THE WORLD BANK

DISCUSSION PAPER NUMBER 8 SEPTEMBER 2010

56801

DEVELOPMENT AND CLIMATE CHANGE

Modeling the Impact of Climate Change on Global Hydrology and Water Availability

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ECONOMICS OF ADAPTATION TO CLIMATE CHANGE

Modeling the Impact of Climate Change on **Global Hydrology** and **Water Availability**

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September 2010

All dollars are U.S. dollars unless otherwise indicated.

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TABLES

ACRONYMS

AR4	Fourth Assessment Report of IPCC
AFR	Africa (World Bank Region)
AAA	analytic and advisory activities
CLIRUN	Climate and Runoff Model
CMI	Climate Moisture Index
CRU	Climate Research Unit
ECHAM4	Fourth-Generation Atmospheric General Circulation Model
EAP	East Asia and Pacific (World Bank Region)
ECA	Europe and Central Asia (World Bank Region)
ET	evapotranspiration
GCM	global climate model
GFDL	Geophysical Fluid Dynamics Laboratory
GRDC	Global Runoff Data Center
HadCM2	Hadley Centre Model
INM	Institute for Numerical Mathematics
IPCC	Intergovernmental Panel on Climate Change
LAC	Latin America and the Caribbean (World Bank Region)
MNA	Middle East and North Africa (World Bank Region)
MIROC	Model for Interdisciplinary Research on Climate
PET	potential evapotranspiration
SAR	South Asia (World Bank Region)
SRES	Special Report on Emissions Scenarios of IPCC
UNH	University of New Hampshire
USGS	United States Geological Survey
WMO	World Meteorological Organization

1. INTRODUCTION

Climate change can have a profound impact on the water cycle and water availability at the global, regional, basin, and local levels. Indeed, according to the recent Technical Report on Climate Change and Water from the Intergovernmental Panel on Climate Change (IPCC), "Observational records and climate projections provide abundant evidence that freshwater resources are vulnerable and have the potential to be strongly impacted by climate change, with wide ranging consequences on human societies and ecosystems" (Bates et al. 2008, p. 4). Developing countries are particularly vulnerable, and estimates show that the negative economic impacts of climate change could be significant (Stern 2006). Appropriate adaptation strategies, however, could mitigate some of the adverse impacts of climate change on the water sector in these highly vulnerable countries.

The World Bank recognizes water as a key affected sector, and potential strategies for adapting to climate change have become central to the dialogue on water policy reforms and investment programs with client countries. In order to support this process and future World Bank initiatives, the Water Anchor is undertaking a two-year analytic and advisory activity (AAA) (FY08–09) on Water and Climate Change. The main objective of the AAA is to provide analytical, intellectual, and strategic support to Bank operations and client countries in order to help them make sound water investment decisions that account for climate variability and change. The output of this AAA will be a series of reports that will address a number of key questions, such as the impacts of climate variability and change on water systems, both natural and engineered; adaptation strategies to reduce vulnerability of water systems to these impacts; and how the Bank can assist client countries in making informed decisions in this sector.

The objective of this technical report is to provide the background to the methodology used to model the impact of climate change on runoff for the Global Track of the EACC project. This report will present findings from computer modeling of the impacts of potential climate change on hydrology and water availability (that is, changes in runoff, basin yield, and flooding).

Chapter 2 provides the framework of analysis. Chapter 3 provides the hydrological drivers and data. Chapter 4 describes selected climate scenarios. Chapter 5 provides the runoff. Chapter 6 describes the basin yield. Chapter 7 summarizes the work and discusses future work. The Appendixes describe the Climate and Runoff (CLIRUN) Model.

2. FRAMEWORK OF THE ANALYSIS

PROCEDURES AND RATIONALE

Resolution and scale

The spatial and temporal scale of hydrologic analyses needed for World Bank investments span a wide range from very small (1–10 km² and daily to weekly) for local village water supply to very large catchments (100,000 km² and monthly to yearly) for major hydropower reservoirs. Climate change will occur at local scales, but presently models used for projecting climate change due to future greenhouse gas emissions have an average global climate model (GCM) resolution of 2.6° x 3.0°. The highest resolution belongs to the Japanese MIROC (Model for Interdisciplinary Research on Climate) Hires at 1.13° X 1.13° and the lowest resolution belongs to the Russian INM (Institute for Numerical Mathematics) at 4.0° X 5.0°.

One potential difficulty with using climate information in impact assessments, including in the water sector, is the "mismatch" between the low spatial (and temporal) resolution of GCMs and the scale at which assessments need typically to be conducted for investment purposes. GCMs provide climate change projections at a low spatial resolution (~2.5° x 2.5° grid; see Table 2.1), while water planning and management analyses often require a much finer resolution (~0.5° x 0.5° grid or even finer for project level analyses). (Table 2.2 provides a list of areas for 1° grid cells at various latitudes for reference.) The goal of the assessment—that is, what is it trying to answer? who is it trying to inform?—should drive the

TABLE 2.1. SPATIAL RESOLUTION OF IPCC FOURTH ASSESSMENT REPORT (AR4) ARCHIVED GCMS

GCM	*LAT*	*LONG*	*Area at 40° (km²)*
bccr_bcm2_0	2.81	2.81	75,115
cccma_cgcm3_1	3.75	3.75	133,538
cccma_cgcm3_1_t63	2.81	2.81	75,115
cnrm_cm3	2.81	2.81	75,115
csiro_mk3_0	1.88	1.88	33,384
csiro_mk3_5	1.88	1.88	33,384
gfdl_cm2_0	2	2.5	47,480
gfdl_cm2_1	2	2.5	47,480
giss_aom	3	4	113,952
giss_model_e_h	3.91	5	185,792
giss_model_e_r	3.91	5	185,792
iap_fgoals1_0_g	3	2.81	80,123
inmcm3_0	4	5	189,920
ipsl_cm4	2.5	3.75	89,025
miroc3_2_hires	1.13	1.13	12,018
miroc3_2_medres	2.81	2.81	75,115
mpi_echam5	1.88	1.88	33,384
mri_cgcm2_3_2a	2.81	2.81	75,115
ncar_ccsm3_0	1.41	1.41	18,779
ncar_pcm1	2.81	2.81	75,115
ukmo_hadcm3	2.47	3.75	87,806
ukmo_hadgem1	1.24	1.88	22,103
Average	**2.6**	**3**	**72,420**

Source: IPCC 2007.

TABLE 2.2. 1º LATITUDE BY 1º LONGITUDE AREAS

Latitude	*1 Degree Longitude km*	*1 Degree Latitude km*	*1 Square Degree km²*
0	111	111	12,393
40	85	111	9,496
60	56	111	6,181
80	17	111	1,876

Source: IPCC 2007.

decisions on the relevant scale and the most appropriate technique for matching GCM output with that scale.

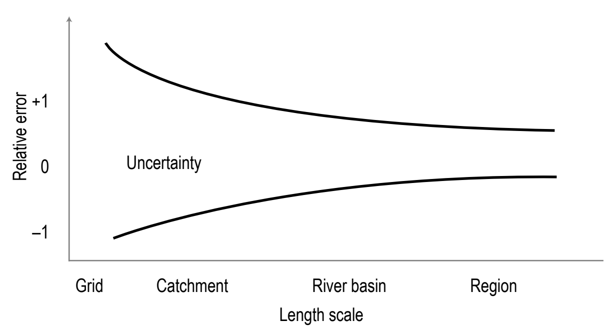
There are several methods available for addressing scale issues, including statistical downscaling (using empirical relationships), dynamical downscaling (using regional climate models), and 'spatial techniques'[1] (linear interpolation, krigging, spline fitting, and intelligent interpolation). Downscaling involves methods used to map the large-scale signals from GCMs to a finer resolution (tens of kilometers versus hundreds of kilometers).

Care needs to be taken in selecting a method. Beyond reproducing the underlying uncertainties of GCMs, many introduce additional uncertainty and biases. For example, downscaling techniques increase the detail of information, but also the uncertainties associated with that information due to fact that the GCM output is manipulated below the scale at which the physics of the GCM itself are mathematically described. Under some downscaling schemes, mass balances of water and energy over the GCM scale are violated by the downscaling algorithm. Use of dynamical and statistical downscaling techniques requires extensive quantification of the sensitivities of the underlying assumptions of both the GCMs and the downscaling algorithms, resulting in the need for exhaustive numerical experimentation. Time and cost constraints often do not allow use of more than a couple of GCMs in downscaling exercises. Running multiple GCMs at a coarse resolution may provide more insight into the range of possible futures than more detailed information obtained from fewer GCMs (see also the following section on Model Scenarios).

There is no one "best" method; the most appropriate method for a particular application will strike a careful balance between precision (resolution) and accuracy (confidence in projections). Figure 2.1 provides a visual representation of the trade-off between precision and accuracy. As resolution increases, so too does the uncertainty associated with the more detailed information. In other words, more "precise" information comes at a cost, and the additional uncertainty must be recognized and taken into account in assessing impacts. Given the trade-off, it is critical to establish at the outset of any impact assessment whether the goal is to have finer resolution or "better" (that is, more reliable) information.

The purpose of this assessment is to establish a common platform of information on the behavior of key hydrologic variables across all World Bank regions. The catchment level was selected because it is the most appropriate scale for water planning and investment. Figure 2.2 shows the different model scales/outputs relative to the catchment level. This figure shows the three different scales: 0.5° by 0.5° grid, 2.5° by 2.5° grid, and the catchments. Aggregating from the 0.5° by 0.5°

FIGURE 2.1. DESCRIPTION OF MODELING SCALE



Source: Authors.

1 "Spatial technique" is often referred to as "spatial downscaling"; technically, however, it does not involve downscaling but rather statistical and spatial relationships. The majority of downscaling being done is with this method.

grid to the catchment level is appropriate for two reasons: First, the average scale of a catchment is approximately the size of the native spatial grid scale of the GCM (~2.5° x 2.5°), which results in less uncertainty by using a scale that the input data was created for. And second, the indicators are representative of what is occurring at the catchment level (including all available runoff and storage in the catchment) and not at individual 0.5° grid cells.

Given that the goal of this work is a broad-scale analysis of the exposure of World Bank investments to potential climate change impacts, examining a range of climate change scenarios at the coarse resolution was preferred to examining a few selected scenarios in a detailed spatial resolution requiring some form of downscaling, as just discussed. For this work the spatial resolution for the use of GCM was at the native grid scale of each GCM (see Table 2.1). The GCM provided relative changes in temperature and precipitation for the years 2030 and 2050 on a monthly level as compared with the model baselines of the twentieth century. These relative changes were then applied directly to the historic climate variables from the Climate Research Unit (CRU) dataset. As seen in Figure 2.2, there are numerous 0.5° by 0.5° CRU grids within each GCM grid box. For this analysis we apply the relative changes from the GCM grid box uniformly to all CRU grid cells within the GCM grid box. Although this leads to some discontinuities at the border of grid boxes, it is the most appropriate technique for this work, given the scope and mathematics of the GCM models.

