Climate change and global water resources: SRES emissions and socio-economic scenarios

Article *in* Global Environmental Change · April 2004

DOI: 10.1016/j.gloenvcha.2003.10.006

Nigel Arnell
University of Reading

ELSEVIER

Global Environmental Change 14 (2004) 31–52

GLOBAL ENVIRONMENTAL CHANGE

www.elsevier.com/locate/gloenvcha

Climate change and global water resources: SRES emissions and socio-economic scenarios

Nigel W. Arnell

School of Geography, University of Southampton, Southampton SO17 1BJ, UK

Abstract

In 1995, nearly 1400 million people lived in water-stressed watersheds (runoff less than 1000 m^3/capita/year), mostly in south west Asia, the Middle East and around the Mediterranean. This paper describes an assessment of the relative effect of climate change and population growth on future global and regional water resources stresses, using SRES socio-economic scenarios and climate projections made using six climate models driven by SRES emissions scenarios. River runoff was simulated at a spatial resolution of $0.5 \times 0.5^\circ$ under current and future climates using a macro-scale hydrological model, and aggregated to the watershed scale to estimate current and future water resource availability for 1300 watersheds and small islands under the SRES population projections. The A2 storyline has the largest population, followed by B2, then A1 and B1 (which have the same population). In the absence of climate change, the future population in water-stressed watersheds depends on population scenario and by 2025 ranges from 2.9 to 3.3 billion people (36–40% of the world's population). By 2055 5.6 billion people would live in water-stressed watersheds under the A2 population future, and "only" 3.4 billion under A1/B1.

Climate change increases water resources stresses in some parts of the world where runoff decreases, including around the Mediterranean, in parts of Europe, central and southern America, and southern Africa. In other water-stressed parts of the world—particularly in southern and eastern Asia—climate change increases runoff, but this may not be very beneficial in practice because the increases tend to come during the wet season and the extra water may not be available during the dry season. The broad geographic pattern of change is consistent between the six climate models, although there are differences of magnitude and direction of change in southern Asia.

By the 2020s there is little clear difference in the magnitude of impact between population or emissions scenarios, but a large difference between different climate models: between 374 and 1661 million people are projected to experience an increase in water stress. By the 2050s there is still little difference between the emissions scenarios, but the different population assumptions have a clear effect. Under the A2 population between 1092 and 2761 million people have an increase in stress; under the B2 population the range is 670–1538 million, respectively. The range in estimates is due to the slightly different patterns of change projected by the different climate models. Sensitivity analysis showed that a 10% variation in the population totals under a storyline could lead to variations in the numbers of people with an increase or decrease in stress of between 15% and 20%. The impact of these changes on actual water stresses will depend on how water resources are managed in the future.

Keywords: Climate change impacts; Global water resources; Water resources stresses; SRES emissions scenarios; Macro-scale hydrological model; Multi-decadal variability

1. Introduction

The UN Comprehensive Assessment of the Freshwater Resources of the World (WMO, 1997) estimated in 1997 that approximately a third of the world's population was living in countries deemed to be suffering from water stress: they were withdrawing more than 20% of their available water resources. The assessment went on to estimate that up to two-thirds of the world's population would be living in water-stressed countries by 2025. Climate change due to an increasing concentration of greenhouse gases is likely to affect the volume and timing of river flows and groundwater recharge, and thus affect the numbers and distribution of people affected by water scarcity. Estimates of the effect of climate change, however, depend not only on the assumed emissions scenario and climate model used to translate emissions into regional climates, but also on the assumed rate of population change.

Since the UN Comprehensive Assessment of the Freshwater Resources of the World was published in

0959-3780/$ - see front matter © 2003 Elsevier Ltd. All rights reserved.
doi:10.1016/j.gloenvcha.2003.10.006

1997, based on rather coarse national-scale data, there have been a number of other global-scale assessments. Seckler et al. (1998, 1999) have assessed future water resource scarcity at the global scale by 2025. They assumed no climate change, and their study concentrated on the development of scenarios for water use, focusing particularly on irrigation use. Alcamo et al. (2000, 2003) refined their earlier assessment (Alcamo et al., 1997) by calculating water resources and resource demands at the river basin scale and using different projections of future demand: they did not, however, consider the effects of climate change. Their model was also used in UNEP's Global Environment Outlook-3 (UNEP, 2001), with different projections of future resource use and including the effects of climate change (although the particular climate models used were not specified). The Pilot Analysis of Global Ecosystems (PAGES) freshwater systems assessment (Revenga et al., 2000; World Resources Institute, 2000) also worked at the major river basin scale, but used a different index of water resources stress: this study too did not consider the effects of climate change, and like Alcamo et al. (1997) and UNEP (2001) projected substantial increases in the numbers of people living in water-stressed basins, due entirely to population growth. Vörösmarty et al. (2000) compared demand growth and climate change scenarios at the $0.5 \times 0.5^{\circ}$ scale, showing that over the next 25 years climate change would have less effect on change in water resources stresses than population and water demand growth. However, they did not explicitly compare the future situation with and without climate change.

The aim of this paper is to present results of an assessment of the implications of climate change for the global and regional numbers of people living in water-stressed watersheds, using consistent climate and socio-economic scenarios: the climatic effects of the different IPCC SRES (IPCC, 2000) emissions scenarios are compared with the assumed populations which generated those emissions. The paper compares the relative effect of emissions scenario and population growth rate on the effects of climate change. It uses a macro-scale hydrological model to translate climate change scenarios constructed from climate model simulations (using six climate models run with SRES emissions scenarios) into runoff at the $0.5 \times 0.5^{\circ}$ scale, and calculates water resources stress indicators at the watershed scale. A companion paper (Arnell, 2003) describes the hydrological changes in more detail.

2. Methodology

The study adopted the conventional approach to climate change impact assessment, following a change in climate through to change in runoff, and then calculating the implications for the number of people at risk of increased water resources pressures. The primary innovation of the study lies in the use of a consistent set of emissions and socio-economic scenarios.

The stages in the study were:

(i) Construct scenarios for change in climate from climate model simulations of the climatic effects of the SRES emissions scenarios. Scenarios were constructed from six climate models run with the SRES emissions scenarios—HadCM3, ECHAM4-OPYC, CSIRO-Mk2, CGCM2, GFDL_r30 and CCSR/NIES2—characterising change in 30-year mean climate relative to 1961–1990 by the 2020s (2010–2039), 2050s (2040–2069) and 2080s (2070–2099).
(ii) Apply these scenarios to a gridded baseline climatology, describing climate over the period 1961–1990 at a spatial resolution of $0.5 \times 0.5^{\circ}$ (New et al., 1999).
(iii) Run a macro-scale hydrological model at the $0.5 \times 0.5^{\circ}$ resolution with the current and changed climates to simulate 30 year time series of monthly runoff. Calculate average annual runoff from these time series.
(iv) Sum the simulated runoff over approximately 1300 watersheds and small islands to estimate watershed-scale runoff volumes.
(v) Determine the watershed population total under each population growth scenario.
(vi) Construct indicators of water resources stress for each watershed from the simulated runoff and estimated watershed population.

These stages are described in more detail in the next section.

3. Emissions, climate, hydrological and socio-economic scenarios

3.1. SRES population and emissions scenarios

The IPCCs Special Report on Emissions Scenarios (SRES) was published in 2000 (IPCC, 2000), and contains a set of new projections of future greenhouse gas emissions: these projections supersede the IS92 family of projections. The starting point for each projection was a "storyline", describing the way world population, economies, political structure and lifestyles may evolve over the next few decades. The storylines were grouped into four scenario families, and led ultimately to the construction of six SRES marker scenarios (one of the families has three marker scenarios, the others one each). The four families can be briefly characterised as follows:

A1: Very rapid economic growth with increasing globalisation, an increase in general wealth, with convergence between regions and reduced differences in regional per capita income. Materialist–consumerist values predominant, with rapid technological change. Three variants within this family make different assumptions about sources of energy for this rapid growth: fossil intensive (A1FI), non-fossil fuels (A1T) or a balance across all sources (A1B).

B1: Same population growth as A1, but development takes a much more environmentally sustainable pathway with global-scale cooperation and regulation. Clean and efficient technologies are introduced. The emphasis is on global solutions to achieving economic, social and environmental sustainability.

A2: Heterogeneous, market-led world, with less rapid economic growth than A1, but more rapid population growth due to less convergence of fertility rates. The underlying theme is self-reliance and preservation of local identities. Economic growth is regionally oriented, and hence both income growth and technological change are regionally diverse.

B2: Population increases at a lower rate than A2 but at a higher rate than A1 and B1, with development following environmentally, economically and socially sustainable locally oriented pathways.

