Report No: XXXXX-XX

Botswana Climate Variability and Change: Understanding the Risks

Draft Policy Note

Draft - November 2010

Document of the World Bank

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Acknowledgments

World Bank Team: Len Wright, Chas Fant, Alyssa McCluskey, Kenneth Strzepek, (Climate and Civil Systems Research Group, University of Colorado at Boulder), and Jaap Arntzen (Centre for Applied Research, Gaborone, Botswana), Rimma Dankova and Glenn Marie Lange (World Bank) and Jean-Christophe Carret (Task Team Leader, TTL).

The peer reviewers were: Vahid Alavian, Winston Yu, Halla Maher Qaddumi and Jacques Morisset. This work was carried out under the guidance of Idah Pswarayi-Riddihough, Herbert Acquay, Timothy Gilbo and Juan Gaviria.

The discussions with Department of Environmental Affairs, the Botswana government and UNDP-financed ESP program (completed earlier this year), the Ministry of Finance and Development Planning, the Office of the President and World Bank staff engaged in policy and operational dialogue with Botswana relating to management and development of water resources, tourism, energy and macro-economic management are gratefully acknowledged.

Abbreviations

BNWMP	Botswana National Water Master Plan
CMI	Climate Moisture Index
DWA	Department of Water Affairs
FAO	Food and Agriculture Organisation
GCMs	Global Circulation Models
GDP	Gross Domestic Product
GW	Groundwater
IWRM	Integrated Water Resources Management
MCM	Million Cubic Metres
NDP 10	Tenth National Development Plan
NRCS	US Department of Agriculture Natural Resources Conservation Service
ODMP	Okavango Delta Managament Plan
PET	Potential Evapotranspiration
SADC	Southern African Development Community
SCS	Soil Conservation Service
SPI	Standardized Precipitation Index
SRES	Special Report on Emissions Scenarios
SW	Surface water
UH	Unit Hydrograph
WEAP	Water Evaluation And Planning
WUC	Water utilities Corporation
ZIACD	Zambezi Integrated Agro-Commercial Development Project

Executive Summary

In Botswana, physical water scarcity is already a constraint to economic development and growth, in particular for agriculture (irrigation) and mining. Future growth will require much more emphasis on water demand management, including efficient water allocation and use, re-use of wastewater, rainwater harvesting and desalination.

In addition to scarcity, **rainfall is already highly variable**, spatially, inter- and intra-annual. As a semi-arid country, droughts have been common in the past (one in four years is a drought year) but floods have also occurred, though much less frequently. Drought in terms of rainfall deficits are most common in northern Botswana, while extreme droughts based on low rainfall and soil conditions are most common in south western Botswana (the Kalahari Desert). High rainfall events with risks of floods are common in north eastern Botswana where several large dams are located.

The economic costs of climate variability can be very high as recent World Bank assessments in other Southern African countries (Zimbabwe, Zambia, Mozambique and Malawi) have shown and could increase under the effect of climate change (Mozambique). It is therefore important that Botswana develops capacity to lessen the extent of vulnerability of the country's economy from climate variability and change.

As a first step, the **World Bank provided technical assistance in using state-of-the-science Global Circulation Models (GCMs) to forecast how the underlying variability in Botswana may change over the coming decades due to climate change**. Climate variability and associated extremes events (droughts and floods) were characterized using five indicators: the Climate moisture index (CMI), the Standard Precipitation Index (PSI, the)Palmer Drought Severity Index (PDSI), the peak flood analysis and the monthly data analysis. The modeling results show that droughts and storms are expected to increase (in frequency and severity) in western and northern Botswana, while in south-mid eastern Botswana (part of Limpopo basin), precipitation is likely to decrease, but with an increased risk in flooding. There is a definite bias towards increased droughts, and groundwater recharge is likely to decline. Overall, in an area of climate science where considerable uncertainty reigns, there is greater consensus in Botswana among normally highly variable GCMs. **Multiple measures, over multiple temporal scales confirm that greater climatic variability over the coming decades is likely in Botswana**.

Increased climatic variability will have a wide range of direct and indirect economic impacts. **Without adaptation**, increased droughts will adversely affect the subsistence and commercial agricultural sectors. A decrease in groundwater recharge would affect groundwater resources and vegetation, affecting primary and secondary land productivity and ecosystem services. Lower run-off would reduce already low safe yields from dams and adversely affect major tourism attractions such as the Okavango Delta.

Rainfall variability and climate change suggest a need to increase investments in water infrastructure, (e.g. additional storage volume) improve efficiency, and review existing national and sectoral policies to ensure they adequately address climate-related challenges. If precipitation intensities do increase over the next decades**, infrastructure design standards will also have to be adjusted** to maintain current levels of service.

1. Introduction

Background

1. Botswana is one of Africa's nine middle income countries and is among the world's great development success stories. It is one of only very few countries in the world that have been able to secure a long period of high economic growth, underpinned by abundant diamond resources but also political stability, strong democratic traditions, good governance and sound macroeconomic and fiscal policies and management.

2. Despite the strong economic progress over the last forty years, the country still has relatively high levels of poverty and inequality and some low human development indicators, particularly in health. The country suffers from the second highest HIV/AIDS adult prevalence rate in the world. Just over 30 percent of the population lives in poverty (the figure is higher in remote rural areas) and unemployment has been persistently high at approximately 20%. Botswana is identified as one of the countries where the rural poor are particularly marginalized[1]. Traditional agriculture remains an important source of rural livelihoods, yet the contribution of the agricultural sector to GDP decreased from 40% at independence in 1966 to less than 3% in 2003.

3. There is growing recognition at the highest level of the Government that in order to further reduce poverty and inequality, Botswana needs to diversify its economy away from the currently dominating diamond sector. The Tenth National Development Plan (NDP 10) identifies tourism, international financial services, energy, agriculture and manufacturing as the main potential sectors for diversification. However, physical water scarcity and high climate variability (resulting in frequent droughts and floods) compounded by inadequate water resources infrastructure and management- could increasingly undermine Botswana's efforts in achieving its development goals.

4. Seventy-seven percent of Botswana's landmass is occupied by the Kalahari Desert, leaving the country with limited supplies of fresh water. The limited physical water endowments are aggravated by Botswana's arid and semi-arid climate, with low rainfall and high rates of evapotranspiration (ET). Drought is the most frequent natural hazard in Botswana; one in four years being a drought year, although in early 2000 and 2009 record rainfall caused serious flooding. Climate change[2] may exacerbate this rainfall variability and increase temperatures. Climate variability is also likely to have negative effects on the macroeconomic performance of Botswana, as demonstrated for a number of Southern Africa countries in the recent World Bank

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[1] ''EU Strategy For Africa'', European Union report, February 2006.

[2] It is expected that there will be increase in temperature stress on agricultural and natural ecosystems in Western Southern Africa (Namibia, Botswana, and Southern Angola), increasing water shortage and intensification of precipitation events that may increase the magnitude and frequency of flooding: World Bank, *Making Development Climate Resilient For Sub-Saharan Africa*, 2009.

studies[3456]. As such, climate variability and change may impose a significant risk to Botswana's economic development. Therefore, it is important that the country develops its capacity in dealing with present and future climate variability to sustain its growth and attain its poverty reduction goals. In that regard, this note is a first attempt to characterize climate relatedrisks.

Objectives and Scope of the Policy Note

5. The objective of this policy note is to provide insights using state-of-the-science Global Circulation Models (GCMs) into the historic climate variability in Botswana and outline how the underlying variability may change over the coming decades due to climate change. The Note also presents a brief discussion of the vulnerability of Botswana's economy, its water-using sectors and national development plans to the climate-related risks.

6. To examine the climate change trends, a database of Global Circulation Model (GCM) output were used for two time periods to examine 21st century climate in Botswana, 2046-2065 and 2080-2100. Specifically, changes in annual and extreme-event frequencies and magnitudes were quantified based on the latest climatic information derived from GCMs. A survey of 64 GCM scenarios was performed to produce a range of possible future climates, assumed to be equally likely to occur. Five indicators were used to screen this database to select which of the 64 to perform a more detailed analysis: the Climate moisture index (CMI), the Standard Precipitation Index (PSI)Palmer Drought Severity Index (PDSI) the peak flood analysis and the monthly data analysis.

7. The simulation analyses performed for this note are not intended to be a comprehensive examination of the current and future climate conditions in Botswana. However, they are believed to improve the understanding of the climate variability and change in Botswana and generate climate risks knowledge to inform national economic development policy.

2. The water sector in Botswana

Water consumption

8. Water consumption has rapidly increased from 140 Million Cubic Metres (MCM) in 1992 to 170 MCM in 2003. Households and the mining sector accounted for the fastest growth. The increase in household consumption results from population growth, better access to water and improved living standards. Increased water consumption in the mining sector is a result of the expansion of the sector. Despite the stagnation of the crop and livestock sectors, the agricultural

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3 World Bank. Zambia Country Water Resources Assistance Strategy. 2009.
4 World Bank. Economic Vulnerability and Disaster Risk Assessment in Malawi, 2009 (in draft)
5 World Bank, Namibia Post-Disaster Needs Assessment, 2009
6 World Bank, *Economics of Adaptation to Climate Change Study (EACC),* 2009.

sector remains the largest water consumer in Botswana (closely followed by the household sector). Key indicators of water use and supply are presented in Table 1.

Table 1: Water Resources Utilization

Estimated water consumption (2003):	170.3 MCM
Per capita water consumption (2003):	100 m^3 per annum (p.a.)
Large dam storage capacity[7]:	372.6 MCM (will more than double with Dikgathong dam of 400 MCM capacity currently under construction)
Per capita large dam storage capacity per capita (2010):	around 200 m^3 ; safe yield per capita(p.c.) around 40 m^3;
Developed groundwater (GW) capacity:	47.9 MCM p.a.
P.c. GW capacity p.a.	26.6 m^3 p.a.
Total water capacity p.c.	around 225 m^3 based on large dam capacity around 90 m^3 p.c. based on the safe yields.

Source: authors' compilation from the literature.

9. In terms of water service providers, so-called self-providers (i.e. most mines and the livestock and nature-base tourism sector), account for over half of the water consumption (50% in 2003); water service providers (WUC, DWA and the District Councils) provide less than half of total consumption. WUC will take over the water provision for the entire country in the next few years.

Water Supply

10. The construction of new dams has led to a more even use of ground and surface water. In 2003, groundwater provided 55.5% of the national demand for fresh water while rivers and dams provided 5.6 and 39.9% respectively. Secondly, more treated effluent (or 'new' water) is being used (though the resource remains heavily underutilized (10.8% of the inflow was re-used in 2003) and yet it is growing fast[8]). The availability of treated wastewater has rapidly expanded due to improved sanitation and sewerage systems.

11. Generally, the reliability of supply is moderate to good. The reliability is reduced during droughts (when groundwater levels drop and dam inflows are less) and when supply systems are over-stretched (e.g. Maun). Water transfer schemes have improved the reliability of supply.

Table 2: Water characteristics by economic sector

Sector	Sources	Suppliers	Use	Water	Current water constraint

[7] The safe yields are less than twenty percent of the capacity (64 MCM; source: WUC). This excludes dams such as Dikgathong, Thune and Lotsane that are currently under construction

[8] Due to the expansion of sewerage and wastewater treatment works (estimated to be 30 MCM). The policy target is to achieve 96% re-use and recycling of treated wastewater by the year 2030 (2003 National Master Plan for Sanitation and WasteWater).

				dependency	
Crop production	Rainfall & some 1800 ha of irrigation mostly surface water	Farmers	Moderate at present (irrigation)	Crops: very high dep. on rainfall High Irrigation fully dependent on SW & GW	Rainfed crops: water is the key constraint
Livestock production	Mostly groundwater; surface water during wet season	Farmers	High related to national herd	High	One of the major constraints, part. In west & north Low opportunity costs for livestock watering
Mining	Diamonds: GW Copper nickel: SW	Mines & WUC	Moderate to high (locally)	Medium to high (depending on production process)	Major constraint for diamond mining and soda ash (GW mining). In case of diamond mining, huge benefits and low opportunity appear to justify GWM mining
Manufacturing	Urban: SW Rural: mostly GW	WUC			Low in urban areas
Utilities (power, water, communication)	Power: GW Water: SW & GW		Power: medium to high Water: high with UfW Communication: low	Power: medium Water: complete Communication: low	Low to medium (power)
Services, including government	Urban: SW Rural: mostly GW with some SW	WUC and own provision in some rural areas	Moderate but growing	Medium	Low
Tourism	Rural: mostly GW Urban: SW	WUC and own provision	Moderate but growing	Low	Low
Households	Urban: SW Rural: mostly GW	WUC	Medium but rapidly growing	Medium	Local & during drought periods Widespread GW mining

Source: author's compilation from the literature.

12. Sectors depend to different extents on water resources. Table 2 shows the main water characteristics of each sector. Water resources are already a major constraint to the agricultural and mining sectors. Mines are location specific and securing a sufficient water supply is a key part of the design and construction of mining projects. This also applies to power generation. Crop production is rainfall dependent and only a small portion of land is under irrigation (around 1 800 ha; BNWMP2). Crop areas around villages have no developed surface water resources for irrigations. Households and productive areas within urban areas and rural villages normally do not face serious water constraints except during droughts. In urban areas, access to water is universal and in rural settlements access is very high.

13. Tourism is not that vulnerable to water supply constraints, compared to primary and secondary production sectors. For 'production' of tourism services, relatively little water is needed. However, nature tourism is water dependent around the Okavango Delta and Chobe River. Tourism is more vulnerable to power and infrastructure problems—problems that can be managed whereas water supply changes due to climate change are less manageable. This is another factor that makes tourism attractive for economic diversification, relative to agriculture, for example.

Water Demand

14. Water demand is expected to rise fast in future due to new mining projects; some of the mega projects (Morupule B and Mmabula power plants and the Zambezi Integrated Agro-Commercial Development Project) will more than double water consumption[9]. Widespread GW mining will require resting of some of the exhausted well fields and use of alternative supply sources. Higher welfare, population growth and economic growth will further increase water demand unless water efficiency is successfully increased. The above suggest that –even without climate change- water constraints will become more severe and more widespread in future, affecting more and more sectors and areas. This will require much more emphasis on Integrated Water Resources Management (IWRM), Water Demand Management (WDM) and increased water efficiency.

Table 3: Water productivity (value added per m^3 by sector; 1993/94 Pula).

User category	1993	1998	2002	2003
Agriculture	6	6	5	4
Mining	274	257	257	260
Manufacturing	194	219	144	138
Water + electricity	190	357	942	654
Construction[10]	2,294	4,890	2,395	2,468
Trade	1,116	1,800	1,543	1,445
Hotels and restaurants	276	373	334	321
Transport + communication	2,448	3,221	2,441	2,428
Insurance, banking, business	2,421	2,884	2,577	2,666
Social and personal services	382	494	1,247	1,282
Government	236	237	270	271
Grand total	***76***	***91***	***93***	***106***

Sources: DEA and CAR, 2006Historic Climate Variability in Botswana

[9] The ZIACD project requires between 150 - 200 MCM per annum and will depend on water abstraction from the Zambezi/ Chobe River.

[10] The water use in construction is underestimated. The water use data for construction is mostly limited to information about water used by construction company offices in towns, (with a bit from DWA towns), this is why it looks more like the service Sector. The water used on construction sites is often self-provided or from standpipes, or somewhere else, which were not accounted for.

15. Increasing competition for water resources requires careful planning of water allocation and maximizing allocated water efficiency after basic human needs and environmental needs are satisfied. This should be the core of the forthcoming IWRM-Water Efficiency Strategy (2010-2012). Using the indicator of value added/m^3, the Botswana water accounts show great variation in water productivity among sectors. The current allocation of water among sectors does not maximize water productivity (Table 3). Economic diversification through development of the tertiary sector[11] should be promoted and agriculture should increase its water use efficiency, particularly where there are competing higher yielding uses and water efficient agricultural technologies are available.

3. Historic Climate variability in Botswana

Context

16. Botswana's highly variable historical precipitation patterns are well-documented. Classified as arid to semi-arid, the historic average annual rainfall varies from 650mm in northern Botswana to 250 mm in the southwest; while remaining prone to severe droughts and floods alike. Moreover, the bulk of the annual rainfall falls between October and March, when temperatures and evaporation rates are at their highest of the year. Open-water evaporation rates range from 1,900 mm to 2,200 mm per annum (FAO 2009). This results in relatively low annual rates of groundwater recharge and surface runoff, diminishing opportunities for storage. Storms can generally be characterized as local showers and convective thunderstorms (as opposed to large frontal systems), which also results in very high spatial rainfall variability (FAO 2009).

As shown in Figures 1 and 2[12], intra-annual variability as well as inter-annual variability is relatively large in Botswana. Average annual rainfall varies nearly threefold, while average monthly rainfall varies by a similar order of magnitude.

[11] Tourism is not a sector in the national accounts, it is a combination of hotels & restaurants (average water productivity) , transportation (high water productivity), and other services

[12] Climate Research Unit, University of East Anglia data processed by International Research Institute (IRI), Columbia University for The World Bank, Africa Water Resources in a Changing World, 2010.

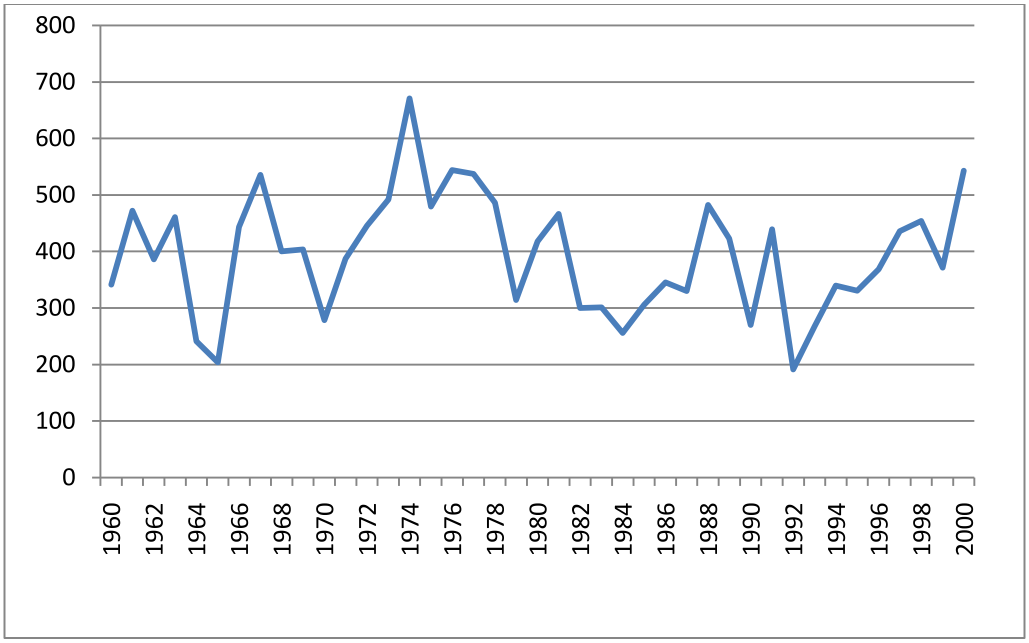


Figure 1. Inter-annual precipitation variability (mm)

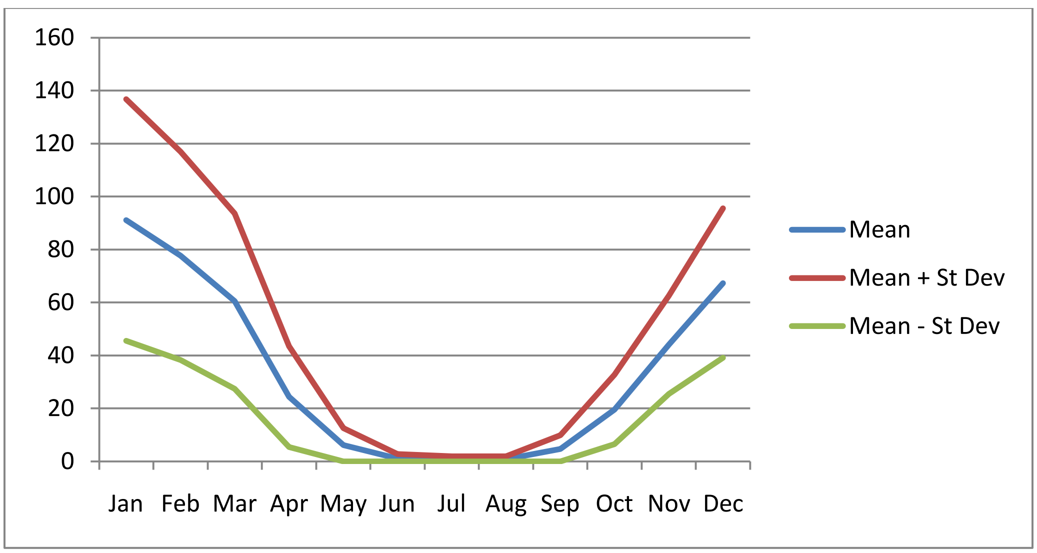


Figure 2. Intra-annual and precipitation variability (mm)

17. In Botswana, recent and long history shows that the Climate is dramatically variable experienced in Botswana. This variability further is characterize below with a specific indicator.

