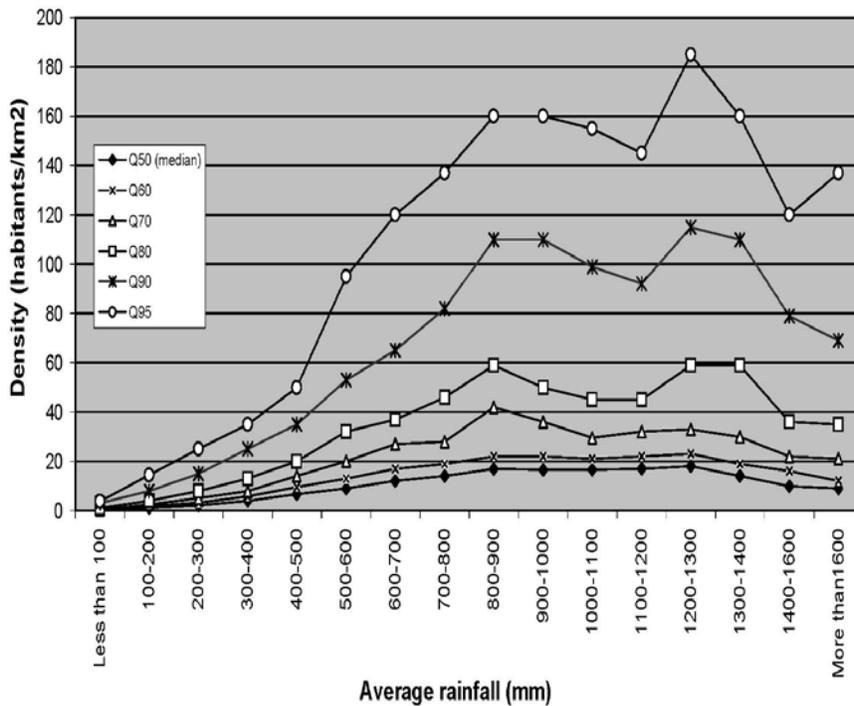
16 As mentioned in section 2, 16 such conditional distributions have been computed, corresponding to 16 rainfall classes whose definition appears in Figure 3.

Figure 2:
Distribution of Human densities in sub-Saharan Africa, 2000



Source: Authors' elaboration.

Figure 3:
Quantiles of Density Distribution Conditional on Average Rainfall, sub-Saharan Africa

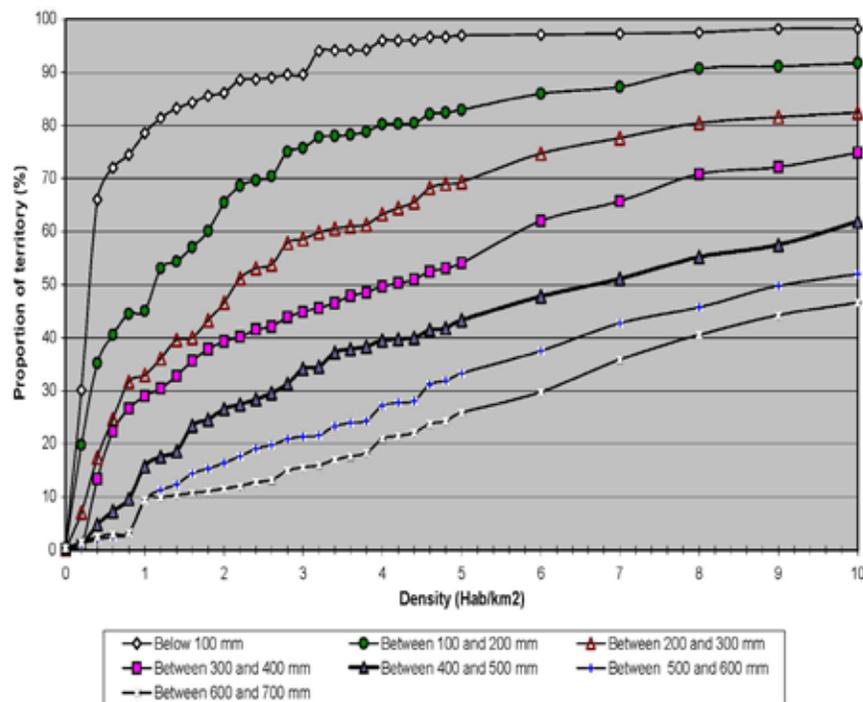


Source: Authors' elaboration.

500 and 600 millimeters of rainfall annually, 70 per cent of cells have densities below 20 people/km²; ten per cent of cells have densities between 20 and 30 people/km²; ten per cent of cells have densities above 50; and five per cent of cells have densities above 100. Thus, even at relatively low levels of precipitation, substantial portions of the territory support high densities.

Another clear pattern of Figure 3 is that below 900 mm of rainfall, quantiles of the conditional distributions (e.g. the median) increase with rainfall. The notion that densities ‘increase’ with rainfall up to 900 mm can be given a precise statistical sense. One checks that up to that limit, conditional distributions of densities computed for higher classes of rainfall statistically dominate those corresponding to lower rainfall classes.¹⁷ Figure 4 graphically illustrates this property. The figure represents the cumulative distribution functions of densities for the seven groups with lowest precipitations. The intersections of horizontal lines with the curves give the respective quantiles of each distribution. It is easy to check from the figure that these quantiles shift to the right as precipitations increase, which reflects the statistical dominance property. Conditional distributions for higher classes of precipitations (beyond 900 mm) do not exhibit the same

Figure 4:
Distribution of Densities in Most Arid Regions, sub-Saharan Africa



Source: Authors' elaboration.

Table 1:
Correlation between rainfalls and log density in SSA

Zones	Correlation index
Rainfall ≤ 900 mm	0.632
Rainfall > 900 mm	-0.028
All sub-Saharan Africa	0.545

Source: Authors' calculations

17 A probability distribution function F_1 (i.e. if the random variable Y has distribution F_1 , then $F_1(x) = Pr(Y \leq x)$) dominates a distribution F_2 defined over the same support, if for any value x of the common support, $F_1(x) \leq F_2(x)$.

property and intersect with each other, as can be inferred from Figure 3. For the highest precipitation classes, the distributions even tend to shift to the left.

This feature of conditional distributions is consistent with the hypothesis that the limit of 900 mm of annual rainfall empirically appears to define the threshold below which water constitutes a binding constraint to high densities. Beyond 900 mm, densities appear to be constrained by other factors. As another check of consistency, we calculate the spatial (cell-wise) correlation between rainfall and the logarithm of density for the whole of SSA, and then for the two groups separated by the threshold level of 900 mm of rainfall. The results, shown in Table 1, are unambiguous. Log density and rainfall are highly correlated below 900 mm of rainfall (the corresponding coefficient equals .63), and virtually uncorrelated beyond that limit.

A last feature of the conditional distributions worth mentioning is that, as expected, their general pattern is reminiscent of the one found by de Wit and Stankiewicz (2006) in their study of the rainfall-runoff relationship in Africa. Median densities slowly increase from 0.4 below 100 mm of rain to 4.2 for the 300-400 mm class. Then in the band between 400 and 900 mm median, densities increase more rapidly (as a function of rainfall) to reach 18 at 900 mm of rainfall. Beyond 900 mm, the median density does not increase, and even falls in the highest precipitation groups. This close resemblance between the patterns of the two relationships (i.e. rainfall-runoff and rainfall-densities) is observed for all quantiles of the conditional distributions.

In summary, we show that the intuition that ‘more rainfall implies higher density’ is not always true for sub-Saharan Africa. This conclusion, however, does hold in the statistical dominance sense below a threshold value which we locate around 900 mm of precipitation. That is, if one tracks a specific quantile of the distributions of densities conditional on rainfall, the values of that quantile increase with rainfall up to 900 mm. Beyond 900 mm, however, there is virtually no spatial correlation between rainfall and density.

