Impacts of climate change on water availability in Botswana

DA Post, J Vaze, J Teng, R Crosbie, S Marvanek, B Wang, F Mpelasoka, L Renzullo

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Report to the Government of Botswana and the World Bank
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LIST OF FIGURES

Figure 1. Location map of Botswana showing the major towns, rivers and drainage basins... 2
Figure 2. Steps involved in the climate and water assessment methodology. ......................... 3
Figure 3. Comparison of wet (left panels) and dry (right panels) season rainfall across Botswana as derived from raingauges, NCEP reanalysis, TRMM, and NOAA datasets. ......... 6
Figure 4. Historical mean annual and dry season rainfall (from TRMM) and areal potential evapotranspiration (APET, from NCEP) across Botswana. .................................................. 7
Figure 5. Location of the 10 stream gauges and associated catchments used for calibrating the rainfall-runoff models. .......................................................... 10
Figure 6. Historical mean annual and dry season runoff across Botswana as derived from the Sacramento rainfall-runoff model driven by TRMM rainfall inputs and NCEP APET inputs. . 11
Figure 7. The rainfall, soils and vegetation used in the recharge modelling. .............................. 13
Figure 8. Historical diffuse groundwater recharge across Botswana (mm). ............................. 15
Figure 9. Example of the method used to determine change in climate variables per degree of global warming. This figure shows projected change in summer rainfall for a grid cell over northwest Botswana from the CSIRO Mk 3.5 GCM. ................................................................. 17
Figure 10. Percent change in annual rainfall across Botswana as projected by 15 GCMs. ... 19
Figure 11. Change in annual rainfall (mm) across Botswana as projected by 15 GCMs....... 20
Figure 12. Percent change in annual APET across Botswana as projected by 15 GCMs..... 21
Figure 13. Change in annual APET (mm) across Botswana as projected by 15 GCMs........ 22
Figure 14. Percent change in annual rainfall and APET across Botswana for the dry, median and wet projections of future climate. ......................................................... 24
Figure 15. Change in annual rainfall and APET (mm) across Botswana for the dry, median and wet projections of future climate. ......................................................... 24
Figure 16. Change in dry season rainfall and APET (mm) across Botswana for the dry, median and wet projections of future climate. ......................................................... 25
Figure 17. Percent change in annual runoff across Botswana as projected by 15 GCMs. .... 27
Figure 18. Change in annual runoff (mm) across Botswana as projected by 15 GCMs .... 28
Figure 19. Percent change in annual runoff across Botswana for the dry, median and wet projections of future climate. ......................................................... 30
Figure 20. Change in annual runoff (mm) across Botswana for the dry, median and wet projections of future climate. ......................................................... 30
Figure 21. Change in dry season runoff (mm) across Botswana for the dry, median and wet projections of future climate. ......................................................... 30
Figure 22. Percent change in diffuse groundwater recharge across Botswana for the dry, median and wet projections of future climate. ......................................................... 31
Figure 23. Change in diffuse groundwater recharge (mm) across Botswana for the dry, median and wet projections of future climate. ......................................................... 31
LIST OF TABLES

Table 1. List of the 10 stream gauges used in calibrating the rainfall-runoff models. ............ 8

Table 2. Daily Nash-Sutcliffe efficiencies for the Sacramento and GR4J rainfall-runoff models calibrated to 10 stream gauges. The best fit is highlighted. ................................................................. 9

Table 3. Soil types and the simplifications used in the modelling. ........................................ 14

Table 4. List of the 15 global climate models used in this study. ......................................... 16
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EXECUTIVE SUMMARY

The information in this report, along with the accompanying data sets are designed to assist with the development of a climate change action plan for Botswana. In this report, we derive the range of projected changes in rainfall, areal potential evapotranspiration, runoff and groundwater recharge due to 1 °C of global warming (corresponding to ~2030 under the A1B emission scenario). This range of results is presented as a ‘wet’, ‘median’ and ‘dry’ future projection, as derived from the outputs from 15 IPCC AR4 global climate models.

Using the TRMM rainfall product and the NCEP potential evapotranspiration reanalysis, Botswana’s average historical rainfall is 485 mm and potential evapotranspiration is 1645 mm. After calibrating the Sacramento rainfall-runoff model to historical streamflow and regionalising the results across the whole country, areal average historical runoff is estimated to be 16 mm. Using the WAVES model, historical diffuse groundwater recharge is estimated to be less than a few mm per year over most of the country, with just a few areas in the far north with appreciable rates (>30 mm/year) of recharge.

Botswana straddles the tropic of Capricorn, where the outputs of global climate models are typically mixed, with some projecting a drier future climate, and some a wetter future climate. However, for Botswana there is more agreement that rainfall will decrease in the future, with 10 of the 15 global climate models used in this study projecting a decrease in mean annual rainfall in the future and only 5 projecting an increase. Averaged across the country, the dry future projection is for a reduction in rainfall of 50 mm (10%), the median projection is for a reduction of 15 mm (3%), and the wet projection is for an increase of 13 mm (also around 3%). Across the dry season, all global climate models project a decrease in rainfall.

Due to the low rates of historical groundwater recharge and the relatively small projected changes in rainfall, changes in diffuse groundwater recharge by ~2030 are projected to be fairly insignificant. Over the far north of the country, however, recharge may decrease by ~50%, or it may increase by ~50%.

For potential evapotranspiration, there is more agreement with all 15 GCMs projecting an increase by ~2030. Averaged across the country, these increases range from 20 mm (1%) up to 60 mm (3%) with the median result being an increase of 35 mm (2%).

These projected changes in rainfall and potential evapotranspiration combine to influence projected changes in runoff. Averaged across the country, under the dry future projection, runoff is projected to decrease by 5 mm (30%); under the median projection, runoff is projected to decrease by 2 mm (12%); while under the wet future projection, runoff is projected to increase by just 1 mm (6%). In the dry season, all projections are for a decrease in runoff, however historical runoff is fairly small at this time of the year in any case, with most rivers ceasing to flow through the dry season. This cease to flow may therefore occur earlier and last longer by ~2030 due to the impacts of climate change.