With the uncertainty inherent in the GCM and the CRU data, it would be unwise to perform this analysis at the lowest level of resolution (0.5° by 0.5°). Aggregating to a higher spatial level would reduce the uncertainty in the model indicators and more correctly reflect the larger-scale climate change projections from the GCM models. Therefore a catchment scale was chosen for this analysis.

The catchments were obtained from the U.S. Geological Survey (USGS) Hydro1K. "HYDRO1k is a geographic database developed to provide comprehensive and consistent global coverage of topographically derived data sets, including streams, drainage basins and ancillary layers derived from the USGS' 30 arc-second digital elevation model of the world (GTOPO30)." (http://eros.usgs.gov/products/elevation/gtopo30/hydro/index.html).

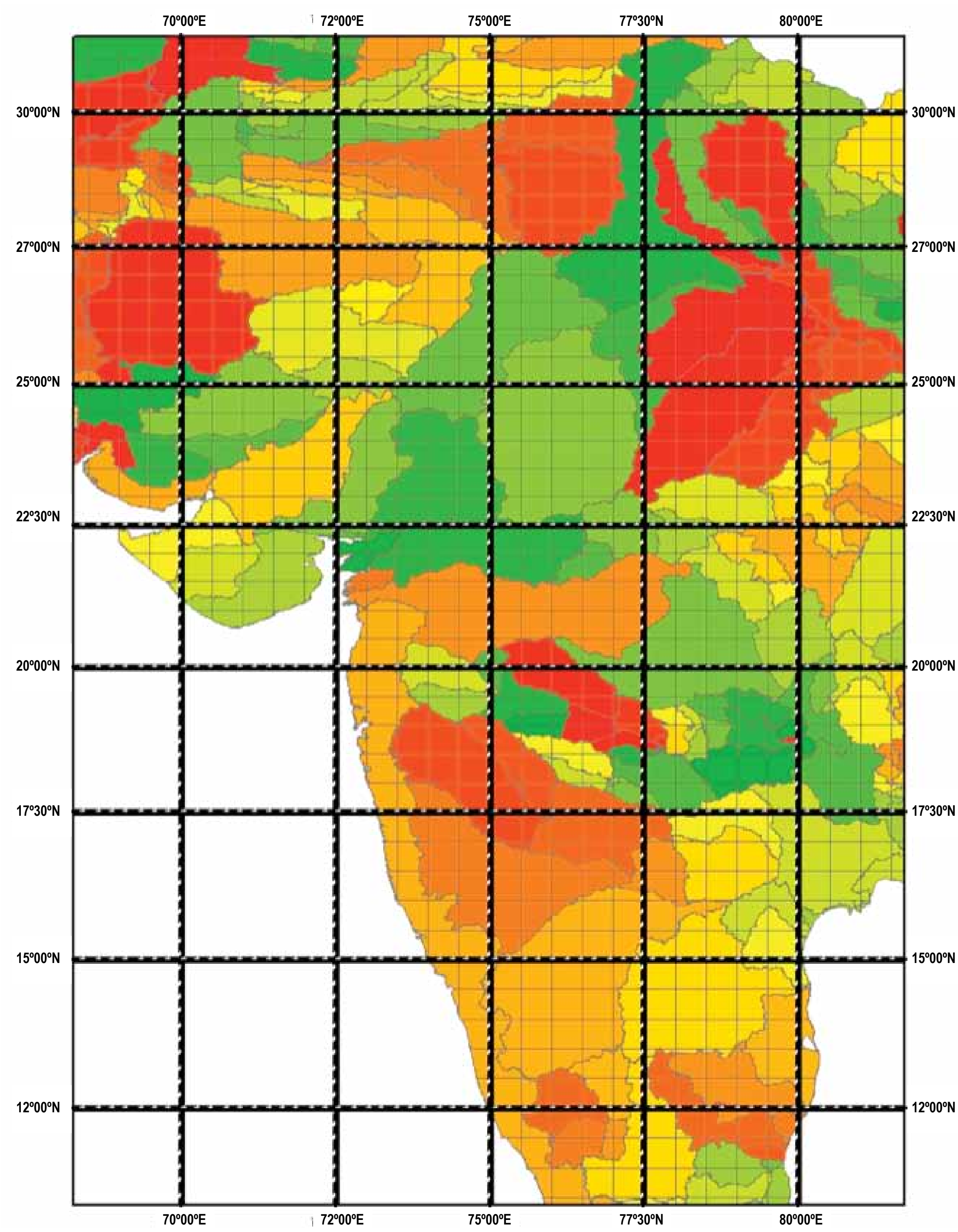
Hydro1K has six levels of catchments. For this analysis, level four was selected for all Bank Regions except Africa, which used level three. There are 8,406 catchments covering the World Bank Regions, which means an average of six CRU grids per catchment. Using geographic information systems, the catchment boundaries were overlaid with the CRU grids and the cells were aggregated by their weighted area in the catchment.

Model scenarios

Another issue with climate change information is how to capture the full range of GCM and Special Report on Emissions Scenarios (SRES) model impacts in a manageable way. Many combinations of GCM and SRES scenarios are available. It takes time and money to evaluate each scenario in an analysis. There are different approaches to choosing which scenarios to use in an analysis (for example, multi-model averages, taking extremes, probabilistic.) First, the goal of the analysis needs to be addressed. In this analysis, with the goal of informing water management, the most appropriate approach is to use the model extremes that may contain the riskiest aspects of climate change for water resources. The spectrum of model projections is being captured here by implementing dry, middle, and wet projections.

As mentioned earlier in the context of downscaling, relying on results from a single or even just a few GCMs is not advisable. This is because there are model errors in any one model and natural variability (randomness) in any particular run. A single model, if run multiple times with differing initial conditions, can provide an estimate of the uncertainty due to natural variability. For any given model, however, there are also uncertainties associated with the assumptions made about model physics and parameterizations, as well as with the structural aspects of the model itself. Using a group of GCMs (multi-model ensembles) as opposed to one individual GCM can somewhat correct for biases and errors. The use of multi-model ensembles raises the question of how to capture the full range of results from model runs.

FIGURE 2.2. SECTION OF THE SAR REGION SHOWING 0.5˚ BY 0.5˚ (HISTORIC HYDROLOGY) GRID SCALE AND 2.5˚ BY 2.5˚ (GCM) GRID SCALE RELATIVE TO CATCHMENT BOUNDARIES



Source: Authors.

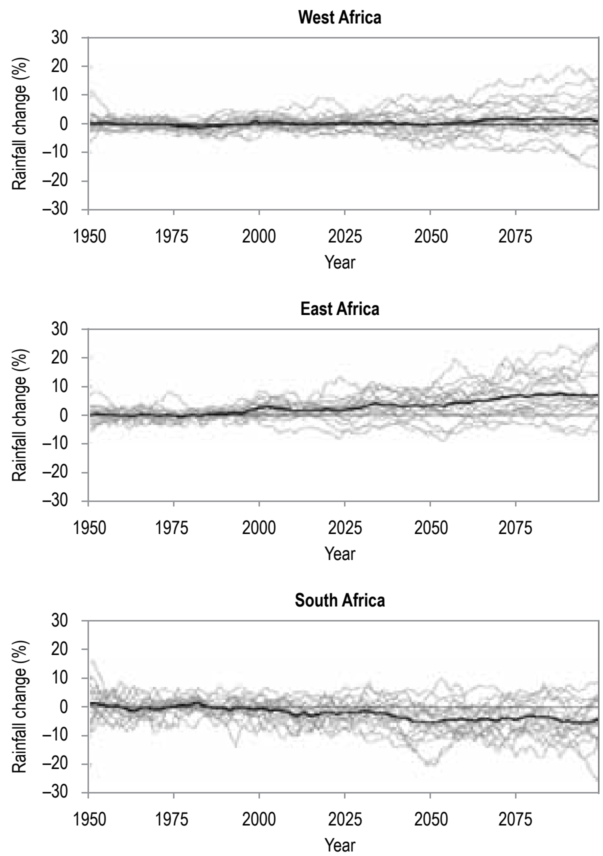
In many applications, the mean of multiple models is used, the rationale being that the mean is representative of all runs. The problem with relying on the mean is that it masks extreme values. A model "average" of near zero could be the result of models predicting near-zero change, but also it could also be the result of two opposing changes that differ in sign, as seen in Figure 2.3. In water management, the risk lies in the "tails" of the full spectrum of model projections, so failing to capture the extremes could be dangerous.

The potential exists for the range of model outcomes to vary so much that it could be construed as "noise." But there is evidence that suggests a degree of consistency in some of the more salient changes generated by a collection of model outcomes. As an example, the trend in precipitation intervals as simulated by the IPCC AR4 models show, statistically and/or probabilistically speaking, agreement in the projection of the change in precipitation interval across latitudes as climate warms. This implies that although no one should rely solely on a single model, each run could potentially contain important information that is more than merely "noise." Indeed, there are regions where a sign change is consistent among the climate models—but with a range that is important to consider explicitly for the assessment of potential impacts.

A related issue is filtering or screening of GCM and SRES scenarios that are implausible or, at the very least, extremely unlikely. This is difficult—if not impossible—to unequivocally determine, as there are no definitive criteria for determining whether a given climate change projection can or should be excluded. One approach in impact assessments is to consider all modeled projections as "equally likely" at the outset of the assessment, and then to exclude in a secondary step those scenarios with minimal or limited impacts (and to focus on those that could cause significant damage/consequence). Techniques are being developed for undertaking a full probabilistic analysis of scenarios to determine which are most applicable to each region, but these are not yet available for practical use.

In this analysis, the full spread of model projections—including extremes—is captured by identifying dry, middle, and wet scenarios, as defined by a change in the Climate Moisture Index (CMI). Model projections are not screened. Dry, middle, and wet scenarios were identified in terms of each World Bank Region (for instance, the driest scenario for LAC). A wet scenario means that the location experienced the smallest impact (or change in CMI); a dry scenario, the largest impact; and a middle scenario, an impact between the two extremes. The advantage of this approach is that it provides a representation of the full range of available scenarios in a "manageable" way. (Further details are given in Chapter 4.)

FIGURE 2.3. RELATIVE CHANGE FROM HISTORICAL CLIMATE FOR DIFFERENT GCMS AND AVERAGE



Source: Giannini et. al., 2008 pg. 376, Fig. 6.

REPORTING

The potential impacts of climate change on the hydrologic cycle and, consequently, the water sector are numerous.