Current water tension

We now turn to defining zones subject to water tension. Given the results presented above, we first consider, as potentially tense, only cells of the grid receiving less than 1,000 mm of rain annually.¹⁸ Above that limit, rain is not considered a binding constraint. Then, for zones receiving less than 1,000 mm of rain, we define as ‘very tense’ all the cells whose density is located in the highest five per cent of the conditional distribution of densities in their rainfall bracket. Cells located between the 80th and 95th percentiles of their conditional distributions are labeled ‘tense’.

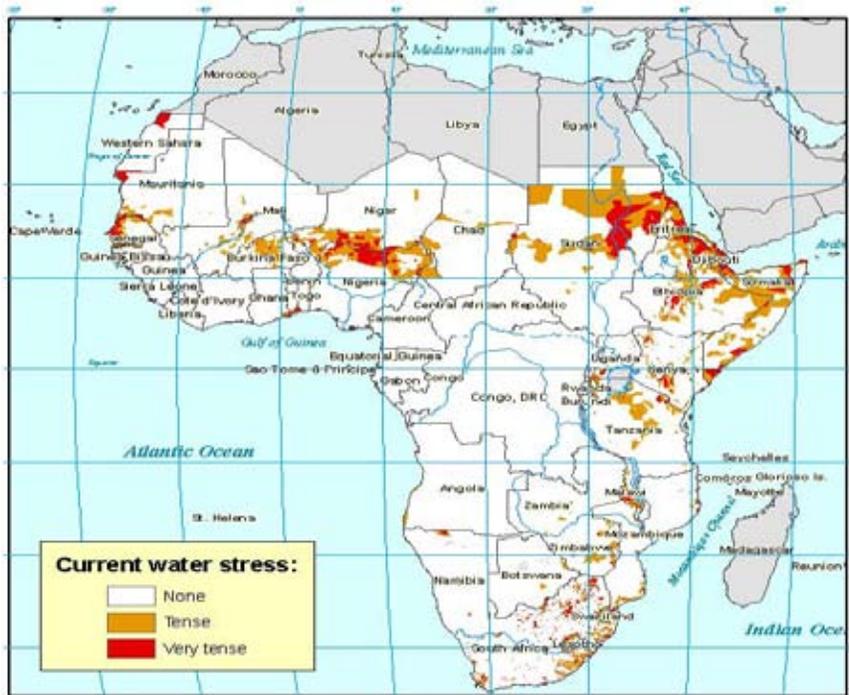
Map 2 illustrates the extent and location of tense and very tense zones as defined above. Three broad areas can be identified. Under strong water stress since the end of the 1970s, East Africa appears to remain the tensest area in Africa. The Southern boundary of the Sahel is also under significant stress. The trans-boundary area between Niger, Nigeria and Chad is particularly affected. A more diffuse zone along the Eastern/Southern coast of the African continent corresponds to a tense area as well. This analysis confirms the results of the literature, such as the continental estimation done by Vörösmarty and others (2005).

The analysis of the current situation reveals that most tense areas are on average highly populated. While the average human density in sub-Saharan Africa is 26 inhabitants per square kilometer (Table 2), it

18 Given the results of the preceding section, we could have chosen 900 mm instead of 1,000 mm as the threshold value for tension zones. We keep 1000 mm to be consistent with other papers, especially de Wit and Stankiewicz (2006). We checked that the main results of the simulations are not affected by this particular choice.

Map 2:

Current tense and very tense zones



Source: Authors' elaboration.

Table 2:

Zonal statistics for tense and very tense areas

	Very tense	Tense	Other	SSA
Average density	159	41	20	26
Standard deviation of densities	555	74	121	156
Share of total surface area (percentage)	3	8	89	100
Share of total population (percentage)	19	14	67	100

Source: Authors' calculations.

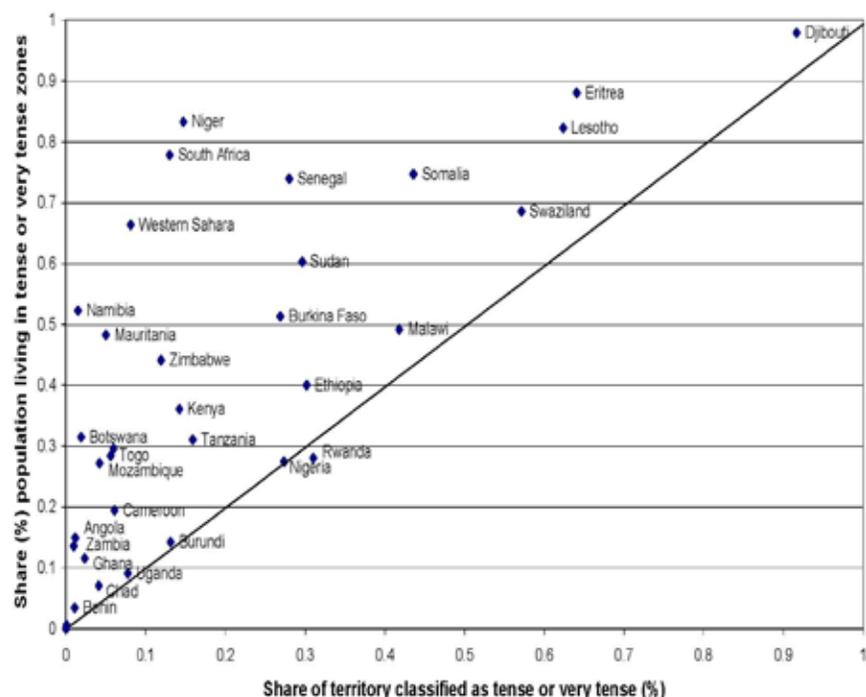
reaches 41 and 159 inhabitants in tense and very tense areas, respectively. Hence, water tension affects only 11 per cent of the sub-Saharan African territory, but roughly one third of the population, i.e. 200 million inhabitants. Focusing the analysis on very tense zones

provides even sharper results, with almost one-fifth of the SSA population living in zones that represent only three per cent of the landmass.

At the national level, water stress levels vary widely. Figure 5 illustrates the point just made that, depending on the concentration of population, countries having a low share of their area classified as tense or very tense can still have large shares of their populations living in those zones. Table 3 proposes a classification of countries into four groups according to these two variables. A first group of countries is not concerned by water stress as defined in this study, as precipitation levels are beyond the threshold of 1000 mm all over those countries. Sierra Leone, Liberia, République Centrafricaine, Côte d'Ivoire and Congo DRC belong to this group.

Another group of countries have limited portions of both their territories and populations affected by water tension. A third group contains countries with less than 15 per cent of their landmass classified as tense or very tense, but a large portion of their populations living in those zones. Mauritania and South Africa belong to this group, with respectively 48 per cent and 77 per cent of their inhabitants living in areas

Figure 5:
Correlation between shares of territory in tense and very tense zones and population living in tense and very tense zones



Source: Authors' elaboration.