The results presented in this report are only valid for those rivers that are sourced from within Botswana. The impact of climate change on large rivers which are sourced outside Botswana (such as the Okavango) would require a far more extensive study, collecting data from all neighbouring countries which contribute to the flow in these rivers. Nevertheless, the outputs of this study indicate that a drying trend is the most likely projected outcome for Botswana by ~2030.

The data underlying this report are available to any person requesting it. In particular, these data should be of use when determining the impact of climate change on the water resources, agriculture and ecosystems of Botswana.
1. INTRODUCTION

This research was undertaken by the CSIRO as their contribution to the development of a climate change action plan for Botswana. The overall program of work to develop this action plan is being carried out by the World Bank in cooperation with the Government of Botswana.

The main aim of this component of the research is to determine current surface water runoff and groundwater recharge for Botswana, as well as to determine how these are likely to change as a result of 1 °C of global warming. This level of global warming reflects the increase in global average surface temperature by ~2030 under the A1B emission scenario (IPCC 2007). As this methodology is based around an increase in global average surface temperature, rather than being for a particular year in the future, the results can be used for a range of future scenarios based on 1 °C of warming. If the rate of global warming is faster than projected, the results may be applicable earlier than 2030. Conversely, if the rate of global warming is slower than projected, the results may be applicable later than 2030.

It is anticipated that data on change in surface water runoff and groundwater recharge derived in this research will be made available to the sector experts charged with drafting a comprehensive climate change action plan for Botswana. In particular, the results of this research should prove very useful in assessing the impacts of climate change on the water resources, agriculture and ecosystem sectors.

1.1. Botswana

Botswana is a land-locked country. It has an area of approximately 580,000 square kilometres and lies across the tropic of Capricorn, between 17° 30’ S and 28° S. A location map of Botswana showing the major rivers, settlements and the Okavango Delta is shown in Figure 1.

Botswana’s climate is primarily semi-arid. Rainfall is low and highly variable from year to year. As a result, most rivers are ephemeral. Physical water scarcity is already a constraint to economic development in Botswana due to the impact of this lack of water on various sectors of the economy.

An excellent summary of the physical, climatic and cultural features of Botswana can be found in the Botswana National Atlas (Government of Botswana 2000).
1.2. Overview of methodology

A policy note was recently prepared by the World Bank to assess the impact of climate variability and change on Botswana’s development plans (World Bank 2011). This document examines the consequences of climate change as it is projected to impact climate as measured by a number of variables such as the Palmer Drought Severity Index, daily precipitation extremes, and the Standardised Precipitation Index. The current research aims to supplement the findings of this policy note by focussing on those climatic variables that are considered to be important in driving surface runoff and diffuse groundwater recharge, and using the projected changes in these variables in order to determine how surface runoff and diffuse groundwater recharge may change due to 1 °C of global warming.

The methods applied in this report were developed as part of the CSIRO Sustainable Yields Assessments that have recently, and are currently being undertaken in Australia (http://www.csiro.au/partnerships/SYP) with key results for the first assessment described in CSIRO (2008). A short description of the methodology will be provided here, while more detail on the overall method can be found in Post et al. (2012). The methods used to determine climate change impacts on runoff are described in detail in Chiew et al. (2009).
A summary of the methodology is illustrated in Figure 2. Firstly the climate scenarios (historical and future) are defined, and the outputs of these scenarios are used as inputs in rainfall-runoff and groundwater recharge modelling. The datasets produced through all three of these steps will be used as inputs into the development of a climate change action plan for Botswana, particularly the components related to the impacts of climate change on water availability, agriculture and the ecosystems of Botswana. The methodology as applied in the CSIRO Sustainable Yields projects also included river system modelling and groundwater modelling. However, as these models could not be sourced for Botswana, they were not considered here.

Figure 2. Steps involved in the climate and water assessment methodology.

1.2.1. Climate scenarios

Two sets of climate data are required – one representing historical climate used to calibrate rainfall-runoff models and determine historical runoff and diffuse groundwater recharge, and the second representing future climate, used to assess the projected changes in runoff and diffuse groundwater recharge.

Four sources of historical climate data were considered. They were derived from (i) raingauges; (ii) NCEP reanalysis; (iii) NASA TRMM; (iv) NOAA RFE 2.0. A comparison of these products is provided in Section 2.1 of this report.

Three projections of future climate were developed, representing a wet, median and dry future projection. The method used to derive these future projections is described in Section 5.1.

1.2.2. Rainfall-runoff modelling

Two rainfall-runoff models were used in this study – the Sacramento (Gan and Burges 2006) and GR4J (Perrin et al. 2003) models. Both models are widely used in water resource modelling; Sacramento tends to be used in the USA and Australia, while GR4J is more popular in Europe. Calibration and application of these models in the context of the current study is described in Section 3.1. Only the runoff that is generated within Botswana was considered in the current study. Thus, no assessment was made of the water flowing into the Okavango Delta from Angola or Namibia. An assessment of current and future streamflow in the Okavango Delta would require a more extensive program of work, sourcing additional climate and streamflow data from these two countries.
1.2.3. Groundwater recharge modelling

The WAVES model (Zhang and Dawes 1998) was used to estimate current diffuse groundwater recharge, as well as projected changes into the future. Note that only estimates of diffuse groundwater recharge were considered, and this is probably not the major mechanism controlling groundwater recharge in Botswana. Far more groundwater recharge probably occurs due to inundation of large portions of land within the Okavango Delta. However, as the water flowing into the Okavango Delta is sourced outside Botswana with the vast majority flowing in from Angola and Namibia, assessment of changes in groundwater recharge due to inundation could not be considered as part of this study.

1.2.4. Development of a climate change action plan for Botswana

The data and information being produced in the current study is intended to be used as input into the development of a climate change action plan for Botswana, particularly as related to the assessment of climate change impacts on the water resources, agriculture and ecosystems of Botswana. That work is beyond the scope of the current report, and will be carried out by the World Bank in conjunction with the Government of Botswana. However, input to the development of this action plan as related to water resources, agriculture and ecosystems will be provided by CSIRO. All of the data produced as part of the current study will be made freely available as described in Section 9.
2. HISTORICAL CLIMATE

2.1. Comparison of rainfall estimates

Before deriving the potential impacts of climate change on water availability, one must first determine historical climate and water availability. Ideally, the historical rainfall sequence chosen should have the following characteristics:

(i) It should have a long period of record in order to capture as much climate variability as possible;

(ii) it should be at a reasonably fine spatial resolution;

(iii) it should have as little missing data as possible;

(iv) as it will be used to determine runoff, it should be of sufficient accuracy to be able to calibrate rainfall-runoff models over the catchments of interest.