Analysis of Historic Variability

18. To evaluate historic climate variability in Botswana (and later, as described in section 4, to screen and evaluate 22 Global Circulation Models –GCM- output), the *Climate Moisture Index* (CMI) is used. The CMI is described below in box 1.

Box 1 Climate Moisture Index (CMI)

The Climate Moisture Index (CMI), is an indicator of the aridity of a region that defines dry, middle and wet scenarios out of the full spread of model projections. The CMI depends on average annual precipitation (P) and average annual potential evapotranspiration (PET). If PET is greater than precipitation, the climate is considered to be dry whereas if precipitation is greater than PET, the climate is moist. Calculated as CMI = (P/PET)-1 {when PET>P} and CMI = 1-(PET/P) {when P>PET}, a CMI of –1 is very arid and a CMI of +1 is very humid. As a ratio of two depth measurements, CMI is

19. All 22 GCM and the historical scenarios were analyzed based on their CMI to identify the dry and wet scenarios for Botswana. A wet scenario is indicated by the largest positive change in CMI (i.e. largest absolute increase in wetness); a dry scenario is indicated by the largest negative change in CMI (i.e largest absolute decrease in wetness). The advantage of this approach is that it provides a representation of the full range of available scenarios in a 'manageable' way. Historical CMI-data presented in Figure 3 demonstrates a well known, fact, that Botswana is arid and that Potential Evapotranspiration (PET) typically greatly outweighs precipitation on an annual basis. Typically, annual CMi ranges between -0.6 - -0.9.

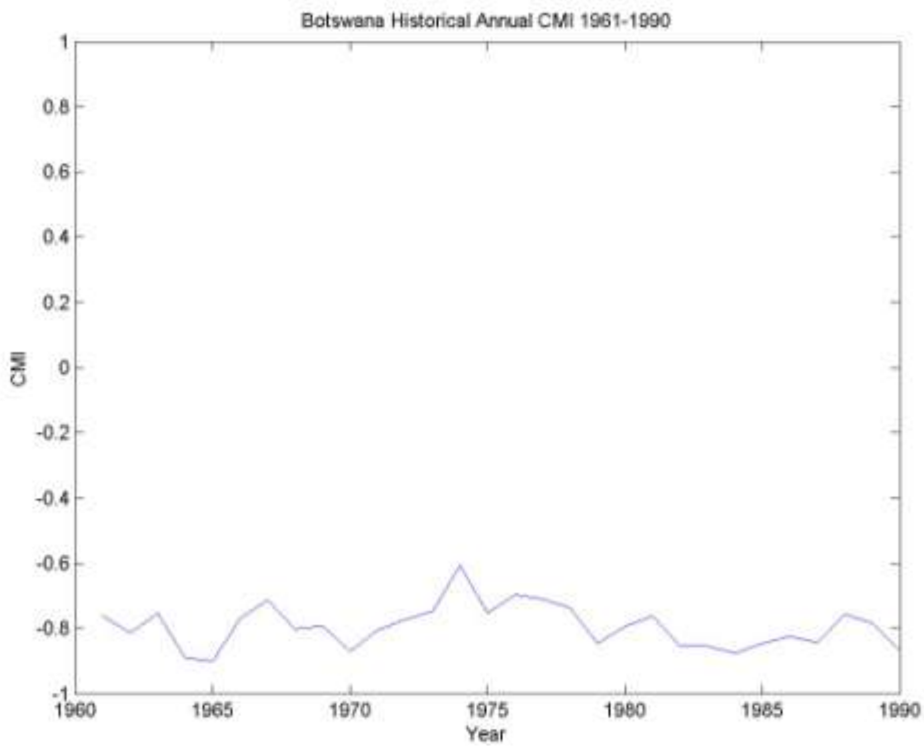


Figure 3. Annual CMI value for Botswana, 1961-1990

20. A graph of the frequency of the annual CMI from 1961-1990 in shown in Figure 4. This graph also highlights the extreme arid nature of Botswana's climate.

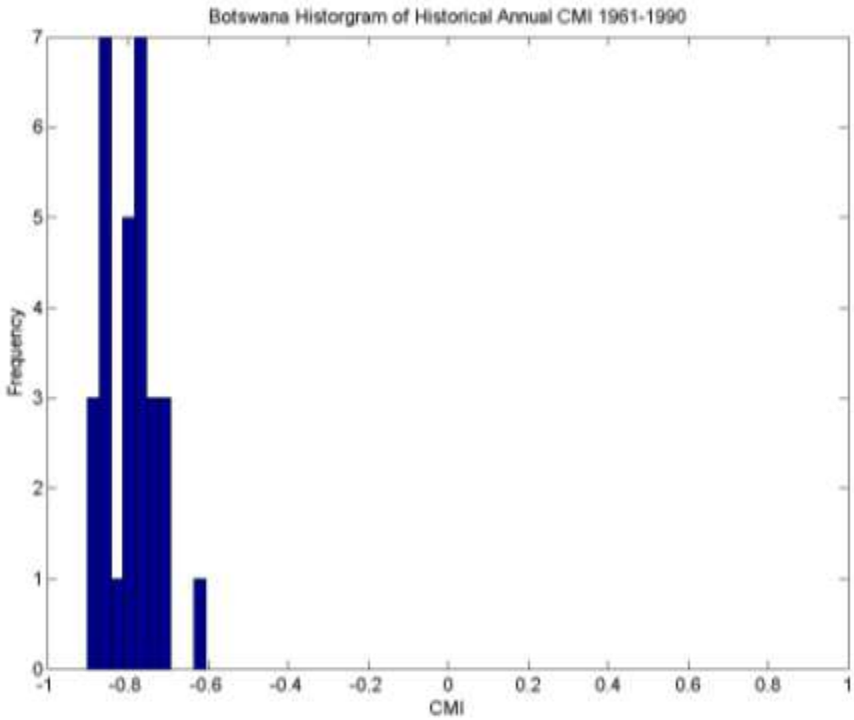


Figure 4. Frequency of historic CMI values, Botswana, 1961-1990

21. CMI is not however a direct measure of either droughts or floods. Drought conditions and record breaking flood events have struck Botswana over the past several years.

22. In 2005 drought diminished agricultural planted area to 72 500 hectares, or only 25% of cultivable land in Botswana (SARPN 2005). Gaborone's main water supply reservoir was down to nearly 20% of its capacity during the drought of 2005, representing approximately 4 months of supply to the capital city.

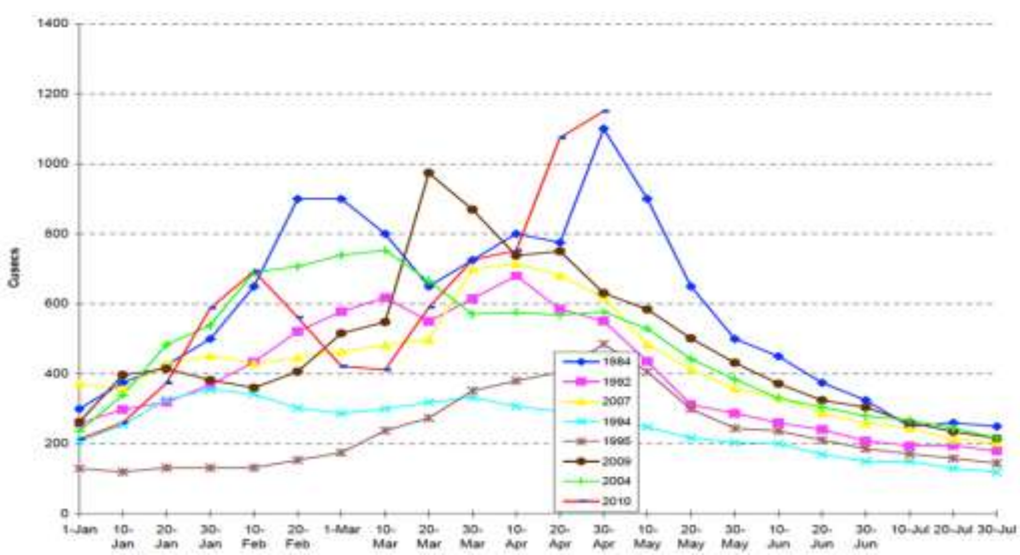


Figure 5. Flow rate (cubic meters per second) on the Okavango near Mohembo (www.eyesonafrica.com, 2010).

23. Flooding on the Okavango occurred in 2009, and those flows have been exceeded during the 2010 annual flood when villagers were displaced. Recorded flow rates at Mohembo, where the Okavango enters Botswana, are shown in Figure 5.

24. Moreover, in March 2009, flash floods struck in the Ngamiland District at the beginning part of the Okavango Delta in the extreme Northwest part of Botswana, near Namibia and Angola. In June 2009, heavy rains flooded seven districts (Serowe/Palapye, Kweneng, Tutume, Boteti, North West, Mahalapye and Bobirwa) in central Botswana and displaced over 4,000 inhabitants when their mud dwellings collapsed in the heavy rains (DREF 2009). These rains were particularly unusual because they came in June, traditionally a dry month. The 24-hour peak rainfall in this area was estimated to exceed 100mm by the Southern African Remote Sensing Unit (DREF 2009).

25. More specific indicators of these extreme hydrologic phenomena are presented below.

Analysis of Historic Droughts

26. Droughts may be indicated in a time series of precipitation and temperature by several statistical indicators (IEc, Strzepek, and Yohe, 2009). Two of them are used in this note to analyze the historical record in Botswana: the *Standardized Precipitation Index* (SPI), and the *Palmer Drought Severity index* (PDSI). The difference between them is the time window of each drought threshold. The SPI must have “consecutive” months below a threshold to record a drought. Therefore severe droughts that have sporadic moist months "break-up" the drought sequence. On the other hand PDSI counts all the months below some threshold, plus the threshold is a result of a more complete picture of the hydrologic factors that influence agriculture. See table 4 below comparing the two indexes.

Table 4: Comparison of the 2 droughts indexes

Characteristics	Standardized Precipitation Index (SPI)	Palmer Drought Severity Index (The Palmer; PDSI)
Overview:	The SPI is an index based on the probability of precipitation for any time scale.	The Palmer is a soil moisture algorithm calibrated for relatively homogeneous regions.
Who uses it:	Many drought planners appreciate the SPI’s versatility.	Many U.S. government agencies and states rely on the Palmer to trigger drought relief programs.
Pros:	The SPI can be computed for different time scales, can provide early warning of drought and help assess drought severity, and is less complex than the Palmer.	The first comprehensive drought index developed in the United States, and has been used for drought estimation world-wide.
Cons:	Values based on preliminary data may change	Palmer values may lag emerging droughts by several months; less well suited for mountainous land or areas of frequent climatic extremes; complex—has an unspecified, built-in time scale that can be misleading.
Developed by	T.B. McKee, N.J. Doesken, and J. Kleist, Colorado State University, 1993.	W.C. Palmer, 1965.

27. The SPI (Box 2) is a probability index that measures drought based on the degree to which precipitation in a given time period (e.g., one-month, six-month, two-year) and geographic area (e.g., county, watershed, state) diverges from the historical median. An SPI of zero indicates rainfall is at the median value, where half of historical precipitation is above the value and half is below. The index was first introduced by McKee et al. in 1993, and has since been used widely (e.g., see NOAA, 2009).

28. Given its focus on precipitation, SPI-droughts are most relevant for rainfall-dependent activities such as rainfed agriculture or municipal supply in certain regions. Runoff, evapotranspiration, and water storage in reservoirs are not considered in calculation of the SPI. SPI-5 and SPI-12 droughts occur when the one-month SPI value for an area remains below statistically defined SPI thresholds for longer than 5 (SPI-5) and 12 (SPI-12) months, respectively.

Box 2. Standardized Precipitation Index Calculation (SPI-5 and SPI-12)

First, 12 monthly gamma probability density functions (PDF) are generated for each of the 12 months in the dataset. The Gamma PDF is known to approximate rainfall (Thom 1951, 1966). Second, these 12 probability density functions to develop 12 cumulative density functions (CDFs), which are transformed to accommodate any zero precipitation values in the dataset. Third, this new CDF is transformed into a standard normal distribution (*i.e.*, with median zero and standard deviation of one). The SPI value for any one month during the period is simply its position on the standard normal distribution for that month. SPI ranges are defined as:

2.0+	**extremely wet**
1.5 to 1.99	very wet
1.0 to 1.49	moderately wet
-.99 to .99	near normal
-1.0 to -1.49	moderately dry
-1.5 to -1.99	severely dry
-2 and less	extremely dry

SPI-5 and SPI-12 droughts occur when the one-month SPI value for an area remains below given SPI thresholds (-1.81 and -1.42 for SPI-5 and SPI-12) for five or more and 12 or more months, respectively. For example, if the SPI for November through March remains below -1.81 but then rises above -1.42 in April, an SPI-5 drought occurred but not an SPI-12 drought. On the other hand, if the SPI from March through February (i.e., one full year) remains below -1.42 but greater than -1.81, an SPI-12 drought is recorded but not an SPI-5 drought. The SPI-5 and SPI-12 drought month counts are the number of months falling into the five- and 12-month droughts. For instance, if an SPI-5 drought lasted from May to November, it would count for seven “SPI-5 drought months” (IeC, Strzepek, and Yohe, 2009).

29. Spatial patterns depicted in Figure 7 and Figure 8 demonstrate that multi-year droughts are present in the 1961-1990 historical record both for the more severe 5-month threshold (SPI <-1.81) as well as the less severe 12 month threshold (-1.81 < SPI < -1.42).

30. Figure 7 shows the historical drought month count according to the SPI-5 method. This method only counts drought months that contain at least 5 consecutive, 'severe' (SPI less than -1.81) months of drought. Similarly, Figure 8 shows the historical drought month count according to the SPI-12 method. In this method, periods that contain 12 or more months with

an SPI less than -1.42 were counted. SPI-5 represents drought spells that were more severe but shorter, while SPI-12 represents drought spells that were slightly less severe than SPI-5, but lasted at least 7 months longer (12 months total). SPI-12 and SPI-5 are calculated separately, so if a drought spell qualifies for both SPI-12 and SPI-5, it was counted for both indicators.

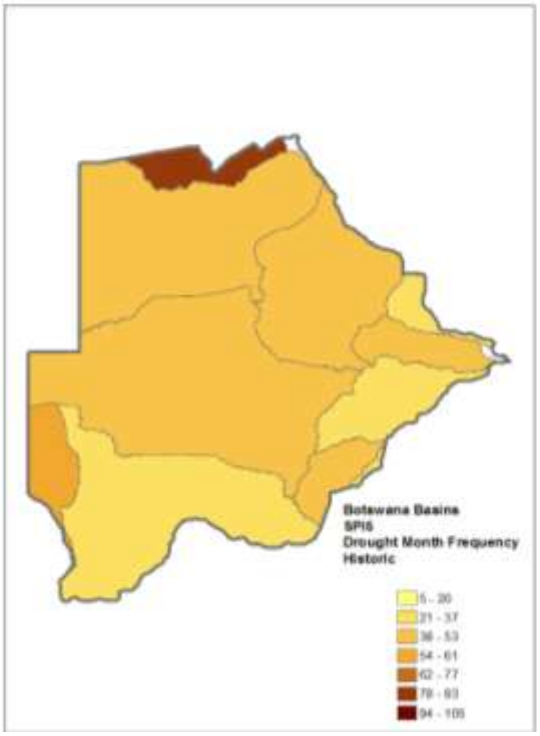


Figure 6. 5 Month Standardized Precipitation Index (SPI), Botswana 1961-1990 rainfall record (360 months); Mitchel and Jones 2005)

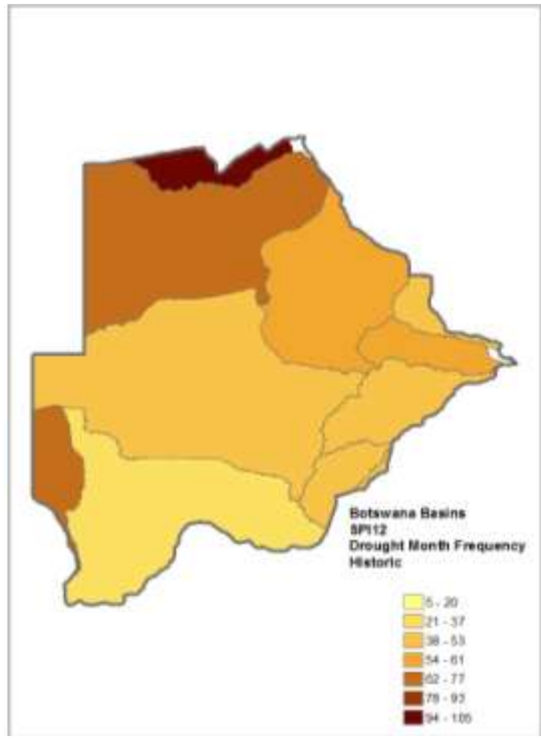


Figure 7. 12 Month Standardized Precipitation Index (SPI), Botswana 1961-1990 rainfall record (360 months); (Mitchel and Jones 2005)

31. The two maps of the SPI calculations (Figures 7 and 8) both show that there is more drought in the north, between 94 and 105 months droughts out of 360, compared to any other regions in Botswana.