Projected impacts on runoff and basin yield, extreme events (floods and droughts), and net irrigation demand are assessed here, as these variables are particularly relevant for water planning and investments. Twenty-two GCMs along with the A1B, A2, and B1 SRES were used to analyze changes in these key hydrologic variables in the years 2030 and 2050. For each World Bank Region, the wettest, driest, and a middle scenario were identified based on the climate moisture index. The results are presented at the catchment level and summarized by Koppen-Geiger climate zones.

Hydrologic variables useful to water planning and investment

There are different methods to representing the impacts of climate change on water systems; most involve the use of hydrologic variables to represent impacts. A variety of approaches exist for generating hydrologic variables, such as mean annual and seasonal runoff and groundwater recharge, within the context of climate modeling.

Waggoner (1990), Faures (1998), Strzepek et al. (2000), Kirshen (2005), Smith and Zhang (2007), UN/WWAP (2003, 2006, 2009), and Esty (2008) are just a few who have proposed hydrologic variables or indicators to help policy makers and planners make decisions related to water resources investment and policies. A number of themes emerge from this literature suggesting a set of indicators that would provide information on the performance of water resource development projects in the near future and under the threat of climate change in the near distant future. The indicators were selected to provide inputs to those involved with the wide range of water resource development projects at the World Bank. The indicators chosen provide information on the mean and extreme values of runoff, the storage requirements for reliable basin yield, groundwater recharge, and net irrigation water demand.

Indicators based on time series – New approach

For the indicators for extreme events, the approach developed in this study is one of the first attempts to develop indicators based on a time series rather than long-term average indicators. There is more uncertainty around extreme event indicators due to the limited sample size of data compared with "mean" value indicators. However, given that mean value indicators do not properly reflect the water resource design or investment and management decisions, it is felt that the appropriate indicators with more uncertainty are preferred.

SRES and GCMs

The Special Report on Emissions Scenarios are emissions scenarios that account for a range of possible future greenhouse gas emissions. They are based on assumptions about population growth, economic development, technological advances, policies on interdependency, and commitment to environmental protection. There are a total of 40 scenarios, organized into 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 (and the lowest CO_2 emissions)
- B2 assumes intermediate levels of economic growth, and less rapid technological development than A1 and B1.

The SRESs were used as a basis for climate projections in the IPCC Fourth Assessment Report (2007).[2]

While it may be interesting to use all 40 SRESs in a climate change analysis, this is not feasible on results that are archived on the IPCC database. The SRES team identified marker scenarios to represent a given scenario family, although they were not considered to be any more "likely" than other scenarios. These included A1B1, A2, B1, B2, and two additional scenarios for the groups A1F1 and A1T (Nakićenovic and Swart 2000). The IPCC based its findings on these six scenarios.

2 The earlier emissions scenarios that served as a basis for the climate projections in the IPCC Third Assessment Report are referred to as the IS92 scenarios.

In this analysis, three SRES scenarios are used: A1B, A2, and B1. These were chosen because they are included in the marker scenarios identified by the IPCC and are in the middle range of SRESs (see Figure 2.4). The three scenarios can be summarized as follows:

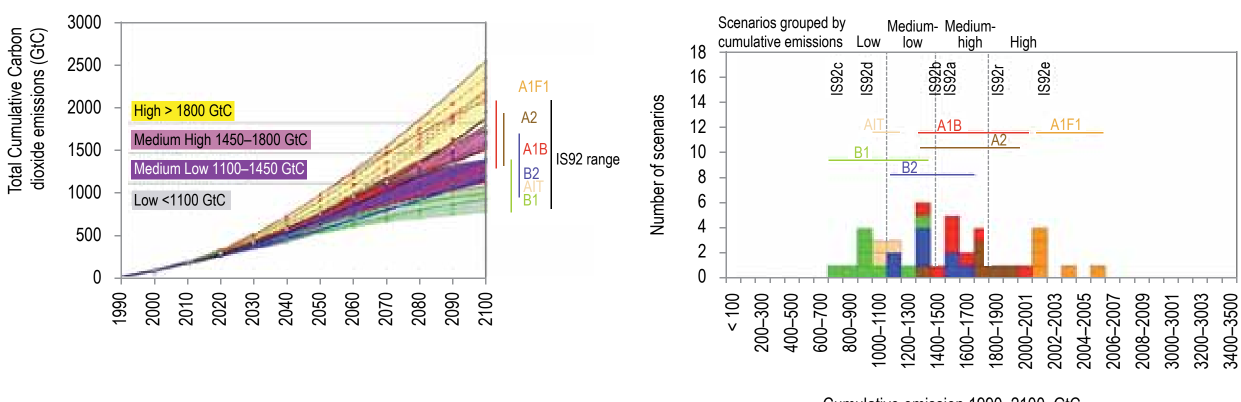
- **A1B storyline and scenario family** (the "B" standing for balanced) assume a world of rapid economic growth, with the most growth in developing countries, the population peaking at 9 billion by mid-century and then declining to 8 billion by 2100, and rapid technological development. It has the highest 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.
- **A2 storyline and scenario family** assume very high population growth (about 15 billion people by 2100) and slower economic growth and technological development than the other storylines. There is also less convergence in the standard of living and technology between developed and developing countries than in the other storylines. It results in the lowest per capita income of the four storylines. CO_2 concentrations would be over 800 ppm by 2100.
- **B1 storyline and scenario family** assume the same population levels as A1B, but with more of a transition to a service- and information-based economy, with more clean technologies and less material intensity than A1B. CO_2 concentrations are the lowest of the SRES scenarios: over 500 ppm by 2100.

Similarly to the 40 SRESs, there are 22 GCMs available in the IPCC Fourth Assessment Report to use in climate change analyses (see Table 2.3). In this analysis, all of the GCMs were evaluated to determine which models would represent the dry, medium, and wet scenarios for each of the World Bank regions, as discussed in Chapter 4.

Future years

Typical climate change analyses will evaluate impacts anywhere from the 2030s to the 2100s. It is important to keep in mind the purpose of the analysis—that is, near-term planning or long-range potential—to help guide which future decades are most important to evaluate. In this study, the years 2030 and 2050 were used to evaluate the impacts of climate change on various hydrologic variables. These years were chosen for two reasons: this is the relevant timeframe for current infrastructure planning, and beyond 2050 uncertainties in projections increase dramatically. As shown in Figure 2.4, SRES scenarios are tightly bunched until 2050, at which time they start to diverge significantly. By limiting the analysis to 2050, uncertainty beyond 2050 is eliminated.

FIGURE 2.4. TOTAL GLOBAL CUMULATIVE CO_2 EMISSIONS FROM 1990 TO 2100 AND HISTOGRAM OF THEIR DISTRIBUTION BY SCENARIO GROUPS



Source: IPCC 2007.

TABLE 2.3. AVAILABLE MODELS, SCENARIOS, AND VARIABLES IN IPCC AR4

MODELS
BCCR:BCM2[anomalies]
CCCMA:CGCM3_1-T47[anomalies]
CCCMA:CGCM3_1-T63[anomalies]
CNRM:CM3[anomalies]
CSIRO:MK3-5[anomalies]
CSIRO:MK3-0[anomalies]
GFDL:CM2[anomalies]
GFDL:CM2_1[anomalies]
INM:CM3[anomalies]
IPSL:CM4[anomalies]
LASG:FGOALS-G1_0[anomalies]
MPIM:ECHAM5[anomalies]
MRI:CGCM2_3_2[anomalies]
NASA:GISS-AOM[anomalies]
NASA:GISS-EH[anomalies]
NASA:GISS-ER[anomalies]
NCAR:CCSM3[anomalies]
NCAR:PCM[anomalies]
NIES:MIROC3_2-HI[anomalies]
NIES:MIROC3_2-MED[anomalies]
UKMO:HADCM3[anomalies]
UKMO:HADGEM1[anomalies]

Source: IPCC 2007.

The years 2030 and 2050 represent decadal averages of monthly GCM output. In other words, when reporting changes in 2030 relative to historical climate, these are actually average changes from 2025 to 2035 relative to average historical climate. The same is true for 2050 (which represents the average from 2045 to 2055). Average monthly changes from the GCMs over the two separate decades are applied to historical monthly hydro-climatology from 1961 to 1990.

Geographic representation

The projected impacts on runoff, basin yield, extreme events, and net irrigation demand for dry, middle, and wet scenarios are presented at the catchment scale. However, for ease of exposition, catchment-level projections are discussed for each World Bank Region according to Koppen's climate classifications (see Figure 2.5). Synthesizing the information in this way allows the identification of broader trends across regions. All projections at the catchment scale can be made available, upon request.

The Koppen-Geiger climate classification system[3] divides climate into five primary classifications (and several types and subtypes), based on regional average annual temperature and precipitation, as well as the seasonality of precipitation. The five primary classifications are equatorial, arid, warm temperate, cold, and polar (see Box 2.1).

3 The classification system—one of the most well known and widely used—was developed in the early twentieth century by Wladimir Koppen. Revised in 1961 by Rudolph Geiger, Koppen's classification system was again updated in 2006 with data from the Climate Research Unit of University of East Anglia and the Global Precipitation Climatology Centre at the German Weather Service to reflect the 1951–2000 climate.

BOX 2.1 KOPPEN-GEIGER CLIMATE CLASSIFICATIONS

Equatorial. The equatorial climate is characterized by relatively hot temperatures; the coldest month in these regions is greater than 18oC. The most water- and heat-demanding crops are typically grown in this climate (FAO 2007). Equatorial climates include northern South America and central Africa.