Four sources of historical rainfall data were sourced across Botswana: (i) raingauges; (ii) NCEP reanalysis; (iii) NASA TRMM; (iv) NOAA RFE 2.0. Raingauge data were supplied by the Department of Meteorological Services, Botswana. The NCEP reanalysis product is a widely-used climate reanalysis product from the National Centers for Environmental Prediction in the USA (Kalnay et al. 1996). The NASA TRMM (Tropical Rainfall Measurement Mission) product is derived from satellite data, ground-truthed against meteorological stations where available (http://trmm.gsfc.nasa.gov/) as is the NOAA RFE 2.0 product (http://www.cpc.ncep.noaa.gov/products/fews/RFE2.0_desc.shtml).

Unfortunately, none of the four products evaluated fulfil all four desirable characteristics listed above. As shown in Figure 3, all four products produce reasonably similar estimates of wet and dry season rainfall across Botswana. The raingauge and NCEP products have a long period of record, but the TRMM and NOAA products do not (being satellite products, they are only available from 1998 and 2001 onwards, respectively).

The spatial resolution of the products is quite variable, with the NOAA product having the highest spatial resolution, followed by TRMM. In comparison, the resolution of the NCEP data is quite poor (Figure 3). Ideally, one would wish to use data from raingauges as the data accuracy is likely to be higher, however, there is a poor spatial coverage of raingauges across Botswana, with only 16 raingauges as shown in Figure 3. Additionally, data from most raingauges contain missing data, and only a few of them are in the calibration catchments used in the rainfall-runoff modelling as shown in Figure 5.

As a result of these issues with the rainfall data, it was decided to use whichever rainfall product gave the best rainfall-runoff model calibrations. Based on this assessment (Section 3.1), the TRMM rainfall product was selected as the baseline rainfall against which the climate change projections would be assessed.

Because of ease of access, and because potential evapotranspiration is a second-order influence on runoff (particularly in a water-limited environment like Botswana), it was decided to use the NCEP potential evapotranspiration product as the baseline potential evapotranspiration against which the climate change projections would be assessed.
Figure 3. Comparison of wet (left panels) and dry (right panels) season rainfall across Botswana as derived from raingauges, NCEP reanalysis, TRMM, and NOAA datasets.
2.2. Historical climate summary

Historical rainfall as derived from TRMM and areal averaged potential evapotranspiration (APET) as derived from NCEP are shown in Figure 4. Note the different scale on the 4 maps. It will be seen that APET exceeds rainfall across the whole country, and during all seasons, although this is particularly pronounced in the dry season, here defined following Government of Botswana (2000) as the 5 months from May to September (with the wet season defined as the 7 months from October to April). As the mean annual rainfall maps are virtually identical to the wet season maps, they will not be reproduced here.

Averaged across the country, mean annual rainfall is 485 mm, of which 464 mm falls in the wet season, and 21 mm in the dry season. In comparison, mean annual APET is 1645 mm, being 1072 mm in the wet season, and 573 mm in the (cooler) dry season. Given that evaporation across Botswana is water (rather than energy) limited, it would be expected that actual evapotranspiration would be much lower than potential evapotranspiration for all locations and in all seasons.

Rainfall is also highly variable in space, ranging from less than 250 mm over the far south-west of the country up to 700 mm across the north-east of the country. Rainfall during the dry season has the opposite pattern, with the north-west of the country receiving less than 10 mm, and the south-east receiving around 50 mm.

Figure 4. Historical mean annual and dry season rainfall (from TRMM) and areal potential evapotranspiration (APET, from NCEP) across Botswana.
3. **HISTORICAL RUNOFF**

3.1. Rainfall-runoff modelling

Two rainfall-runoff models were used in this study – the Sacramento (Gan and Burges 2006) and GR4J (Perrin et al. 2003) models. As mentioned in Section 2.1, these two rainfall-runoff models were calibrated with all four sets of available rainfall data. This had two purposes; (i) to select the best rainfall-runoff model for use in the study, and (ii) to select the optimal rainfall product for use in this study.

Streamflow data were obtained from 25 locations, primarily in the north-west and eastern part of Botswana. However, as we require data from unimpaired sites (ie. those without major dams), for the streamflow to be sourced within the study area of Botswana and nearby areas (ie. excluding the Okavango Delta), and for the data to be relatively intact (ie. not too many missing values), rainfall-runoff models were only calibrated for 10 catchments. These catchments are listed in Table 1 and are shown in Figure 5.

The rainfall-runoff models were applied to each grid cell in a catchment and the catchment runoff calculated as the mean depth of runoff from each contributing grid cell. The grid cell size was defined by the rainfall inputs and thus was different for all four rainfall inputs (see Figure 3).

The quality of these calibrations were assessed using the Nash-Sutcliffe Efficiency (NSE), a commonly used statistic in hydrological modelling (Nash and Sutcliffe 1970). The results for both rainfall-runoff models using all four sets of input rainfall data are shown in Table 2. As in some cases, the period of record of streamflow data does not overlap with the period of record of available rainfall data, models could not be calibrated for all catchments using all four sets of rainfall inputs. These are represented by a ‘-’.

The TRMM rainfall product is the most applicable to use in calibrating these rainfall-runoff models, with TRMM producing the highest value of NSE in 7 of the 10 catchments and being only 0.06, 0.08 and 0.27 lower than the optimal result in the other 3 catchments. As a consistent baseline is required to determine what future changes in rainfall are likely to be, only one rainfall product can be used. As a result, rainfall presented from this point on in this report will be from the TRMM rainfall product.