Analysis of Droughts: Palmer Drought Severity Index

32. Unlike SPI, the Palmer Drought Severity index (PDSI) (Palmer 1965, 1968) is a drought indicator that uses soil characteristics, precipitation, and potential evapotranspiration (based on temperature) data in a formula to determine the water balance of a particular region (see box 3). PDSI is generally calculated on a monthly time scale, and considers the meteorological conditions of both the current month and those of past months, accommodating the cumulative nature of drought (NOAA 2010).

Box 3. Palmer Drought Severity Index (PDSI) Calculation

Step 1: Generate potential evapotranspiration data. First ,GCM output is transformed into monthly potential evapotranspiration data using the Modified Hargreaves Method (Droogers and Allen 2002).
Step 2: Generate PDSI values. Next, these potential evapotranspiration data are used to calculate PDSI values, following procedures outlined by Palmer (1965, 1968). PDSI values for "normal" months are zero, drier months are less than zero, and wetter months are greater than zero.
Step 3: Assign PDSI drought severity levels. Finally, four subsets of these monthly PDSI values are used that correspond to drought severity levels. Values from -1 to greater than -2 are mild droughts; -2 to greater than -3 are moderate droughts; -3 to greater than -4 are severe droughts; and -4 or lower are extreme droughts.
The result is that some fraction of the 360 months in each 30-year period falls into one of these four categories

33. Figure 9 shows the PDSI Severe drought, which is the number of drought months that result in a PDSI between -3 and -4. Figure 10 shows the PDSI Extreme drought, which is the number of drought months with a PDSI value less than -4. So, as defined, months that qualify as PDSI Extreme, do not count toward PDSI Severe and vice versa. These figures indicate that more extreme drought has occurred in the south of Botswana, while moderate drought has had a higher frequency elsewhere in Botswana.

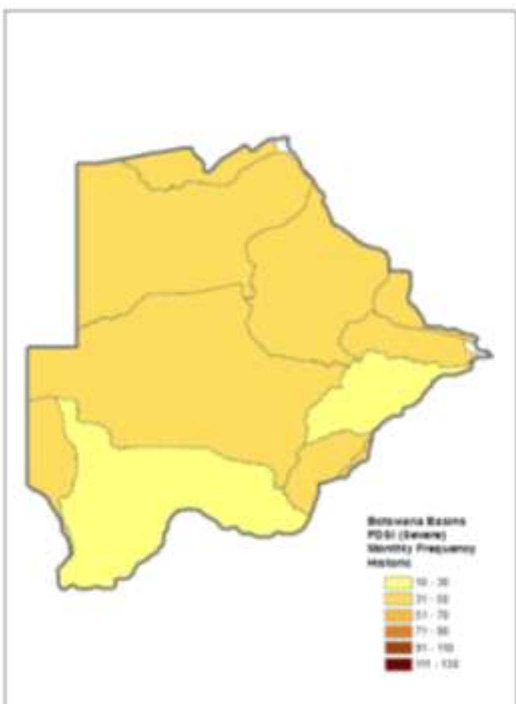


Figure 8. PDSI Severe Monthly Frequency, Historic (1960-1990 or 360 months).

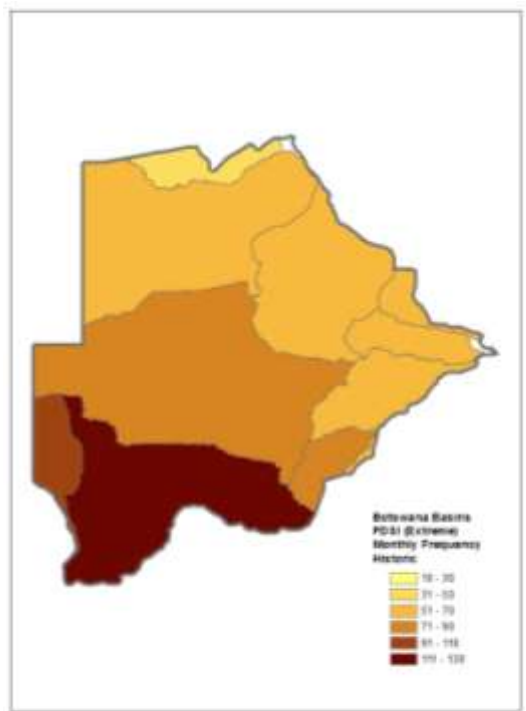


Figure 9. PDSI Extreme Monthly Frequency, Historic (1960-1990 or 360 months).

34. Comparing PSI and PDSI seems indeed to suggest that the drought in the north is more severe but shorter (generally less than 5 months), while the drought in the south generally lasts longer (at least 5 months), but is less severe. Also, SPI is better used as a "change" in expected drought, rather than showing historical results, because it detects the deviation from the

median precipitation of each basin. For example, the basins in the Kalahari Desert (in south western Botswana) show fewer droughts according to SPI because the median precipitation amount is already quite low. In the map of the PDSI Extreme (Figure 9), on the other hand, South Western Botswana shows a very high count of drought months.

Analysis of Historic Floods

35. Floods are more difficult to discern from a historical precipitation record because flooding represents an extreme response to a complex set of watershed processes, only one of which is precipitation. Two flood-related evaluations were made for this analysis, both of which were estimates of the change in flow from the historic; therefore a direct estimate of flooding in the historic record was not made. The results of these estimates are presented below in Section 4 that deals with future climate change and its impact on droughts and floods. In this note, relative future changes in precipitation and flow from the historic record were estimated, and flooding was not directly estimated from the historic record.

36. However a statistical analysis was completed based solely on the historic daily precipitation record. This analysis shows the precipitation depth for various "design storms" with various return periods, or average frequencies, over 24-hour duration. These storms are commonly used in engineering and water resource evaluations to provide a consistent basis to estimate required capacity in the context of a particular level of performance (e.g. hydraulic flood protection up to the 20-year event).

37. The historic precipitation record was used to fit an extreme value hydrologic probability density function, in this case a Gumbel distribution. This distribution is commonly used in hydrology to estimate extreme events. The storm event depths with specific return periods are obtained from the distribution (e.g. 2 year, 5 year event, etc). "Return period" is defined as the average period that any particular depth is equaled or exceeded over a lengthy period of record. The rainfall depth evaluated as a "20 year event" means that on average, that rainfall depth is equaled or exceeded every 20 years in a long-term record.

Figure 10. Historic 24 hour precipitation depths for the 20 year event based on the Gumbel distribution.

38. The depths for each 0.5 degree x 0.5 degree grid cell in Botswana and neighboring tributary lands are shown below in Figure 10 for the 20 year return period. For this design storm, the 24-hour design rainfall depths range from cells in the 10-20 mm bin to cells in the 71-80 mm bin. Individual cell values are calculated more precisely than they are depicted on the map, however, bins are used for graphical presentation. The depths depicted in Figure 10 were used to compare to depths taken from GCM data, and then also fit to a Gumbel distribution.

39. The results of the extreme precipitation analysis demonstrate the spatial distribution and severity of potential flood events for the 20 year return period. The North- East of the country has had relatively more severe rain events; however, this may not necessarily translate directly to flood events. The depth indicator looks at a relative change in peak flow for a particular frequency – not whether that frequency is a damage-inducing type flood.

40. The following conclusions are drawn from the historical analysis. The CMI confirms that Botswana is arid or semi-arid. Droughts in terms of rainfall deficits (SPI) are most common in northern Botswana, indicating that this area may be most affected by on-going climate change. Extreme droughts based on low rainfall and soil conditions are most common in south western Botswana (PDSI). High rainfall events with risks of floods are most likely in north eastern Botswana. Several large dams are located in this area. Overall, droughts have been more common than floods.

4. Climate Change: Adding to the Risks

41. As shown in section 1, the future development of the country depends heavily on water availability. Both insufficient rainfall (droughts) and too much rainfall (floods) will therefore have significant impacts on development. In this note, the impacts of climate change on droughts and floods in Botswana are examined based on climate scenarios.

Climate Scenarios (GCM and SRES)

42. A Global Circulation Model (GCM) is a mathematical model (using computers) of the planetary atmosphere or ocean that calculates and predicts what climate patterns will look like in a number of years. The GCM programs look at several equations at once that are the basis for complex computer programs. They take into account conservation of mass, energy, momentum in a spatialized grid box system. The model focuses on each grid box and the transfer of energy between grid boxes. Once calculated a number of climate patterns can be determined: from ocean and wind currents to patterns in precipitation and evaporation rates that could affect lake-levels and agricultural levels. A list of the GCMs from various institutions is provided in annex 2.

43. Special Reports on Emissions Scenarios (SRES) are emissions scenarios "story-lines" that account for a range of possible future greenhouse gas emissions. SRES scenarios are based on assumptions about population growth, economic development, technological advances, policies on interdependency, and commitment to environmental protection. There are a total of 4 SRES scenarios. These scenarios are organized into the following four 'scenario families'. **A1** assumes

a world of rapid economic growth with the most growth in developing countries (includes three technology scenarios A1F1, A1T, and A1B). **A2** assumes very high population growth and slower economic growth and technological development. **B1** assumes the same population levels as A1, but with more clean technologies (lowest CO_2 emissions of the group). **B2** assumes intermediate levels of economic growth, and less rapid technological development than A1 and B1. Various SRES scenarios are compared below in Figure 11.

44. The GCMs and SRES are combined to create 56 climate change scenarios. Each of these scenarios is considered equally plausible. Ideally one should evaluate the impacts from each climate scenario. Unfortunately this is too costly for most detailed modeling analyses. The question then becomes how to choose which scenario(s) to evaluate. The next section describes the process for this policy note.

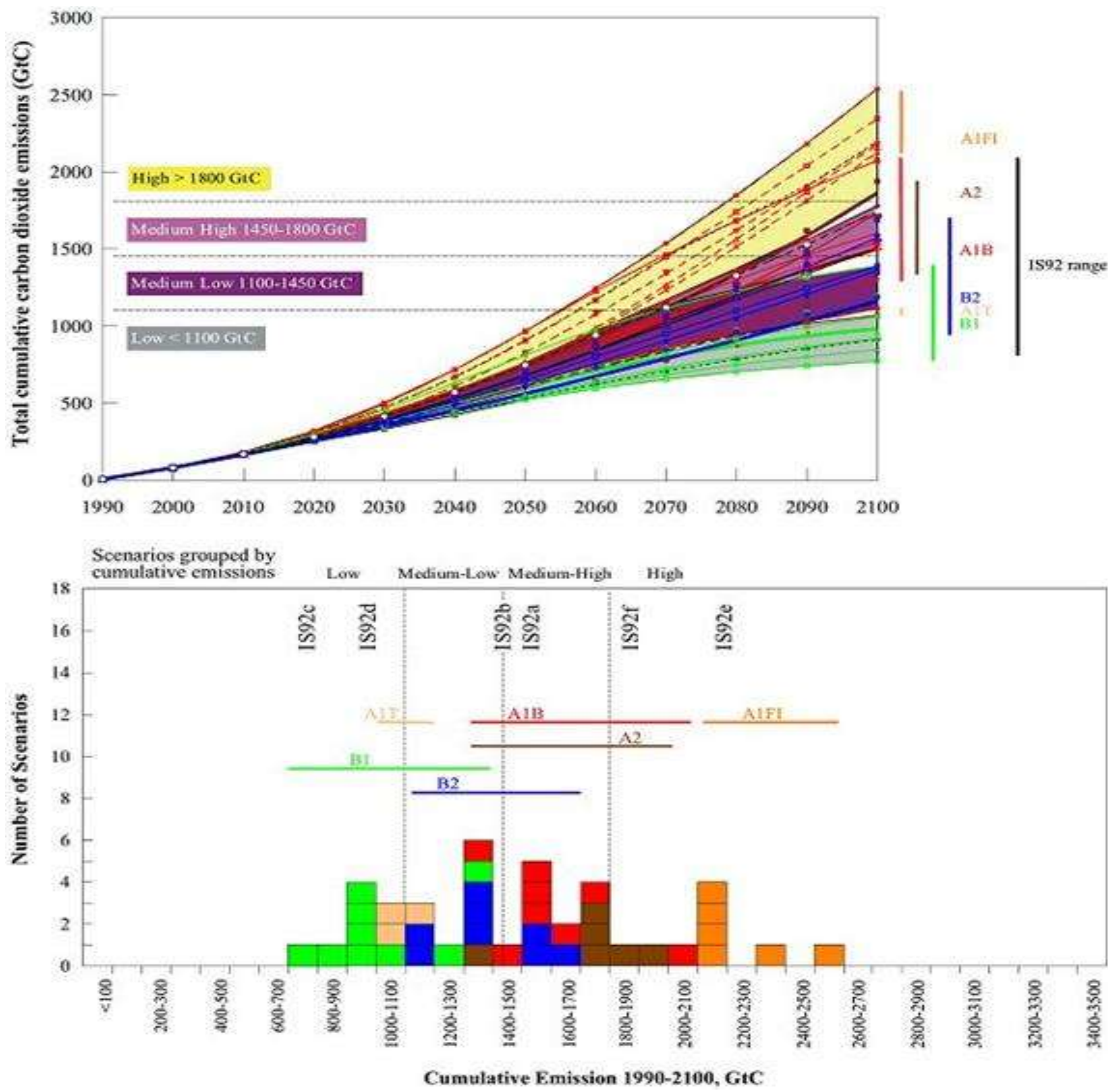


Figure 11. Total global cumulative CO2 emissions (GtC) from 1990 to 2100 (top chart) and histogram of their distribution by scenario groups (bottom chart) (IPCC, 2007).

Scenario Selection

45. In this policy note, all of the GCM/SRES combinations were evaluated to determine which models would represent the extreme dry and extreme wet scenarios for Botswana. The selection process chosen for the wettest climate change projection is based on the work completed by the World Bank Water Anchor Group. (Strzepek and McCluskey 2009). A wet scenario means that the location experienced the most wetness (or increase in) CMI; a dry scenario, the most drying: the rest will be somewhere in between. The advantage of this approach is that it provides a representation of the full range of available scenarios in a 'manageable' way.

46. In this policy note, four statistic indicators are used at to characterize the impact of climate change on extremes events in Botswana under two scenarios, a dry scenario and a wet scenario, these scenarios are not the same for each indicators. The *Standardized Precipitation Index* (SPI), and the *Palmer Drought Severity index* (PDSI) are used to characterize the evolutions of droughts, the *peak flood index* is used to characterize the evolution of floods and the monthly data analysis to look at both, droughts and floods.

Drought Analysis – SPI

47. The SPI drought index described in section 3 is used again to estimate future drought conditions using the "gfdlcm21-A1b" GCM-sres projection. This GCM-sres projection was chosen because it presents the worst (on average) drought scenario according to the SPI calculation. In addition, an additional GCM scenario was evaluated as described below to compare with the PDSI drought indicator.

48. The SRES description for A1B is: "The A1B storyline and scenario family (the "B" standing for balanced) assume a world of rapid economic growth with the most growth in developing countries, the population peaking at 9 billion by mid-century and then declining to 8 billion by 2100, and rapid technological development. It has the highest per capita income of the four storylines. This scenario assumes a mix of fossil intensive and non-fossil fuel energy sources. CO_2 concentrations would be about 700 ppm by 2100.

49. Data from this GCM-sres was taken for two time periods, 2041-2060 and 2081-2100. The SPI drought index is used to estimate the change in future expected drought frequency from the historic record. The map in Figure 12 shows significant increases in the 5 month drought duration during the period of 2046 to 2065. However, more dramatic negative impacts are seen for the A1b scenario for the 2080-2100 time period (Figure 13), especially for the SPI-12 (Figure 15).

50. The conclusion reached is that the durations of droughts indicated in this GCM simulation are expected to increase over time, especially for Northern and Central Botswana.

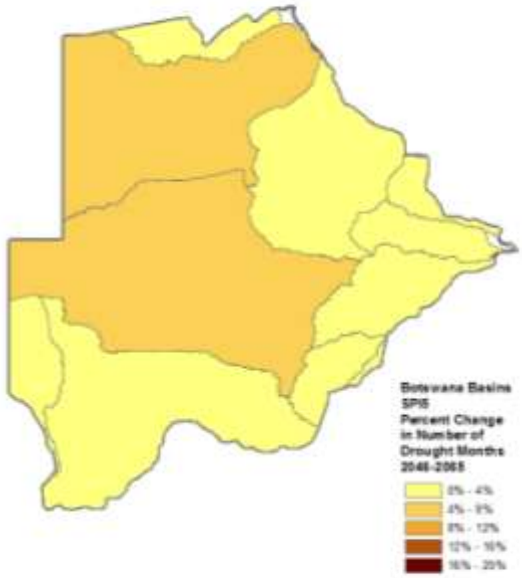


Figure 12. Percentage change in the frequency of the 5-Month Standardized Precipitation Index (SPI5) due to predicted Climate Change in Botswana, gfdlcm21, A1b emissions scenario, 2046-2065,.

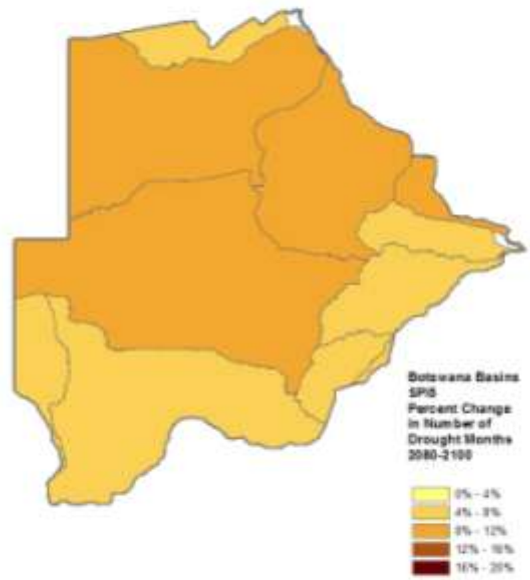


Figure 13. Percentage change in the frequency of the 5-Month Standardized Precipitation Index (SPI5) due to predicted Climate Change in Botswana, gfdlcm21, A1b emissions scenario, 2080-2100.

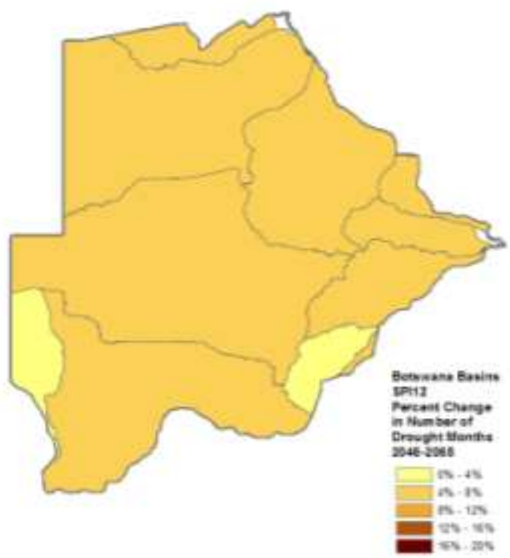


Figure 14. Percentage change in the frequency of the 12-Month Standardized Precipitation Index (SPI12) due to predicted Climate Change in Botswana, gfdlcm21, A1b emissions scenario, 2046-2065.