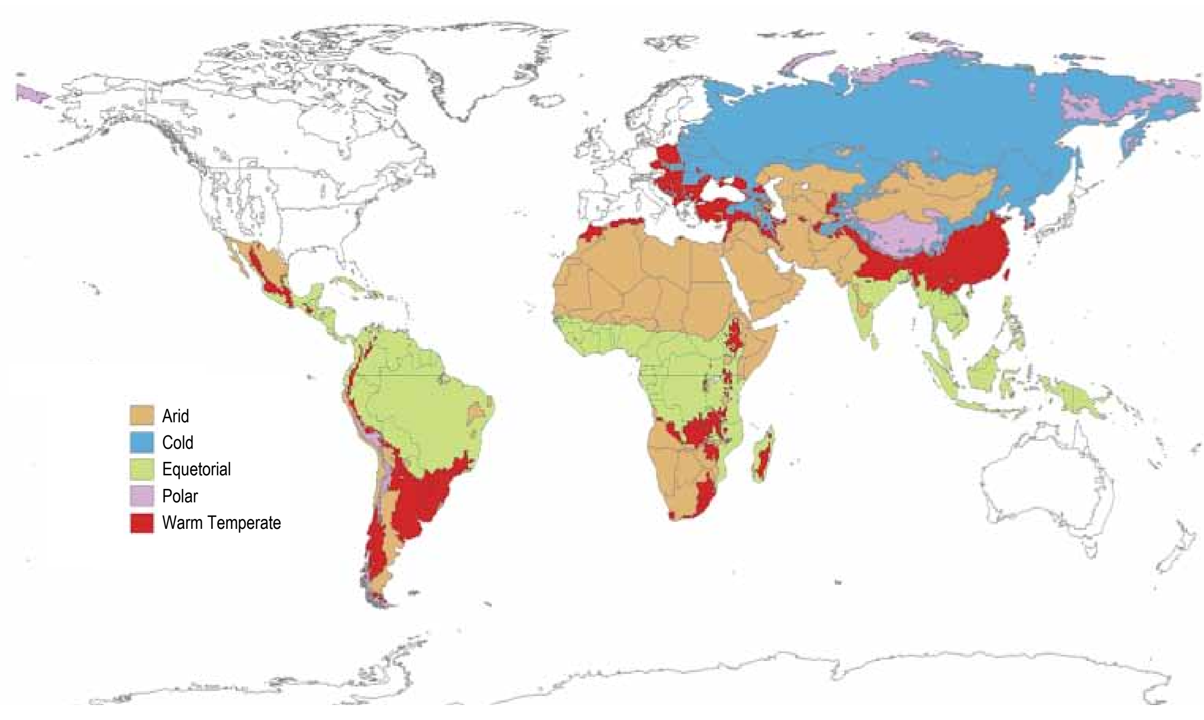
Arid. In arid climates, annual evapotranspiration exceeds annual precipitation and there is a distinct dry season. Sunshine in these regions is typically high (FAO 2007). Examples of arid climates include the Sahara, the Sudan, and parts of the Middle East.

Warm Temperate. The warm temperate climate is characterized by a relatively mild range of temperatures; the average temperature of the coldest month ranges between –3o and 18oC and the average of the warmest month is greater than 10oC. Some regions may be typified by this general temperature range but fall into a different classification due to precipitation characteristics (for instance, North Africa is considered arid due to the very limited rainfall in the region) (FAO 2007). Examples of warm temperate climates include southeastern Brazil, southeastern South Africa, and southeastern China.

Cold. The cold climate experiences colder temperatures than warm temperate regions; the average temperature in the coldest month is less than –3oC. Growing seasons in cold climates are similar to, but shorter than, warm temperate regions and are typically limited by frost (FAO 2007). Examples of cold climates include parts of Russia, Kazakhstan, and Mongolia.

Polar. The average temperature of the warmest month in polar climates is less than 10oC. The biome typical of polar regions is tundra. Examples of polar climates include southwestern China and the Andes (parts of Peru, Chile, and Argentina).

FIGURE 2.5. KOPPEN-GEIGER CLIMATE CLASSIFICATIONS FOR WORLD BANK REGIONS



Source: Authors.

3. HYDROLOGIC DRIVERS AND DATA

Historical hydrologic conditions in this analysis are addressed at three different levels: historical climate, historical observed runoff, and historical modeled runoff.

HISTORICAL CLIMATE

The historical climate was taken from a database provided by the Climate Research Unit at the University of East Anglia, Norwich, U.K. The CRU 2.1 data set provides a time series of monthly precipitation data and the climate variables required to compute potential evapotranspiration (PET) from 1901 to 2002. These data, provided on a 0.5° longitude/latitude grid, represent the World Meteorological Organization's (WMO) standard reference "baseline" for climate change impact studies. The climate change scenarios (plausible descriptions of how things may change in the future) are expressed as changes from this baseline. There are 67,420 grids (0.5° x 0.5°) over the global land area, excluding Antarctica (see Table 3.1).

HISTORICAL OBSERVED RUNOFF

Long-term average monthly runoff has been developed by the University of New Hampshire (UNH) for the WMO Global Runoff Data Center (GRDC). This UNH-GRDC Composite Runoff Fields V1.0 data set is the combination of observed river discharge information with a climate-driven Water Balance Model to develop composite runoff fields that are consistent with observed discharges. Such combined runoff fields preserve the accuracy of the discharge measurements as well as the spatial and temporal distribution of simulated runoff, thereby providing the "best estimate" of terrestrial runoff over large domains. The method applied in the preparation of this data set uses a gridded river network at 0.5° spatial resolution to represent the riverine flow pathways and to link the continental land mass to oceans through river channels. This data set provides 12 monthly mean values and a mean annual value of runoff for over 50,000 grids (0.5° x 0.5°) over the global land area, excluding permanent ice cover such as much of Greenland and all of Antarctica (see Figure 3.1 and Table 3.1).

TABLE 3.1. SOURCES OF DATA IN THIS STUDY

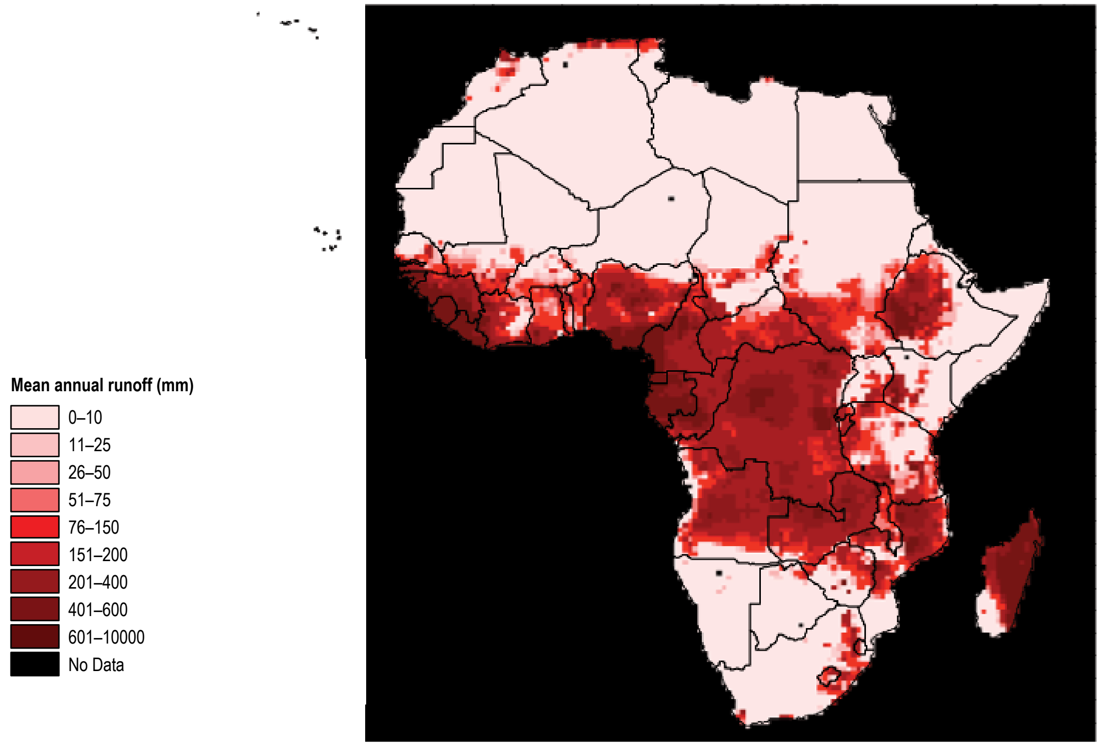
Data	*Description*	*Source*
Precipitation and temperature	CRU-TS2 1.0 dataset. A dataset of mean monthly surface climate over global land areas, excluding Antarctica. Interpolated from station data to 0.5° lat./long. Monthly from 1901 to 2002. Climatic Research Unit, University of East Anglia	http://www.cru.uea.ac.uk/cru/data/hrg/cru_ts_2.10
Calibration runoff	Simulated runoff (monthly totals in mm) 0.5o grid. University of New Hampshire CD – UNH/GRDC Composite runoff fields V1.0	http://www.grdc.sr.unh.edu/

Source: Author's Data.

HISTORICAL MODELED RUNOFF

Water resource development and management are primarily a process to reduce the variability in runoff in

FIGURE 3.1. MEAN ANNUAL RUNOFF IN AFR REGION GRIDDED AT 0.5º LATITUDE/LONGITUDE RESOLUTION (*UNIVERSITY OF NEW HAMPSHIRE*)



Source: Authors.

order to provide reliable water supplies. In order to project the impacts of climate change on water resources development projects, a time series of global runoff fields is needed to examine the impacts on extreme events (droughts and floods) and variability, since an observed global runoff time series does not exist. The GRDC has an extensive data base of stream flow data, but this is gauged (with all the development impacts included) and at a highly varying spatial scale. The UNH/GRDC global gridded runoff fields are a wonderful resource but are only available for average monthly runoff. A modeled data set was developed. The University of Colorado has taken the CRU Historical Climate Data base and the UNH-GRDC Composite Runoff Fields together with their Global Runoff Model–CLIRUN-II (see Appendix C) to produce a 30-year monthly time series of runoff at the 50,000 plus grids of the UNH-GRDC data set. The time series used the monthly data from 1961 to 1990 to produce a historic or base scenario runoff time series.

So using the UNH/GDRC gridded runoff fields and the CRU gridded climate database, the CLIRUN-II model (Strzepek et al. 2008) was calibrated to match the UNH/GRDC runoff fields using the CRU data from 1961 to 1980. The calibration was good and provided confidence that the model was capturing the underlying hydrology at the grid level and even more confidence that the model was reflecting the "catch-ment" level hydrology.

With a historic runoff time series, statistical and stochastic process indicators can be estimated and compared with modeled climate change runoff scenar-ios to examine the projected changes in important design and planning indicators.

4. SELECTED CLIMATE CHANGE SCENARIOS

The scenario categorization is defined by the Climate Moisture Index, which is an indicator of the aridity of a region. The CMI depends on average annual precipitation and average annual potential evapotranspiration.[4] 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.

As mentioned in the Model Scenarios section in Chapter 2, the full spread of model results was captured by selecting the driest, the wettest, and a middle scenario. There was no screening: the historical and all 22 GCM scenarios were analyzed based on their CMI for 2050 to identify the dry, middle, and wet scenario for each World Bank region (see Tables 4.1 and 4.2). The scenarios used for 2050 CMIs were also used for the 2030 analysis.

Figure 4.1 shows the range of CMI for all scenarios for the globe and World Bank Regions as a whole and the remaining land mass. Figure 4.2 shows the CMI for all scenarios individually for each World Bank Region. The red line represents the median CMI, and the top of the box represents the 25th percentile while the bottom of the box represents the 75th percentile. The whiskers show the extremes and the cross-hairs show the model outliers. The dashed lines represent the historical CMI (averaged from 1960 to 1990). For example, in the LAC region, there is a 75 percent chance of drying with all three scenarios. The CMI for the SAR region has the largest spread because of the way the different GCMs model the monsoons. In the MNA region, there is not much variation because the area is so dry.