Table 3:
Typology of sub-Saharan African countries based on the proportions of territory and population affected by water tension

<i>Countries not affected by water stress</i>	<i>Countries with less than 15% of their landmass classified as tense or very tense</i>		<i>Countries with less than 15% of their landmass and more than 50% of their population affected</i>		<i>Countries with more than 15% of their landmass and 25% of their population affected</i>	
Country	Country	Share of population affected (%)	Country	Share of population affected (%)	Country	Share of population affected (%)
Central African Republic	Zambia	14	Namibia	52	Tanzania	31
Congo	Benin	3	Western Sahara	66	Burkina Faso	51
Cote d'Ivoire	Angola	15	South Africa	78	Nigeria	27
Equatorial Guinea	Botswana	32	Niger	83	Senegal	74
Gabon	Ghana	12	Zimbabwe	44	Sudan	60
Guinea	Chad	7	Mauritania	48	Ethiopia	40
Guinea-Bissau	Mozambique	27			Rwanda	28
Liberia	Togo	28			Malawi	49
Sierra Leone	Mali	30			Somalia	75
Congo DRC	Cameroon	19			Swaziland	69
	Uganda	9			Lesotho	82
	Burundi	14			Eritrea	88
	Kenya	36			Djibouti	98

Source: Authors' calculations.

flagged as tense or very tense despite the limited share of their territory affected. Niger is also representative of this category, as only 15 per cent of its land but 83 per cent of its inhabitants are water constrained. A last group includes countries with large shares of both territory and resident population subject to water tension. In this group, a significant number of countries have the majority of their inhabitants affected. The Horn of Africa, which has experienced dramatic droughts in recent decades, is particularly affected, with the proportion of population affected reaching, respectively, 40 per cent in Ethiopia, 75 per cent in Somalia, 88 per cent in Eritrea and 98 per cent in Djibouti.

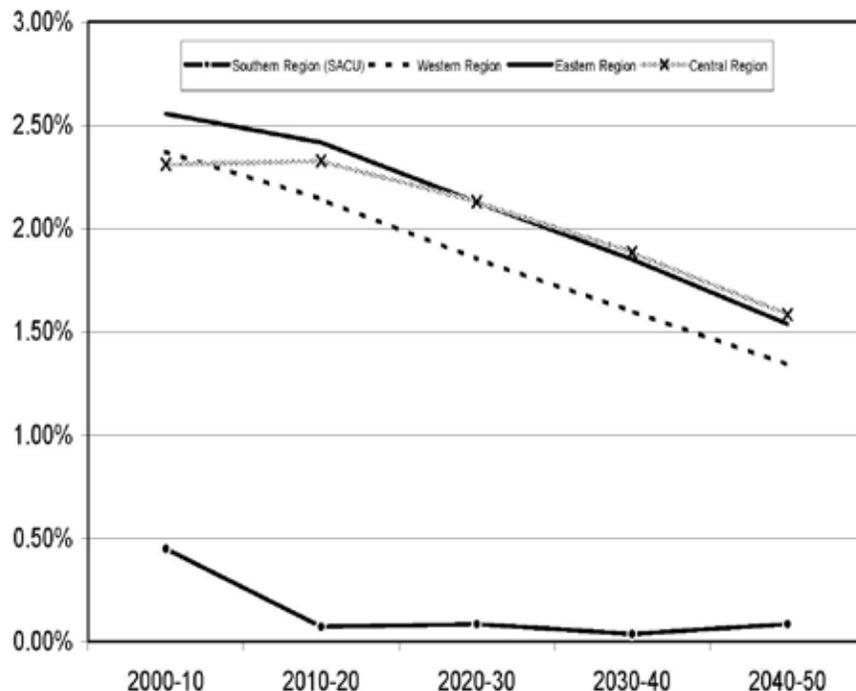
Water Tension in 2050

The impact of population growth

The population of sub-Saharan Africa was estimated at around 650 million in 2000 (UN, 2004). Generally speaking, Africa has registered very high population growth rates in recent decades, compared to all other continents. Rapid population growth is expected to continue, so that sub-Saharan Africa could count as many as 1.6 billion people in 2050. This constitutes the horizon of our study. However, not all sub-regions of Africa are expected to grow at the same pace. As shown by Figure 6, populations in Southern African countries are expected to grow much more slowly than in the rest of sub-Saharan African countries, notably due to the lasting impact of the HIV/AIDS epidemic on the population structure. By limiting the density growth, these differentiated dynamics should impact the evolution of tense zones.

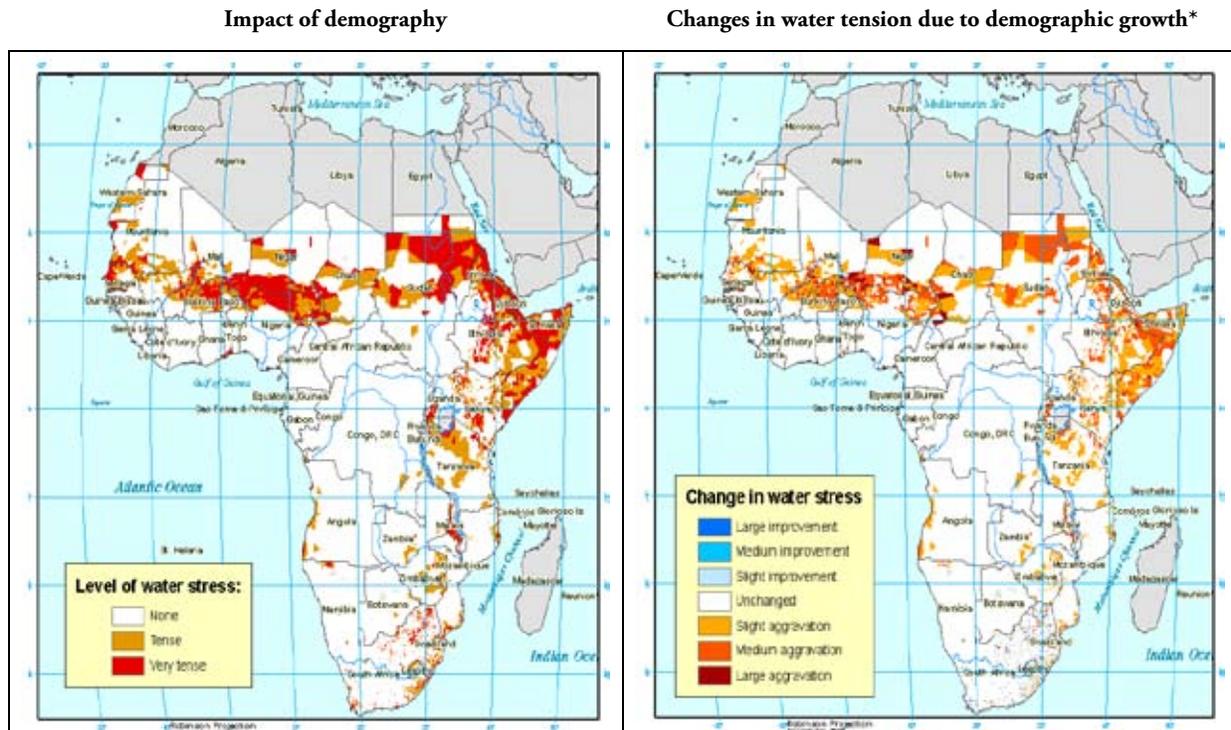
We now present the results of the first part of the simulation, which projects demographic growth to 2050 while keeping average rainfall constant at the level observed today. Projected tense and very tense zones are represented in Map 3. While the spatial pattern of tense zones remains the same, the comparison of

Figure 6:
Projected Average Annual Population Growth Rates at the sub-Regional Level



Source: Authors' elaboration.

Map 3:

Projected tense zones in 2050 due to demographic changes only

Source: Authors' calculations

* Categories represented on the map have been defined in the following way: Large Improvement: the area goes from very tense currently to no tension in the future. Medium Improvement: the area goes down one category in the tension scale from very tense currently to tense in the future. Slight Improvement: the area goes down one category in the tension scale from tense currently to no tension to in the future. The same concepts apply to the aggravation categories.