It can also be seen in Table 2 that the Sacramento model outperforms the GR4J model in 7 of the 10 catchments. This is not surprising as the GR4J model tends to perform better in more humid catchments, while the Sacramento model with its 17 parameters tends to

<table>
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<th>Longitude</th>
<th>Area (km²)</th>
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The rainfall-runoff models were applied to each grid cell in a catchment and the catchment runoff calculated as the mean depth of runoff from each contributing grid cell. The grid cell size was defined by the rainfall inputs and thus was different for all four rainfall inputs (see Figure 3).

The quality of these calibrations were assessed using the Nash-Sutcliffe Efficiency (NSE), a commonly used statistic in hydrological modelling (Nash and Sutcliffe 1970). The results for both rainfall-runoff models using all four sets of input rainfall data are shown in Table 2. As in some cases, the period of record of streamflow data does not overlap with the period of record of available rainfall data, models could not be calibrated for all catchments using all four sets of rainfall inputs. These are represented by a ‘-’.

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It can also be seen in Table 2 that the Sacramento model outperforms the GR4J model in 7 of the 10 catchments. This is not surprising as the GR4J model tends to perform better in more humid catchments, while the Sacramento model with its 17 parameters tends to
outperform most other rainfall-runoff models in semi-arid catchments. For this reason, Sacramento was chosen as the most applicable model to use in the present study. Runoff presented from here on in this report will be from the Sacramento model.

Table 2. Daily Nash-Sutcliffe efficiencies for the Sacramento and GR4J rainfall-runoff models calibrated to 10 stream gauges. The best fit is highlighted.

<table>
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<th>TRMM</th>
<th>NOAA</th>
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<td>0.71</td>
<td>-</td>
</tr>
<tr>
<td>5211</td>
<td>0.38</td>
<td>0.02</td>
<td>0.04</td>
<td>0.08</td>
</tr>
<tr>
<td>5311</td>
<td>0.22</td>
<td>0.02</td>
<td>0.47</td>
<td>-</td>
</tr>
</tbody>
</table>

Having calibrated rainfall-runoff models to 10 catchments, it was then necessary to regionalise the results from these models in order to predict runoff across the reminder of the country. The characteristics of the runoff from the eastern portion of the country are likely to be different from those elsewhere (due to the eastern part of the country being on hard-veldt, compared to the sand-veldt found elsewhere (Government of Botswana 2000)). However, the runoff estimates are likely to be adequate across the remainder of the country as (i) we are primarily concerned with comparing future runoff to historical runoff, and (ii) rainfall is the primary driver of runoff and is represented reasonably well by TRMM. In addition, with no runoff gauges to calibrate to elsewhere, there is little alternative. In order to utilise information from all gauges, it was decided to calibrate one set of model parameters which provide the best representation of runoff from all 10 catchments. Having done this, these model parameters were then applied across the whole country. These results are presented in Section 3.2.

The rainfall-runoff modelling of the impact of climate change on runoff only considers the sensitivity of future runoff to changes in the rainfall and APET patterns. It does not take into account potential changes in the rainfall-temperature-runoff relationship or dominant
hydrological processes in a warmer and higher CO2 environment. Nevertheless, Vaze et al. (2010) suggest that the approach is reasonable for the near to medium term projections examined here and for the small to medium changes in rainfall projected for the region.

The adequacy of this approach will be presented by Vaze et al. (2012) at HydroPredict 2012 to be held 24-27 September in Vienna, Austria, and Post et al. (2012) at the Prediction in Ungauged Basins wrap-up workshop to be held 22-26 October in Delft, The Netherlands. These presentations will consider the problems of regionalising hydrologic response to ungauged basins in data-poor areas, as well as presenting the results of the various rainfall-runoff/climatic input combinations and assessing how much this would alter the results of the study.

Figure 5. Location of the 10 stream gauges and associated catchments used for calibrating the rainfall-runoff models.
3.2. Historical runoff summary

Historical runoff as modelled using the Sacramento model driven by rainfall inputs from TRMM and APET inputs from NCEP are shown in Figure 6. Averaged across the country, mean annual runoff is 16 mm, with over 15 mm occurring during the wet season and less than 1 mm during the dry season.

The spatial pattern of runoff follows the spatial pattern of rainfall (Figure 4) fairly closely. Runoff is lowest in the south-west of the country, being less than 5 mm, increasing to around 50 mm across the wetter north-east of the country. During the dry season, runoff is less than 5 mm across most of the country, reflecting the very low rainfall during those months. Any runoff that does occur tends to be in May, responding to rain that has fallen throughout the wet season.

![Figure 6. Historical mean annual and dry season runoff across Botswana as derived from the Sacramento rainfall-runoff model driven by TRMM rainfall inputs and NCEP APET inputs.](image)
4. HISTORICAL DIFFUSE GROUNDWATER RECHARGE

4.1. Recharge modelling

For most of the 20th century it was assumed that recharge did not occur beneath the Kalahari Sands, this assumption began with Passage in 1906 (cited in Mazor (1982)) and continued through until the 1980s (Foster et al. 1982). After this time, evidence of recent recharge was found through field studies using tritium, $^{14}$C and the observation of water level rises in response to rainfall (Mazor 1982). There have been limited field studies that have quantified recharge in Botswana. Using chloride profiles through the Kalahari Sands, de Vries et al. (2000) estimated recharge to be 5 mm/yr in the east under 450 mm/year of rainfall and 1 mm/yr in the centre of the country where rainfall is 300 mm/year. On a different soil type in the south-east, Gieske et al. (1990) estimated recharge to be 2.5% of the 550 mm/year rainfall but concluded that due to the heterogeneity this recharge figure could not be relied upon.

More recent recharge investigations have focused upon modelling, Brunner et al. (2004) used remote sensing to regionalize recharge estimates for part of the north of the country and Wanke et al. (2008) used a water balance model over a similar region. These modelling studies were for higher rainfall areas than the field estimates of recharge and so are not directly comparable.

The method used in the present study for modelling the baseline historical recharge and the recharge under a future climate is based upon the methods used in Australia for the Murray-Darling Basin (Crosbie et al. 2010) and Tasmania (Post et al. 2012).