It is important to note that the CMI is only calculated over land masses and not over the ocean. Many climate change analyses discuss GCMs with regards to their properties/results over land Identify the dry, middle and wet as only based on precipitation.

4 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.

TABLE 4.1. GCM AND ASSOCIATED BASE CMIS USED FOR EACH SCENARIO AND FOR REGIONS EAP, ECA, AND LAC

	EAP	*–0.069*	*ECA*	*–0.205*	*LAC*	*–0.075*
Base	*Model*	*CMI*	*Model*	*CMI*	*Model*	*CMI*
A2-Dry	csiro mk3 5	(–0.143)	¡psl cm4	(–0.252)	gfdl_cm2_0	(–0.228)
A2-Middle	mri_cgcm2_3_2a	(–0.082)	ukmo hadcm3	(–0.215)	ukmo hadcm3	(–0.151)
A2-Wet	cccma_cgcm3_1_t63	(–0.033)	giss_model_e_r	(–0.177)	cnrm_cm3	(–0.068)
A1B-Dry	csiro_mk3_5	(–0.135)	¡psl_cm4	(–0.251)	ukmo_hadgem1	(–0.202)
A1B-Midde	inmcm3_0	(0.097)	mpi_echam5	(–0.212)	mpi_echam5	(–0.129)
A1B-Wet	cccma _cgcm3_1	(–0.054)	cccma_cgcm3_1	(–0.184)	bccr_bcm2_0	(–0.076)
B1-Dry	csiro_mk3_5	(–0.122)	¡psl_cm4	(–0.243)	miroc3_2_hires	(–0.153)
B1-Middle	mri_cgcm2_3_2a	(–0.084)	mpi_echam5	(–0.216)	cccma_cgcm3_1	(–0.11)
B1-Wet	cccma_cgcm3_1_t63	(–0.048)	gfdl_cm2_1	(–0.177)	cnrm_cm3	(–0.074)

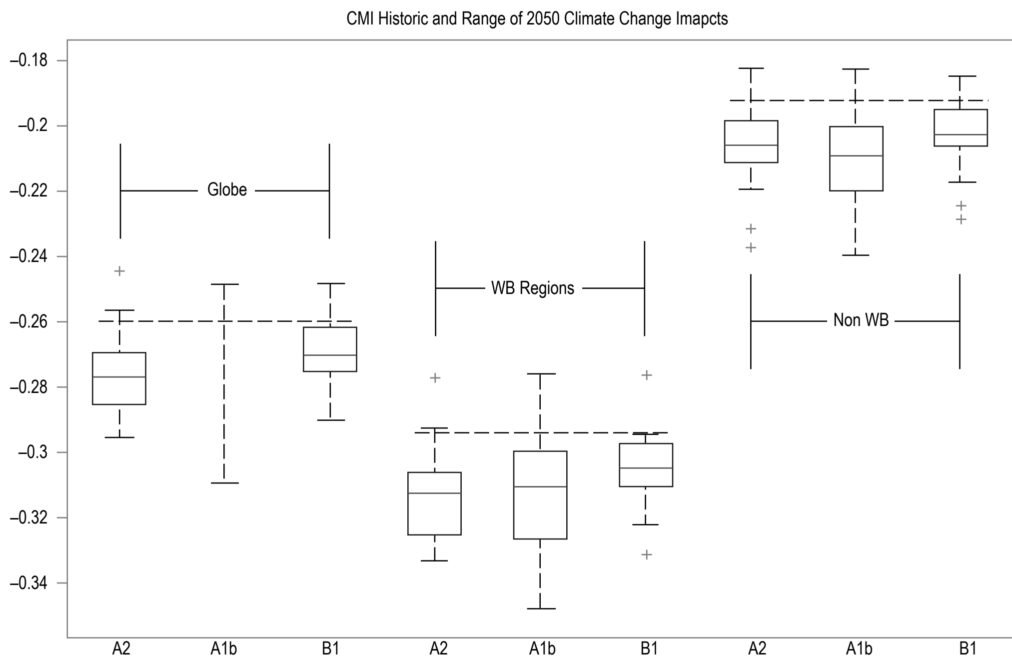
Source: IPCC 2007.

TABLE 4.2. GCM AND ASSOCIATED BASE CMIS USED FOR EACH SCENARIO AND FOR REGIONS MNA, SAR, AND AFR

	MNA	*–0.91*	*SAR*	*–0.372*	*AFR*	*–0.5*
Base	*Model*	*CMI*	*Model*	*CMI*	*Model*	*CMI*
A2-Dry	gldl_cm2_1	–0.942	ipsl_cm4	–0.466	inmcm3_0	–0.552
A2-MIddle	ukmo_hadgem1	–0.920	ukmo_hadcm3	–0.312	mpi_echam5	–0.519
A2-Wet	ncar_pcm1	–0.898	mri_cgcm2_3 _2a	–0.055	ncar_ccsm3_0	–0.488
A1B-Dry	gfdl_cm2_1	–0.941	ipsl_cm4	–0.496	gfdl_cm2_1	–0.537
A1B-Midde	ukmo_hadcm3	–0.916	ukmo_hadgem1	–0.294	ukmo_hadgem1	–0.501
A1B-Wet	mpi_echam5	–0.891	mri_cgcm2_3_2a	–0.003	cnrm_cm3	–0.484
B1-Dry	gfdl_cm2_1	–0.930	csiro_mk3_5	–0.433	ipsl_cm4	–0.539
B1-Middle	inmcm3_0	–0.907	inmcm3_0	–0.291	miroc3_2_medres	–0.517
B1-Wet	mpi_echam5	–0.882	mri_cgcm2_3_2a	–0.051	cnrm_cm3	–0.486

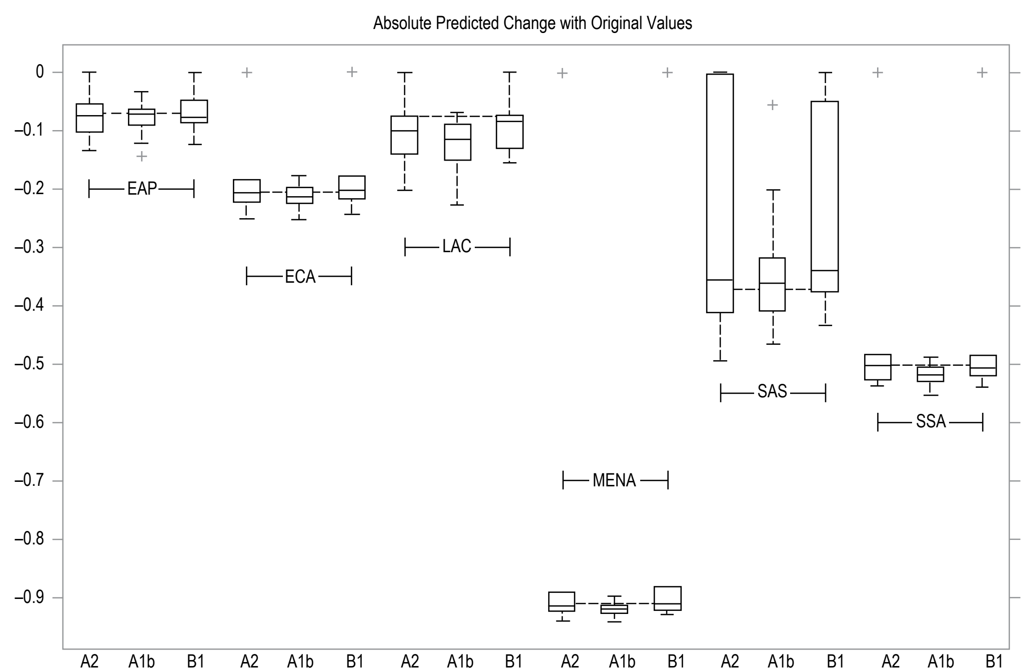
Source: IPCC 2007.

FIGURE 4.1. CLIMATE MOISTURE INDEX SPREAD FOR EACH SCENARIO AND GLOBAL LAND MASS AND FOR EACH REGION



Source: Authors.

FIGURE 4.2. CLIMATE MOISTURE INDEX SPREAD FOR EACH SCENARIO AND FOR EACH REGION (WILLMOTT AND FEDDEMA)



Source: Authors.

5. RUNOFF

As discussed in Procedures and Rationale in Chapter 2, there are different methods to representing the impacts of climate change on water systems. The first goal is to understand the impact of the water resource, namely the annual runoff. Analyzing the climate change impact on this key indicator is discussed in this chapter.

METHODOLOGY

A variety of approaches/models exist for generating runoff. These include using runoff estimates derived directly from GCMs, using GCM output as input into offline macro-scale hydrologic models, and downscaling GCM output and using resulting data in offline hydrologic models.[5] Runoff estimates derived directly from GCMs should be interpreted (and used) with a great deal of caution; the limitations of downscaling are discussed in Chapter 2. For this analysis, GCM output was used as input into an offline hydrologic model.

The hydrologic model CLIRUN-II (Strzepek et al. 2008) was chosen for this analysis. 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. A more detailed description of the model can be found in Appendix C.

Milley et al. (2005) spatially integrated annual runoff fields (using runoff from GCMs) from 62 runs of the 20C3M experiment on 21 different models (one to nine runs per model) over 165 river basins with long-term (28–99 years, median 59 years) stream flow measurements. While this work was extremely important to highlight areas of the globe at risk to changes in runoff, it was based on very poor spatial and temporal scale and, more important, on the hydrologic models of the GCMs.

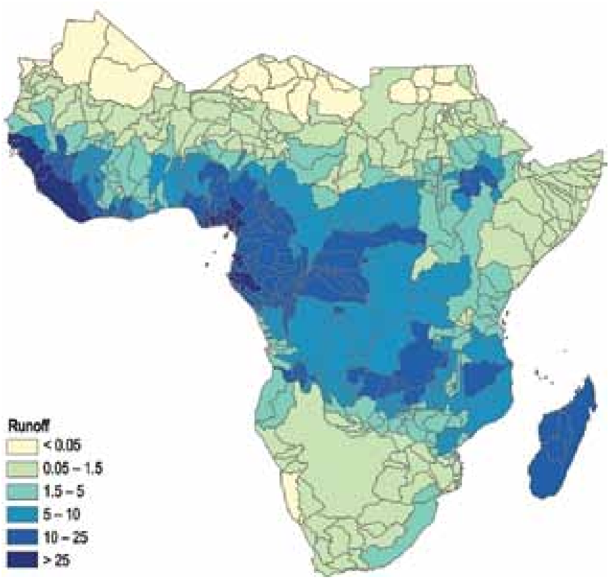
The analysis presented here addresses the spatial and temporal resolution as well as methodological limitations of the Milley approach. Outputs of climate change projections on climatic variables are input to a calibrated hydrologic model with a 0.5° by 0.5° resolution, running on a monthly time scale. Simulating monthly over a 30-year base period, from 1961 to 1990, provides an 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.