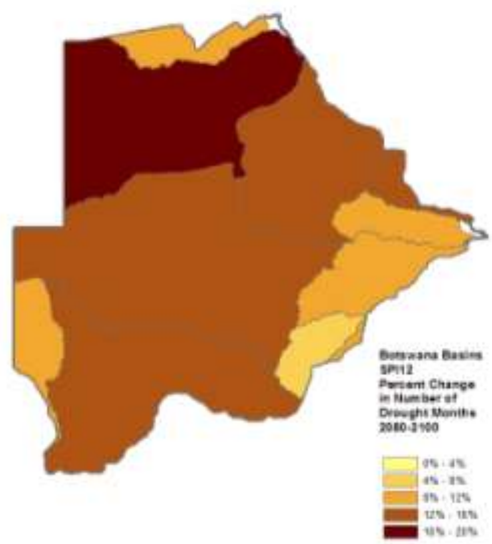


Figure 15. Percentage change in the frequency of the 12-Month Standardized Precipitation Index (SPI12) due to predicted Climate Change in Botswana, gfdlcm21, A1b emissions scenario, 2080-2100.

Drought Analysis: Palmer Drought Severity Index (PDSI)

51. The PDSI drought index described in section 3 is also used to estimate future drought conditions under the "inmcm30_sresA2" GCM-sres projection. This GCM-sres projection was chosen because it presents the worst (on average) drought scenario according to the PDSI calculation, i.e. the GCM that produced the worst droughts based on the SPI described above did not produce the worst droughts based on the PDSI. Data from this GCM was taken for the same two time periods, 2041-2060 and 2081-2100. An additional GCM scenario was evaluated as described below to compare results with the SPI drought indicator.

52. The SRES description for the "A2" family of emision scenarios is: "a very heterogeneous world with a continuously increasing global population, and regionally oriented economic growth that is more fragmented and slower than in other storylines. The A2 scenario has the highest greenhouse gas (GHG) emissions of the three scenarios and results in CO_2 concentrations around 850 ppm by 2100."

53. The PDSI drought index is used to estimate the change in future expected drought frequency from the historic record. The map in Figure 16 shows significant increases in the extreme PDSI drought during the period of 2041 to 2060. However, more impacts are seen for the A2 scenario for the 2081-2100 time period (Figure 17). Again, it is concluded that droughts indicated in this GCM simulation are expected to worsen with time, especially in the Western and South Western part of the country. At first glance it could seem suspect that western Botswana has both the lowest and the highest change next to each other but it is the result of basin weighted values and the way the map was created. In this case, the blue basin extends well into Namibia – so the values are not quite as neighboring as they appear. The change takes place over the whole large basin to the west.

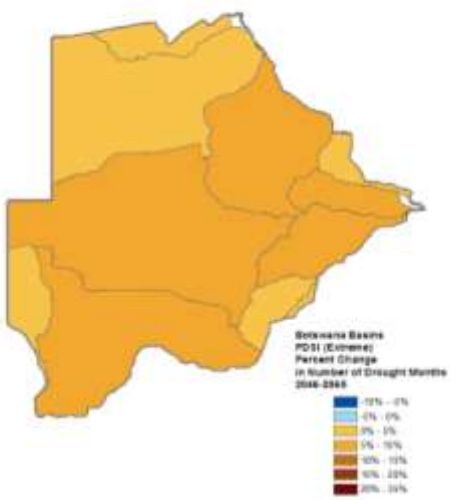


Figure 16. Percentage change in the frequency of the Palmer Drought Severity Index for extreme drought levels, due to predicted Climate Change in Botswana, GCM inmcm30, A2 emissions scenario, 2046-2065.

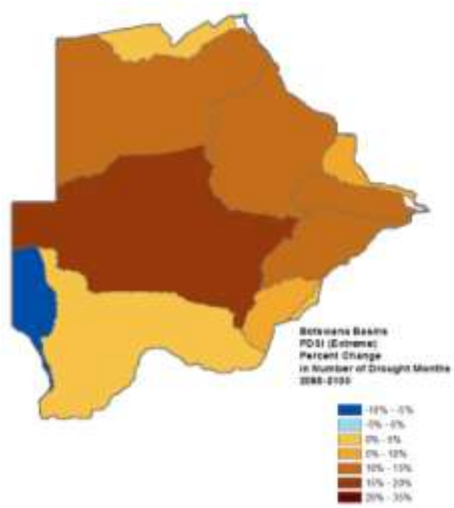


Figure 17. Percentage change in the frequency of the Palmer Drought Severity Index for extreme drought levels, due to predicted Climate Change in Botswana, GCM inmcm30, A2 emissions scenario, 2081-2100.

Comparing SPI and PDSI as a Drought Indicator

54. As described above, the worst-case GCM for each of the two drought indicators was different. A comparison of the sensitivity of the results to the GCM selected was performed by switching the GCMs, i.e. by running the worst case SPI GCM with PDSI, and vice versa. The results of this comparison are given in Annex 4. These results indicate similar results to those described above for PDSI and SPI. However it does appear that SPI, in this case, is less sensitive to the GCM selection, providing results very similar to those found in this section. PDSI, however, did show some sensitivity to the GCM selection, especially in the South Western part of Botswana. See figures in Annex 4 for additional detail.

Runoff Analysis – Peak Runoff

55. Each of the GCM/SRES scenarios was ranked by their Country Moisture Index (CMI) for Botswana (annex 1). A description of CMI is provided above in Box 4 above. The ranking showed that the wettest scenario (highlighted in blue) is MPI ECHAM 5 A1B (CMI delta is 13%). The description of the A1B family of emission scenarios is presented above in the section on SPI.

56. Runoff is a watershed response to precipitation that results from a complex array of physical processes that includes infiltration, evaporation, soil properties, slope, land cover, etc. Runoff is important because it is a direct measure of flooding; it is an integration of watershed processes that generate flood events. Runoff is a function of precipitation, but not in a direct one-one relationship, due to nonlinear watershed processes (e.g. storage) and antecedent watershed conditions.

> **Box 4: SCS method of peak flow estimation**
>
> The US Department of Agriculture Natural Resources Conservation Service (NRCS) developed a runoff estimation procedure commonly called the "SCS" method (The former name of the NRCS was the "Soil Conservation Service"). This method is based on a generalized watershed response to rainfall called a "Unit Hydrograph" (UH). The SCS UH is a function of watershed land cover (using a parameter called a "Curve Number" which is an integer index of previousness, varying from 1 to 100), slope, and roughness. Details of this method are given in Annex 5.

57. The SCS method (see Box 4) is used to estimate peak runoff values from historic and GCM rainfall depths for watersheds in Botswana. Peak flow is an important feature of a flood hydrograph, it determines the maximum extent of inundation. It is also a key feature in many engineering design codes, affecting designed capacity of many drainage features.

58. The peak flow ratio for the 2041-2060 period is given in Figure 18, and the period 2081-2100 is given in Figure 19. These figures depict unit-less ratios, as the ratio is computed by dividing the GCM-based flow in cubic meters per second by the historic peak flow in cubic meters per second. It is apparent from the ratios presented in Figure 18 and Figure 19 Figure 19 that overall, peak runoff rates are increasing over time for this GCM and SRES scenario (2046-2065 compared to 2080-2100) and exhibit some spatial variance: storm risks move to West and North from North East. It is also notable that the extreme southwest portion of Botswana in the Kalahari Desert shows some of the more significant impacts. These results should be reviewed

with some caution as they are a result of the low historical value used in the denominator of the ratio, therefore very small changes in precipitation depth may result in very large ratios. However spatial variance tends to increase with time. The results for the two other GCM/SRES are presented in annex 5.

59. The changes in peak flood may have direct impacts on several aspects of flood damage mitigation and drainage design standards. For example, recent work by The World Bank in Mozambique, Ethiopia, and Ghana suggest that road design standards will need to be increased over the coming decades to maintain a minimum level of service. Other examples include drainage structures, culverts, bridges, etc. which will require greater capacity to maintain current performance frequency characteristics.

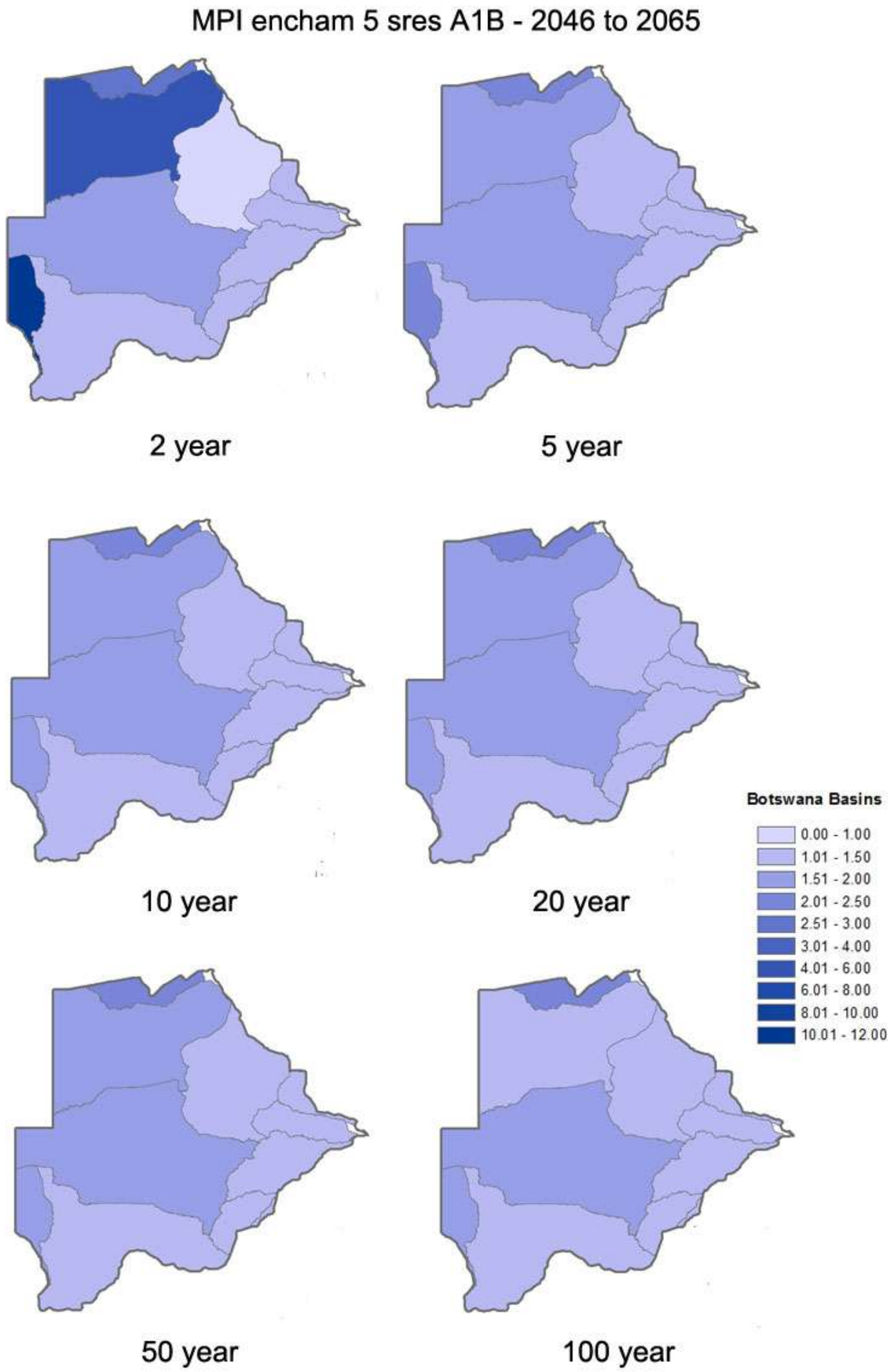


Figure 18. Change in Gumbel 24-hour runoff due to predicted Climate Change in Botswana, Echam5 GCM, A1b emissions scenario, 2046-2060.

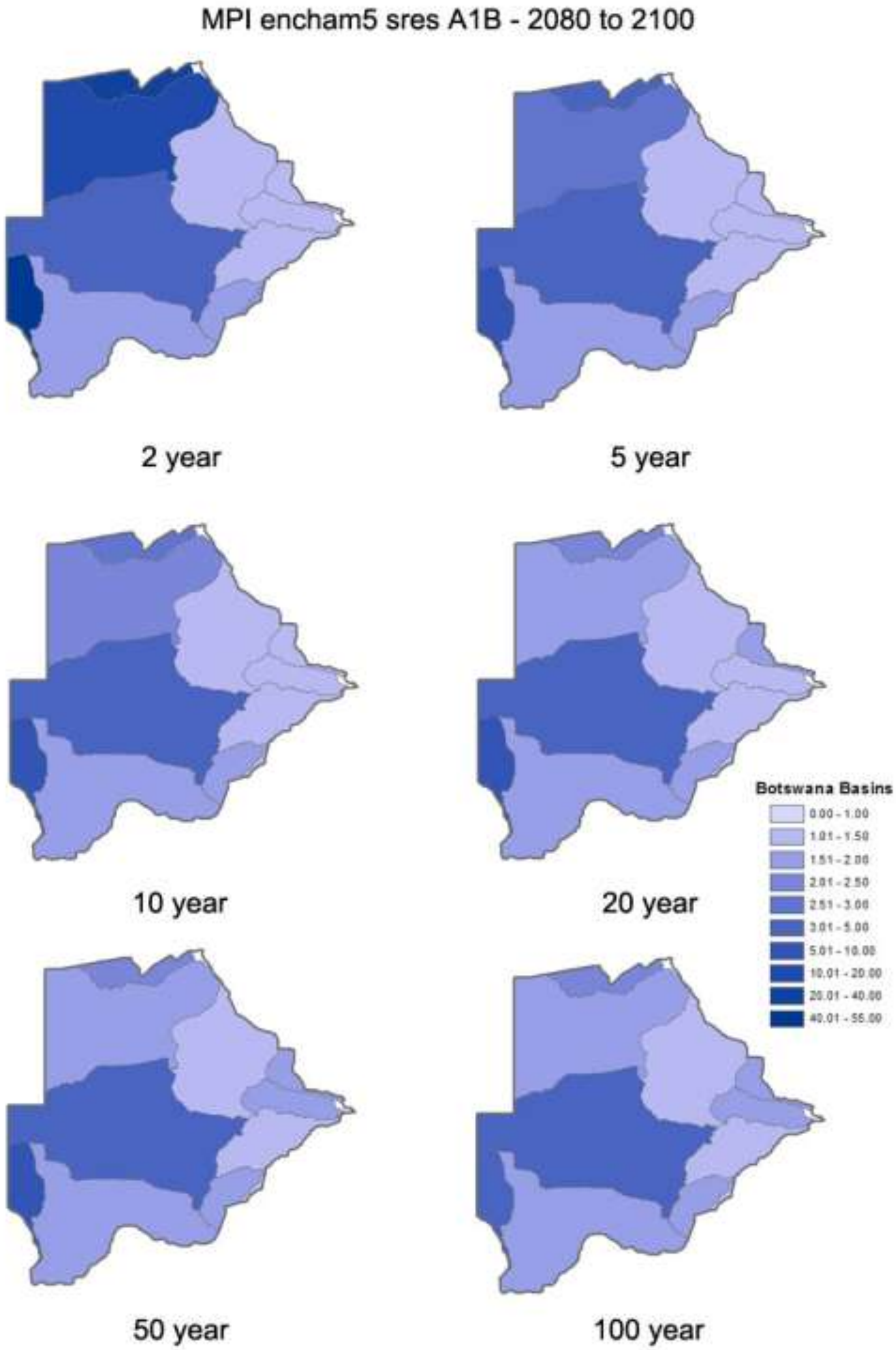


Figure 19 . Change in Gumbel 24-hour runoff due to predicted Climate Change in Botswana, Echam5 GCM, A1b emissions scenario, 2080-2100.

Monthly Data Analysis

60. In addition to the SPI, PDSI, and peak flood index (PFI) presented above, an analysis of monthly precipitation and simulated runoff (see box 5) is used to show other means of drought and flood expectation. Detailed explanation of annual indicator statistics (annual average, based on monthly values) of this analysis are presented in Annex 6.

Box 5: Montly Data Analysis

Runoff can be used as an indicator of water scarcity in a region. While it doesn't take into account available storage, it does give an idea of available water. Strzepek and McCluskey 2009 (work completed for the World Bank Water Anchor Group) used GCM output as input into an offline hydrologic model, CLIRUN-II (Strzepek, et al, 2008). This model was developed specifically to assess the impact of climate change on runoff and to address extreme events at the annual level by modeling low and high flows.

Outputs of climate change projections on climatic variables are input to a calibrated hydrologic model with a half degree by half degree resolution, running on a monthly time scale. Simulating monthly over a 30 year base period, from 1961 to 1990 provides for excellent estimation of annual runoff but also provides time series data to examine other statistical and stochastic variables from the 30 year monthly time series. It is important to note that the runoff analysis does not include storage which could improve the amount of available water. Runoff results are provided for the decades of 2030 and 2050. Additional decades could be modeled if desired. More details can be found in Strzepek and McCluskey 2009.

61. In all areas of Botswana in 2030, temperature is increasing from 0.5 degrees to over 2 degrees Celsius. The Climate Moisture Index (CMI), a measure of aridity, ranges from increasing by 0.5 to decreasing by -0.75 with most models agreeing that CMI will decrease and the area will become more arid. The PET increases slightly around 5% with agreement among all the models.

62. Due to the importance of the Limpopo basin (5927 in the model –see annex 3, i.e. south central eastern in Botswana) for water supply, the statistics computed for this basin are highlighted in this section. Other basin statistics are given in Annex 6.

63. In 2030, along the south eastern corridor of Botswana, changes in precipitation range from ~+/-20% with a bias towards less precipitation as seen in Figure 20. Runoff changes range from over 100% increases to ~40% decreases. The model predictions have a wide range. Changes in flooding range from a ~25% decrease to over a 150% increase with a bias towards increases in flooding. Drought changes range from a ~40% increase to a ~20% decrease. There is a definite bias towards more droughts. Groundwater changes range from a ~40% decrease to a ~25% increase with most models showing a decrease in groundwater recharge.

64. In 2050, along the south eastern corridor of Botswana, the models show agreement in decreasing precipitation, runoff, and groundwater as shown in Figure 21. The models also show agreement with increasing droughts. There is large range of predictions for flooding ranging from ~40% decreases to over 150% increases.