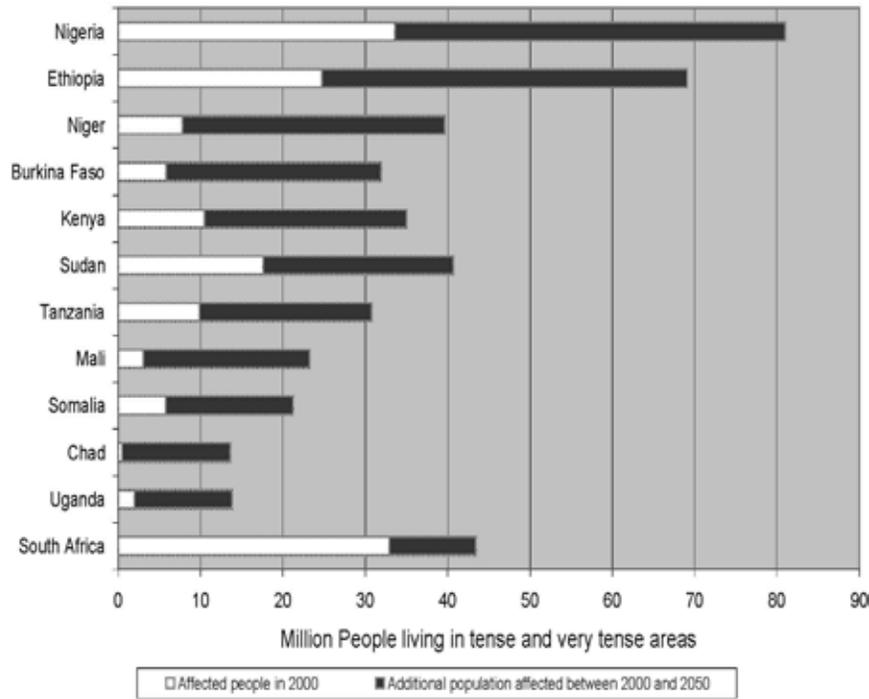
Map 3 with Map 2 reveals that tense and very tense zones are going to expand considerably in the Sahel, as well as in the Horn of Africa. To a lesser degree, the great lakes region is also affected. On the contrary, and as could be expected from much lower population growth rates, Southern Africa is far less affected.

This extension of tense zones combined with explosive growth of the population has dramatic implications for the number of people affected by water tension. At the scale of sub-Saharan Africa, the number of people living in tense and very tense zones should increase from about 200 million currently to 560 million, a 180 per cent increase. The single country registering the largest increase in the number of people affected by water tension would be Nigeria, with an additional 47 million people, followed by Ethiopia, Niger, and Burkina Faso. Figure 7 shows the results of the simulation for the 12 countries registering the largest absolute increases in the number of people affected.

Given the tremendous population growth that will affect most countries in our sample, it is interesting to look not only at absolute numbers, but also at the share of the population that will be affected by water tension. Figure 8 plots countries according to the share of their population living in tense and very tense zones in 2000 and the projected increase in that share between 2000 and 2050. Virtually all countries are located above the x-axis, indicating that a larger part of their population is expected to live in tense zones in the future.

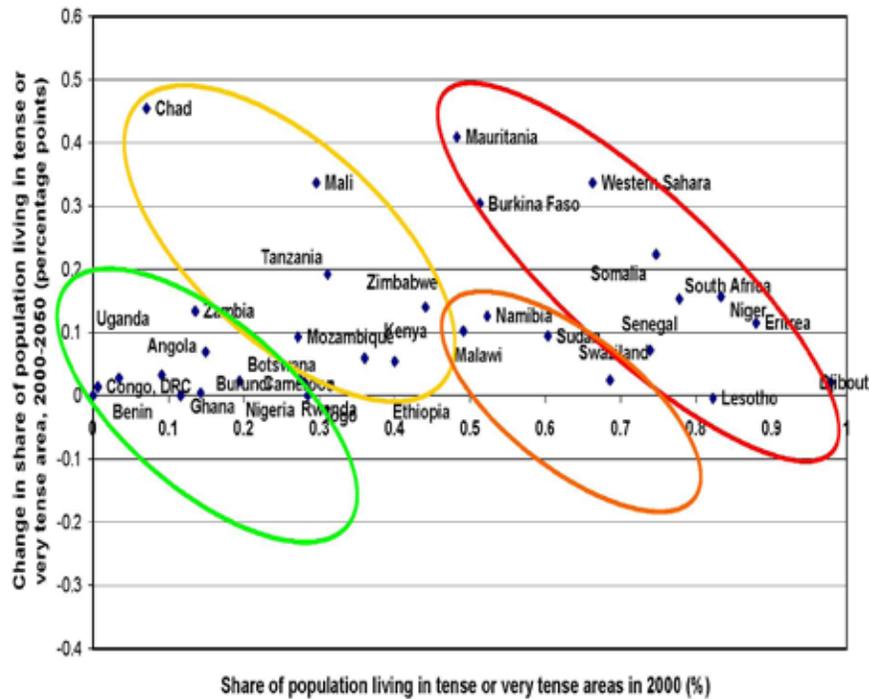
Four groups of countries can be distinguished, depending on the current proportion of the population living in tense zones and on the expected change in that share between 2000 and 2050 (see Figure 8).

Figure 7:
Projected Increase in the Number of People Affected by Water Tension between 2000 and 2050 (selected countries)



Source: Authors' elaboration.

Figure 8:
Correlation between the shares of population living in tense and very tense areas in 2000 and 2050 - Demographic Changes only



Source: Authors' elaboration.

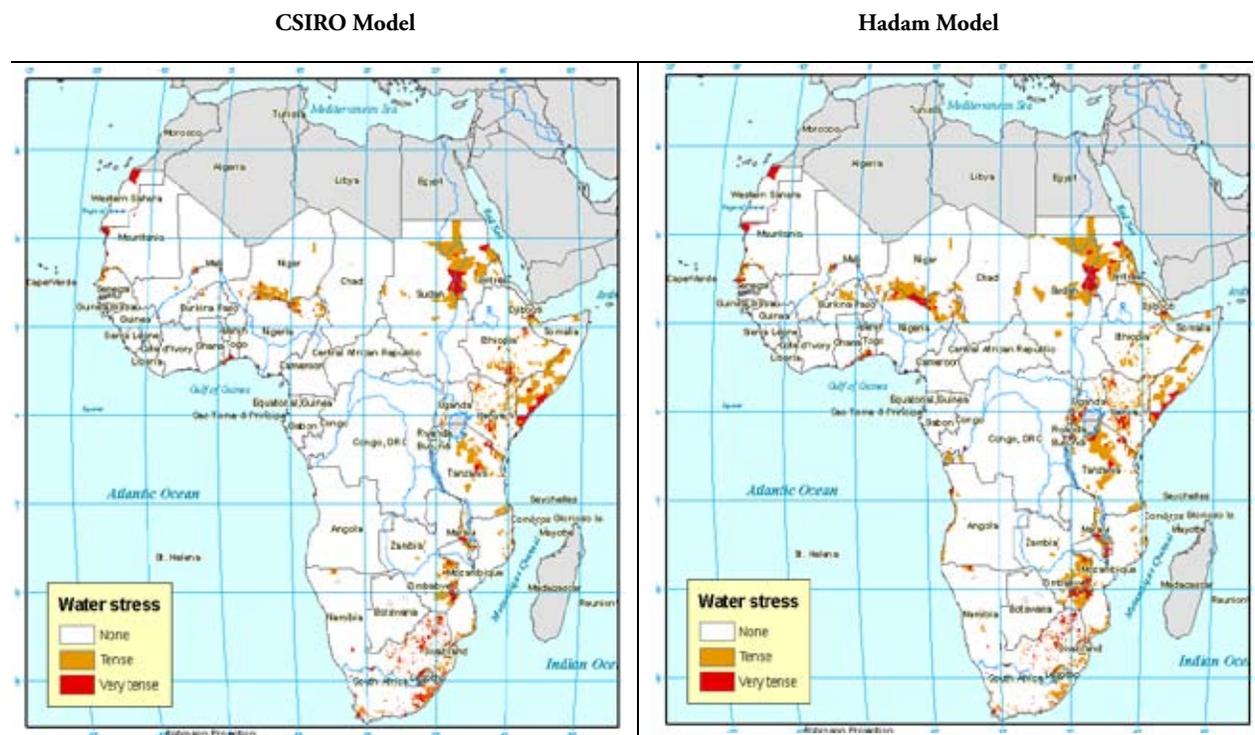
Going from the left to the right of the graph, one finds groups of countries with increasing parts of their populations predicted to live in zones subject to water tension. Countries belonging to the right-most group on the graph already have a very high proportion of their population living in tense or very tense areas, or will see that proportion rise to more than 80 per cent by 2050. This group includes Burkina Faso, Djibouti, Eritrea, Lesotho, Mauritania, Niger, Senegal, Somalia, South Africa, and Western Sahara. The second group from the right gathers four countries, namely Malawi, Namibia, Sudan and Swaziland, whose proportion of population living in tense zones is expected to lie between 50 per cent and 60 per cent. These four countries are expected to incur only moderate demographic pressure. Five countries stand out in that they are predicted to register a more than 30 point rise in that share: Chad, Mali, Mauritania, Burkina Faso, and Western Sahara. Four out of these five countries are bordering the Sahel, confirming that demographic growth will dramatically increase water tension in this sub-region over the next decades.