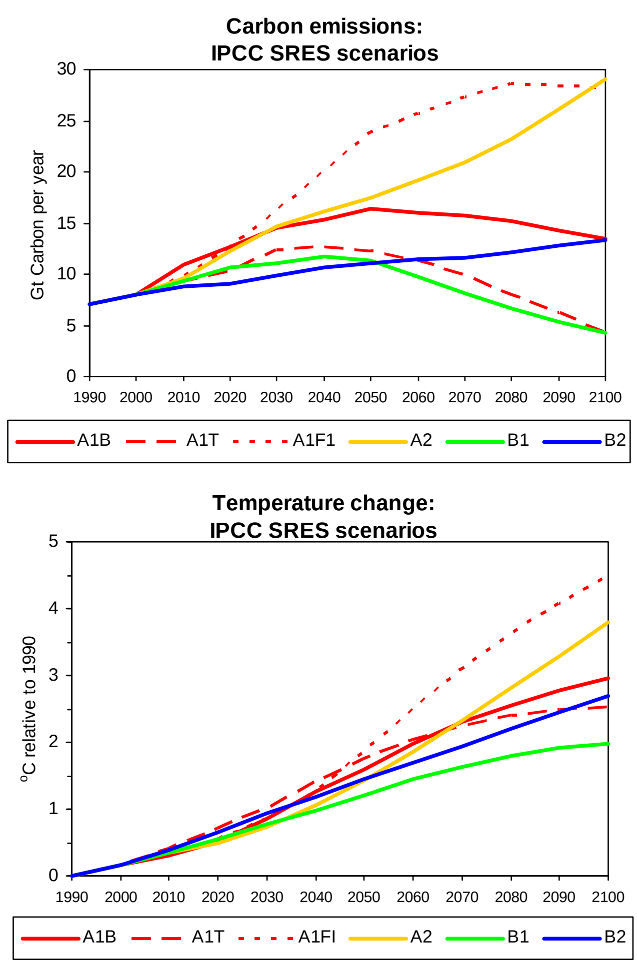

Fig. 1. Global emissions and changes in average temperature associated with each SRES emissions scenario.

Table 1
Global population under the four SRES scenario families

	A1	B1	A2	B2
Population (millions)				
2025	7926	7926	8714	8036
2050	8709	8709	11778	9541
2085	7914	7914	14220	10235

In terms of climate forcing, B1 has the least effect, followed by B2. The greatest forcing is caused by the fossil fuel-intensive A1F1 scenario, followed by A2 (IPCC, 2001a). Fig. 1 shows total carbon emissions under the six marker scenarios, and the estimated change in global average temperature under each scenario (as estimated from a simple energy balance model).

Table 1 shows the global population totals under the four scenario families. A1 and B1 have the same population projections, based on the IIASA "rapid" fertility transition projection, which assumes low fertility and low mortality rates. A2 is based on the IIASA "slow" fertility transition projection, with high fertility and high mortality rates. The B2 population scenario was based on the UN 1998 Medium Long Range Projection for the years 1995–2100 (Gaffin et al., 2003). Like climate projections, projections of future population under a given storyline depend on assumptions about model parameters and form. The SRES scenarios give no indication of the possible uncertainty in future population projections, but this study explores briefly the effect of varying population totals under each storyline.

3.2. Estimating watershed-scale population totals

The original population projections used to characterise the SRES storylines were made at the regional level and published in the SRES report for four world regions. These needed to be disaggregated first to the national level, and then down to the $0.5 \times 0.5°$ scale from which watershed totals could be calculated. The population scenarios were downscaled to the national scale by CIESIN (see Arnell et al., 2003 and Gaffin et al., 2003 for details) using a combination of national projections to 2050 (UN 2000 medium projection for A1/B1, UN 2000 high population for A2, and UN 1998 medium population for B2) and regional projections after 2050. This produces some discontinuities where national and regional growth rates are substantially different (Arnell et al., 2003).

The national populations for 2025, 2055 and 2085 were then disaggregated to the $0.5 \times 0.5°$ resolution using the Gridded Population of the World (GPW) Version 2 data set (CIESIN, 2000), which has a spatial resolution of $2.5 \times 2.5'$, and summed to the watershed scale. This involved the following stages:

(i) rescale the $2.5 \times 2.5'$ resolution 1995 data to 2025, 2055 and 2085 assuming that each grid cell in a country changes at the national rate;
(ii) sum the populations in each $0.5 \times 0.5^\circ$ grid cell;
(iii) sum the population in each watershed.

The key assumption is that population changes everywhere within a country (and after 2050 a region) at the same rate. A more sophisticated approach would allow for differential growth rates between urban and rural areas, but this would not give substantially different results when populations are summed back up to the watershed scale.

3.3. Climate scenarios

The Third Assessment Report of the IPCC (IPCC, 2001a) describes the results from nine climate models run with two or more of the SRES emissions scenarios. This study uses the results from six of these climate models (Table 2).

HadCM3 is the most recent version of the Hadley Centre climate model used to project the climatic effects of future emissions scenarios. It includes updated representations of some of the key processes in the atmosphere and ocean, and importantly does not need to use a flux correction to maintain a stable climate. It has a spatial resolution of $3.75^\circ \times 2.5^\circ$ (Gordon et al., 2000). The Hadley Centre has conducted the following seven climate change experiments with HadCM3 (Johns et al., 2003):

(i) A1FI emissions scenario: one simulation.
(ii) Three ensemble simulations with the A2 emissions scenario. The three ensemble members have the same forcing but different initial boundary conditions, and the differences between them reflect natural climatic variability.
(iii) B1 emissions scenario: one simulation.
(iv) Two ensemble simulations with the B2 emissions scenario.

The spatial patterns in change in both temperature and precipitation are very similar between the seven scenarios (Johns et al., 2003). Temperature increases are greatest at high latitudes, and in most scenarios there is a cooling or only a small increase in the North Atlantic. Annual precipitation increases in high latitudes and across most of Asia: precipitation in winter increases across most mid-latitude regions. Annual precipitation decreases around the Mediterranean and in much of the Middle East, Central America and northern South America, and Southern Africa.

Climate scenarios for A2 and B2 worlds only were constructed from the other five climate models (A1 and B1 simulations with CSIRO and CCSR/NIES were not used). The broad patterns of temperature change are similar between the six models, although the rates of change are different. For a given emissions scenario, the CCSR/NIES2 model produces the greatest increase in temperature, and GFDL_R30 the least. There are also broad similarities in precipitation changes, but there are some important regional differences between the models. For example, HadCM3 and ECHAM4 simulate increases in precipitation across east Asia, whilst the others simulate decreases at least in part of the region. CGCM2, GFDL_r30 and CCSR/NIES simulate reductions in precipitation across eastern North America, but the others simulate an increase (see maps in Arnell, 2003).

Table 2
Summary of climate change experiments using the SRES emissions scenarios, with summary data on the IPCC-DDC

Model name	Emissions				Resolution (atmosphere) lat. × long.[a]
	A1FI	A2	B1	B2	
HadCM3	Y	Y	Y	Y	$2.5 \times 3.75^\circ$
CGCM2		Y		Y	$3.8 \times 3.8^\circ$
CSIRO Mk 2	Y	Y	Y	Y	$3.2 \times 5.6^\circ$
ECHAM4/OPYC		Y		Y	$2.8 \times 2.8^\circ$
GFDL_R30_c		Y		Y	$2.25 \times 3.75^\circ$
CCSR/NIES2	Y[b]	Y	Y	Y	$5.6 \times 5.6^\circ$

[a] Resolution varies with latitude for some of the models.
[b] A1b and A1t also run: A2 and B2 only used in this paper see IPCC (2001a) for full model references.

3.4. Changes in runoff

The macro-scale hydrological model used to simulate runoff across the world at a spatial resolution of $0.5 \times 0.5^\circ$ has been described by Arnell (1999b, 2003). In brief, it calculates the water balance in each cell on a daily basis, generating streamflow from precipitation falling on the portion of the cell that is saturated and by drainage from water stored in the soil. The model parameters are not calibrated and are estimated from spatial data bases, and a validation exercise (Arnell, 2003) has shown that the model simulates average annual runoff reasonably well.

However, the model has two important omissions. First, it does not simulate transmission loss along the river channel, which is common in dry regions, and it does not incorporate the evaporation of water which runs across the surface of the catchment and either infiltrates downslope or enters ponds or wetlands. It, therefore, tends to overestimate the river flows in dry regions—by up to a factor of three (Arnell, 2003)—although arguably it provides a reasonable indication of the resources potentially available for use in such areas (many rural communities in dry areas take water from river beds or wetlands). Second, it does not include a glacier component, so river flows in a cell do not include any net melt from upstream glaciers.