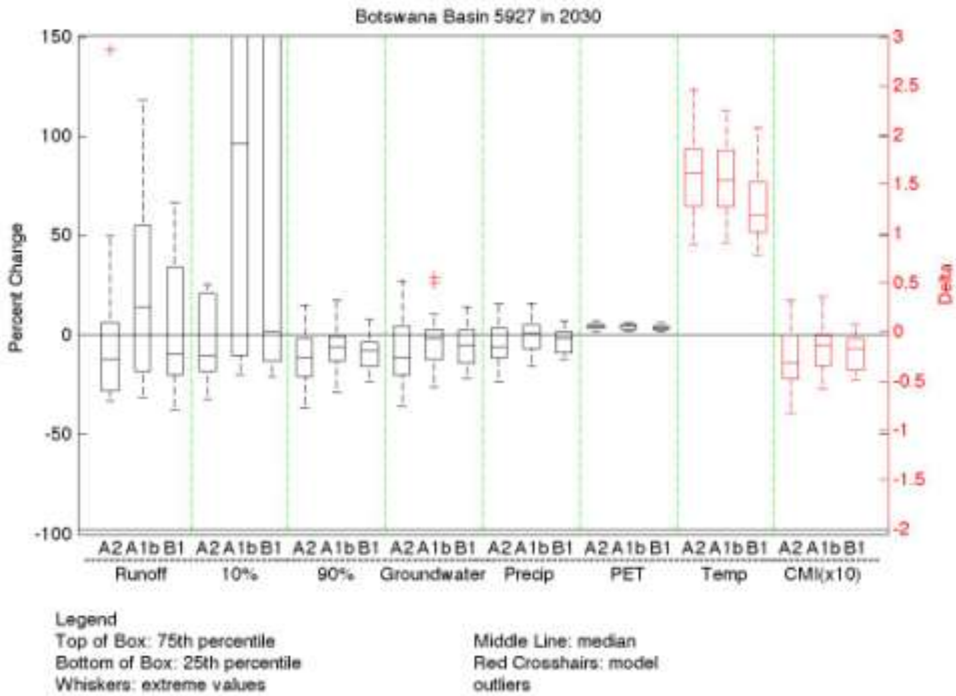


Figure 20. Box plot of average annual indicator statistics for south central eastern Botswana (Basin 5927) for 2030-2039.

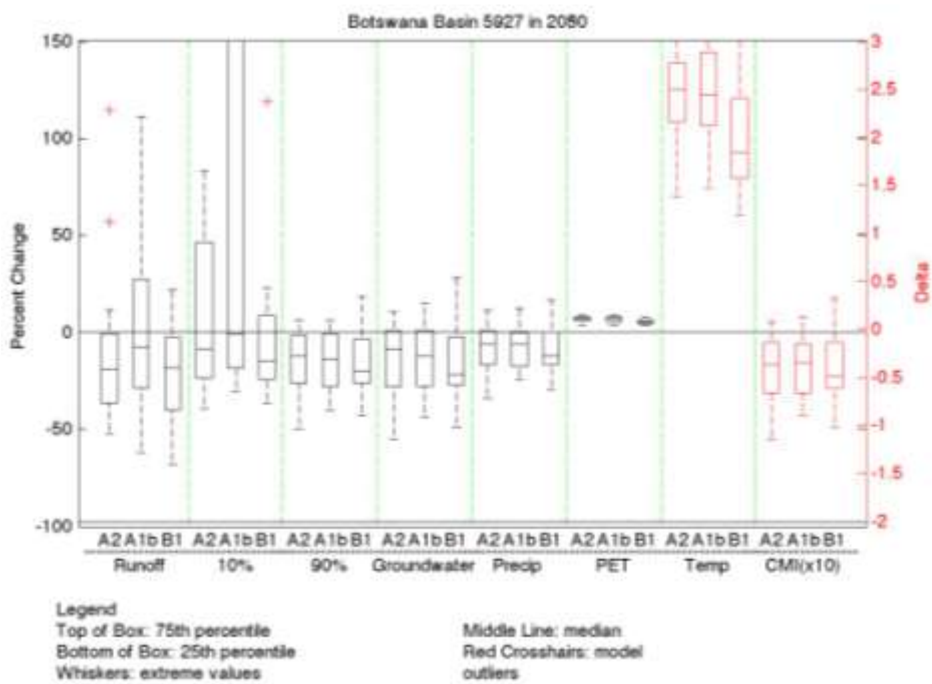


Figure 21. Box plot of average annual indicator statistics for south central eastern Botswana (Basin 5927) for 2050-2059.

65. From the monthly analysis it is observed that, in general, the non-desert areas of Botswana show decreasing precipitation and groundwater with increasing droughts. Model results for future runoff and flooding are varied, but generally agree with the flood index

presented above; flooding is likely to be exacerbated by climate change. The result obtained with this fourth indicator reinforces the results obtained with the three previous ones.

5. Discussion and Way Forward

66. The objective of the note was to quantify with statistic indicators the impact of climate change on extremes events in Botswana under two extreme scenarios and discuss risks for the water sector and development plans.

Main findings

67. The assessment of the water sector has shown that water is already a constraint to economic development and growth, in particular for agriculture (irrigation) and mining. Future growth requires much more emphasis on water demand management, including efficient water allocation and use, re-use of wastewater, rainwater harvesting and desalination

68. As a (semi-) arid country, droughts have been common in the past and floods have also occurred (though much less frequently). The historical analysis shows that:

- Rainfall has been highly variable, spatially, inter and intra annual (CMI; 1960-1990).
- Droughts in terms of rainfall deficits (SPI) are most common in northern Botswana, indicating that this area may be most affected by on-going climate change.
- Extreme droughts based on low rainfall and soil conditions are most common in south western Botswana (PDSI).
- High rainfall events with risks of floods are most likely in north eastern Botswana. Several large dams are located in this area.

69. The scenario analysis of climate change and rainfall variability used two extreme scenarios (driest and wettest), which show that as a result of climate change:

- Droughts are expected to increase in frequency and severity, particularly in the period 2080-2100; the changes are largest in western and northern Botswana. The SPI and PDSI results show similar patterns but differ on details.
- The run-off analysis shows that the frequency of storms will increase in western and northern Botswana.
- The monthly data analysis shows that aridity will increase (declining CMI) and that PET will increase by around 5%.
- In south-mid eastern Botswana (part of Limpopo basin), precipitation is likely to decrease but there is a likely increase in flooding; there is a definite bias towards increased droughts and groundwater recharge is likely to decline.

70. In an area of climate science where considerable uncertainty reigns, there is greater consensus among normally highly variable GCMs in Botswana. Multiple measures, over multiple temporal scales confirm that greater climatic variability over the coming decades is likely in Botswana. Therefore, climate change is expected to put *additional* pressure on the country's water resources. Prudent analysis of risk-mitigation is warranted.

Main economic impacts

71. Increased rainfall variability and climate change may have a wide range of direct and indirect economic impacts. Without adaptations, increased droughts will adversely affect the subsistence and commercial agricultural sector. A decrease in groundwater recharge would affect groundwater resources and the vegetation, affecting primary and secondary land productivity and ecosystem services. Lower run-off would reduce already low safe yields from dams and adversely affect major tourism attractions such as the Okavango Delta..

72. The economic costs of climate variability can be very high as experiences in other Southern African countries have shown (Box 6).

Box 6. Economic Impact of Climate Variability in Southern Africa Countries

It has become evident that recurrent drought and floods cause significant losses and negatively impact economic growth in a number of the Southern African countries. For example, in 1992 drought-related losses constituted 8-9% of GDP in Zimbabwe and Zambia[1]. The recent analysis showed that in Zambia, rainfall variability lowers agricultural growth by one percentage point each year and will cost $4.3 billion in foregone GDP over the next ten years. It is also estimated that rainfall variability slows poverty reduction. For example, if Zambia is to experience a 10 year rainfall pattern similar to that of 1984 to 1995, then most of the country's potential reductions in poverty reduction over the next 10 years would be lost and the numb er of poor people would rise by 200,000 people[1]. Results for Malawi indicate that, on average, droughts and floods together reduce total GDP by about 1.7 percent per year[1]. Floods are among the most devastating natural hazards. It is estimated that the economic impact of the 2009 floods in Northern Namibia is about 1% of 2009 GDP[1]. In Mozambique, the shock of the flood of 2000 led to the abrupt fall of the GDP growth rate to 1.5% in 2000 (in 1994-2003 the average growth rate was 7.5%).

73. Overcoming rainfall variability poses a significant challenge to maintaining economic growth and significantly reducing poverty in the country. Rainfall variability effects also heighten concern over potentially negative impacts of climate change. Together rainfall variability and climate change show considerable reasons to increase investments in water infrastructure, (e.g. additional storage volume) improve efficiency, and review existing national and sectoral policies to ensure they adequately address climate-related challenges. Adaptation and mitigation costs could divert funds from other development priorities.

Recommendations

74. Botswana already has significant experience with *drought monitoring and management* and has well established procedures for drought monitoring and implementation of drought mitigation strategies. Handling the impacts of increased rainfall variability and climate change has to be linked to and to strengthen this process. It is recommended that the drought monitoring process could be expanded to incorporate floods and that the CMI, SPI and PDSI are monitored to make the assessment objective.

75. *Water resources management*. Physical water scarcity and high climate variability (resulting in frequent droughts and floods), compounded by inadequate water resources

infrastructure and management, increasingly undermines Botswana's efforts in achieving its development goals, and the water sector, along with the electricity and transport, are now presenting bottlenecks to future sustained growth. High climate variability and decreasing natural runoff require more water storage, greater efforts towards (artificial) recharge of groundwater and greater interconnectivity between surface water and groundwater sources (to increase safe yields of the country's entire water infrastructure). It gives also further impetus for the urgent need to implement water demand management measures. It is therefore timely that the new water sector institutional structure in Botswana includes an institution (Department of Water Affairs (DWA) solely responsible for water resources management. The integration of climate related risks into water resources management in Botswana should be integral part of the activities of DWA.

76. *Resiliencies of long term water supplies.* Climate risks have significant implications to investments in and operations and management of water systems associated both with delivering water services and with managing water. Water systems for delivering water services include irrigation, urban water, sanitation and drainage. Water resources management systems include delivery of bulk water to for irrigation, watersheds, water supply and sanitation and also multi-purpose storage and flood control. Increasing climate variability and change would affect water demand by water-using sectors through decreased rainfall, increased evapotranspiration, placing additional pressure on irrigation and water supply systems. Changes in river flows will have direct impacts on hydropower production. Extreme variability and / or reduced supplies could stress the national infrastructure and institutional capacity of the water sector in managing water resources across sectors. The extent to which each water system will be impacted by climate risks will depend on its ability to adapt to the existing and future climate-related risks.

77. *Flood damage and mitigation.* If precipitation intensities do increase over the next century, design standards will have to be adjusted to maintain current levels of service. If these levels of service are also raised as a result of economic development (irrespective of climate change) then climate change in effect "adds-on" additional infrastructure costs. In other recent climate change adaptation work in Africa it is evident that sound adaptation is inextricably linked to sound development practices. It is virtually impossible to separate the two. With this in mind, flood damage mitigation policy should reflect a balance of "hard" (i.e. infrastructure-based) and "soft (i.e. behavior modification, risk sharing, land management, etc) strategies that are consistent at the national, regional, watershed and community scales.

Further Analysis

78. This Policy Note is a first building block of what could be a more comprehensive assessment of the impact of climate change in Botswana. The World Bank has already developed such assessments in other countries. Their main objective is to help decision makers assess the risks posed by climate change and design national strategies for adapting to them. Once future climate outcomes (temperature, precipitation, droughts, floods) are modeled with extreme GCM (the biophysical assessment presented in this policy note), the impacts of climate

change are established for selected vulnerable sectors (for example water supply, infrastructure, agriculture, and health in Botswana) and further integrated into an economy wide model (a Computable General Equilibrium -CGE) model in order to identify cross-sector effects without and with adaptation investments and policies. The latter needs to include a national and regional analysis of the shifts in comparative advantages of the leading economic sectors due to increased rainfall variability and climate change. Special attention needs to be given to the future of the irrigation sector. Such an analysis will inform investment decisions in public infrastructure around the country.

79. Such a comprehensive approach would assist the Government of Botswana in determining the extent of vulnerability of the country's economy to climate vulnerability and change, and identify anticipatory strategies for adapting to drought and flood risks and conditions of chronic hydrological variability. It will build a better understanding of the economy-wide impacts of droughts and floods and what measures and strategies are required to de-link the economy of Botswana from the effects of climate variability. The study could also lay the ground for discussions and analysis of the effectiveness and viability of various measures to adapt to the risks of drought and floods, and how to incorporate them into the countries' economic policies and sectoral strategies.

80. Another possible follow up work to this policy note could to do more precise analyses of increased rainfall variability and climate change at the level of economically important watersheds such as the Okavango Delta or the Makgadikgadi wetland system. This will bring into the analysis of the impacts on tourism, mining, agriculture and other sectors and the economic costs of in-action.

6. References

CIESIN, Columbia University , 2005, Gridded Population of the World, Version 3 (GPWv3) Data Collection, Palisades, NY, http://sedac.ciesin.columbia.edu/gpw/index.jsp

FAO (2009). Aquastat, Botswana.

Funk, C., J. Michaelsen, J. Verdin, G. Artan, G. Husak, G. Senay, H. Gadain, and T. Magadazire, 2003: The Collaborative Historical African Rainfall Model: Description and Evaluation. International Journal of Climatology, 23, 47-66

http://www.eyesonafrica.net/updates/flood-update.htm

http://www.gazettebw.com/index.php?option=com_content&view=article&id=6090:botswana-has-lowest-water-reservoir-capacity-&catid=13:business&Itemid=2

http://www.irinnews.org/Report.aspx?ReportId=84393

http://www.sarpn.org.za/documents/d0001403/index.php

http://www.wrc.org.za/Knowledge%20Hub%20Documents/Water%20Wheel/Articles/Archive/WW_03_sep-oct_Water_news_p_4-7.pdf

Intergovernmental Panel on Climate Change. [Online]. 2000. *The SRES Emissions Scenarios*. http://sedac.ciesin.columbia.edu/ddc/sres/. [Accessed: June 25, 2009]

Intergovernmental Panel on Climate Change. [Online]. 26 November 2008. *Climate model output: period-averages*. http://www.ipcc-data.org/ddc_climscen.html. [Accessed: June 25, 2009]

Lawrence Livermore National Laboratories. *Daily Atmospheric Data Availability*. [Online]. 27 February 2008. http://www-pcmdi.llnl.gov/ipcc/data_status_tables.htm. [Accessed 5 June 2009]

Mitchell, Timothy D., and Jones, Philip Dd, 2005, An Improved Method of Constructing A Database of Monthly Climate Observations and Associated High-Resolution Grids, International Journal of Climatology.

Nicklow, J.W., Boulos, P., Muleta, M.K. (2006). “Comprehensive urban Hydrologic Modeling Handbook”. MWH Soft, Pasadena, CA.

Sieber, J. and Purkey, D. 2007. User Guide for WEAP21. Stockholm Environment Institute, US Center. http://weap21.org/downloads/WEAP_User_Guide.pdf

South African Water Research Commision. WW_03_Sept-Oct_Water_news_p_4-7.pdf

Texas Department of Transportation. Hydraulic Design Manual. [Online]. 1 March 2009. http://onlinemanuals.txdot.gov/txdotmanuals/hyd/statistical_analysis_of_stream_gauge_data.htm. [Accessed 5 June 2009]

UN ECA, 2005, Draft Botswana country water report. (Botswana UNECA Water Report – draft final 2006.pdf)

US Department of Agriculture National Resource Conservation Service (NRCS) National Engineering Handbook. 2009.

USDOT FHA 1995 (1995) Recording and Coding Guide for the Structural Inventory and Appraisal of the Nation’s Bridges. Office of Engineering, Bridge Division. Report number FHWA-PD-96-001.

World Bank. (2009). Botswana Economic Impact of Climate Variability and Change (P118526), Concept Note.

Wright, L.T., Strzepek, K, Arndt, C., Fant, C., Fathelramen, E., Mayotte, J-M., Carret, JC., Bachofen, C., Kuriakose, A., Uiene, R., Nucifora, A. and Thurlow, J. (2010). Economics of Adaptation to Climate Change (EACC), Mozambique Country Case Study, Draft. The World Bank, Washington D.C.

Wright, L.T., Strzepek, K, Smith, J., Jones, R., Streeter, R., Mayotte, J.M., and Powell, A. (2009). “Climate change impacts on transportation infrastructure”. Draft report to U.S. Environmental Protection Agency, Climate Change Division, 1200 Pennsylvania Avenue, NW, Mailcode 6207J, Washington, DC 20460

Annex 1: Changes in CMI for Botswana

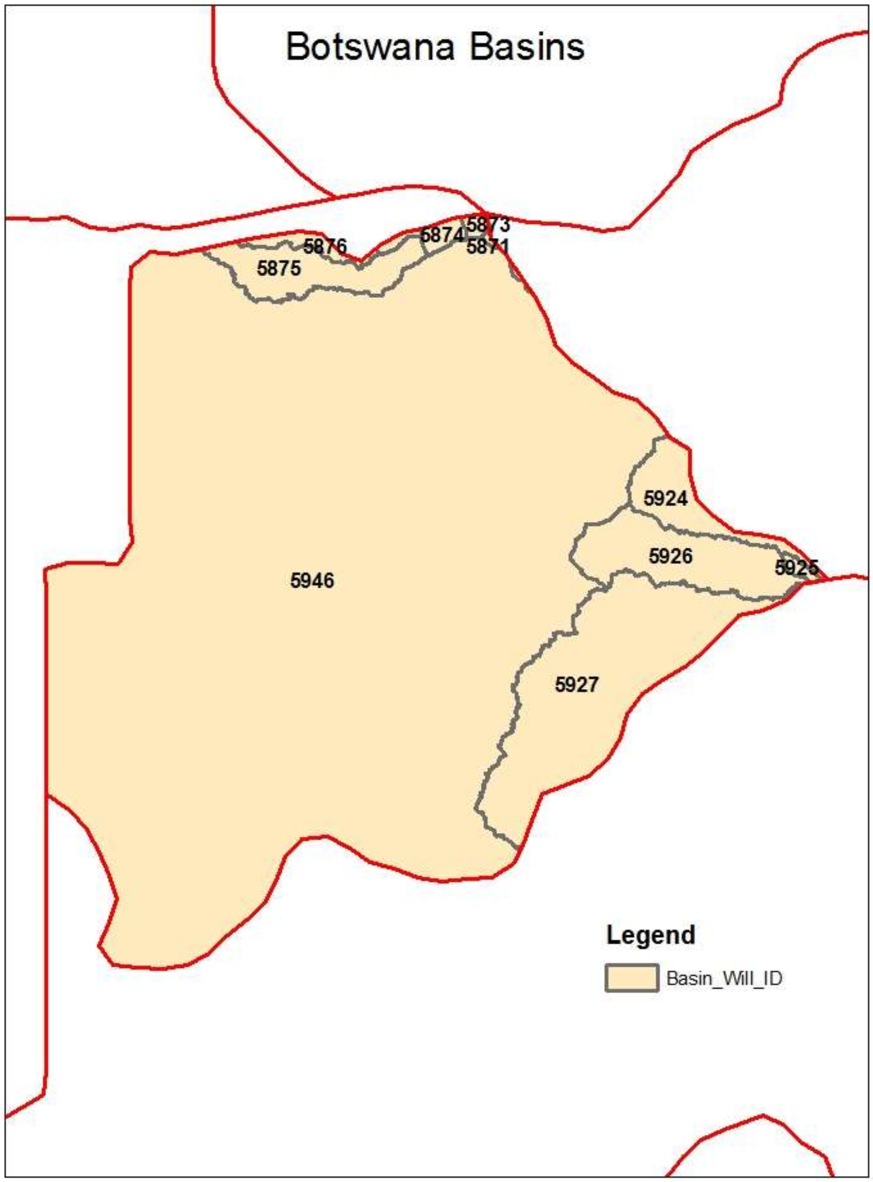
BOTSWANA BASE CMI		-0.797
GCM	SRES	CMI (percent change from base)
bccr_bcm2_0	sresa1b	11%
bccr_bcm2_0	sresa2	5%
bccr_bcm2_0	sresb1	2%
cccma_cgcm3_1	sresa1b	6%
cccma_cgcm3_1	sresa2	10%
cccma_cgcm3_1	sresb1	5%
cccma_cgcm3_1_t63	sresa1b	10%
cccma_cgcm3_1_t63	sresa2	N/A
cccma_cgcm3_1_t63	sresb1	5%
cnrm_cm3	sresa1b	-4%
cnrm_cm3	sresa2	7%
cnrm_cm3	sresb1	7%
csiro_mk3_0	sresa1b	-5%
csiro_mk3_0	sresa2	1%
csiro_mk3_0	sresb1	-11%
csiro_mk3_5	sresa1b	2%
csiro_mk3_5	sresa2	4%
csiro_mk3_5	sresb1	1%
gfdl_cm2_0	sresa1b	9%
gfdl_cm2_0	sresa2	7%
gfdl_cm2_0	sresb1	N/A
gfdl_cm2_1	sresa1b	8%
gfdl_cm2_1	sresa2	7%
gfdl_cm2_1	sresb1	8%
giss_aom	sresa1b	1%
giss_aom	sresa2	N/A
giss_aom	sresb1	2%
giss_model_e_h	sresa1b	-3%
giss_model_e_h	sresa2	N/A
giss_model_e_h	sresb1	N/A
giss_model_e_r	sresa1b	2%
giss_model_e_r	sresa2	6%
giss_model_e_r	sresb1	4%
iap_fgoals1_0_g	sresa1b	4%
iap_fgoals1_0_g	sresa2	N/A
iap_fgoals1_0_g	sresb1	3%
inmcm3_0	sresa1b	9%