HISTORICAL RESULTS

Figure 5.1 shows the average annual runoff from the 30 year historic (1961–90) monthly modeling of runoff for the AFR Region . The results show the great spatial variability of runoff and highlight the arid and semiarid conditions at the northern and southern ends of the region and the extreme humid conditions at the region's equatorial central region. These conditions are driven by the rainfall associated with the movement of Inter-Tropical Convergence Zone.

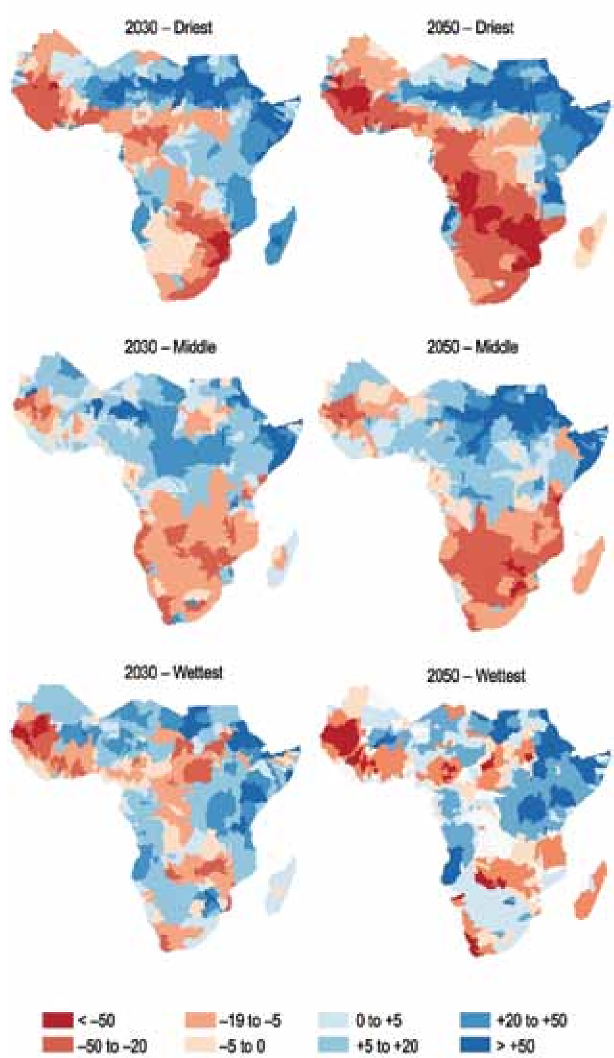
5 These various approaches are discussed in depth in the companion report on the Science of Water and Climate Change.

FIGURE 5.1. HISTORICAL ANNUAL RUNOFF IN AFR REGION (MM/YR)



Source: Authors.

FIGURE 5.2. PROJECTED CHANGE IN ANNUAL RUNOFF IN AFR REGION (PERCENT)



Source: Authors.

CLIMATE CHANGE RESULTS

Figure 5.2 shows the percentages of change of annual runoff at catchment level (2030 and 2050; A1B, A2, and B1—wet, mid, and dry) from the 30-year historic (1961–90) monthly modeling of runoff for the AFR Region. The results show the great spatial variability of changes, but there are a few trends and consistency in the results that are worth noting.

There is an increase in runoff in the northeast of the region for all three scenarios and particular the 2050 dry scenario. West and Southeast Africa experience drying in all scenarios, while West Africa experiences significant drying even in the wet 2050 scenario.

These results again show that "average" conditions for World Bank Regions may be an increase in runoff, but specific countries or regions may be projected to see the opposite conditions.

6. 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.

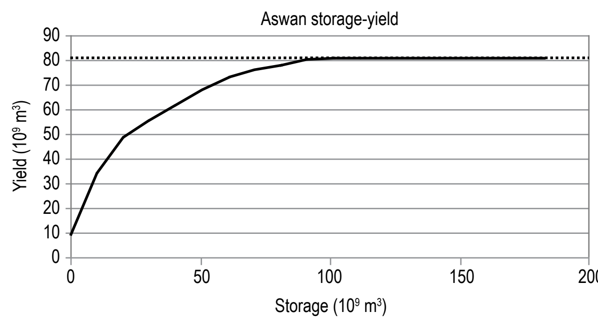
METHODOLOGY

The basin yield is a measure of annually reliable water supply from the basin. It 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. This is an estimated time series of annual or monthly flows in the basin, which gives the planner a tool to answer two questions: How much storage is needed to provide a certain amount of annual reliable yield? And for a certain amount of storage, what is the reliable yield from the base?

Figure 6.1 is an example of a storage-yield curve the Nile River at Aswan. Two points of the curve are easily estimated. The maximum yield, ignoring evaporation, is the average annual runoff in the basin, while the minimum yield is the lowest measured or modeled flow in the time series. Thus without any storage (zero on the x-axis), it is assumed that one will reliably get the minimum yearly flow or the lowest recorded. The shape of the curve that ends at the average annual runoff is a function of the within-year and year-to-year variability of the stream flow. A steep curve reflects low variability and a flatter curve is reflective of high variability. A highly variable basin will require more storage for the same basin yield than a basin with less variability. The storage-yield curve can be presented in absolute terms of volume of storage versus annual flow; in some cases, it is preferred to present it as a ratio to average annual runoff. Climatic change has the potential to affect not only the average annual runoff in a basin but also the annual runoff's variability in the shape of the storage-yield curve.

If the policy is to maximize the head for hydropower while at the same time delivering a reliable yield, then the reliable yield actually declines with increased storage

FIGURE 6.1. IMPACTS OF EVAPORATIVE LOSSES ON THE STORAGE-YIELD CURVE FOR LAKE NASSER



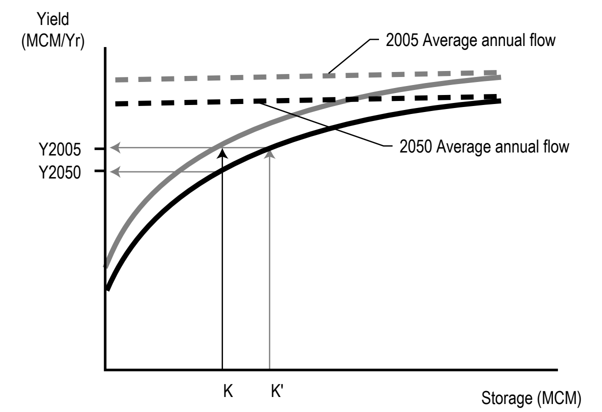
Source: Authors.

at higher storage levels due to the greater surface area and higher evaporation.

Figure 6.1 is an illustration of how climate change will shift the storage-yield curve due to changes in annual runoff. The change in annual runoff translates into the change in maximum basin yield for a fixed storage. Figure 6.2 shows the increase in storage required to maintain a constant basin yield. The storage-yield curves for nine regions in China are shown in Figure 6.3 as an example. Storage-yield curves were created for each catchment in the analysis and then aggregated to the regions for reporting.

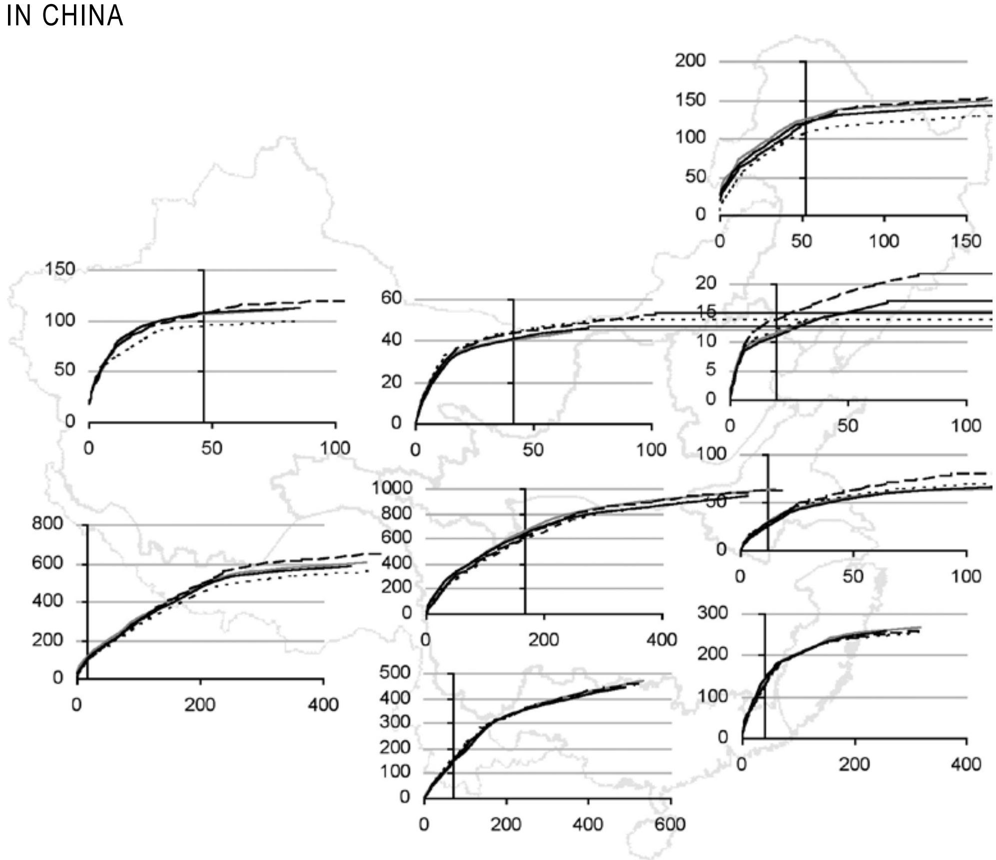
The solid line represents the base case, the solid gray line the HadCM2 scenario, the dotted line the CGCM1 scenario, and the dashed line the ECHAM4 scenario. The horizontal axis is storage in billions of cubic meters, and the vertical axis is yield in billions of cubic meters (Wiberg and Strzepek 2006).

FIGURE 6.2. IMPACT OF CLIMATE CHANGE ON RESERVOIR YIELD AND ADAPTATIONS



Source: Authors.

FIGURE 6.3. IMPACTS OF THE GCM SCENARIOS ON THE STORAGE-YIELD CURVES FOR NINE REGIONS IN CHINA



Source: Authors.