Climate change must be seen in the context of multi-decadal variability, which will lead to different amounts of water being available over different time periods even in the absence of climate change. The effect of this multi-decadal variability on runoff was assessed by constructing eight scenarios for change in 30-year mean precipitation and temperature from a long "unforced" HadCM3 run (Gordon et al., 2000) in which the concentration of greenhouse gases was assumed constant. The precise patterns and magnitudes of the effect of this multi-decadal variability depend of course on which of the eight scenarios is used as the baseline, but the average standard deviation in 30-year average annual runoff is typically under 6% of the mean, but up to 15% in dry regions (Arnell, 2003).

Fig. 2 shows the simulated change in average annual runoff across the world by the 2050s, under the seven HadCM3 scenarios, with changes less than the standard deviation of change in 30-year mean runoff due to natural multi-decadal variability shown in grey. Fig. 2 shows increases in high latitudes, east Africa and south and east Asia, and decreases in southern and eastern Europe, western Russia, north Africa and the Middle East, central and southern Africa, much of North America, most of South America, and south and east Asia. This pattern of change is consistent with that in Arnell (1999a) also IPCC (2001b), which used scenarios constructed from HadCM3 run with the IS92a emissions scenario. There is little difference in pattern of change between the seven HadCM3 scenarios, and this is confirmed by pattern correlation analysis which shows

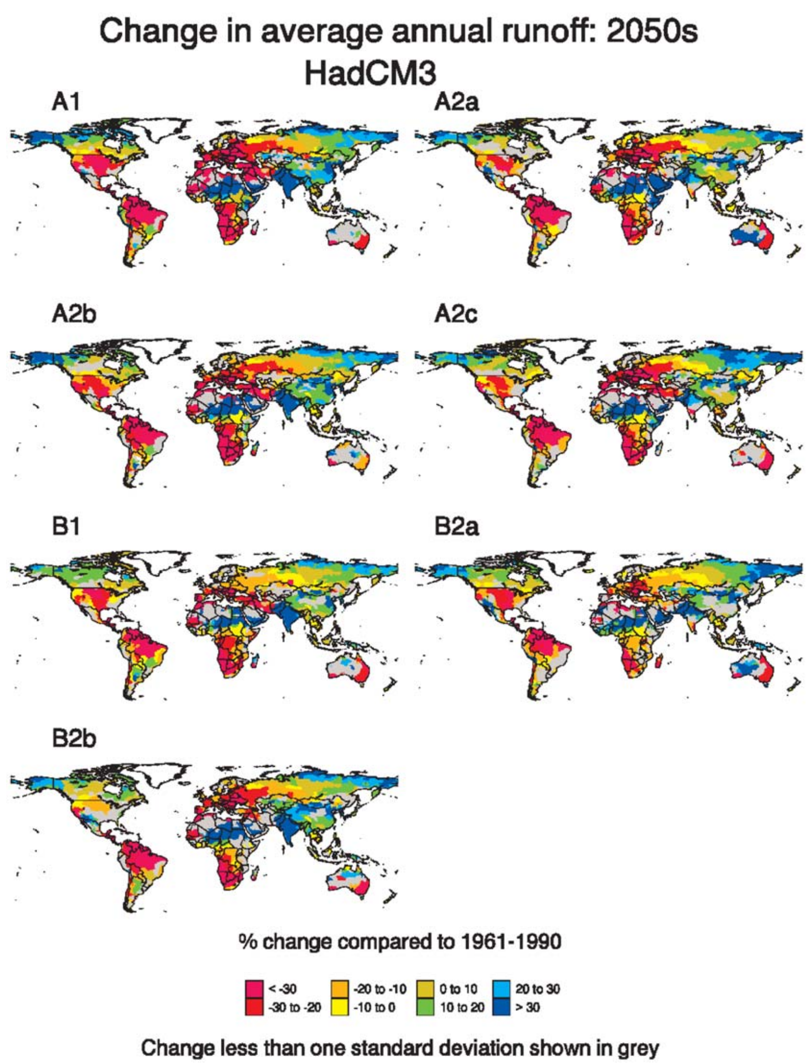

Fig. 2. Percentage change in average annual runoff: "2050s" (2040–2069) compared with 1961–1990. HadCM3 scenarios.

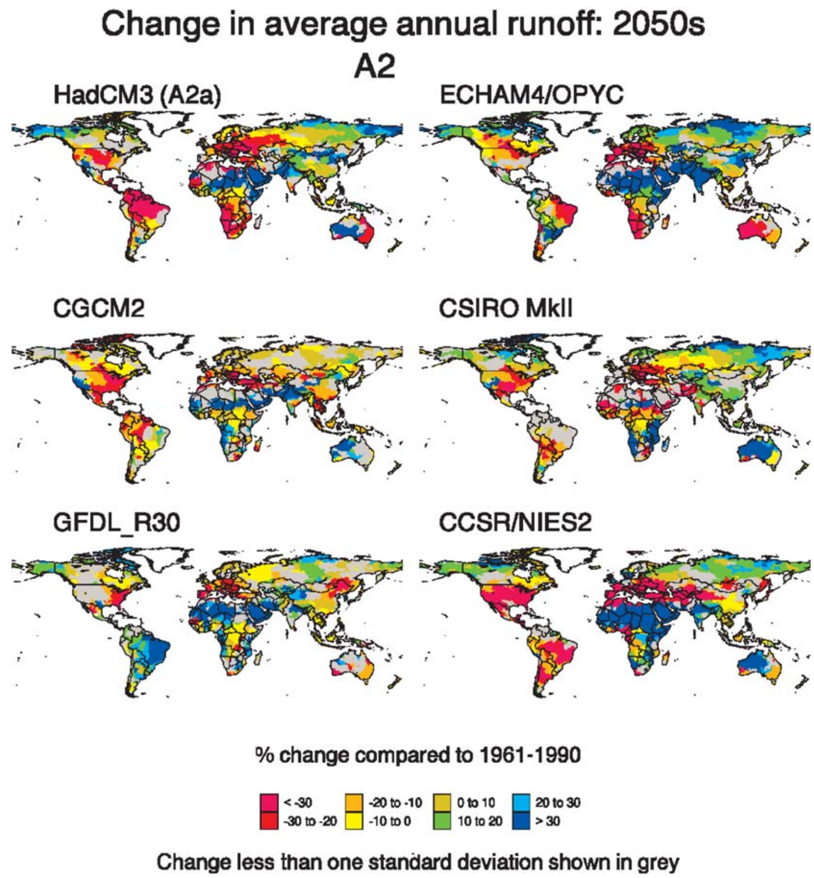

Fig. 3. Percentage change in average annual runoff "2050s" (2040–2069) compared with 1961–1990. A2 scenarios.

that the correlations between the three A2 ensemble members or the two B2 ensemble members are generally no higher than between any pair of scenarios. It would be expected that the changes from the A1FI scenario would be greater than those from A2 and B2, with the smallest changes from the B1 scenario. One measure of the magnitude of change in runoff is the standard deviation of change across all watersheds (Arnell, 2003). This shows little systematic difference by the 2020s, and by the 2050s there are only slight indications that A1FI produces the biggest change and B1 the smallest. By the 2080s the differences between the scenarios are clearer. This implies that until the 2080s, it is possible to treat all seven climate scenarios as members of a single ensemble set.

Fig. 3 shows the simulated change in runoff under the A2 emissions scenario for all six climate models. The patterns are, like those for precipitation, broadly similar, but with some regional differences. Areas where more than half of the simulations show a significant decrease in runoff (greater than the standard deviation of natural multi-decadal variability) include much of Europe, the Middle East, southern Africa, North America and most of South America. Areas with consistent increases in runoff include high latitude North America and Siberia, eastern Africa, parts of arid Saharan Africa and Australia, and south and east Asia.

4. Indicators of water resources stress

There is a wide range of potential indicators of water resources stress, including measures of resources available per person, and populations living in defined stressed categories. This study concentrates on the *numbers* of people affected by water resources stress, rather than hydrologically based indicators which are difficult to compare with those constructed for other impact sectors. There are a number of key issues associated with the development of appropriate indicators.

The first relates to the scale at which the indicators are calculated. As noted in the introduction, the earliest assessments of global water resources stresses were based on national scale indices, because that is the level at which information is generally available. However, national indices can hide very significant sub-national variability, particularly in China, Russia and North America, and it is preferable to work at a finer spatial resolution. Like the Alcamo et al. (2000), PAGE (Revenga et al., 2000) and GEO-3 (UNEP, 2001) studies, *the current study calculates indices at the watershed scale*, assuming implicitly that resources in a watershed are equally available throughout that watershed. A number of major world basins are divided into several watersheds. In this study, each watershed is treated independently and there is no import of water from upstream watersheds. In practice there will also be different stresses *within* a watershed. It is possible to calculate indices at the $0.5 \times 0.5^\circ$ scale—both population and simulated runoff data are available at that scale—but this will underestimate resource availability in areas where large volumes of water are imported from upstream.