inmcm3_0	sresa2	6%
inmcm3_0	sresb1	4%
ipsl_cm4	sresa1b	6%
ipsl_cm4	sresa2	5%
ipsl_cm4	sresb1	2%
miroc3_2_hires	sresa1b	5%
miroc3_2_hires	sresa2	N/A
miroc3_2_hires	sresb1	3%
miroc3_2_medres	sresa1b	8%
miroc3_2_medres	sresa2	7%
miroc3_2_medres	sresb1	6%
mpi_echam5	**sresa1b**	**13%**
mpi_echam5	sresa2	3%
mpi_echam5	sresb1	-7%
mri_cgcm2_3_2a	sresa1b	-2%
mri_cgcm2_3_2a	sresa2	-6%
mri_cgcm2_3_2a	sresb1	-6%
ncar_ccsm3_0	sresa1b	6%
ncar_ccsm3_0	sresa2	3%
ncar_ccsm3_0	sresb1	-4%
ncar_pcm1	sresa1b	8%
ncar_pcm1	sresa2	11%
ncar_pcm1	sresb1	N/A
ukmo_hadcm3	sresa1b	7%
ukmo_hadcm3	sresa2	-1%
ukmo_hadcm3	sresb1	N/A
ukmo_hadgem1	sresa1b	10%
ukmo_hadgem1	sresa2	3%
ukmo_hadgem1	Sresb1	N/A

Annex 2: Available AR4 models, scenarios, and variables via IPCC

Models	Description	**Comments**
BCCR:BCM2		
CCCMA:CGCM3_1-T47		
CCCMA:CGCM3_1-T63		
CNRM:CM3		
CSIRO:MK3-5		
CSIRO:MK3-0		
GFDL:CM2	Geophysical Fluid Dynamics Laboratory (Princeton, New Jersey, USA)	
GFDL:CM2_1		
INM:CM3		
IPSL:CM4	Institut Pierre-Simon Laplace (Paris, France)	
LASG:FGOALS-G1_0		
MPIM:ECHAM5		
MRI:CGCM2_3_2		
NASA:GISS-AOM	Goddard Institute for Space Studies	
NASA:GISS-EH		
NASA:GISS-ER		
NCAR:CCSM3	National Center for Atmospheric Research (Boulder, Colorado, USA)	
NCAR:PCM		
NIES:MIROC3_2-HI		
NIES:MIROC3_2-MED		
UKMO:HADCM3		
UKMO:HADGEM1		

Annex 3: Basin Identification map of Botswana



Annex 4.Comparison of SPI and PDSI Drought Indicators

In the drought analyses described in this note, the "worst case" climate scenario for each indicator resulted in a different GCM SRES combination for SPI and PDSI. There is also value in performing the inverse analysis, i.e. using the PDSI indicator with the worst case GCM based on GCM, and vice versa, use the SPI indicator with the worst case GCM based on the PDSI. Results of this analysis are presented in the maps below.

The SPI indicator results using the "inmcm30_sresA2" GCM-sres projection are given below in Figure 22 through Figure 25. The results are fairly similar to the SPI results in Figure 12 through Figure 15 using the gfdlcm21-A1b scenario presented in the main text of the policy note.

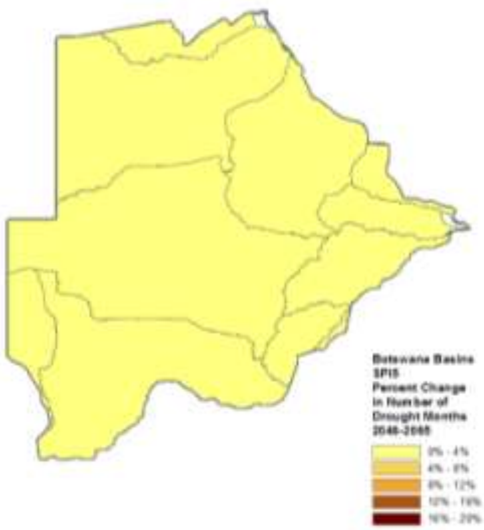


Figure 22. Change in the frequency of the SPI 5 month drought, using the inmcm30_sresA2 GCM scenario, for the period 2046-2065.

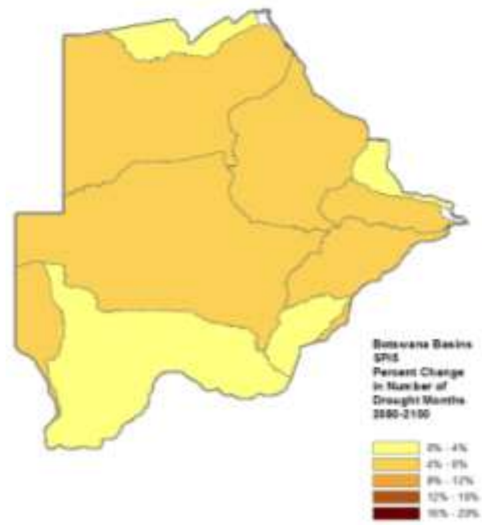


Figure 23. Change in the frequency of the SPI 5 month drought indicator, using the inmcm30_sresA2 GCM scenario, for the period 2080-2100.

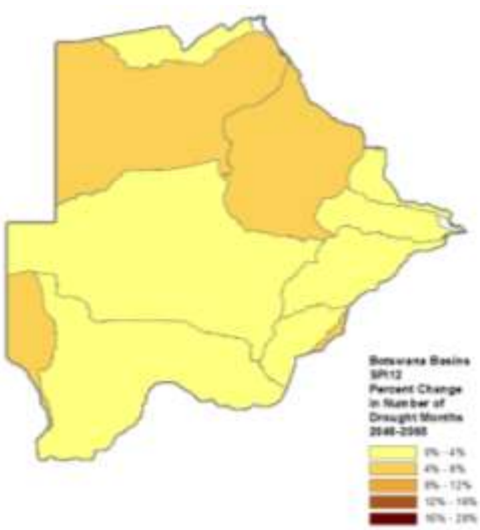


Figure 24. Change in the SPI 12 month drought, using the inmcm30_sresA2 GCM scenario, for the period 2046-2065

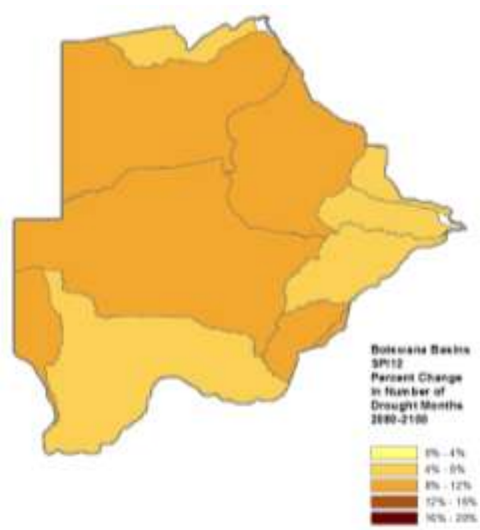


Figure 25. Change in the frequency of the SPI 12 month drought, using the inmcm30_sresA2 GCM scenario, for the period 2080-2100.

The PDSI indicator results using the "gfdlcm21-A1b" scenario shown below in Figure 26 and Figure 27 however are somewhat less severe than those found using the "inmcm30_sresA2" shown above in Figure 16 and Figure 17. One conclusion that may be drawn is that the PDSI indicator results appears to be somewhat more sensitive to the GCM scenario than the SPI results, which appear, on the basis of this limited comparison, to be more stable.

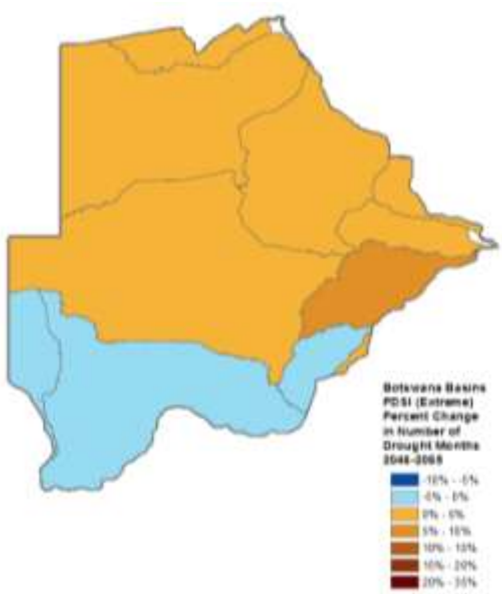


Figure 26. Change in the frequency of the Palmer Drought Severity Index for extreme drought levels, due to predicted Climate Change in Botswana, GCM gfdlcm21-A1b emissions scenario, 2046-2065.

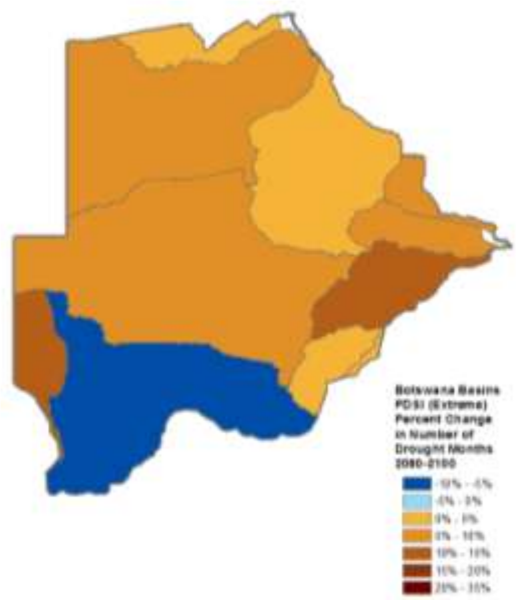


Figure 27. Change in the frequency of the Palmer Drought Severity Index for extreme drought levels, due to predicted Climate Change in Botswana, GCM gfdlcm21-A1b emissions scenario, 2080-2100.

Annex 5: SCS Method of Peak Flow estimation and 24 Hour Runoff Maps

The USDA National Resource Conservation Service (NRCS, formerly Soil Conservation Service (SCS)) “curve number” method originally developed in the computer model TR-20 is a widely used empirical rainfall-runoff method based on unit hydrograph theory (NRCS 2009). Key watershed attributes and characteristics used to estimate the runoff hydrograph include watershed area, the time of concentration, and the “curve number (CN)” (a measure of the proportion of precipitation that runs off the watershed (NRCS 2004)).

Measured runoff data from a large number of watersheds in the United States were used to develop the “SCS Dimensionless unit Hydrograph”, given in Figure 28 (NRCS 2004, Bedient et al. 2008). Given changes in 24-hour precipitation predicted by a particular GCM simulation, consequential changes to the peak flow computed from the NRCS dimensionless unit hydrograph for the same watershed attribute parameters were used as a proxy of how a watershed’s runoff response might change due to climate change. 24-hour precipitation depths were taken from four GCM simulations, implying that the computed values of change in peak flow due to climate change were representative for watersheds within a grid cell (.5 degree by .5 degree for this analysis, defined by the resolution of the historic precipitation record) that reached equilibrium flow from constant rainfall in 24 hours or more.

To apply this method to estimating potential peak flooding flow changes within a grid, a representative response time of a watershed within the grid cell is needed. The response time of the watershed is a function of the velocity of surface runoff; which in turn is a function of watershed slope, the distance runoff is conveyed within the watershed, and characteristics of the watershed surfaces over which runoff must travel (surface roughness). The “time of concentration” is formerly defined as the time it takes a wave to travel from the farthest portions of the watershed (Bedient et al 2009). This can rarely be directly measured, and is instead estimated using empirical approximations. For this study, velocity was calculated based on the land surface cover, as described by Nicklow et al. (2006).

$$V = K\sqrt{S} \tag{4}$$

$$T_c = \frac{L}{60V} \tag{5}$$

Where: V = Velocity of runoff in ft/sec

K = Coefficient based on land cover

L = Length of overland flow in feet

S = dimensionless slope

T_c = Time of concentration in minutes

T_c was calculated based on the associated Land Use Codes, the slope of the cell, and “K” values in Table 5.

Watershed storage is computed in the NRCS method using the well known Curve Number (CN); which is an integer value ranging between 1 and 99 that represents the ratio of watershed storage to runoff. CN is defined by equations 3 through 6. CN values for various soil types are given below in Table 6.

The geometrical properties of the NRCS (SCS) unit hydrograph were used to directly compute the peak flow (i.e., without the need to compute the complete hydrograph).

In Figure 1 shown above, ΔD is the duration of excess rainfall (total precipitation less losses) of the unit hydrograph as well as the time step of the unit hydrograph, and is defined as 0.133Tc.

The time-to-peak and the peak flow rate are calculated as:

$$T_p = \frac{\Delta D}{2} + L_t \tag{6}$$

$$q_p = \frac{(484AQ)}{T_p} \quad (7)$$

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \quad (8)$$

$$S = \frac{1000}{CN} - 10 \quad (9)$$

Where:

T_p = Time to peak (hours)
L_t = Watershed lag time (hours)
q_p = peak flow rate (cfs)
A = watershed area in square miles
Q = Depth of runoff (inches)
S = watershed storage (inches)
P = Depth of precipitation (inches)
CN = Curve number (dimensionless)

While the above procedure may result in an imperfect estimate of the magnitude of peak flow for a particular rainfall depth and frequency, its use to estimate the change in peak flow is useful for understanding how to formulate a feasible engineering response to nonstationary precipitation. Because watershed attributes are held constant and only precipitation depth of a specified frequency is altered, the flow change may be estimated. This method was used to estimate how design conditions may be altered by climate change. Imperfect assumptions of slope, land cover, and time of concentration are the same for both historic and GCM-predicted rainfall, the resulting change in flow reported as a ratio reflects the change resulting purely from a change in rainfall. In this case the change in rainfall represents the change in rainfall for a particular design storm that is of importance for infrastructure planning and climate adaptation strategizing.

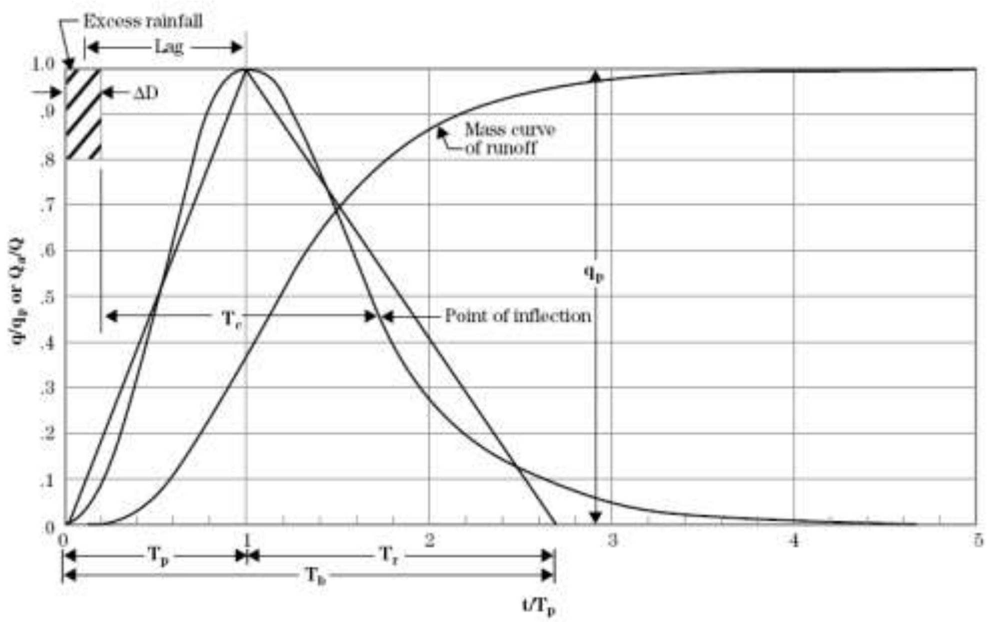


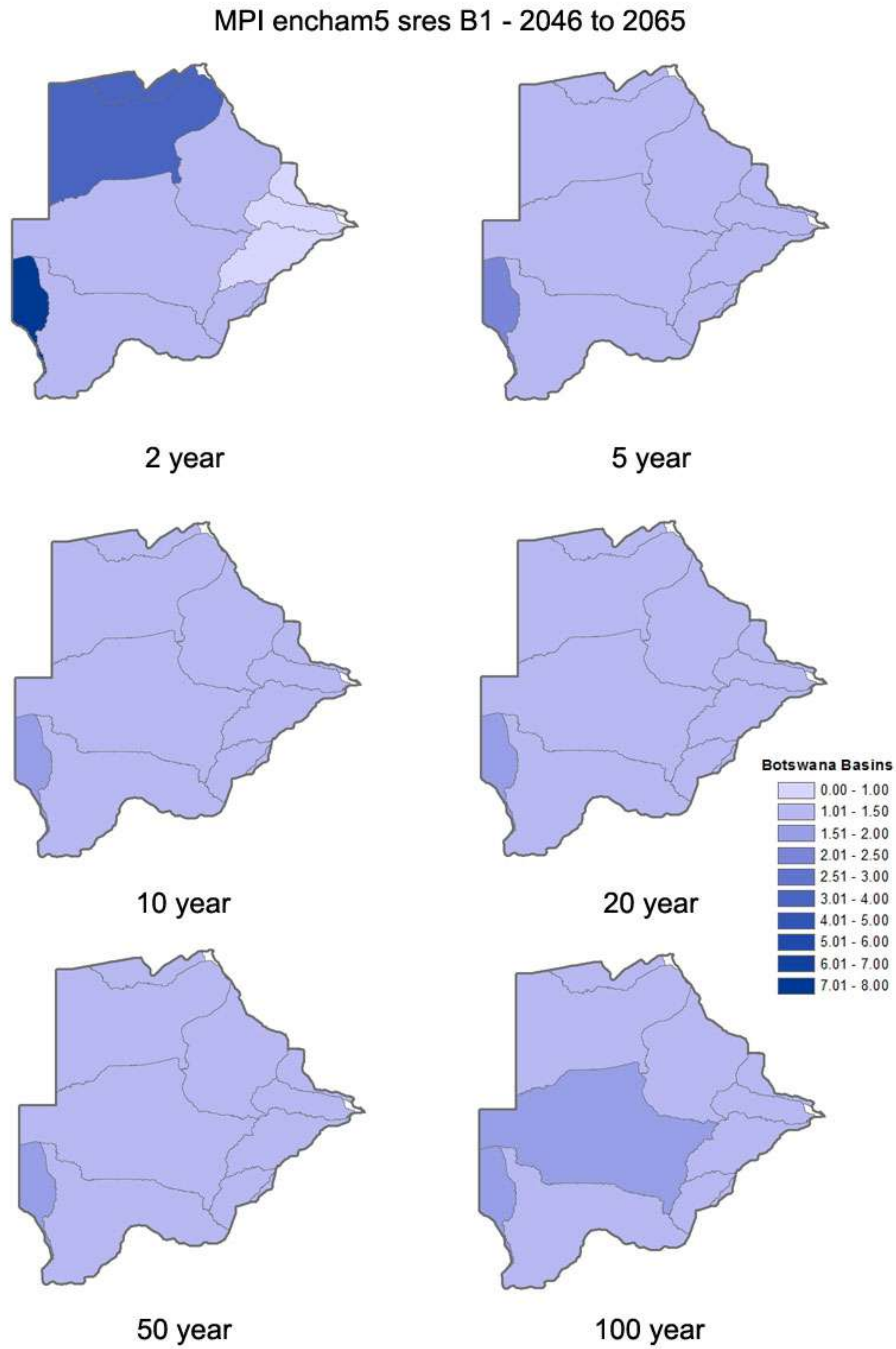
Figure 28. NRCS Dimensionless unit hydrograph (NRCS 2009).