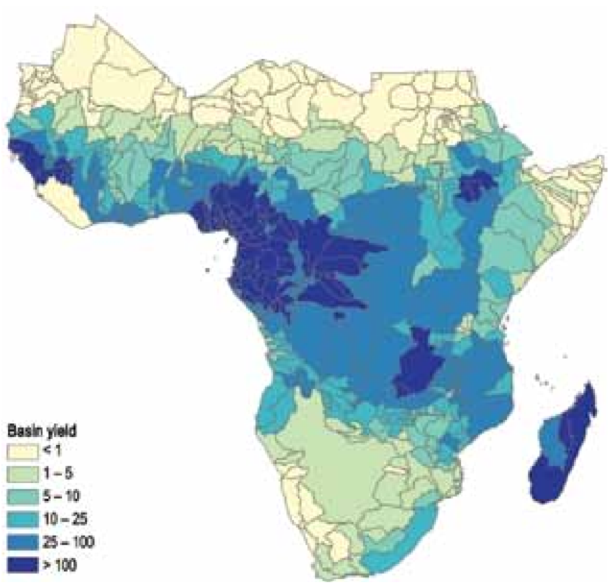
HISTORICAL RESULTS

Figure 6.4 shows the basin yield calculated from the 30-year historic (1961–90) monthly modeling of runoff for the AFR Region. The results show similar spatial patterns as the average annual runoff results in Figure 5.1.

CLIMATE CHANGE RESULTS

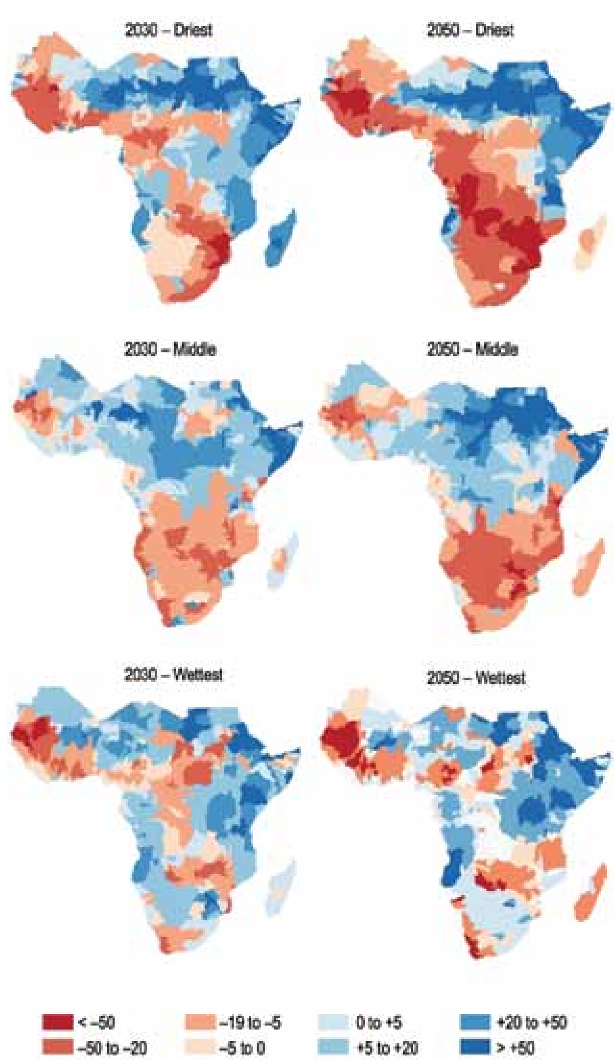
Figure 6.5 presents the climate change impacts on Basin Yield for the AFR Region. Since basin yield is a function of average runoff and variability, it exhibits a non-linear behavior to changes in climate. This can be seen as the spatial pattern of changes are similar but in many case more dramatic for the wet and dry parts of the region.

FIGURE 6.4. HISTORICAL ANNUAL BASIN YIELD IN AFR REGION (MM/YEAR)



Source: Authors.

FIGURE 6.5. PROJECTED CHANGES IN ANNUAL BASIN YIELD IN AFR REGION (PERCENT)



Source: Authors.

7. SUMMARY OF RESULTS

Tables 7.1 through 7.6 summarize the results for the each of the indicators for three IPCC SRES scenarios (A2, A1B, and B1) and for the decades surrounding 2030 and 2050. The Tables provide results for the average of all catchments in the World Bank Regions.

It is important to remember that these summaries reflect only the general trend over the entire Region. Subregions and even individual catchments can vary widely from the mean conditions. Another confounding condition is when two significant Regions exhibit exactly the opposite climate change impact (for example, significant increase or significant decrease in runoff), so that the average result is little climate change impact at all.

TABLE 7.1. RUNOFF

SRES scenario	*Year*	*Projection*	*AFR*	*EAP*	*ECA*	*LAC*	*MENA*	*SAR*
A2	2030	Dry	–5%	–13%	5%	–16%	–17%	–7%
		Medium	6%	–4%	9%	–3%	–17%	26%
		Wet	30%	7%	13%	15%	24%	31%
	2050	Dry	–13%	–11%	8%	–31%	–50%	–52%
		Medium	14%	3%	18%	–9%	–5%	20%
		Wet	31%	11%	18%	7%	31%	39%
A1B	2030	Dry	–5%	7%	9%	–9%	–25%	18%
		Medium	3%	5%	13%	–5%	12%	18%
		Wet	–1%	11%	10%	9%	15%	43%
	2050	Dry	–20%	–12%	14%	–25%	–46%	24%
		Medium	0%	–2%	21%	–16%	–16%	24%
		Wet	6%	21%	19%	7%	20%	37%
B1	2030	Dry	–1%	–8%	6%	–13%	–15%	–20%
		Medium	–9%	2%	11%	–11%	12%	–5%
		Wet	10%	14%	16%	11%	18%	36%
	2050	Dry	–8%	–8%	5%	–9%	–30%	–14%
		Medium	–12%	–1%	14%	–9%	19%	38%
		Wet	23%	15%	19%	9%	49%	33%

Source: Authors.

The results show the indicators tend to be well correlated and generally show the same sign and magnitude for each indicator for each Region. One exception is that in most cases the water deficit index increases for all scenarios, especially in 2050, due to the non-linear increase of potential evapotranspiration.

All Regions tend to show decreases in runoff for dry and mid scenarios. However, the Europe and Central Asia Region shows an increase in runoff for all scenarios wet to dry. This is due to the significant increase in precipitation and lower response of potential evapotranspiration to temperature increases at the colder temperatures of the Region.

The other Regions exhibit reduction in runoff for dry scenarios and increase in runoff for wet scenarios. The results are mixed for the mid scenarios.

Detailed results by catchment area are available for anyone interested by contacting the World Bank Water Anchor.

TABLE 7.2. 10% FLOOD EXCEEDENCE

SRES scenario	*Year*	*Projection*	*AFR*	*EAP*	*ECA*	*LAC*	*MENA*	*SAR*
A2	2030	Dry	–4%	–13%	5%	–16%	–15%	–8%
		Medium	5%	–3%	8%	–2%	–16%	23%
		Wet	27%	7%	13%	14%	25%	32%
	2050	Dry	–11%	–10%	7%	–28%	–48%	–50%
		Medium	13%	3%	17%	–9%	–4%	21%
		Wet	27%	11%	17%	7%	36%	39%
A1B	2030	Dry	–4%	7%	8%	–8%	–24%	18%
		Medium	3%	5%	13%	–4%	10%	18%
		Wet	–1%	10%	10%	9%	13%	43%
	2050	Dry	–18%	–12%	12%	–21%	–43%	24%
		Medium	1%	–2%	20%	–14%	–13%	24%
		Wet	6%	20%	19%	7%	27%	35%
B1	2030	Dry	–1%	–8%	6%	–11%	–13%	–18%
		Medium	–7%	2%	10%	–9%	12%	–5%
		Wet	9%	13%	17%	11%	22%	36%
	2050	Dry	–7%	–8%	4%	–7%	–26%	–12%
		Medium	–10%	–1%	13%	–7%	20%	34%
		Wet	20%	15%	19%	8%	52%	32%

Source: Authors.

TABLE 7.3. 90% LOW FLOW

SRES scenario	Year	Projection	AFR	EAP	ECA	LAC	MENA	SAR
A2	2030	Dry	–4%	–14%	7%	–18%	–19%	–5%
		Medium	6%	–4%	10%	–2%	–18%	31%
		Wet	37%	8%	14%	19%	18%	31%
	2050	Dry	–15%	–11%	10%	–35%	–52%	–55%
		Medium	19%	3%	21%	–11%	–8%	21%
		Wet	40%	13%	19%	9%	17%	41%
A1B	2030	Dry	–5%	7%	11%	–11%	–29%	20%
		Medium	3%	5%	15%	–5%	9%	20%
		Wet	–1%	12%	10%	9%	13%	47%
	2050	Dry	–23%	–13%	18%	–32%	–50%	25%
		Medium	0%	–2%	23%	–18%	–24%	25%
		Wet	7%	21%	19%	8%	3%	40%
B1	2030	Dry	0%	–9%	9%	–17%	–19%	–22%
		Medium	–12%	2%	13%	–15%	9%	–3%
		Wet	13%	14%	17%	10%	12%	37%
	2050	Dry	–8%	–9%	7%	–13%	–34%	–17%
		Medium	–14%	–1%	17%	–13%	8%	48%
		Wet	30%	14%	20%	9%	37%	37%

Source: Authors.

TABLE 7.4. BASEFLOW

SRES scenario	Year	Projection	AFR	EAP	ECA	LAC	MENA	SAR
A2	2030	Dry	–14%	–32%	21%	–24%	–7%	–14
		Medium	–7%	–13%	12%	–7%	–19%	33%
		Wet	27%	6%	19%	17%	4%	32%
	2050	Dry	–12%	–30%	26%	–37%	–51%	–44%
		Medium	–8%	–6%	33%	–18%	–9%	25%
		Wet	12%	10%	33%	21%	58%	35%
A1B	2030	Dry	–9%	2%	20%	–11%	–30%	27%
		Medium	5%	2%	24%	–10%	4%	27%
		Wet	0%	9%	23%	16%	5%	47%
	2050	Dry	–17%	–34%	33%	–33%	–57%	27%
		Medium	–3%	–12%	40%	–19%	–17%	27%
		Wet	13%	35%	29%	8%	17%	37%
B1	2030	Dry	–4%	–19%	19%	–14%	–18%	–10%
		Medium	–10%	–2%	6%	–6%	–13%	–16%
		Wet	8%	23%	20%	21%	15%	28%
	2050	Dry	–14%	–21%	18%	–14%	–39%	–5%
		Medium	–13%	–13%	33%	–2%	12%	24%
		Wet	10%	21%	23%	2%	87%	29%

Source: Authors.