The second issue concerns the definition of an appropriate indicator of pressures on water resources. One widely used indicator is the ratio of withdrawals to average annual runoff (as used in the UN Comprehensive Assessment of the Freshwater Resources and in the Alcamo et al., 2000, 2003; Vörösmarty et al., 2000 and GEO-3 studies), but this requires estimates of future water withdrawals which will depend not only on future population but also assumed future water use efficiency. There are currently three global data bases on *current* water withdrawals: one developed for the UN Comprehensive Assessment of the Freshwater Resources of the World (Shiklomanov, 1998; Raskin et al., 1997), one presented in publications of the World Resources Institute (e.g. WRI, 2000) and most recently updated in Gleick (1998), and one collated by FAO and stored on AQUASTAT (www.fao.org/ag/agl/aglw/aquastat/main/index.shtm). A fourth data set covering 118 countries has been prepared at the International Water Management Institute (Seckler et al., 1998, 1999). However, due to the use of different baselines and in some cases assumptions, the four data sets rarely give the same estimates for current water use, with some very large differences. Projections of *future* withdrawals were made for the UN Comprehensive Assessment (Raskin et al., 1997), by Seckler et al. (1998) and for GEO-3 (UNEP, 2001), and again there are substantial differences reflecting different assumptions in particular about future irrigation use, population growth and water use efficiency in general. The first two projections were based on baseline data from the early 1990s, and in many countries in eastern Europe and central Asia water withdrawals have fallen substantially since then: Moldova's withdrawals fell by around 50% between 1990 and 1996, for example (UNEP, 1999). Indicators based on estimated future water withdrawals are therefore highly sensitive to some key, uncertain, assumptions.

A second indicator is the amount of water resources available per person, expressed as m^3/capita/year. The advantage of this index is that it does not require assumptions about future water withdrawals: the disadvantage is that it tends to underestimate stresses in areas where there are very large withdrawals (principally for irrigation). This index was used by the PAGE study (Revenga et al., 2000). *The current study concentrates on resources per capita*.

The third issue concerns the measure of water resource availability. The most widely used measure is average annual runoff, both generated within the unit of assessment and imported from upstream. However, in some areas pressures on water resources may be determined by the amount of water available in "dry" years, and the relationship between mean and extreme runoff varies from region to region (in general, the variability in runoff from year to year increases as the climate becomes drier). *The current study uses both average annual runoff and the 10-year return period minimum annual runoff to characterise available water resources*.

The fourth issue concerns the definition of who is water stressed, and revolves around the specification of critical thresholds. Table 3 shows a widely used classification of water resources stresses (Falkenmark et al., 1989), based originally on a comparison of national resource availability data with an assessment of whether a country was experiencing water-related problems. In practice, the thresholds are arbitrary, and all are well above minimum physiological requirements. *The current study assumes that areas with less than 1000 m^3/capita/year are water-stressed.* Revenga et al. (2000) use thresholds of both 1700 and 1000 m^3/capita/year.

The final issue relates to the characterisation of the effects of a *change* in the amount of resources available on water resources stresses. A simple measure is the number of people who move into, or out of, the water-stressed category. It is not appropriate simply to determine the net change, because this assumes that "winners" exactly compensate "losers", and this is not necessarily the case: the economic and social costs of people becoming water-stressed are likely to outweigh the economic and social benefits of people ceasing to be water-stressed (although this suggestion needs further investigation). Also, the increase in runoff tends to occur during the wet season, and if not stored will lead to little benefit during the dry season, and may be associated with an increased frequency of flooding (Arnell, 2003).

Table 3
Water resources index classes

Resources per capita (m^3/capita/year)	
Index	Class
>17001	No stress
1000–1700	Moderate stress
500–1000	High stress
<500	Extreme stress

Table 4
People living in water-stressed countries in the absence of climate change

	Millions of people			As % of total population		
	A1/B1	A2	B2	A1/B1	A2	B2
Water-stressed countries have runoff less than 1700 m^3/capita/year						
1995		401			7	
2025	2701.1	4579.6	2786.5	34.3	52.9	34.8
2055	3565.3	7172.1	4108.3	41.2	61.3	43.3
2085	3101.3	9617.1	4711.8	39.4	68.1	46.3
Water-stressed countries have runoff less than 1000 m^3/capita/year						
1995		91.8			2	
2025	620.6	860.2	823.6	7.9	9.9	10.3
2055	1203.2	2104.3	1947.4	15.3	24.3	24.4
2085	1206.9	3170.1	2320.2	15.3	36.6	29.0

A more complicated measure combines the number of people who move into (out of) the stressed category with the numbers of people already in the stressed category who experience an increase (decrease) in water stress. The key element here is to define what characterises a "significant" change in runoff, and hence water stress. Because the variation in runoff from year to year varies between watersheds, a given percentage change has a different significance from location to location: a decrease in mean runoff of 5% may be much more extreme in one watershed than in another which has higher year-to-year variability. There are two ways of defining geographically variable thresholds. One is to define a "significant" change as occurring when the change in mean runoff is outside the range of past variability in long-term mean runoff, or more than k times the standard deviation of the long-term mean runoff. The other approach would be to assume that a "significant" change occurs when "droughts" become substantially more frequent—for example when the probability that annual runoff is below the baseline 10-year return period value increases from 10% to, say, more than 20%. *The current study assumes a "significant" change in runoff, and hence water stress, occurs when the percentage change in mean annual runoff is more than the standard deviation of 30-year mean annual runoff due to natural multi-decadal climatic variability*.

Finally, it is important to emphasise that the indicators of water resources stress used in this study do *not* reflect issues such as access to safe drinking water, which is dependent on the availability and quality of local sources and distribution systems rather than the quantity of water available in a catchment.

5. Water resources stress in the absence of climate change

In 1995, around 401 million people were living in countries with less than 1700 m^3/capita/year, or around 7% of the world's population: 91.8 million lived in countries with less than 1000 m^3/capita/year. By 2025 this figure increases dramatically—in the absence of climate change—as shown in Table 4 and Fig. 4, with the total change depending on the assumed rate of population growth. Countries in water-stressed conditions are generally located in eastern and southern Africa, southwest Asia, and the Middle East, and around the Mediterranean. Under the A1/B1 and B2 growth scenarios, countries in east and west Africa join the "stressed" class by 2025, and India has less than 1700 m^3/capita/year (which accounts for much of the increase over 1995). Under the A2 growth scenario, China has less than 1700 m^3/capita/year by 2025. By 2055, Pakistan has less than 1700 m^3/capita/year under all growth scenarios, although it drops out by 2085 under the A1/B1 population scenario. By 2085, Turkey, Mexico, the UK, Thailand, Sudan and Chad move into the stressed category under the A2 scenario.

Calculations made at the national level, however, are rather crude, and hide substantial within-country variation. In 1995 approximately 2230 million (39% of the world's population) lived in watersheds with less than 1700 m^3/capita/year, and 1368 million lived in watersheds with less than 1000 m^3/capita/year[1] (Revenga et al., 2000 estimate 2.3 billion and 1.7 billion, respectively, they used fewer separate river basins). These figures are considerably higher than the numbers living in water-stressed countries, and as shown in Fig. 4 this is primarily due to the presence of water-stressed watersheds in China, India and Pakistan. Table 5 shows the numbers of people living in water-stressed *watersheds* by 2025, 2055 and 2085 under each population growth scenario. The increase compared to 1995 is less dramatic (because there are no major areas of population

[1] If indices are calculated at the $0.5 \times 0.5°$ scale, the figures are 3350 million and 2554 million for thresholds of 1700 m^3/capita/year and 1000 m^3/capita/year, respectively.