Table 5. Land cover coefficient for velocity method (adapted from Nicklow et al. 2006)

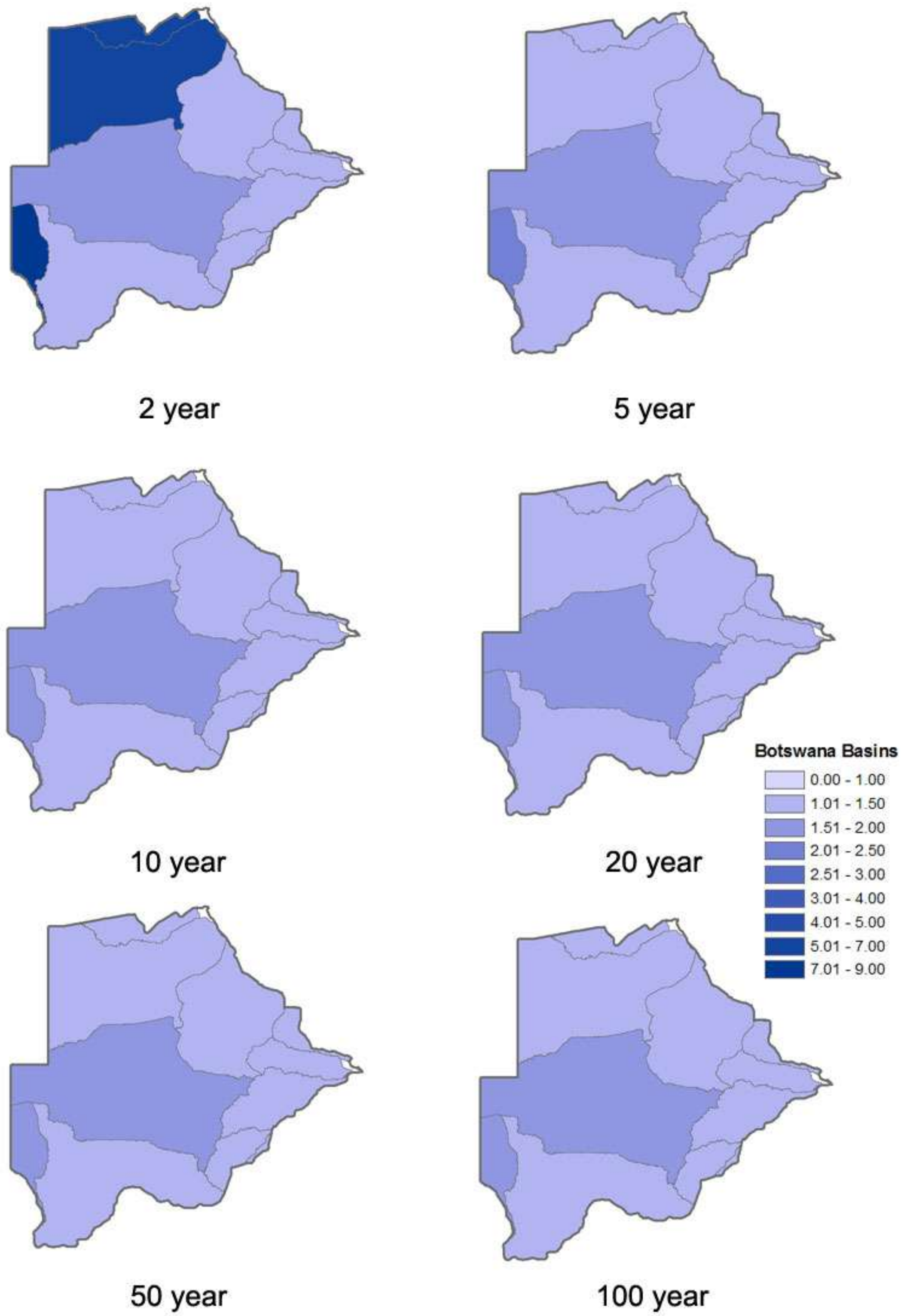
Land Cover	K
Urban	20
Crop Land	14
Fallow	10
Trees	2
Shrubs	3
Grass	7

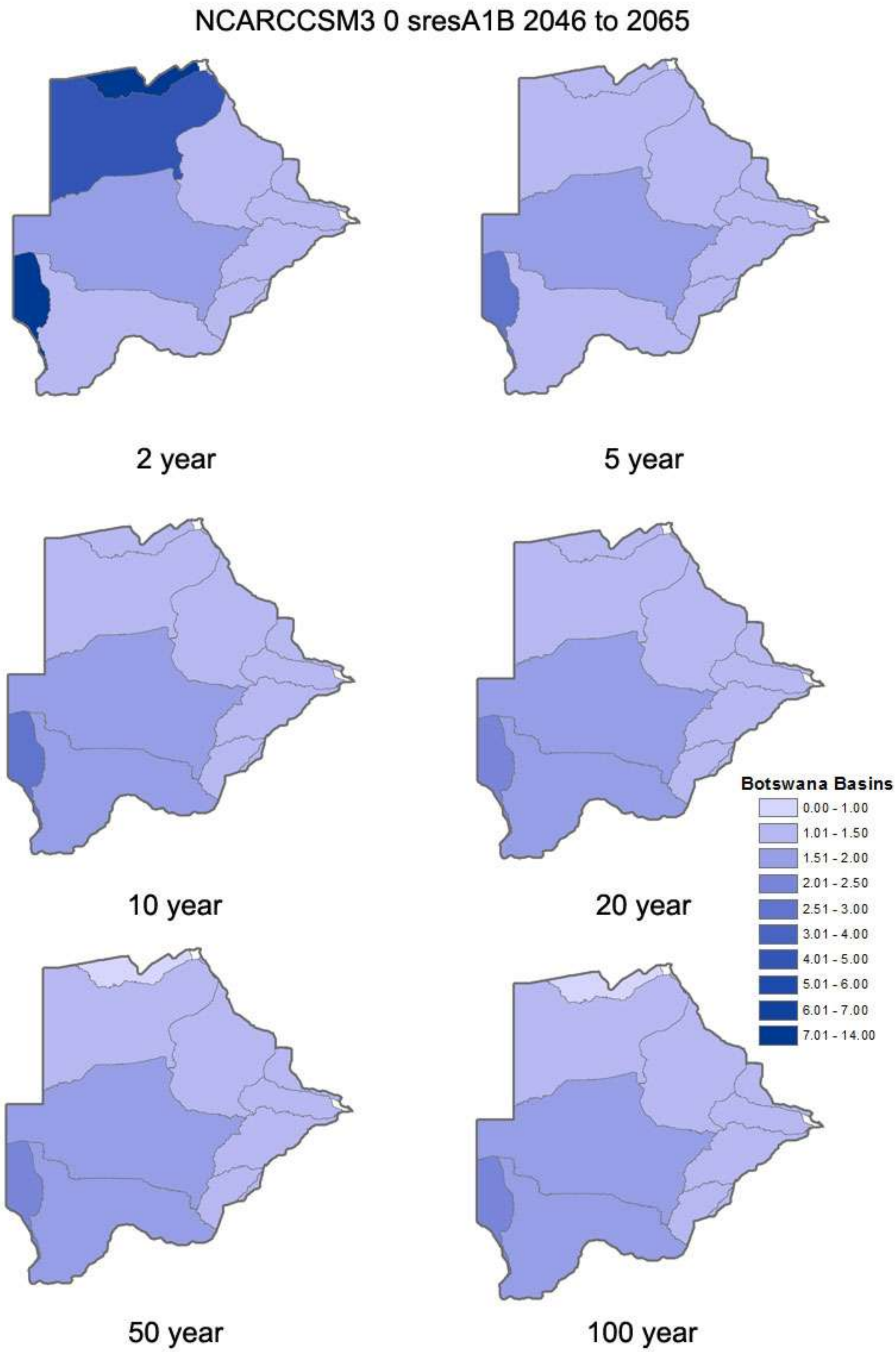
Table 6. Values of runoff curve numbers as a function of land cover and soil type (USDA NRCS, 2009).

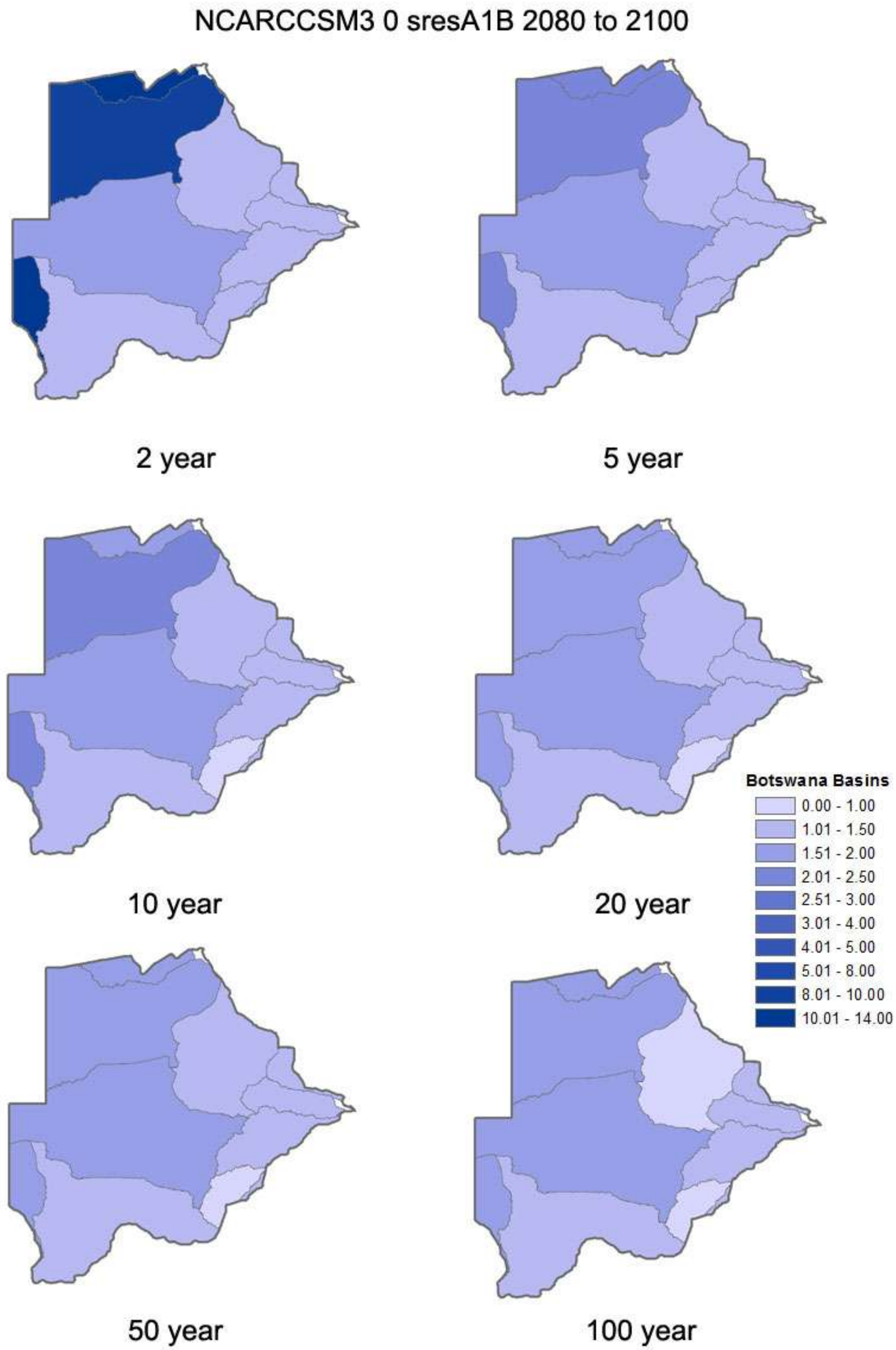
	Land Use Type	Curve Number for Hydrologic Soil Group			
		A	B	C	D
	Low Intensity Residential	61	76	84	88
	High Intensity Residential	81	88	91	93
	Commercial, Industrial, Transportation	91	94	95	96
	Rock, Sand, Clay	77	86	91	94
	Surface Mining	70	75	80	85
	Transitional	77	86	91	94
	Deciduous Forest	36	60	73	79
	Evergreen Forest	36	60	73	79
	Mixed Forest	36	60	73	79
	Shrubland	35	56	70	77
	Orchard, Vineyard	43	65	76	82
	Grassland	49	69	79	84
	Pasture, Hay	49	69	79	84
	Row Crop	69	79	86	90
	Small Grain	64	75	83	87
	Fallow	77	86	91	94
	Urban Grass	49	69	79	84
	Woody wetland	98	98	98	98
	Herb wetland	98	98	98	98


MPI encham5 sres B1 - 2046 to 2065
2 year
5 year
10 year
20 year
50 year
100 year
Botswana Basins
0.00 - 1.00
1.01 - 1.50
1.51 - 2.00
2.01 - 2.50
2.51 - 3.00
3.01 - 4.00
4.01 - 5.00
5.01 - 6.00
6.01 - 7.00
7.01 - 8.00

MPI encham5 sres B1 - 2080 to 2100




NCARCCSM3 0 sresA1B 2046 to 2065
2 year
5 year
10 year
20 year
50 year
100 year
Botswana Basins
0.00 - 1.00
1.01 - 1.50
1.51 - 2.00
2.01 - 2.50
2.51 - 3.00
3.01 - 4.00
4.01 - 5.00
5.01 - 6.00
6.01 - 7.00
7.01 - 14.00


NCARCCSM3 0 sresA1B 2080 to 2100
2 year
5 year
10 year
20 year
50 year
100 year
Botswana Basins
0.00 - 1.00
1.01 - 1.50
1.51 - 2.00
2.01 - 2.50
2.51 - 3.00
3.01 - 4.00
4.01 - 5.00
5.01 - 8.00
8.01 - 10.00
10.01 - 14.00

Annex 6: Indicator Analysis. Box plots of 6 climate indicators

Climate Moisture Index

The climate moisture index (CMI) is an indicator of the aridity of a region. The CMI depends on average annual precipitation and average annual potential evapotranspiration (PET).[13] If PET is greater than precipitation, the climate is considered to be dry whereas if precipitation is greater than PET, the climate is moist. Calculated as CMI = (P/PET)-1 {when PET>P} and CMI = 1-(PET/P) {when P>PET}, a CMI of –1 is very arid and a CMI of +1 is very humid. As a ratio of two depth measurements, CMI is dimensionless.

Runoff

Strzepek and McCluskey 2009 used GCM output as input into an offline hydrologic model, CLIRUN-II (Strzepek, et al, 2008). This model was developed specifically to assess the impact of climate change on runoff and to address extreme events at the annual level by modeling low and high flows. Outputs of climate change projections on climatic variables are input to a calibrated hydrologic model with a half degree by half degree resolution, running on a monthly time scale. Simulating monthly over a 30 year base period, from 1961 to 1990 provides for excellent estimation of annual runoff but also provides time series data to examine other statistical and stochastic variables from the 30 year monthly time series. More details can be found in Strzepek and McCluskey 2009.

Basin Yield

Annual runoff is a good measure of the potential water resource available in a basin. However the variability of that runoff within a year and in between years can make the amount available for economic development only a small fraction of the total amount. Through the use of dams and reservoirs water resource engineers have been able to increase the percentage of annual runoff that is reliably available for development. An indicator to express the ability and accessibility of runoff for economic use is the basin yield.

The basin yield is a measure of annually reliable water supply from the basin. Basin yield is directly related to the amount of reservoir storage in a basin. Water resource planners have developed methodologies to estimate reliable water supply or basin yield as a function of reservoir storage in a basin. The result of these methodologies is a concept known as the storage yield curve. Storage yield curve is an estimated time series of annual or monthly flows in the basin and provides the planner with a tool to answer two different questions. 1. How much storage is needed to provide a certain amount of annual reliable yield? 2. For a certain amount of storage, what is the reliable yield from the base? For more details, please refer to Strzepek and McCluskey 2009.

Flood Indicator

The flood indicator is taken as the flow that is exceeded 10% of the time (q10) which means there is a 90% chance in each time period of a flow lower than this. If this q10 increases it means that the likelihood of higher flows and floods will likely increase. These indicators were calculated for the base 1961-1990 runoff and then for the climate change 30 year time series. The relative changes in the q90 and q10 will provide and "indication" of how this climate change scenario is projecting changes in these key variables. For more details, please refer to Strzepek and McCluskey 2009.

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[13] Average annual PET is a parameter that reflects the amount of water lost via evaporation or transpiration (water consumed by vegetation) during a typical year for a given area if sufficient water were available at all times. Average annual evapotranspiration (ET) is a measure of the amount of water lost to the atmosphere from the surface of soils and plants through the combined processes of evaporation and transpiration during the year (measured in mm/yr). ET, which is both connected to and limited by the physical environment, is a measure that quantifies the available water in a region. Potential evapotranspiration is a calculated parameter that represents the maximum rate of ET possible for an area completely covered by vegetation with adequate moisture available at all times. PET is dependent on several variables including temperature, humidity, solar radiation and wind velocity. If ample water is available, ET should be equal to PET.