4.2. Choice of model code

The model chosen for the recharge modelling in this study was WAVES. It is a Soil-Vegetation-Atmosphere-Transfer model that can be used to estimate the components of an unsaturated zone water balance. It achieves a balance in its modelling complexity between soil physics, plant physiology, energy and solute balances. WAVES has been shown to be able to reproduce the water balance of field experiments in many studies in Australia and throughout the world (Zhang et al. 1996; Salama et al. 1999; Slavich et al. 1999; Zhang et al. 1999; Wang et al. 2001; Dawes et al. 2002; Yang et al. 2003; Crosbie et al. 2008). Some changes were made to the model code to tailor its use for climate change impact studies; these are detailed in McCallum et al. (2010). The WAVES model requires three different data sets; these are the climate, soil and vegetation inputs. The input files for the model were created for each combination of climate, soil and vegetation found in Botswana.

A four metre deep soil profile was modelled with a free draining lower boundary condition. It was assumed that the deep drainage from the bottom of the model was equivalent to groundwater recharge and did not become lateral flow within the unsaturated zone. The assumption was made that diffuse recharge in dryland areas was not affected by depth to groundwater; this assumption will result in errors where the water table is close to the surface.

4.3. Model Inputs

The WAVES model needs three data sets to run: climate, soils and vegetation (Figure 7). The intersection of these three data layers results in 196 polygons with 142 unique combinations of climate, soils and vegetation that require modelling with WAVES. These inputs are described in the following sections.
4.3.1. Climate

The WAVES model requires daily inputs of rainfall, maximum and minimum temperature, vapour pressure deficit and net radiation. It also requires a long model spin-up period and a correspondingly long model run period. Unfortunately these data streams were not available for this length of time from the observed station data or the TRMM data and so the NCAR/NCEP reanalysis data was used. This is a global gridded dataset at a spatial resolution of 2.5° with a time period spanning from 1 January 1948 to 31 December 2010. For the historical baseline modelling the climate data was looped twice with the first 63 years discarded from the results as a model spin-up period to avoid any influence of the initial conditions on the reported modelled recharge.

As the WAVES model has a carbon balance within its vegetation growth routine, it needs the atmospheric CO$_2$ concentration as a parameter. For the historical climate the observed CO$_2$ concentration in 1990 was used, 353 ppm (IPCC 2007). For the future climate scenario a CO$_2$ concentration of 478 ppm was used. This was inferred from the IPCC (2007) to cover the range of SRES scenarios (Nakicenovic et al. 2000).

For the future climate scenarios, the historical climate data was modified using the results of 15 GCMs under a 1 °C global warming scenario to produce 15 time series of future climate variants. The downscaling method is described in Chiew et al. (2009). The future climate variants were modelled in WAVES similarly to the historical baseline data using the looped time series as a model spin-up period.

4.3.2. Soils

The soils information required is in the form of soil moisture retention and hydraulic conductivity curves. The Broadbridge-White (Broadbridge and White 1988) functions are used so that numerical convergence is most stable within WAVES. The soil types identified in Figure 7 (Government of Botswana 2000) were simplified down to six different soil types as shown in Table 3.
Table 3. Soil types and the simplifications used in the modelling.

<table>
<thead>
<tr>
<th>AREA</th>
<th>Soil</th>
<th>Simplification</th>
</tr>
</thead>
<tbody>
<tr>
<td>43.5%</td>
<td>Arenosols</td>
<td>Deep Sands</td>
</tr>
<tr>
<td>14.7%</td>
<td>Vertisols</td>
<td>Heavy Clay</td>
</tr>
<tr>
<td>12.7%</td>
<td>Chernozem</td>
<td>Calcareous</td>
</tr>
<tr>
<td>5.4%</td>
<td>Cambisols</td>
<td>Light Gradational</td>
</tr>
<tr>
<td>4.6%</td>
<td>Solonetz</td>
<td>Duplex</td>
</tr>
<tr>
<td>4.1%</td>
<td>Phaeozems</td>
<td>Light Gradational</td>
</tr>
<tr>
<td>3.6%</td>
<td>Calcisols</td>
<td>Calcareous</td>
</tr>
<tr>
<td>2.8%</td>
<td>Fluvisols</td>
<td>Skeletal</td>
</tr>
<tr>
<td>2.6%</td>
<td>Acrisols</td>
<td>Duplex</td>
</tr>
<tr>
<td>1.9%</td>
<td>Regosols</td>
<td>Skeletal</td>
</tr>
<tr>
<td>1.6%</td>
<td>Lixisols</td>
<td>Duplex</td>
</tr>
<tr>
<td>0.9%</td>
<td>Solonchaks</td>
<td>Duplex</td>
</tr>
<tr>
<td>0.5%</td>
<td>Luvisols</td>
<td>Duplex</td>
</tr>
<tr>
<td>0.4%</td>
<td>Gleysols</td>
<td>Heavy Clay</td>
</tr>
<tr>
<td>0.4%</td>
<td>Planosols</td>
<td>Duplex</td>
</tr>
<tr>
<td>0.3%</td>
<td>Leptosols</td>
<td>Skeletal</td>
</tr>
</tbody>
</table>

4.3.3. Vegetation

The vegetation layer (Government of Botswana 2000) was simplified to two categories (Figure 7):

- Grassland – aquatic grassland, grass savanna, semi-arid shrub savanna and shrub savanna
- Trees – close tree savanna, dry deciduous forest, riparian forest, tree savanna and woodland

The WAVES parameters required for these two vegetation types were based upon those used across Northern Australia (Crosbie et al. 2009) due to a lack of local information on parameterization.
4.4. Historical diffuse groundwater recharge summary

Historical diffuse groundwater recharge as modelled by the WAVES model is shown in Figure 8. In general, diffuse groundwater recharge across most of Botswana is less than 1 mm/year and is unlikely to contribute greatly to groundwater in comparison with the recharge due to inundation by the Okavango Delta. Only in the far north-east of the country, where heavy rainfall occurs in conjunction with the sandveld, does recharge exceed 30 mm/year.