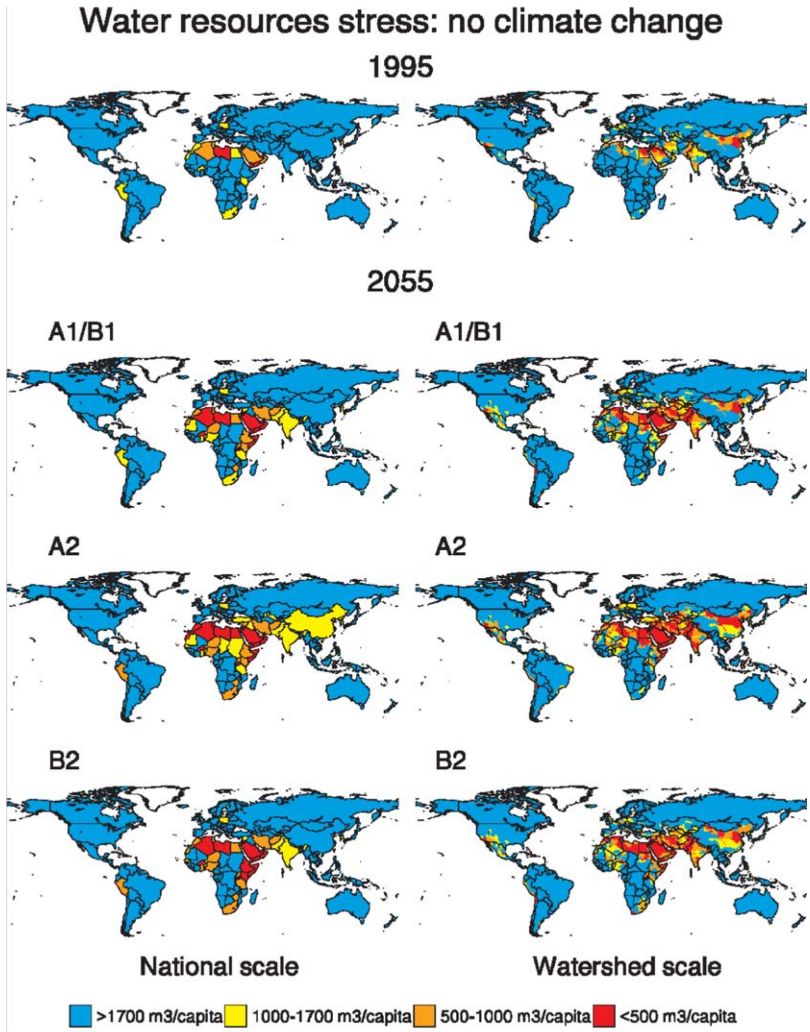

Fig. 4. Water resources stress classes by country and watershed in the absence of climate change: 1995 and 2055.

Table 5
People living in water-stressed watersheds in the absence of climate change

	Millions of people			As % of total population		
	A1/B1	A2	B2	A1/B1	A2	B2
Water-stressed watersheds have runoff less than 1700 m^3/capita/year						
1995		2320			39	
2025	4349.1	4951.3	4503	55.4	57.4	56.5
2055	4632.9	7689.3	5608.3	53.7	65.9	59.4
2085	4104.5	9978.6	6208.2	52.4	70.8	61.3
Water-stressed watersheds have runoff less than 1000 m^3/capita/year						
1995		1368			24	
2025	2882.4	3319.5	2883.4	36.7	38.5	36.2
2055	3400.1	5596	3987.7	39.4	47.9	42.2
2085	2859.8	8065.4	4530.3	36.5	57.2	44.7

changing class), and is caused partly by general increases in population and partly by increases in the numbers of water-stressed watersheds (Table 6). These increases are mostly in China, western Africa, Mexico and the south west of the United States. Revenga et al. (2000) estimated that 2.4 billion people would be living in watersheds with less than 1000 m^3/capita/year by 2025: these figures are lower than those in Table 5, partly because their population projections are lower and partly because they used fewer, larger river basins.

Table 7 shows the numbers of people in each of the major world regions defined in the UNEP Global Environment Outlook 2000 report (UNEP, 1999) living in watersheds with less than $1000\,m^3$/capita/year, both in millions and as a percentage of total regional population, in the absence of climate change. Clearly, some regions are much more generally water-stressed than others, with particularly high percentages in the Middle East and around the Mediterranean, and to a lesser extent in the Northwest Pacific region (which includes China) and southern Asia (which has by far the largest absolute numbers of people living in water-stressed watersheds). By 2055 eastern Africa, western Europe, meso-America and central Asia have high populations in water-stressed watersheds, particularly under the A2 population projection.

Table 6
Cause of increase in populations living in water-stressed watersheds

	% of increase due to population increase in currently stressed watersheds			% of increase due to additional watersheds become stressed		
	A1/B1	A2	B2	A1/B1	A2	B2
2025	66	63	66	34	37	34
2055	60	52	56	40	48	44
2085	64	46	52	36	54	48

6. Effects of climate change

6.1. Using average annual runoff as the indicator of resource availability

Table 8 shows the number of people living in watersheds in each water-stress class, with and without climate change. Table 9 shows the global totals of people moving into and out of the stressed class, and Table 10 shows the numbers experiencing an increase or decrease in stress. Tables 11 and 12 show the regional breakdown of people with an increase and decrease in stress, respectively. Fig. 5 maps the effect of climate change on water resources stress by the 2050s under the HadCM3 scenarios, and Figs. 6 and 7 show all the A2 and B2 scenarios, respectively.

Table 7
People (millions) living in water-stressed watersheds by region, in the absence of climate change

		1995		2025			2055			2085		
			%	A1/B1	A2	B2	A1/B1	A2	B2	A1/B1	A2	B2
Africa	Northern Africa	124.4	94	209.9	239.9	201.4	269	403.1	264.6	302.2	603	310.7
	Western Africa	0.1	0	34.3	35.8	30.8	89.8	118.4	113.3	70.1	217.6	245.7
	Central Africa	0	0	25.7	26.8	2.4	35	41.5	38	33.5	45.2	46
	Eastern Africa	6.5	5	34.2	40.6	27	52.3	186.7	255.4	74.2	283.7	316.1
	Southern Africa	3.1	2	35.6	37.6	32.9	50.3	60.8	126.7	48.2	100.5	187.6
West Asia	Mashriq[a]	19.4	43	73.2	104.6	70	122.2	192	126.1	133.1	279.5	147.5
	Arabian Peninsula	29.4	72	116.7	131.8	90.7	196.2	308.7	146.9	186.3	429.8	172.3
Asia and the Pacific	Central Asia	0.3	1	6	7	5.4	7.6	126.2	6.5	6.6	166.8	7.4
	South Asia	382.5	29	1361.6	1519.9	1391	1646.5	2447.6	1818.5	1376.6	2798.7	1988.8
	Southeast Asia	3.7	1	5.5	5.7	4.9	5.5	6.2	5	5.8	11.4	4.9
	Greater Mekong	0	0	0	0	0	0	15.2	0	0	53.2	0
	Northwest Pacific	617	43	727.9	876.7	773.7	608.7	1185.7	785	329	2291.1	759.8
	Australasia	0	0	0	0	0	0	0	0	0	0	0
Europe	Western Europe	110.6	29	122.4	124.7	113.9	140.4	151.3	102.7	116.5	207.6	104.3
	Central Europe	7.5	4	17.9	33.7	17.5	35.1	62.6	33.8	31.9	88.3	34
	Eastern Europe	1.8	1	2.2	2.6	2.5	2.5	5.4	2.8	2.6	26.7	2.9
North America	Canada	4.9	16	6	6.1	6.1	6.8	7.1	6.1	7.7	9	6.2
	USA	34	13	67.6	70.1	66.1	78.2	91.6	69.4	87.9	142.4	71.3
Latin America and the Caribbean	Caribbean	0	0	0	0	0	0	36.4	27.6	0	48	33.9
	Meso-America	19.3	16	29.7	36.4	30	34.8	104.8	38.5	30.3	174.5	68.4
	South America	2.9	1	6	19.5	17.3	19.2	44.5	20.9	17.4	88.1	22.2

Water-stressed watersheds have less than $1000\,m^3$/capita/year.
[a] The Mashriq region comprises Iraq, Jordan, Lebanon, Syria, and the occupied Palestinian territories.

Table 8
Numbers of people (millions) in water stress classes, with climate change

	A1		A2									B1		B2							
	No climate change	HadCM3	No climate change	HadCM3	HadCM3	HadCM3	ECHAM	CGCM	CSIRO	GFDL	CCSR	No climate change	HadCM3	No climate change	HadCM3	HadCM3	ECHAM	CGCM	CSIRO	GFDL	CCSR
2025																					
> 1700	*3501*	3772	*3680*	3632	3790	3559	3802	3634	3600	3715	3736	*3501*	3975	*3463*	3346	3461	3570	3422	3561	3535	3575
1000–1700	*1467*	1141	*1632*	2265	2230	1594	2122	2434	2320	1692	2188	*1467*	1508	*1620*	1626	2099	2091	2048	2077	2119	2070
500–1000	*1508*	1664	*1717*	1565	1494	1856	1498	1355	1220	1763	1267	*1508*	1170	*1530*	1967	1473	1372	1527	1059	1164	1093
< 500	*1375*	1274	*1603*	1170	1118	1622	1209	1209	1492	1461	1441	*1375*	1198	*1354*	1027	933	934	969	1269	1148	1229
2055																					
> 1700	*3995*	4368	*3981*	3806	3990	3897	3955	3594	4276	4048	4053	*3995*	4106	*3838*	3788	3878	3930	3655	3658	3793	3841
1000–1700	*1233*	1747	*2093*	2299	3071	2026	3319	2545	1798	2149	2191	*1233*	1767	*1621*	2391	2488	2751	2401	2435	1696	2361
500–1000	*1733*	1588	*2499*	2805	1913	2722	2324	2824	2453	2409	2646	*1733*	1939	*2170*	1423	1855	1824	1781	1564	2198	1613
< 500	*1668*	924	*3097*	2761	2697	3025	2027	2707	3144	3064	2780	*1668*	816	*1817*	1843	1224	942	1609	1789	1760	1632
2085																					
> 1700	*3736*	4420	*4112*	3945	3934	3670	4092	3694	4453	4215	4198	*3736*	3770	*3917*	3651	4381	3733	3756	4225	3992	3845
1000–1700	*1245*	1754	*1913*	2141	4190	2354	3035	2552	3666	2914	2780	*1245*	1845	*1678*	1840	2151	3159	2293	2038	1622	2529
500–1000	*1531*	628	*3683*	3735	2473	3550	3506	3557	1788	2685	3077	*1531*	1282	*2492*	2381	2298	2050	1978	2070	2489	1668
< 500	*1328*	1039	*4383*	4270	3493	4516	3458	4288	4183	4276	4035	*1328*	943	*2038*	2253	1295	1184	2098	1791	2022	2082

Class totals in the absence of climate change are shown in italics.