TABLE 7.5. 10% BASIN YIELD

SRES Scenario	Year	Projection	AFR	EAP	ECA	LAC	MENA	SAR
A2	2030	Dry	21%	42%	–2%	44%	61%	40%
		Medium	9%	14%	–9%	17%	60%	–14%
		Wet	–22%	–7%	–13%	–10%	–4%	–22%
	2050	Dry	38%	42%	–3%	74%	136%	53%
		Medium	–2%	0%	–14%	39%	24%	–5%
		Wet	–19%	–13%	–18%	5%	4%	–29%
A1B	2030	Dry	26%	–4%	–9%	29%	85%	–19%
		Medium	3%	–2%	–16%	26%	–17%	–19%
		Wet	7%	–12%	–7%	–1%	–11%	–29%
	2050	Dry	53%	49%	–12%	57%	141%	–18%
		Medium	12%	10%	–24%	53%	55%	–18%
		Wet	–4%	–25%	–21%	6%	–19%	–32%
B1	2030	Dry	8%	35%	–2%	38%	46%	45%
		Medium	27%	1%	–15%	35%	13%	27%
		Wet	–5%	–17%	–15%	–6%	–7%	–26%
	2050	Dry	30%	26%	4%	27%	103%	30%
		Medium	37%	7%	–16%	30%	26%	–31%
		Wet	–14%	–20%	–21%	–5%	–29%	–28%

Source: Authors.

TABLE 7.6. WATER DEFICIT INDEX

SRES Scenario	Year	Projection	AFR	EAP	ECA	LAC	MENA	SAR
A2	2030	Dry	0%	122%	10%	40%	–5%	9%
		Medium	–1%	91%	–15%	30%	–1%	–6%
		Wet	–10%	70%	–18%	12%	–4%	–10%
	2050	Dry	–2%	127%	17%	69%	6%	26%
		Medium	4%	87%	–16%	37%	0%	–3%
		Wet	5%	74%	–16%	21%	–12%	–5%
A1B	2030	Dry	13%	106%	30%	59%	14%	33%
		Medium	13%	97%	19%	59%	7%	4%
		Wet	10%	90%	19%	25%	7%	3%
	2050	Dry	29%	141%	44%	87%	23%	33%
		Medium	18%	114%	28%	64%	15%	4%
		Wet	5%	65%	19%	39%	11%	11%
B1	2030	Dry	15%	125%	35%	41%	10%	23%
		Medium	16%	104%	9%	23%	10%	22%
		Wet	9%	71%	6%	13%	8%	5%
	2050	Dry	20%	132%	44%	48%	14%	17%
		Medium	18%	117%	25%	22%	8%	12%
		Wet	16%	67%	5%	44%	–5%	10%

Source: Authors.

8. CONCLUSIONS

It is difficult to come up with one simple result from this analysis. But there are a series of universal messages about potential climate change impacts over the World Bank Regions of operation:

1. There is a wide range of Climate Change impacts within each Region.
2. The IPCC SRES scenario and the specific GCMs analyzed greatly influence the results of climate impact modeling.
3. For a risk-based approach to planning, it is important to use a wide range of SRES and GCM scenarios rather than focusing on a few to address the full range of uncertainty regarding future climate that the water resource planner is facing.
4. A wide range of climate change indicators are needed to assist the assessment of operational risk to the varied Water System investment projects undertaken by the World Bank.
5. Some results suggest that World Bank projects may be facing a much different climatic and thus hydrologic regime threatening their economic performance as early as 2030.
6. Climate change is an additional uncertainty facing water resource planners and should be included as a regular part in any hydrologic assessment.

The data and models used are monthly data, and the stream flow data used for calibration are monthly averages not time series. This produces increased uncertainty in extreme values or tails of the distributions. The GCM data are raw output at an average spatial scale of 2.5° by 3°. This provided significant uncertainty for climate change at the subgrid scale level.

Future work that could build on this analysis should focus on three areas of improvement: climate scenarios, hydro climatic data, and hydrologic modeling:

1. *Probabilistic Climate Scenarios*. Since it is suggested to cast climate change in a risk planning framework, this calls for explicit probabilistic characterization of GCM results.
2. *Statistical and Dynamic Downscaling*. Current 2.5° x 3° GCM grids are not sufficient to capture many orographic climate processes. An effort to statistically or dynamically (regional climate models) a wide range of IPCC CGM is very costly. The result is that just for one or two models are done whilte a wide range of models, say a minimum of 10 models is needed. *Finer Temporal Resolution of Climate Model Result*. Hydrology and flood flows occur at the hourly and daily scale. Working with climate modelers to archive data at the daily and lower time step for longer time periods and for more variables needed for the potential evapotranspiration calculations (such as tmin, tmax, vapor pressure) is an important step needed to solve this issues*Finer-scale Hydrologic Models. This involves developm*ent of daily hydrologic model at the 500 to 1000 km^2 watershed scale.
3. *Improvement in Global Scale Stream-flow Time Series Data* for calibration of hydrologic model at the monthly and daily levels is needed with detailed meta data on time periods and human influences on the stream records.

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APPENDIX: REFERENCE FOR MODELS AND DATA

CLIRUN-II RAINFALL RUNOFF MODEL

CLIRUN-II is the latest model in a family of hydrologic models developed specifically for the analysis of the impact of climate change on runoff. Kaczmarek (1993) presents the theoretical development for a single-layer lumped watershed rainfall runoff model-CLIRUN. Kaczmarek (1998) presents the application of CLIRUN to the Yellow River in China.

Yates (1996) expanded on the basic CLIRUN by adding a snow-balance model and providing a suite of possible PET models and packaged it in a tool WATBAL. WATBAL has been used on a wide variety of spatial scales from small to large watersheds and globally in 0.5° by 0.5° grid (Strzepek et al. 1999; Huber-Lee et al. 2005 ; Strzepek et al. 2005).

CLIRUN-II (Strzepek et al. 2008) is the latest in the "Kaczmarek School" of hydrologic models. It incorporates most of the features of WATBAL and CLIRUN but was developed specifically to address extreme events at the annual level modeling low and high flows. CLIRUN and WATBAL did very well in modeling mean monthly and annual runoff, important for water supply studies, but they did not model well the tails of runoff distribution.

CLIRUN-II has adopted a two-layer approach following the framework of the SIXPAR hydrologic model (Gupta and Sorooshian 1983, 1985), and a unique conditional parameter estimation procedure was used. This Appendix presents a brief description of the components of the model.

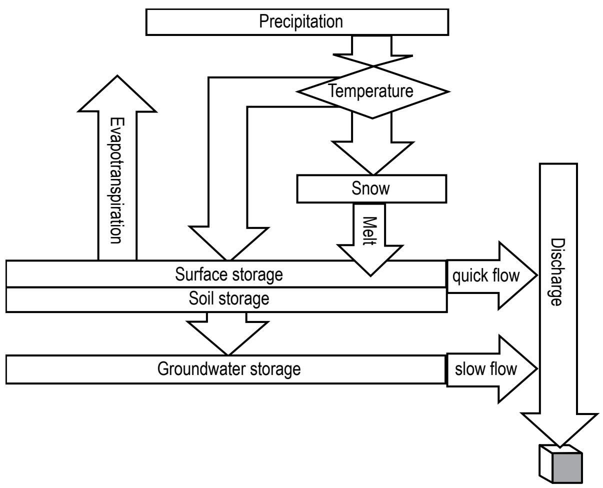
Spatial and Temporal Scale. CLIRUN II is models runoff as a lumped watershed with climate inputs and soil characteristics averaged over the watershed simulating runoff at a gauged location at the mouth of the catchment. CLIRUN can run on a daily or monthly time step. For this study, climate and runoff data were available only on a monthly basis so monthly was used.

Snow-Balance Model. The snow accumulation and melt model used in this study is based on concepts frequently used in monthly water balance models (McCabe and Wolock 1999). Inputs to the model are monthly temperature (T) and precipitation (P). The occurrence of snow is computed as a function of average watershed temperature and two parameters, Temp_snow and Temp_rain. These two parameters are calibrated for each watershed. Snowmelt is added to any monthly precipitation to form effective precipitation available for infiltration or direct runoff.

The figure shows the mass balance of water in the CLIRUNII system. Water enters via precipitation and leaves via evapotranspiration and runoff. The difference between inflow and outflow is reflected as change in storage in the soil or groundwater.

Evapotranspiration. A suite of potential evapotranspiration models is available for use in CLIRUNII. For this study the Blaney-Criddle (temperature based) method

FIGURE C.1. CLIRUN-II CONCEPTUAL HYDROLOGIC MODEL SCHEMATIC



(FAO 1996) was used to be consistent with State of Colorado practices. Actual evapotranspiration is a function of potential and soil moisture state following the FAO method.

Soil Water Modeling. Soil water is modeled as a two-layer system: a soil layer and a groundwater layer. These two components correspond to a quick and a slow runoff response to effective precipitation.

Quick Runoff. The soil layer generates runoff in two ways. First there is a direct runoff component, which is the portion of the effective precipitation (precipitation plus snowmelt) that directly enters the stream systems. The remaining effective precipitation is infiltration to the soil layer. The direct runoff is a function of the soil surface, and models differently for frozen soil (winter and spring) and non-frozen (summer and fall). The infiltration then enters the soil layer. A non-linear set of equations determines how much water leaves the soil as runoff, how much is percolated to the groundwater, and how much goes into soil storage. The runoff is a linear relation of soil water storage, and percolation is a non-linear relationship of both soil and groundwater storages.

Slow Runoff. The groundwater receives percolation from the soil layer, and runoff is generated as a linear function of groundwater storage.

The soil water processes have six parameters similar to the SIXPAR model (Gupta and Sorooshian 1983) that are determined via calibration of each watershed.

Modeling Dry and Wet Years. When CLIRUNII is calibrated in a classical rainfall-runoff framework, the results are very good for the 25th to 75th percentile of the observed stream flows, producing R2 of 0.3 to 0.7 For most water resource systems, however, the tails of the stream flow distribution are important. for design and operation planning. To address this issue, a concept developed by Block and Rajagopalan (2007) for hydrologic modeling of the Nile River, know as localized polynomial, was extended to calibration of rainfall runoff modeling in CLIRUNII (Strzepek et al. 2008).

Briefly, when calibrating, each observed year is categorized as to whether it falls into a dry year 0–25 percent of the distribution, a normal year 25–75 percent, or wet year greater than 75 percent. A separate set of model parameters was estimated for the three different class of annual stream flow. This increased the R2 from 0.7 to 0.92.

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