Figure 8. Historical diffuse groundwater recharge across Botswana (mm).
5. PROJECTIONS OF ~2030 CLIMATE

5.1. Methods

The steps undertaken to derive future climate data for Botswana were as follows:

Archived monthly simulations from 15 IPCC AR4 global climate models (GCMs) as listed in Table 4 were analysed to estimate the change in rainfall and other climate variables per degree of global warming. Each GCM was analysed separately. Data from each of the four seasons (DJF, MAM, JJA, and SON) were also analysed separately. The results of this analysis provide the change in each climate variable per degree of global warming.

Figure 9 shows one example of this for one grid cell over north-western Botswana (centred on 17.5°S, 22.5°E) for one variable (rainfall) in one season (summer) and one GCM (CSIRO Mk 3.5) where summer (DJF) rainfall for the years 2001-2100 are plotted against global annual temperature for each year. In the example shown, summer rainfall is projected to decrease by 45 mm per degree of global warming for this grid cell (a change of 8% relative to the long-term historical average rainfall (1871-2000) of 537 mm).

<table>
<thead>
<tr>
<th>Model name</th>
<th>Originating Group(s)</th>
<th>Country</th>
<th>CMIP3 ID</th>
<th>Resolution (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCCMA_T47</td>
<td>Centre for Climate Modelling &amp; Analysis</td>
<td>Canada</td>
<td>CGCM3.1(T47)</td>
<td>3.8 x 3.7</td>
</tr>
<tr>
<td>CCCMA_T63</td>
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<td>Canada</td>
<td>CGCM3.1(T63)</td>
<td>2.8 x 2.8</td>
</tr>
<tr>
<td>CNRM</td>
<td>Météo-France / Centre National de Recherches Météorologiques</td>
<td>France</td>
<td>CNRM-CM3</td>
<td>2.8 x 2.8</td>
</tr>
<tr>
<td>CSIRO</td>
<td>CSIRO</td>
<td>Australia</td>
<td>CSIRO-Mk3.0</td>
<td>1.9 x 1.9</td>
</tr>
<tr>
<td>GFDL</td>
<td>US Department of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory</td>
<td>USA</td>
<td>GFDL-CM2.0</td>
<td>2.5 x 2</td>
</tr>
<tr>
<td>GISS_AOM</td>
<td>NASA/Goddard Institute for Space Studies</td>
<td>USA</td>
<td>GISS-AOM</td>
<td>4 x 3</td>
</tr>
<tr>
<td>IAP</td>
<td>LASG / Institute of Atmospheric Physics</td>
<td>China</td>
<td>FGOALS-g1.0</td>
<td>2.8 x 2.8</td>
</tr>
<tr>
<td>INMCM</td>
<td>Institute for Numerical Mathematics</td>
<td>Russia</td>
<td>INM-CM3.0</td>
<td>5 x 4</td>
</tr>
<tr>
<td>IPSL</td>
<td>Institut Pierre Simon Laplace</td>
<td>France</td>
<td>IPSL-CM4</td>
<td>3.8 x 2.5</td>
</tr>
<tr>
<td>MIROC</td>
<td>Center for Climate System Research, National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC)</td>
<td>Japan</td>
<td>MIROC3.2-M</td>
<td>2.8 x 2.8</td>
</tr>
<tr>
<td>MIUB</td>
<td>Meteorological Institute of the University of Bonn and Meteorological Research Institute of KMA.</td>
<td>Germany/Korea</td>
<td>ECHO-G</td>
<td>3.8 x 3.7</td>
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<tr>
<td>MPI</td>
<td>Max Planck Institute for Meteorology</td>
<td>Germany</td>
<td>ECHAM5/MPI</td>
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<td>MRI</td>
<td>Meteorological Research Institute</td>
<td>Japan</td>
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<tr>
<td>NCAR_CCCSM</td>
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<td>CCSM3</td>
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<tr>
<td>NCAR_PCM</td>
<td>National Center for Atmospheric Research</td>
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<td>PCM</td>
<td>2.8 x 2.8</td>
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</tbody>
</table>
The mean average modelled rainfall for this grid cell of 537 mm as derived from the CSIRO Mk3.5 model is slightly lower than the observed rainfall (shown in Figure 4). However, as the technique used derives change in rainfall per degree of global warming, the impacts of this error are minimised. An assessment of the adequacy of GCMs in climate impact studies is beyond the scope of this report, but is addressed in Beven (2011), Kiem and Verdon-Kidd (2011), and Post and Moran (2011).

The percent changes in the climate variables per degree of global warming for each of the four seasons for each GCM grid cell from all 15 GCMs were then used as ‘seasonal scaling’ factors. For the rainfall-runoff modelling, these seasonal scaling factors were then used to scale the historical daily (TRMM) rainfall data and NCEP APET data from 1998 to 2010 to obtain 15 future climate variants, each with 13 years of daily climate data. Because of the different requirements for the recharge modelling, the historical data used was the NCEP rainfall and APET data from 1948 to 2010, producing 63 years of daily climate data.

![Graph](Image)

**Figure 9.** Example of the method used to determine change in climate variables per degree of global warming. This figure shows projected change in summer rainfall for a grid cell over northwest Botswana from the CSIRO Mk 3.5 GCM.
5.2. Global climate model projections

5.2.1. Rainfall

Change in mean annual rainfall across Botswana for 1°C of global warming as projected by 15 GCMs is shown as a percentage change (Figure 10) and mm change (Figure 11). There is a large degree of variability between the 15 GCMs, ranging from a decrease in rainfall averaged across the country of 56 mm (12%) from the MRI model to an increase in rainfall of 14 mm (3%) from the CCCMA_T47 model. However, on average across the country, 10 GCMs project less rainfall on average and only 5 GCMs project more rainfall on average. This is true both annually and for the wet season. Across the dry season (not shown), no GCMs project an increase in rainfall.

In order to facilitate comparison between maps, the order of GCMs is kept the same for all GCM comparison figures in this report, starting with the MRI model and ending with CCCMA_T47. This order is somewhat arbitrary, but for ease of comparison is based on the projected percent changes in mean annual rainfall for 1°C of global warming, ranging from the driest (MRI) to the wettest model (CCCMA_T47).