Table 9
Numbers of people (millions) moving into and out of the water-stressed category

2025	HadCM3	ECHAM4	CGCM2	CSIRO	GFDL	CCSR	2055	HadCM3	ECHAM4	CGCM2	CSIRO	GFDL	CCSR	2085	HadCM3	ECHAM4	CGCM2	CSIRO	GFDL	CCSR
Become stressed																				
A1	126						A1	280						A1	380					
A2	115–216	206	119	121	67	175	A2	342–423	293	983	302	262	431	A2	493–565	718	756	494	99	788
B1	123						B1	261						B1	235					
B2	131–209	119	298	201	53	105	B2	136–140	147	156	185	56	476	B2	247–396	177	445	325	187	417
Stop being stressed																				
A1	71						A1	1168						A1	1573					
A2	58–823	818	875	729	163	787	A2	191–1375	1493	1048	301	385	601	A2	522–2663	1820	976	2589	1202	1742
B1	637						B1	907						B1	870					
B2	98–609	697	685	755	624	666	B2	857–1048	1369	754	820	85	1219	B2	293–1184	1474	899	994	206	1197

Water-stressed watersheds have less than 1000 m^3/capita/year.

Table 10
Numbers of people (millions) with an increase or decrease in water stress

2025	HadCM3	ECHAM4	CGCM2	CSIRO	GFDL	CCSR	2055	HadCM3	ECHAM4	CGCM2	CSIRO	GFDL	CCSR	2085	HadCM3	ECHAM4	CGCM2	CSIRO	GFDL	CCSR
Increase in stress																				
A1	829						A1	1136						A1	1256					
A2	615–1661	679	915	500	891	736	A2	1620–1973	1092	2761	2165	1978	1805	A2	2583–3210	2429	4518	2845	1560	3416
B1	395						B1	988						B1	1135					
B2	508–592	557	1183	594	374	601	B2	1020–1157	885	1030	1142	670	1538	B2	1196–1535	909	1817	1533	867	2015
Decrease in stress																				
2025	HadCM3	ECHAM4	CGCM2	CSIRO	GFDL	CCSR	2055	HadCM3	ECHAM4	CGCM2	CSIRO	GFDL	CCSR	2085	HadCM3	ECHAM4	CGCM2	CSIRO	GFDL	CCSR
A1	649						A1	2364						A1	1818					
A2	1385–1893	2423	1583	1675	1140	1539	A2	2804–3813	4286	2604	1805	2595	3167	A2	4688–5375	6005	3372	4099	4671	4460
B1	1819						B1	2359						B1	1732					
B2	1651–1937	2202	1261	1488	1721	1612	B2	2407–2623	3138	1788	2087	2154	2508	B2	2791–3099	3460	2473	2358	2610	2317

Water-stressed watersheds have less than 1000 m^3/capita/year.

Consider first just the HadCM3 scenarios, using the same climate model with different rates of climate change. In most cases, climate change reduces the global total number of people living in water-stressed watersheds (Table 8), because more people move out of the stressed category than move in. These people, however, are almost entirely in south and east Asia, whilst many parts of the world—Europe, around the Mediterranean and in the Middle East, southern and eastern Africa, North and South America—include watersheds which move into the stressed category (Fig. 5). Substantially more people in water-stressed watersheds experience an increase in water stress due to a reduction in runoff, than move into the water-stressed category (Table 9). By the 2020s, 829 million people experience an increase in water stress under the A1 world, and between 615 and 1661 million, 395 million and 508–592 million experience increases in stress under the A2, B1 and B2 worlds, respectively. By the 2050s the totals are 1136, 1620–1973, 988, and 1020–1057 millions for A1, A2, B1 and B2, respectively.

This clear difference arises partly due to the different rates of climate change under each world, but are largely due to the different population totals. This is shown clearly in Fig. 8, which shows the numbers of people with an increase in water stress under the A2 population plus A2 climate, A2 population plus B2 climate, B2 population plus A2 climate and B2 population plus B2 climate, for all six climate models. There is little clear difference between the two different population projections by 2025, but by 2055 the effect of the difference between the populations is greater than the effect of the different climate emissions, for each model. The difference is greater still by the 2080s.

In northern, central and southern Africa, considerably more people are adversely affected by climate change than see a reduction in stress (Tables 11 and 12). In eastern Africa the numbers are more evenly balanced, and in western Africa more people experience a reduction in stress than an increase. Very large numbers of people in south Asia and the Northwest Pacific region have an increase in runoff and hence an apparent reduction in water-resources stress, and indeed these two regions account for virtually all of the global total of people with a reduction in stress. Western, central and eastern Europe and the Mashriq all see an increase in water stress due to climate change, as do the Caribbean, central and southern America. Under most scenarios climate change has a greater effect on the numbers of people with an increase in stress in North America.

By the 2020s, four of the five other climate models produce estimates for the global number of people with an increase in water resources stress under the A2 world within the range of that produced from the three HadCM3 A2 ensemble members (Table 10). By

Table 11
Numbers of people (millions) with an increase in water stress by region

	A1	A2						B1	B2					
	HadCM3	HadCM3	ECHAM4	CGCM2	CSIRO	GFDL	CCSR	HadCM3	HadCM3	ECHAM4	CGCM2	CSIRO	GFDL	CCSR
2025														
Northern Africa	86	4–112	106	186	56	55	144	48	15–104	98	173	51	66	93
Western Africa	0	4–7	21	2	25	0	13	15	0–5	18	12	37	0	18
Central Africa	26	25–27	0	0	3	27	0	26	0–26	0	0	26	0	0
Eastern Africa	35	16–26	0	2	13	5	0	25	33–43	0	2	43	5	0
Southern Africa	44	43–47	4	0	15	29	6	46	26–61	5	13	54	17	18
Mashriq	30	61–70	51	88	0	2	97	28	56–57	73	95	39	23	57
Arabian Peninsula	2	1–18	0	1	3	0	1	0	0	0	1	6	0	0
Central Asia	0	0–6	3	5	2	0	45	2	1–4	2	43	6	1	6
South Asia	186	1–218	18	71	135	0	95	6	60–71	44	390	89	25	76
Southeast Asia	0	0	6	6	0	0	6	0	0	5	6	0	0	5
Greater Mekong	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Northwest Pacific	243	109–842	151	317	6	620	136	83	44–129	61	393	4	84	149
Australasia	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Western Europe	110	45–119	191	65	93	87	74	38	56–73	147	81	126	131	61
Central Europe	29	41–48	66	48	49	13	57	33	42–45	42	57	44	10	43
Eastern Europe	2	2–12	12	2	3	1	18	3	2–13	11	18	4	0	12
Canada	6	0–6	6	6	6	6	0	0	0	6	6	6	0	6
USA	3	3–61	45	49	45	45	24	12	3–18	43	49	61	10	52
Caribbean	0	0–22	0	0	0	0	0	0	0–21	0	0	0	0	0
Meso-America	27	32–35	0	70	33	0	17	1	1–29	1	70	0	2	3
South America	1	14–33	1	0	13	0	3	29	11–52	1	0	1	0	2
2055														
Northern Africa	218	224–310	192	299	115	109	198	138	134–151	205	286	69	80	142
Western Africa	23	10–32	29	0	95	58	140	23	0–21	33	16	177	4	150
Central Africa	65	41–78	0	1	5	43	0	36	37	0	0	5	4	0
Eastern Africa	13	26–68	2	125	157	75	2	100	108–120	2	123	133	143	2
Southern Africa	56	86–108	18	37	41	81	4	66	105–141	47	19	82	62	30
Mashriq	126	122–176	157	169	114	72	128	119	69–118	110	168	62	64	110
Arabian Peninsula	23	0–17	1	1	202	0	0	4	1–3	1	1	84	1	1
Central Asia	7	3–123	0	123	9	1	137	6	0–5	4	123	9	1	73
South Asia	136	227–551	7	571	924	165	181	125	93–366	71	155	221	13	148
Southeast Asia	0	0–6	10	10	0	0	0	0	0	0	6	0	0	5
Greater Mekong	0	27	42	105	0	42	27	0	0	0	42	0	0	0
Northwest Pacific	0	0–81	140	800	116	856	469	20	22	108	822	112	119	486
Australasia	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Western Europe	183	146–199	224	142	39	182	92	140	85–123	146	137	16	115	77
Central Europe	80	106–140	122	126	140	79	161	59	50	54	115	49	19	110
Eastern Europe	15	21–23	17	21	22	16	30	7	15–16	16	10	7	0	21
Canada	7	0–7	7	7	7	7	10	7	0–6	6	7	6	0	6
USA	85	18–104	72	77	79	83	152	37	21–23	47	73	64	45	102
Caribbean	21	36–37	0	0	0	36	0	21	32–32	0	0	0	0	0
Meso-America	33	74–108	4	125	77	55	71	34	35–36	2	98	28	2	77
South America	46	70	48	21	25	19	4	46	49	33	22	19	0	0