Drought Indicator

The monthly drought indicator based on surface flow is taken as the flow that is exceeded 90% of the time (q90) which means there is a 10% chance in each time period of a flow lower than this. If this q90 decreases it means that the likelihood of low flows and droughts will likely increase. These indicators were calculated for the base 1961-1990 runoff and then for the climate change 30 year time series. The relative changes in the q90 and q10 will provide and "indication" of how this climate change scenario is projecting changes in these key variables. For more details, please refer to Strzepek and McCluskey 2009.

Groundwater

In this analysis, average baseflow was used as a proxy indicator for climate change'simpact on groundwater. Winter et al and the understanding from the fundamentals of hydrology suggest that baseflow is directly connected to the shallow ground water and percolation from the root zone. Climate change will impact these soil moisture processes and percolation. CLIRUNII (used in the runoff analysis) models the root zone and shallow aquifer and thus the impacts of climate change on groundwater is modeled and reported indirectly via impacts on baseflow. For more details, please refer to Strzepek and McCluskey 2009.

Net Irrigation

To represent net irrigation demand, the Water Deficit Index (WDI) was used. The WDI calculates the difference between the precipitation and crop water requirement each month over the year. Irrigation is a major use for water resources development projects, and the economic performance of irrigated agriculture is a key component in a benefit-cost analysis. Therefore some indicator of climate change impact on irrigation performance attached to water resource development projects is needed. "The Water Deficit Index (WDI) – has recently been developed for the reference crop, grass, as a generic index for quantifying crop water stress for various crops." Woli and others have employed this simple method for climate change analyses at local and regional levels.

The Water Deficit Index (WDI) calculates the difference between the precipitation and crop water requirement each month over the year.

$$WDI = \Sigma (CWR - Precip)_t \quad \text{if } CWR_t - Precip_t > 0 \text{ else } 0$$

Where

$$CWR = K_c(t) * PET(t)$$

K_c = crop factor (crop per drop)

PET = Potential Evapotranspiration

The box plots were created for each basin within or intersecting Botswana and also there is an area weighted average presented for Botswana as a whole (labeled 'mean').

In most climate change analyses it is difficult to understand the full range of impacts from all climate scenarios. To address this, box plots were created for Botswana and each of the catchments that are within or intersect Botswana (Figure 1). The box plots display the different climate model's (GCM's) projection spreads for the three SRES's (A2, A1b, B1) as a percentage change from historical values. The items covered in the box plots are the runoff indicator, flood indicator (10%), drought indicator (90%), groundwater indicator, precipitation, PET, temperature and CMI (Climate Moisture Index). (Files contained separately). Temperature and CMI are represented as delta or absolute changes, not percentages. The CMI delta is multiplied by 10 so that it can be displayed on the same scale as delta temperature.

Box plots are very useful in understanding the average and spread of impacts from all of the climate scenarios. The box plots also show the variability in the outputs from the GCMs contributing to the variability in the analysis.

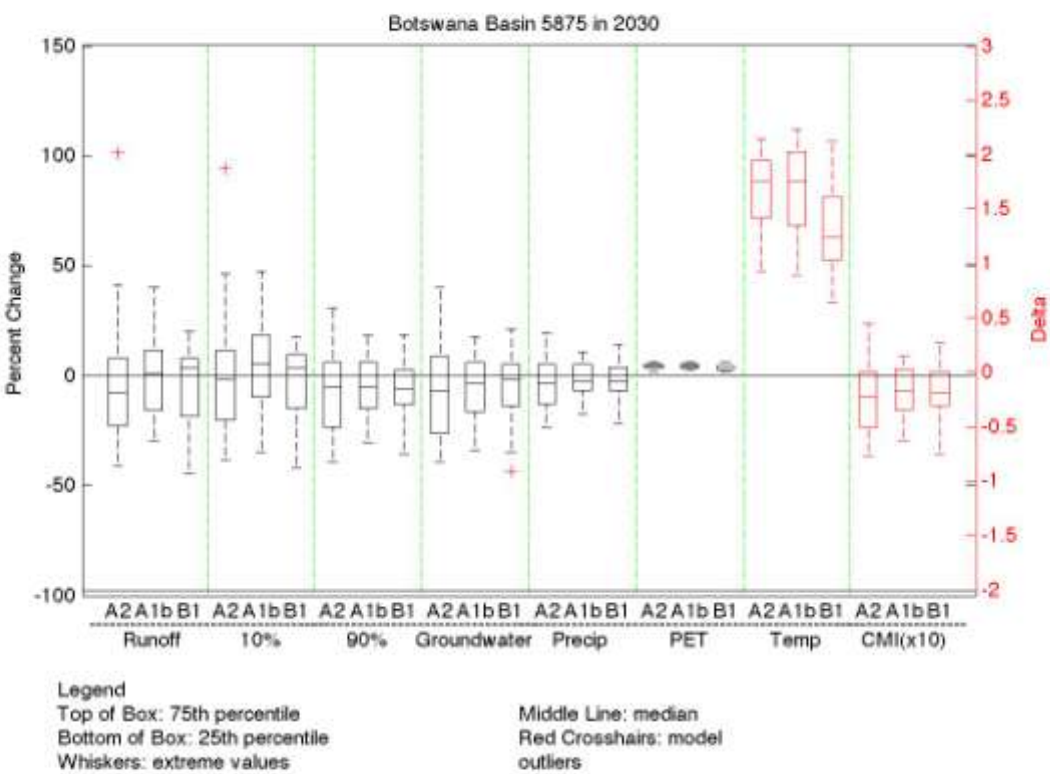
The red line represents the mean projected parameter; the top of the box represents the 75th percentile while the bottom of the box represents the 25th percentile. The whiskers show the extremes and the cross-hairs show the model outliers. The outliers are any data point that exceeds the "whiskers," which extend to 1.5*IQR (inter-quartile range). The outliers are kept in the analysis because it is considered informative and the GCMs are plausible. Therefore it does provide information on possible worst case scenarios for the indicators.

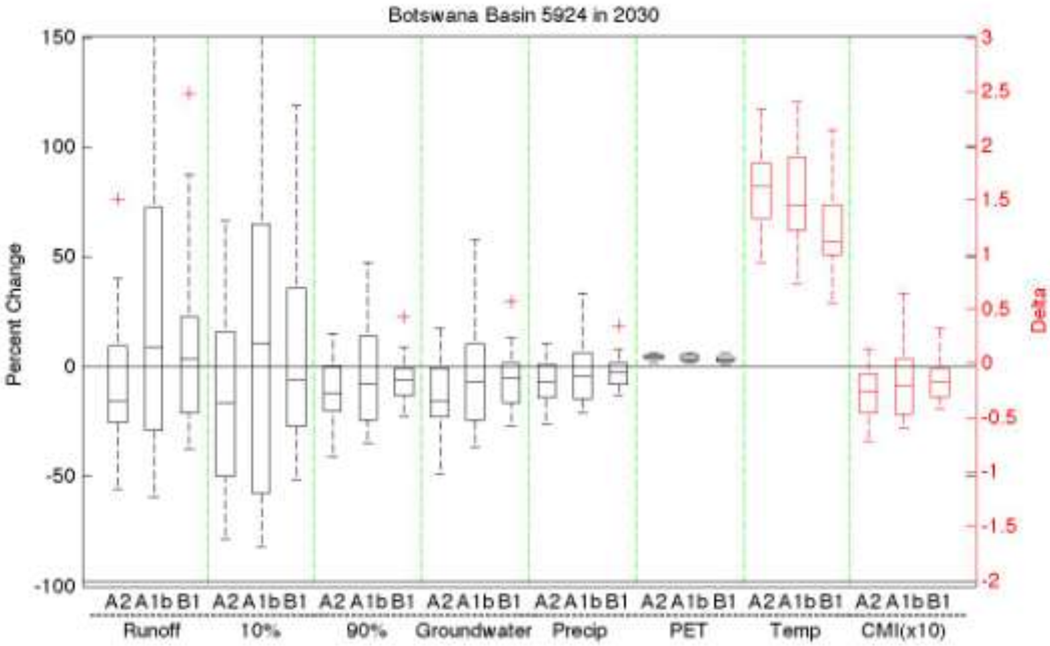
In the northern area of Botswana in 2030, basin #5875, precipitation changes range from ~20% decreases to ~20% increases with most predictions showing slight decreases. The runoff change ranges from +/- 45% changes with models showing both increases and decreases. Flooding changes range from ~50% increases to ~45% decreases with a spread among the models. Drought changes range from ~+/- 40% changes with most models leaning towards an increase in droughts. The groundwater changes vary from ~+/-45% with a bias towards a decrease in groundwater.

In 2050 in basin #5875, we see similar trends with a bit more intensity. We see more model agreement reporting decreases in runoff, groundwater, precipitation, and CMI and increases in droughts and temperature. There is not much difference between 2030 and 2050 in PET changes. There is still a large spread in the models in reporting changes to floods, with a very slight bias towards less floods.

In 2030, in the middle eastern area of Botswana (basins # 5924 and 5926), precipitation change ranges from ~35% increase to ~25% decrease with most models agreeing on decreases to precipitation. Runoff changes range from ~60% decreases to over 150% increases. The models are very distributed on runoff predictions. In basin 5926, floods ranges from ~20% increases to ~15% decreases with models showing a very slight bias towards less floods. In basin 5924, the models are much more spread out with changes ranging from ~80% decreases to over 150% increases. In both basins there is a bias towards more droughts with changes ranging from 45% increases to 50% decreases. Both basins also show model agreement on decreases in groundwater, ranging from 50% increases to 50% decreases.

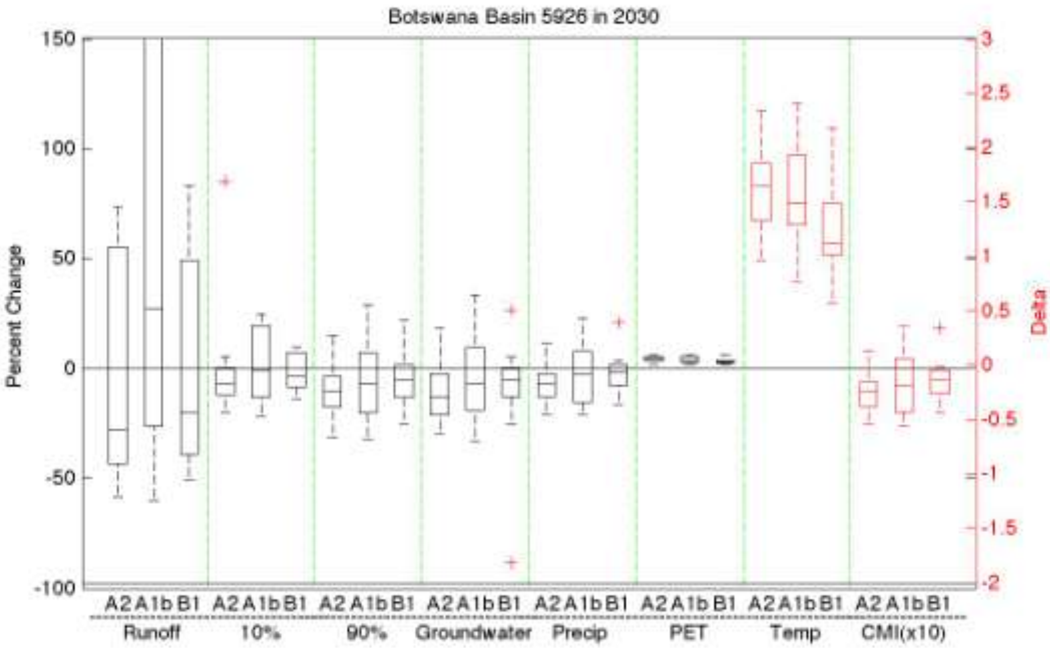
In 2050, middle eastern Botswana basins 5924 and 5926 show model agreement with increasing temperature, PET, and droughts. The models also agree on decreasing CMI, precipitation, runoff, floods, droughts, and groundwater.





Legend
Top of Box: 75th percentile
Bottom of Box: 25th percentile
Whiskers: extreme values

Middle Line: median
Red Crosshairs: model outliers



Legend
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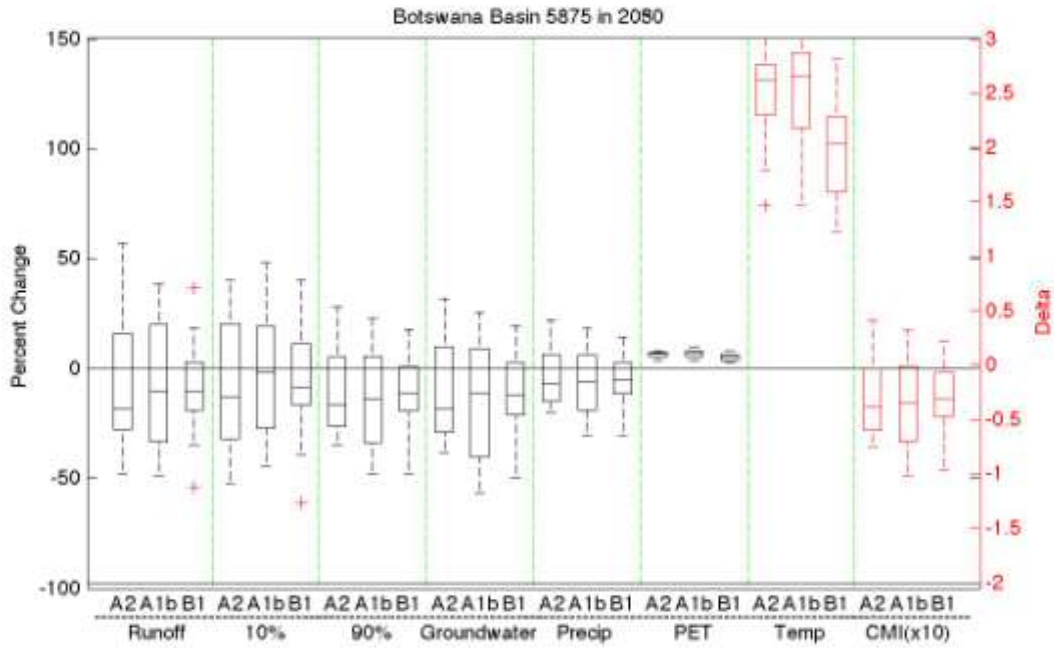
Middle Line: median
Red Crosshairs: model outliers



Legend
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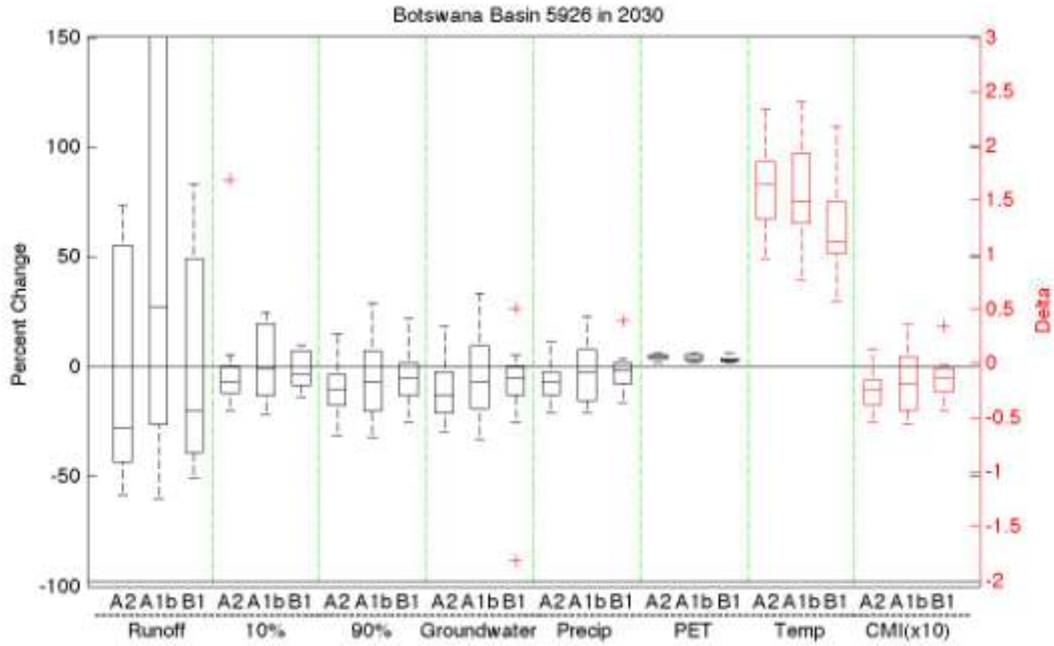

Legend
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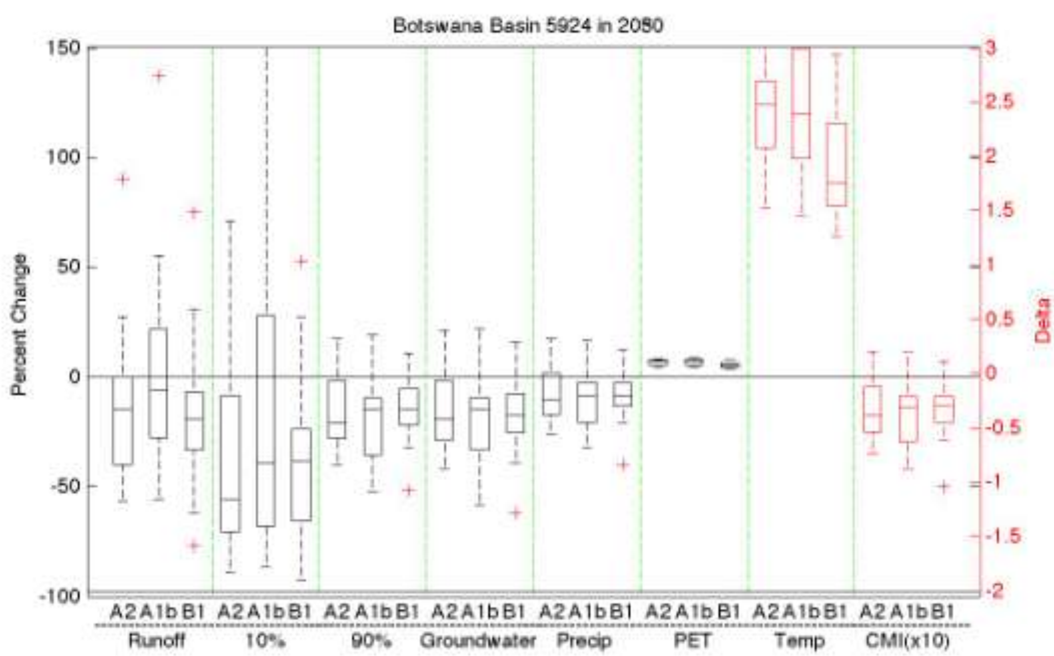

Legend
Top of Box: 75th percentile
Bottom of Box: 25th percentile
Whiskers: extreme values
Middle Line: median
Red Crosshairs: model outliers