5.2.2. APET

Change in mean annual APET across Botswana for 1°C of global warming as projected by 15 GCMs is shown as a percentage change (Figure 12) and mm change (Figure 13). For APET, there is less variability between the 15 GCMs, with APET projected to increase by all 15 GCMs. Averaged across Botswana, this increase ranges from 3 mm (0.2%) from the MRI model to 74 mm (4.5%) from the CCCMA_T63 model. For the dry season (not shown), just one GCM (MRI) projects a small (1 mm) decrease in APET, with the other 14 projecting an increase of up to 26 mm from the CCCMA_T63 model.
Figure 10. Percent change in annual rainfall across Botswana as projected by 15 GCMs.
Figure 11. Change in annual rainfall (mm) across Botswana as projected by 15 GCMs.
Figure 12. Percent change in annual APET across Botswana as projected by 15 GCMs.
Figure 13. Change in annual APET (mm) across Botswana as projected by 15 GCMs.
5.3. Summary of projected changes in rainfall and APET

While the projections from the 15 GCMs provide the full range of modelled future responses, it can be difficult to work with 15 sets of time series. As a result, the projected changes have been summarised into 3 projections – one representing a ‘dry’ future climate, one representing a ‘wet’ future climate, and one representing the ‘median’ future climate.

To capture the range of results but exclude the outliers, the dry projection was taken to be the result from the second driest GCM, while the wet projection was taken to be the result from the second wettest GCM. The median projection was taken to be the result from the 8th wettest (and by definition as there are 15 GCMs considered, also 8th driest) GCM. This was done for rainfall, APET, recharge and runoff separately as the GCM chosen for one variable may not be the same GCM chosen for another. This was done on a grid cell by grid cell basis across the whole country (on either TRMM 0.1° or NCEP 2.5° grids). Thus, a different GCM may be chosen for adjacent grid cells. Averaged across the whole country, this may slightly bias the results, however it is considered superior to using one GCM as the dry or wet extreme everywhere, as the dry GCM across one part of the country may predict an increase in rainfall across another part of the country. This would not give an accurate projection of a future ‘dry’ or ‘wet’ (or indeed ‘median’) scenario across the whole country.

Figure 14 shows the percent change in future annual rainfall and APET under the dry, median and wet future projections, while Figure 15 shows the same projections expressed as a change in mm from historical conditions.

Under the dry future projection, annual rainfall is projected to decrease across the entire country, ranging from 7% to 13%, with an average reduction of 10%. This equates to a reduction of around 80 mm in the north and around 20 mm in the south of the country, with an average reduction of 50 mm. Annual APET is projected to increase by between 2% and 4%, with an average increase of just over 3%. This equates to an increase of between 30 mm and 70 mm with an average increase of 60 mm.

Under the median future projection, annual rainfall is also projected to decrease across the entire country, ranging from 1% to 6%, with an average reduction of 3%. This equates to a reduction of between 5 mm and 35 mm, with an average reduction of 15 mm. Annual APET is projected to increase by between 0% and 3%, with an average increase of 2%. This equates to an increase of between 0 mm and 50 mm with an average increase of 35 mm.

Under the wet future projection, annual rainfall is projected to stay around the same or increase across the whole country, but only by between 0% and 6%, with an average increase of 3%. This equates to an increase of between 2 mm and 30 mm, with an average increase of 13 mm. Even under the least severe (wettest) of future projections, annual APET is still expected to increase by between 0% and 2%, with an average increase of 1%. This equates to an increase of between 0 mm and 40 mm with an average increase of 20 mm.

Changes in rainfall and APET in mm during the dry season is shown in Figure 16. Reductions in rainfall and increases in APET are projected for most of the country under all future projections, even the wet future projection. Based on this, we can be fairly confident that dry season rainfall will decrease and APET will increase. However, as historical dry season rainfall is quite small (see Figure 4), these changes are also quite small (compare the legend on Figure 16 to that on Figure 15). These changes are not important in terms of the annual water balance, but may be important regionally, particularly for ecosystems that rely on dry season rainfall.
Figure 14. Percent change in annual rainfall and APET across Botswana for the dry, median and wet projections of future climate.

Figure 15. Change in annual rainfall and APET (mm) across Botswana for the dry, median and wet projections of future climate.
Figure 16. Change in dry season rainfall and APET (mm) across Botswana for the dry, median and wet projections of future climate.
6. PROJECTIONS OF ~2030 RUNOFF

6.1. Methods

Having derived 15 projections of future rainfall and APET consisting of 13 years of daily climate data (Section 5), these 13 years of data were used as inputs into the regionally calibrated Sacramento rainfall-runoff model to produce 15 estimates of future runoff across the whole country. These were then compared to the historical estimates of runoff (Section 3.2) in order to derive the projected changes in runoff characteristics.

6.2. Global climate model projections

Change in mean annual runoff across Botswana for 1°C of global warming as projected by 15 GCMs is shown as a percentage change (Figure 17) and mm change (Figure 18). In general, these patterns reflect those shown in the percentage change and mm change in annual rainfall (Figure 10 and Figure 11 respectively). As a percentage change, the changes in runoff tend to be amplified compared to the percent changes in rainfall, while, obviously, the change in runoff in mm is less than the change in rainfall in mm.

The driest GCM (MRI) projects a decrease in runoff averaged across the country of 5.4 mm (32%), while the wettest GCM (CNRM) projects an increase in runoff of slightly less than 1 mm (6%). While 10 GCMs project a decrease in annual rainfall, because of the increase in APET, 12 GCMs project a decrease in annual runoff. For the wet season (not shown), 10 GCMs project a decrease in both rainfall and runoff, and in the dry season (not shown), no GCMs project an increase in rainfall or runoff.
Figure 17. Percent change in annual runoff across Botswana as projected by 15 GCMs.
Figure 18. Change in annual runoff (mm) across Botswana as projected by 15 GCMs.
6.3. Summary of projected changes in runoff

As described in Section 5.3 for rainfall and APET, to capture the range of results but exclude the outliers, the dry projection was taken to be the result from the second driest GCM, while the wet projection was taken to be the results from the second wettest GCM. The median projection was taken to be the result from the 8\textsuperscript{th} wettest (and by definition also 8\textsuperscript{th} driest) GCM.

Figure 19 shows the percent change in future annual runoff under the dry, median and wet future projections, while Figure 20 shows the same projections expressed as a change in mm from historical conditions.