Water-stressed watersheds have less than 1000 m^3/capita/year.

Table 12
Numbers of people (millions) with a decrease in water stress by region

	A1	A2						B1	B2					
	HadCM3	HadCM3	ECHAM4	CGCM2	CSIRO	GFDL	CCSR	HadCM3	HadCM3	ECHAM4	CGCM2	CSIRO	GFDL	CCSR
2025														
Northern Africa	107	49–119	65	2	27	62	50	115	39–84	42	2	8	39	108
Western Africa	23	18–23	18	23	12	36	18	17	18–31	13	18	0	25	13
Central Africa	0	0	0	27	0	0	27	0	0	0	27	0	2	2
Eastern Africa	16	21–29	29	36	9	26	39	20	9–17	20	33	1	18	26
Southern Africa	0	0–4	3	38	2	0	32	0	0	12	32	2	5	2
Mashriq	31	0–5	13	1	16	63	5	6	0–8	11	5	12	0	29
Arabian Peninsula	28	31–125	81	112	24	106	102	48	6–83	88	118	47	34	78
Central Asia	2	0–5	4	0	0	3	0	6	0	2	0	0	2	0
South Asia	207	1219–1328	1455	1251	1220	658	1203	1166	1077–1266	1341	1129	1185	1131	1178
Southeast Asia	6	6	0	0	0	6	0	6	5	0	0	0	5	0
Greater Mekong	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Northwest Pacific	171	11–333	728	73	358	103	4	405	339–533	633	69	200	408	131
Australasia	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Western Europe	12	0–7	0	0	0	5	29	2	2–14	0	0	0	0	34
Central Europe	0	0	0	0	0	20	0	0	0	0	0	0	10	0
Eastern Europe	0	0–1	1	0	0	2	0	0	0	0	0	0	1	0
Canada	0	0–6	0	0	0	0	0	0	0	0	0	0	0	0
USA	39	5–22	22	19	5	19	0	21	11–34	23	21	5	0	0
Caribbean	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Meso-America	2	0–3	3	0	0	31	31	3	2–3	3	0	27	29	0
South America	5	2–6	2	2	0	0	0	5	2	13	3	2	12	11
2055														
Northern Africa	3	4–80	84	7	4	100	207	129	49–56	52	3	20	15	69
Western Africa	67	88–110	91	95	0	48	96	73	79–105	81	75	5	67	94
Central Africa	0	1	41	1	36	0	42	0	1	37	1	33	1	38
Eastern Africa	35	130–154	185	97	45	83	185	19	61–109	254	71	93	92	254
Southern Africa	0	0	52	5	57	5	52	0	0	74	13	50	8	66
Mashriq	0	1–10	14	2	0	29	63	0	0–38	11	1	18	7	13
Arabian Peninsula	153	63–305	296	274	0	308	309	145	40–71	130	242	5	92	145
Central Asia	0	0–52	121	0	61	115	0	0	1–4	3	0	0	5	0
South Asia	1530	1600–2223	2358	1710	1280	1723	1780	1530	1382–1677	1752	1604	1520	1438	1610
Southeast Asia	6	0–6	0	0	0	6	0	6	0–5	0	0	0	5	0
Greater Mekong	0	0–15	0	0	15	0	15	0	0	0	0	0	0	0
Northwest Pacific	546	822–1120	912	371	247	127	235	445	577–653	643	249	307	335	133
Australasia	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Western Europe	0	0–2	0	0	9	0	69	6	0–15	0	0	4	4	42
Central Europe	0	0	0	0	0	0	0	0	0	0	0	1	3	0
Eastern Europe	0	0	3	0	1	2	0	0	0	0	0	0	1	0
Canada	0	0	0	0	0	0	0	0	0–6	0	0	0	0	0
USA	6	0–27	6	31	24	4	0	0	21–35	20	31	0	20	0
Caribbean	0	0	4	4	4	0	36	0	0	28	0	28	28	28
Meso-America	0	3–40	82	7	1	43	43	0	2–3	35	7	3	34	3
South America	19	25–44	37	1	19	1	34	6	20	20	1	2	1	14

Water-stressed watersheds have less than 1000 m^3/capita/year.

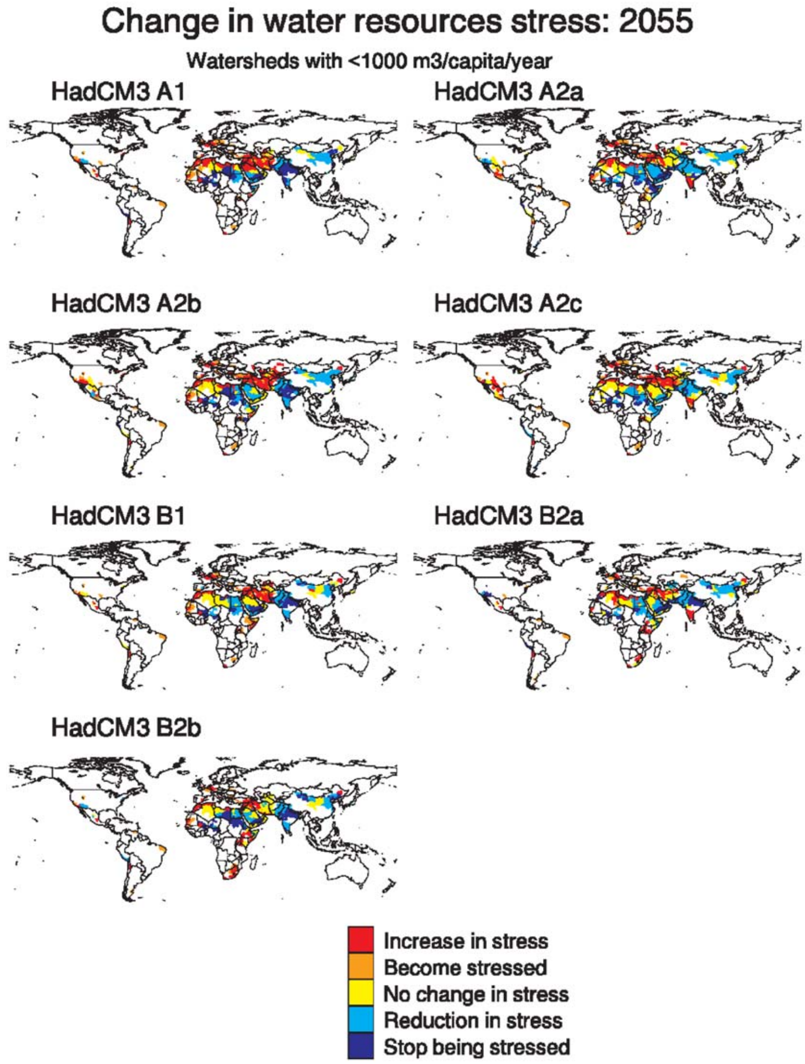

Fig. 5. Effect of climate change on water-stressed watersheds, 2055: HadCM3 scenarios.

the 2050s, however, only the estimate from the CCSR model falls within the HadCM3 range, with ECHAM4 particularly low (it produces increases rather than decreases in runoff in southern Asia) and CGCM2 particularly high (it produces reductions in runoff in eastern Asia). By the 2050s, the range in estimated number of people with an increase in water resources stress is between 1092 and 2761 million, which compares with the HadCM3 range of 1620–1973 million. Whilst the broad pattern of change in resource availability is similar across the climate models (Fig. 6), there are some major differences in some heavily populated Asian watersheds.