The consequences of climate change

We now turn to the examination of the impact of changes in rainfall, as predicted by two disaggregated climate models. This subsection aims to highlight the impact on our results of the uncertainty still inherent in existing climate models with respect to projections of future rainfall patterns for Africa. Map 4 shows how tense and very tense zones would evolve, if current rainfall was replaced by rainfall predicted from the CSIRO and Hadley Center models. At the scale of the continent, changes in rainfall are predicted to ease the pressure on water, more so for the CSIRO model. Applying rainfall patterns from the CSIRO model results in a decrease in the number of people affected by water tension from 200 million to 132 million, while the decrease predicted by the Hadley Center model is only half as large, with 168 million people affected. The share of sub-Saharan population living in tense zones would drop from 32 per cent currently to respectively 22 per cent and 28 per cent under the two models.

Map 4:

Tense zones under projected climate for 2050 with current population distribution

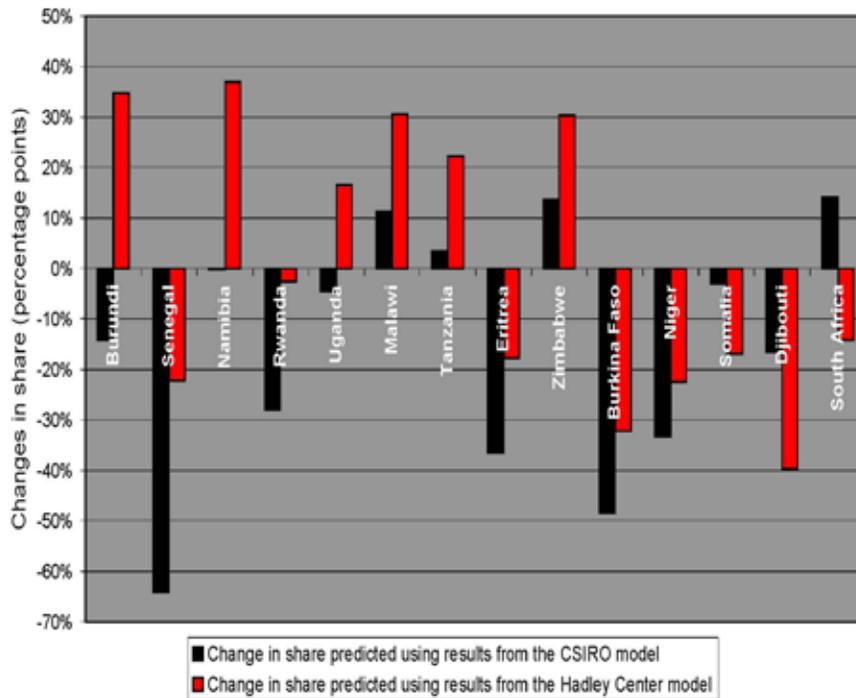


Source: Authors' calculations

Although the two maps look similar, there are important local differences which are visible at the country level. The projected impacts of changes in rainfall on water tension, as measured by the number of people affected, vary both in size and sometimes in sign for the two models (see Appendix one). That is, for some countries, one model predicts favorable effects of rainfall changes, while the other model implies the reverse. Figure 9 illustrates those differing impacts for the countries for which the effects of the CSIRO model are the highest.

Figure 9:

Changes in the share of population living in tense zones predicted by the two disaggregated climate models



Source: Authors' elaboration.

In conclusion, the high variability of predictions of future rainfall patterns across Africa makes predictions based on this variable highly uncertain.

Combined impacts of population growth and climate change

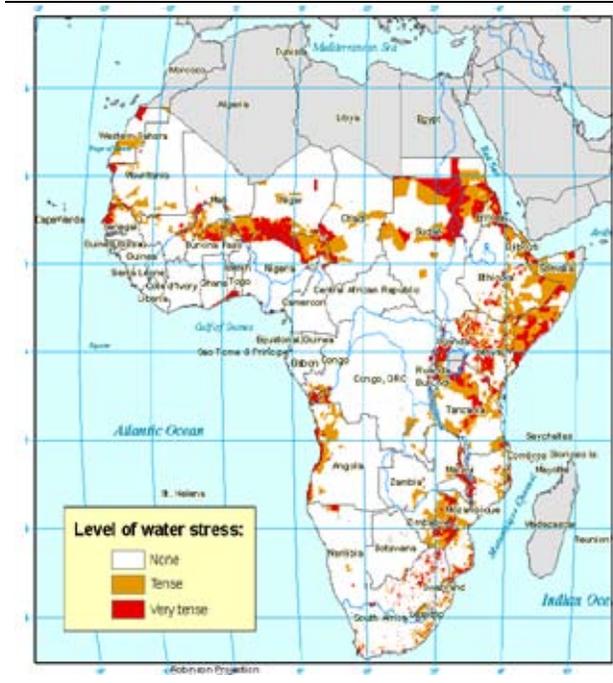
We now turn to the examination of the combined impacts of demographic changes and changes in rainfall. Having illustrated the variability of predicted rainfall changes in the previous section, for the remainder of the paper we use only predicted rainfall from the CSIRO model. The results from this last simulation exercise are shown on Map 5. As a result of climate change, water tension should be somewhat eased in the Sahel, due to predicted increases in average rainfall in that zone. However, this trend must be taken with caution due to the current uncertainties associated with the outcomes of climate change models for sub-Saharan Africa.¹⁹ Regardless of the real climate outcome in the Sahel, the important point is that favorable climate change in the form of more abundant rainfall could only mitigate, not compensate totally, the tremendous increases in population occurring in that zone. In fact, tense and very tense zones, as well as the number of people living in these zones, significantly increase from the baseline figure for 2000 with the global scenario. This is illustrated by Map 6.

¹⁹ As mentioned in section 2, whether Sahel will indeed be wet in the next decades is still a pending issue, subject to heated debates within the scientific community. Let us emphasize again that our purpose is not to take position on this controversial issue, but rather to illustrate the relative impacts of demographic changes and climate variations.