Under the dry future projection, annual runoff is projected to decrease across the entire country, ranging from 20\% to 80\%, with an average reduction of 30\%. This equates to a reduction of around 15 mm in the north and little to no change in the drier south of the country, with an average reduction of 5 mm.

Under the median future projection, annual runoff is also projected to decrease across the entire country, ranging from little or no change in some parts up to reductions of 35\%, with an average reduction of 12\%. This equates to little or no change in absolute (mm) terms up to reductions of 8 mm elsewhere with an average reduction of 2 mm.

Under the wet future projection, annual runoff is projected to increase across most of the country, with some areas experiencing a 10\% reduction, but others experiencing increases of over 100\%, averaging a 6\% increase over the whole country. The areas experiencing a large percentage increase in runoff however have little runoff historically, and thus the increases are relatively modest, up to a maximum of just 5 mm, with reductions in the north-east of up to 2 mm. Averaged across the whole country, annual runoff is projected to increase by just 1 mm.

Projected changes in dry season runoff are shown in Figure 21. As expected, based on the projected changes in dry season rainfall (Figure 16), reductions in runoff are projected across the entire country. However, as the historical runoff is quite small (see Figure 6), these changes in runoff are also quite small (compare the legend in Figure 21 to that in Figure 20) and are very minor in terms of the annual water balance. These changes may however be important for ecosystems that rely on the small amounts of streamflow that do occur during the dry season.
Figure 19. Percent change in annual runoff across Botswana for the dry, median and wet projections of future climate.

Figure 20. Change in annual runoff (mm) across Botswana for the dry, median and wet projections of future climate.

Figure 21. Change in dry season runoff (mm) across Botswana for the dry, median and wet projections of future climate.
7. PROJECTIONS OF ~2030 DIFFUSE GROUNDWATER RECHARGE

Projected changes in diffuse groundwater recharge are shown as a percent change from historical recharge in Figure 22 and as mm change in Figure 23. Change in diffuse groundwater recharge expressed as a percentage is projected to decrease considerably under the dry future scenario and increase considerably under the wet future scenario. However, as will be seen from Figure 8 and Figure 23, as rates of historical diffuse groundwater recharge are so low across most of the country, these projected changes are small in terms of change in the volume of groundwater recharge. Additionally, as much of the historical groundwater recharge takes place through inundation of the Okavango Delta, and this has not been assessed in the current study, these projected changes in diffuse groundwater recharge are probably not important at a national scale, although they may be important regionally.

Figure 22. Percent change in diffuse groundwater recharge across Botswana for the dry, median and wet projections of future climate.

Figure 23. Change in diffuse groundwater recharge (mm) across Botswana for the dry, median and wet projections of future climate.
8. CONCLUSIONS

Historically, Botswana averages 485 mm of rainfall and 1645 mm of APET. These numbers are derived from the TRMM rainfall product and the NCEP APET reanalysis product. After calibrating the Sacramento rainfall-runoff model to historical streamflow and regionalising the results across the whole country, historical runoff is estimated to be just 16 mm. Using the WAVES model, historical diffuse groundwater recharge is estimated to be less than a few mm per year over most of the country, with just a few areas in the far north with appreciable rates (>30 mm/year) of recharge.

Botswana straddles the tropic of Capricorn, where the outputs of GCMs are typically mixed, with some projecting a drier future climate, and some a wetter future climate. However, for Botswana there is more agreement that rainfall will decrease in the future, with 10 of the 15 GCMs projecting a decrease in mean annual rainfall in the future and only 5 projecting an increase. When these projections are summarised into ‘wet’, ‘median’ and ‘dry’ future projections for ~2030 (representing 1 °C of global warming), the dry projection is for a reduction in rainfall of 50 mm (10%), the median projection is for a reduction of 15 mm (3%), and the wet projection is for an increase of 13 mm (also around 3%). In the dry season, all GCMs project a decrease in rainfall.

Due to the low rates of historical groundwater recharge and the relatively small projected changes in rainfall, changes in diffuse groundwater recharge by ~2030 are projected to be mostly insignificant. Over the far north of the country, however, recharge may decrease by ~50%, or it may increase by ~50%.

For APET, there is more agreement with all 15 GCMs projecting an increase. These increases range from 20 mm (1%) up to 60 mm (3%) with the median result being an increase in APET of 35 mm (2%).

These projected changes in rainfall and APET combine to influence projected changes in runoff. Averaged over the whole country, under the dry future projection, runoff is projected to decrease by 5 mm (30%), under the median projection, runoff is projected to decrease by 2 mm (12%), while under the wet future projection, runoff is projected to increase by just 1 mm (6%). In the dry season, all future projections are for a decrease in runoff, however historical runoff is fairly insignificant at this time of the year in any case, with most of the rivers ceasing to flow. This cease to flow may occur earlier and last longer by ~2030 due to the impacts of climate change.
9. DATA AVAILABILITY

All of the data produced as part of this project are freely available. Copies of the data have been provided to the World Bank and the Government of Botswana. These should be the first point of contact for accessing data. Questions can be sent to the primary author of this report at David.Post@csiro.au.

Historical and future rainfall and runoff data are derived on a 0.25° grid, with 1,764 grid cells covering Botswana and small surrounding portions of Zimbabwe, Zambia, Namibia and South Africa in a square from 20°E to 30°E and 17°S to 27°S.

The naming of the rainfall and runoff files reflects the centre of each 0.25° grid cell with longitude (5 digits) and latitude (5 digits). Thus, the extreme NW corner is given by cell 1987516875, and the extreme SE corner is given by cell 3012527125.

Historical APET are on a 1.9° grid with 26 files covering Botswana and small surrounding portions of Zimbabwe, Zambia, Namibia and South Africa in a square from 20°E to 30°E and 17°S to 27°S.

The naming of the APET files reflects the centre of each 1.9° grid cell with longitude (4 digits) and latitude (4 digits). Thus, the extreme NW corner is given by cell 20621809, and the extreme SE corner is given by cell 30002190.
REFERENCES

Beven, K. (2011). *I believe in climate change but how precautionary do we need to be in planning for the future?* Hydrological Processes 25(9): 1517-1520.