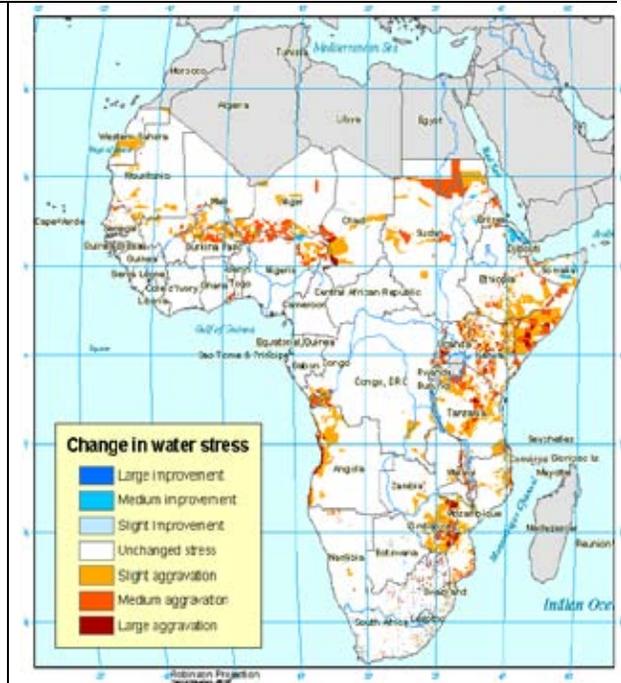
Map 5:

Projected tense zones in 2050

Impact of demography and climate change on water stress in 2050



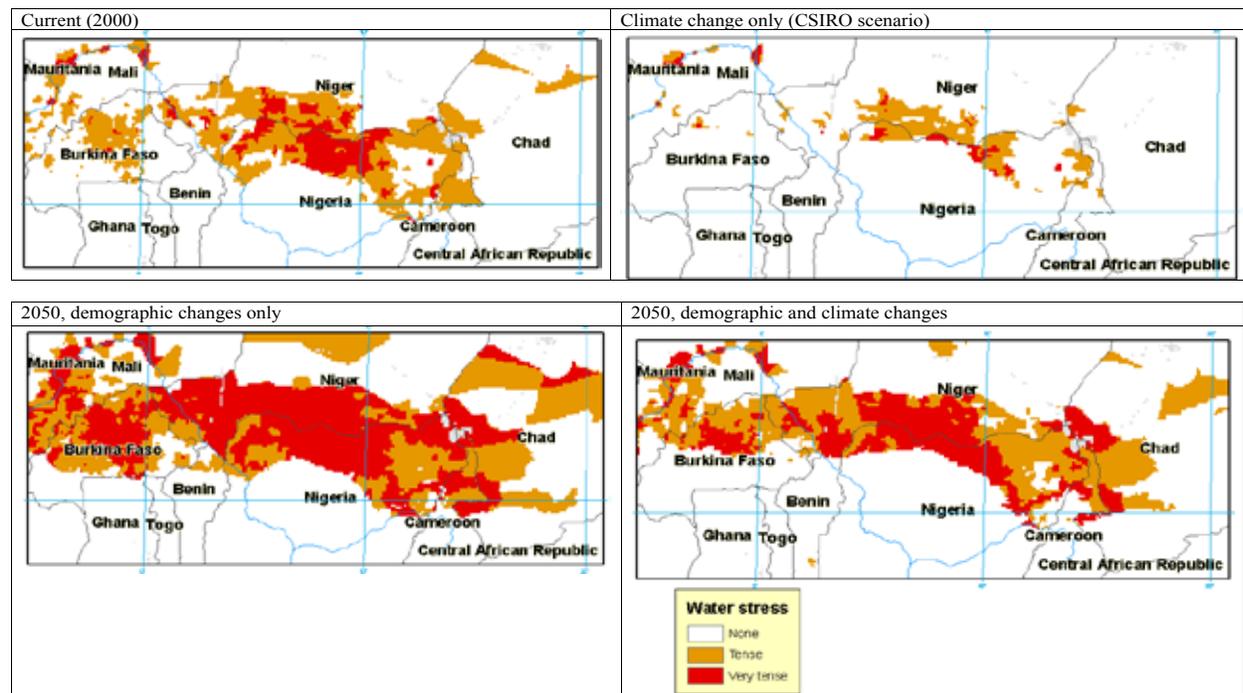
Change in water stress due to demography and climate changes



Source: Authors' calculations

Map 6:

Projected Extension of tense and very tense zones in the Sahel



Source: Authors' calculations

Second, in the Eastern part of Africa, from the Horn of Africa to Mozambique, decreased or stable precipitations generally tend to reinforce the impact of demographic growth in the direction of higher tension. This is especially visible around Lake Victoria, as well as in Malawi, Mozambique, and Zambia. Lastly, compared to the demographic scenario taken in isolation, a new 'patch' of tension appears on the western coast of Africa, corresponding to Angola.

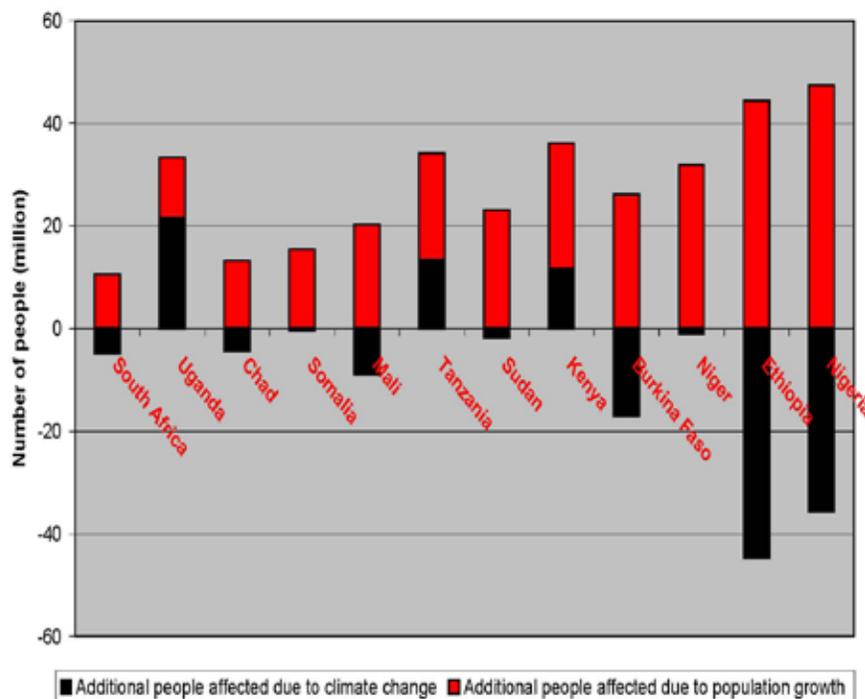
At the continental level, climate changes in the form of changed average rainfalls will affect water tension in sub-Saharan Africa, but these tensions will be mainly driven by increased demographic pressure. The number of affected people changes only marginally when rainfall changes are added to demographic growth, decreasing from 560 to 535 million. However, a more detailed look at the results by country shows that, in some countries, the magnitude of the impacts of changed weather patterns could be at least as important as demographic impacts, as highlighted by figures 10 and 11.

Figure 10 compares the effects of demography and climate on the number of people living in tense zones for the twelve countries represented in Figure 7. The figure clearly shows that the impact of changes in rainfall can be very significant, to the point that it nearly offsets the impact of population growth for some countries, for example Nigeria and Ethiopia. However, for other countries, such as Uganda, Tanzania, and Kenya, overall decreases in rainfall combine with demographic growth to increase water tension.

Figure 11 displays countries according to the strengths of the demographic and climate effects on the change in water tension, measured as the change in the share of population living in tense and very tense areas. Specifically, the demographic effect is calculated as the change in that share resulting from simulating demographic changes to 2050 while keeping rainfall constant. The climate effect is obtained as the difference in the projected share between the complete simulation and the demographics-only simulation.²⁰

Figure 10:

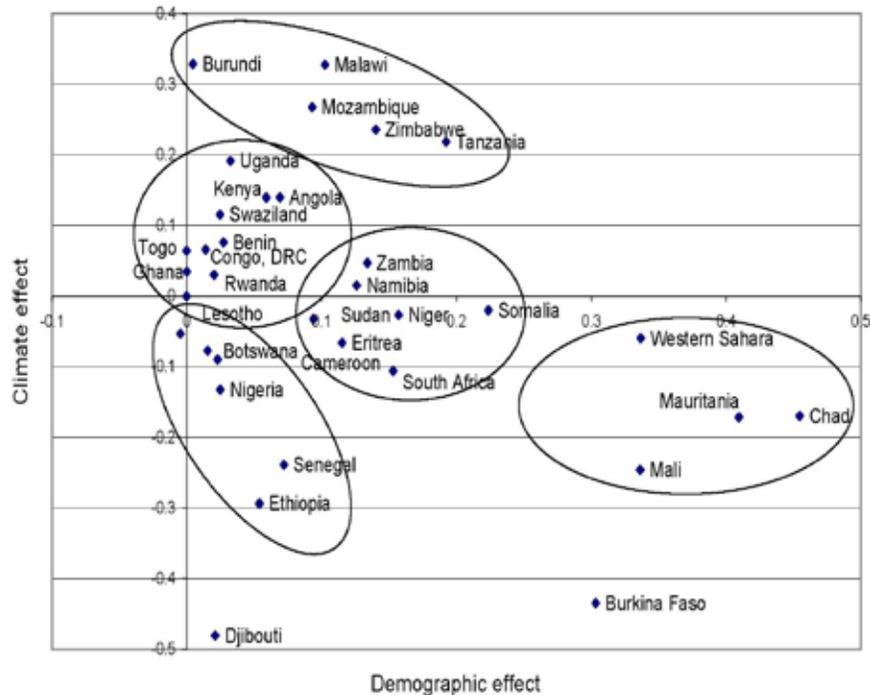
Additional people affected by water tension between 2000 and 2050 (selected countries)



Source: Authors' elaboration.

²⁰ Thus, in this section, the climate effect is measured with respect to population levels for 2050.

Figure 11:
Changes in the share of country population living in tense and very tense areas between 2000 and 2050 : Demographic versus climate effects



Source: Authors' elaboration.

Figure 11 reveals at least five groups of countries with different dynamics that will condition the evolution of water tension. Some countries, including Botswana, Burkina Faso, Cameroon, Djibouti, Ethiopia, Lesotho, Nigeria, and Senegal, are projected to incur decreases in the shares of their populations living in tense zones. Since that does not happen for any country in the demographics-only scenario, this can only result from increased rainfall, at least for some parts of those countries. On the other hand, many countries are projected to experience worse outcomes than would be the case with demographic changes only, meaning that rainfall changes will on average exacerbate the effects of population growth. The most prominently affected countries are Burundi, Malawi, Mozambique, Zimbabwe, and Tanzania.

Apart from the two groups mentioned above, a third group comprising Western Sahara, Chad, Mali and Mauritania, is characterized by the strongest demographic effects, which could be mitigated but not fully compensated by beneficial climate effects. Most of these countries belong to the Sahel belt, confirming once again that the Sahel is likely to become a hotspot for water tension over the next half-century. Another group of countries, comprising Cameroon, Eritrea, Namibia, Niger, Somalia, South Africa, Sudan, and Zambia, will witness substantial increases in the shares of their population living in tense zones (between 10 and 20 percentage points), essentially due to demographic growth. For that group, changes in rainfall will only have small impacts.

Conclusion

This study aimed to quantify current and future water tension in sub-Saharan Africa, based on a direct examination of the spatial relationship existing between rainfall and human density. Specifically, we estimate the empirical distribution of human densities conditional on average rainfall for sub-Saharan Africa. In a second step, we show how projected population changes and changes in average rainfall predicted by climate change models would affect the extent and distribution of zones exposed to water tension across the sub-continent.

We show that below 900 mm of annual rainfall, rainfall and human density are strongly correlated in sub-Saharan Africa. Below that threshold, conditional distributions of densities ‘shift to the right’ as precipitations increase. Beyond the 900 mm threshold however, there is virtually no spatial correlation between density and rainfall. Both features are consistent with the hypothesis that, for zones receiving more than 900 mm, water is not the binding constraint to human settlement.

Our approach identifies zones, which can be called ‘tense’, in the sense that they belong to the right tail of the distribution of densities conditional on rainfall. Some robust conclusions emerge from our analysis. First, demographic growth will cause increased pressures on already tense zones, in particular the Sahel. At the scale of the continent, demographic impacts will by and large drive the extension of water stressed zones. However, changes in rainfall will modulate substantially the demographic impacts, and may have very different implications in different sub-regions, with a somewhat favorable effect predicted for Sahelian Africa, and a negative predicted impact on Eastern Africa. Eastern Africa is likely to see its situation worsen because demographic and climate impacts will play in the same direction towards increasing water stress. At the country level, changes in average rainfall may be more important than population growth in contributing to increased water tension in some countries, such as Burundi, Malawi, Mozambique, Tanzania, and Zimbabwe. However, local effects of changes in rainfall as of 2050 are inherently uncertain, given the high variability of rainfall projections produced by current climate models. Reducing that uncertainty would greatly help progress toward a clearer assessment of the impacts of climate change on water tension.

Our approach, by permitting us to identify zones that run the risk of coming under increased water stress in the next decades, could allow for informed decision making and policy planning, at both the national and international levels. This approach however raises many questions in terms of policy recommendations. In cases of gross imbalances between water supply and demand, one of the two must adjust in the long run. Thus, either supply has to be augmented through technological investments (such as dams, water pipelines, irrigation schemes, as well as changes in crop varieties and agricultural methods), or densities have to adjust downwards by virtue of migrations from tense zones. Although it is clear that investments in water tense zones are costly, migrations also entail costs.²¹ From a public policy perspective, questions deserving attention at the national level include determining the optimal margin between investing in water stressed zones (e.g. in irrigation or water diversion) and facilitating migration from those zones in order to reduce those stresses. Where migration will occur, governments need to consider how best to prepare for increased migration from water-stressed zones (facilitation of migrations; support to migrants coming to cities; etc.). In the case of border regions expected to suffer worsening water stress, the challenge arises of how neighboring governments and the international community can prevent water-related conflicts.

21 Above and beyond the direct monetary and non-monetary costs to the migrants, other costs to society involve costs from rapid and often unplanned urbanization stemming from migrations to cities, for example in terms of additional infrastructure and basic services.

Satisfactorily answering the questions raised in this paper would require knowledge of how populations in water stressed zones adjust to new conditions as well as an understanding of the 'response function' of local populations to increased water scarcity.²² There seems to be a dearth of policy research on these critical issues. Given the forecasted impacts on water scarcity of demographic trends, which have a high degree of inertia and are difficult to deflect, addressing relevant policy questions should be a priority, for both affected countries and the international community.

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22 Among the issues at stake are: how does heterogeneity of the population affect decisions to migrate from affected zones (i.e. who's going to emigrate first)? And, how can externalities (if my neighbor leaves, I'll benefit from it because the pressure will be lowered) be managed optimally?

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Table A1. (continued)

	Initial (2000)						Projected rainfall, CSIRO model						Projected rainfall, HadAm model					
	% Land		Other		% Population		% Land		Other		% Population		% Land		Other		% Population	
	Vtense	Tense	Vtense	Tense	Vtense	Tense	Vtense	Tense	Vtense	Tense	Vtense	Tense	Vtense	Tense	Vtense	Tense	Vtense	Tense
Namibia	1%	1%	98%	31%	21%	48%	0%	1%	99%	23%	29%	48%	1%	1%	98%	68%	21%	11%
Niger	3%	12%	85%	32%	51%	17%	0%	6%	94%	3%	47%	50%	0%	8%	92%	4%	57%	39%
Nigeria	10%	18%	73%	18%	10%	73%	2%	5%	93%	4%	3%	93%	4%	10%	85%	8%	6%	86%
Rwanda	17%	14%	69%	22%	6%	72%	0%	0%	100%	0%	0%	100%	23%	16%	60%	21%	4%	75%
Senegal	10%	18%	72%	55%	19%	26%	1%	5%	94%	3%	7%	90%	4%	7%	89%	41%	11%	48%
Sierra Leone	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%
Somalia	9%	34%	56%	36%	38%	25%	7%	27%	66%	41%	31%	28%	6%	20%	74%	29%	29%	42%
Sudan	8%	21%	70%	39%	21%	40%	3%	12%	85%	27%	21%	52%	3%	16%	80%	29%	25%	46%
Swaziland	1%	57%	43%	2%	67%	31%	1%	53%	46%	2%	63%	35%	1%	65%	35%	2%	72%	26%
Tanzania	1%	15%	84%	4%	27%	69%	3%	14%	83%	13%	22%	66%	4%	23%	73%	16%	37%	47%
The Gambia	0%	52%	48%	0%	31%	69%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%
Togo	3%	2%	94%	18%	10%	72%	3%	2%	95%	25%	2%	72%	3%	6%	91%	18%	8%	74%
Uganda	3%	5%	92%	4%	5%	91%	1%	3%	96%	2%	3%	95%	1%	8%	80%	15%	10%	74%
Western Sahara	8%	0%	92%	65%	1%	34%	7%	0%	93%	68%	0%	32%	7%	0%	93%	64%	0%	36%
Zambia	0%	1%	99%	10%	4%	86%	0%	1%	99%	12%	4%	83%	0%	1%	99%	10%	5%	85%
Zimbabwe	1%	11%	88%	27%	17%	56%	5%	19%	76%	34%	24%	42%	12%	33%	55%	44%	31%	26%
South Africa	6%	7%	87%	58%	20%	22%	7%	7%	85%	81%	11%	8%	5%	7%	88%	50%	13%	36%
Total	3%	8%	89%	19%	14%	68%	2%	5%	93%	15%	8%	78%	2%	7%	91%	16%	12%	72%

Table A2. (continued)

	Initial (2000)						2050, population growth only						2050, population and climate changes					
	% Land			% Pop			% Land			% Pop			% Land			% Pop		
	Vtense	Tense	Other	Vtense	Tense	Other	Vtense	Tense	Other	Vtense	Tense	Other	Vtense	Tense	Other	Vtense	Tense	Other
Namibia	1%	1%	98%	31%	21%	48%	1%	98%	51%	14%	35%	1%	1%	97%	54%	13%	34%	
Niger	3%	12%	85%	32%	51%	17%	22%	13%	65%	94%	5%	1%	12%	13%	76%	77%	19%	
Nigeria	10%	18%	73%	18%	10%	73%	23%	14%	63%	26%	4%	70%	11%	11%	77%	14%	3%	
Rwanda	17%	14%	69%	22%	6%	72%	30%	13%	57%	28%	2%	70%	33%	12%	55%	31%	2%	
Senegal	10%	18%	72%	55%	19%	26%	21%	22%	56%	70%	11%	19%	10%	14%	77%	50%	7%	
Sierra Leone	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%	
Somalia	9%	34%	56%	36%	38%	25%	43%	43%	14%	77%	20%	3%	27%	51%	22%	67%	28%	
Sudan	8%	21%	70%	39%	21%	40%	25%	15%	59%	55%	14%	30%	16%	19%	65%	46%	20%	
Swaziland	1%	57%	43%	2%	67%	31%	1%	58%	42%	2%	69%	29%	1%	64%	35%	10%	72%	
Tanzania	1%	15%	84%	4%	27%	69%	5%	29%	66%	17%	34%	50%	14%	33%	54%	36%	28%	
The Gambia	0%	52%	48%	0%	31%	69%	21%	54%	25%	17%	23%	60%	0%	0%	100%	0%	0%	
Togo	3%	2%	94%	18%	10%	72%	6%	0%	94%	28%	0%	72%	9%	0%	91%	35%	0%	
Uganda	3%	5%	92%	4%	5%	91%	11%	8%	81%	11%	1%	88%	30%	11%	59%	30%	2%	
Western Sahara	8%	0%	92%	65%	1%	34%	7%	27%	66%	68%	32%	0%	7%	27%	66%	63%	32%	
Zambia	0%	1%	99%	10%	4%	86%	0%	5%	95%	15%	12%	73%	0%	6%	93%	15%	17%	
Zimbabwe	1%	11%	88%	27%	17%	56%	1%	23%	76%	28%	30%	42%	19%	37%	43%	50%	31%	
South Africa	6%	7%	87%	58%	20%	22%	6%	7%	87%	80%	13%	7%	6%	7%	88%	71%	17%	
Total	3%	8%	89%	19%	14%	68%	8%	10%	82%	28%	8%	64%	6%	11%	83%	26%	9%	65%

Appendix 2: Details of the computation of detailed rainfall predictions

There are 740 climate stations in the CSAG databases. However, as apparent from Map A1, these stations are not distributed evenly across the African continent. South Africa and Northern Africa (Maghreb) are very densely covered, whereas the whole Zaire, most of Angola, parts of Ethiopia, Somalia and Eritrea, parts of Chad, and the interior of the Sahara desert in general are not or very sparsely covered.

Map A : Spatial distribution of Climate Stations Used for Extrapolating Rainfall

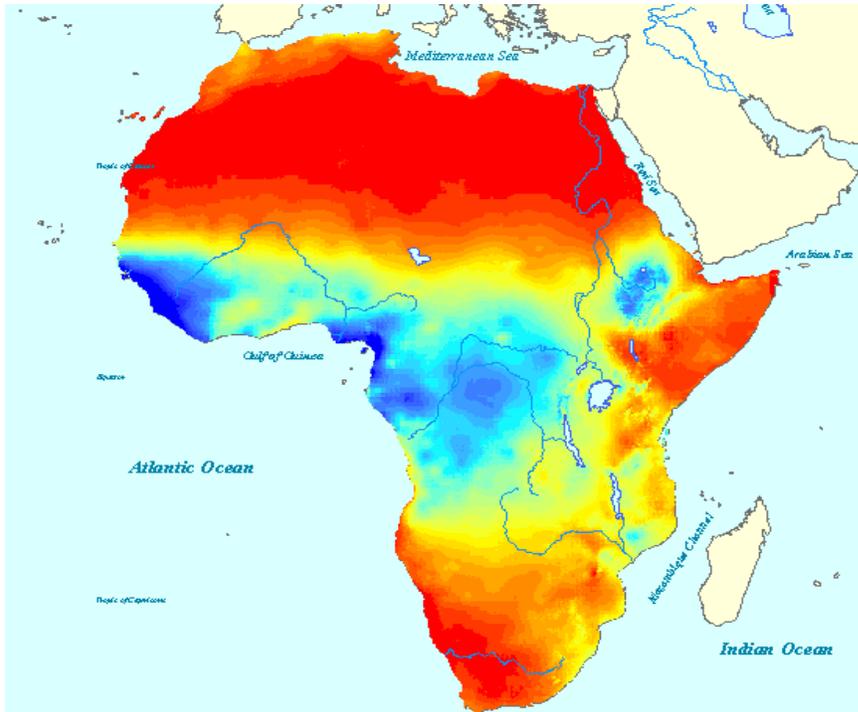


Source: CSAG

This spatially uneven distribution poses a problem for the interpolation of climate variables to all areas of Africa, and dictates our strategy for obtaining rainfall predictions for the different scenarios.¹ We start from the GIS rainfall dataset published by FAO. For each climate scenario considered for the simulations, we use the CSAG data on current and predicted rainfall to calculate predicted changes in average rainfall for each climate station. We then interpolate those changes to the whole continent, and add them cell-wise to current rainfall to produce a predicted rainfall map.

The resulting precipitation patterns predicted for the two models are shown below on Maps A2 and A3. The scales of the maps are the same as that of Map1 in the main text. Both models predict a wetter Sahel. Overall, predictions from the CSIRO model are 'wetter' than those of the Hadley model.

MapA2 Predicted rainfall pattern, CSIRO model



Source: CSAG and authors' calculations

MapA3 Predicted rainfall pattern, Hadley Center model