Broadly similar results are also seen with the B2 emissions scenario. Several of the climate models produce estimates outside the range defined by the two HadCM3 ensemble runs, with ECHAM4 in particular producing low estimates.

6.2. Using drought runoff as an index of resource availability

The previous section used average annual runoff as a measure of water resource availability: this section measures resource availability by the 10-year return period minimum annual runoff (termed here "drought runoff"). Using this measure obviously increases the number of people in different water resources stress classes (Table 12)—although it is important to emphasise that the class limits (1700 and 1000 m^3/capita/year) were initially developed with average annual runoff as the measure of resource availability. In 1995 approximately 3310 million people were living in watersheds with a "drought runoff" less than 1700 m^3/capita/year, an increase of just over a billion on those living in watersheds with an average runoff less than 1700 m^3/capita/year. The figures for a threshold of 1000 m^3/capita/year are 2228 million

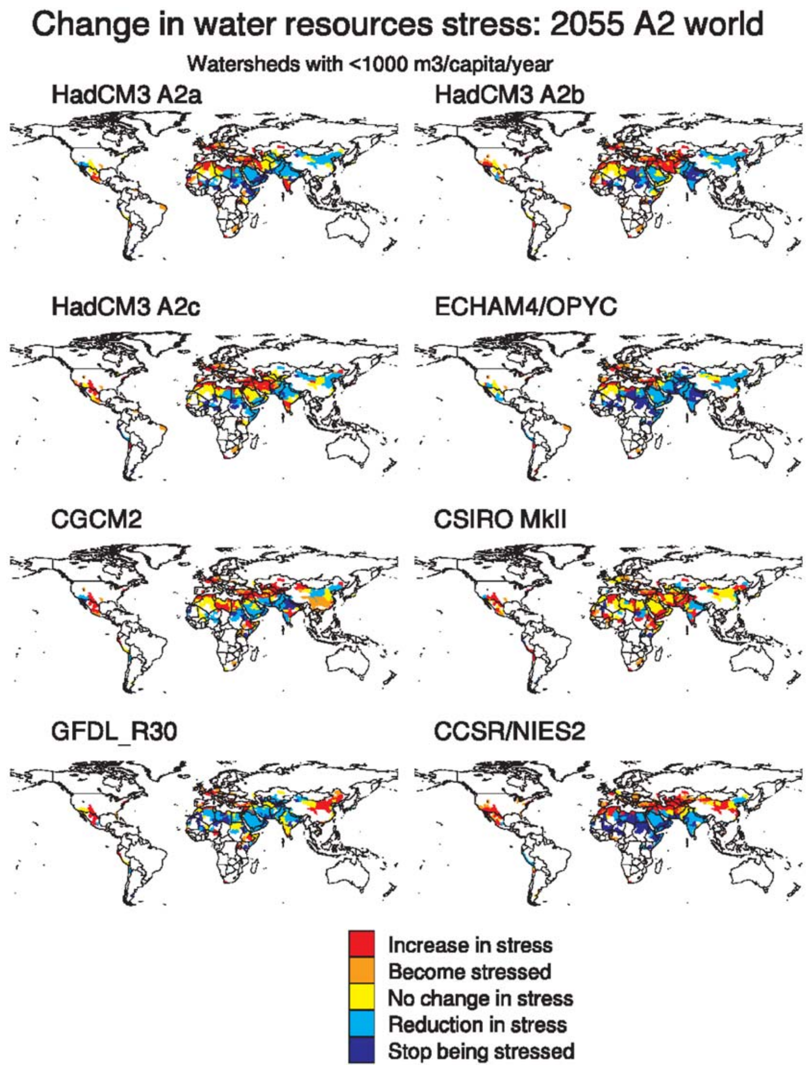

Fig. 6. Effect of climate change on water-stressed watersheds, 2055: A2 scenarios.

compared with 1368 million. The use of a different definition of resource availability generally expands the extent of regions with water-stressed watersheds, and does not introduce large new regions to water stress.

Table 13 shows the effect of climate change (HadCM3 scenarios only) on water stress using drought runoff, and should be compared with Table 10. Use of drought runoff as an indicator consistently adds between 400 and 500 million people to those with an increase in stress, and between 300 and 700 million to those with an apparent decrease in stress. The relative differences between the emissions scenarios, however, are the same.

7. Effect of uncertainty in population projections

The population projections used for the four SRES storylines are uncertain: estimates depend on assumptions about fertility, mortality and migration rates. A sensitivity analysis was, therefore, undertaken by simply increasing or decreasing population by 10% consistently across the entire world.

Reducing populations by 10% obviously lowers the numbers of people living in water-stressed watersheds (by both removing some watersheds from the stressed category and reducing populations in watersheds that remain stressed), and increasing populations raises the numbers of people living in water-stressed watersheds. Table 14 shows the percentage difference from the "core" population estimates under the three different SRES worlds, and it is clear that the percentage change in water-stressed people is greater than the percentage change in population.

Table 14 shows the percentage change in the numbers of people with an increase or decrease in water stress due to climate change (HadCM3 scenarios only). Usually, but not always, a lower population reduces the apparent impact of climate change, whilst higher

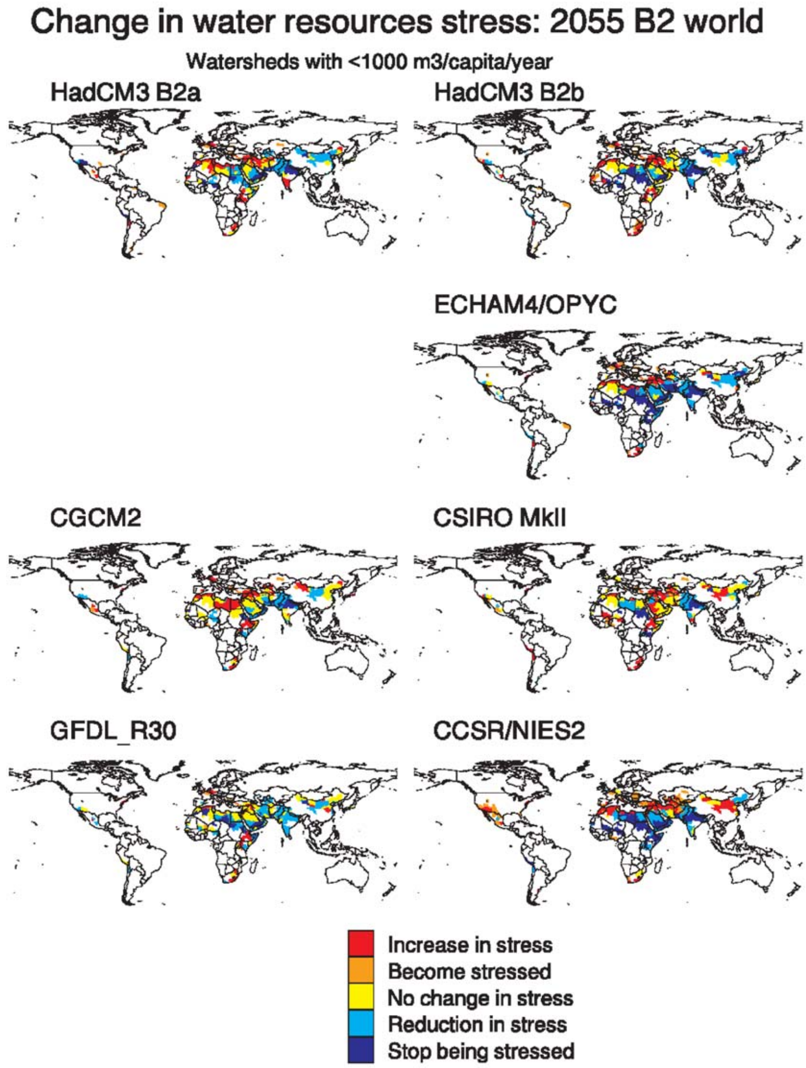

Fig. 7. Effect of climate change on water-stressed watersheds, 2055: B2 scenarios.

population increases its apparent impact. There are, however, some departures from this general trend, particularly when the numbers of people who either become stressed or cease to be stressed are considered. There are instances where the adverse effects of climate change are *greater* with a lower population, and *smaller* with a higher population. These apparent anomalies arise because the baseline cases are different with different population totals. With a lower population some watersheds move out of the stressed category in the absence of climate change. Some of these watersheds, however, move into the stressed category when runoff decreases, and therefore contribute to the numbers of people moving into the stressed category: with the higher population these people were already stressed, so climate change would not cause them to move class (for example, 71 m people move into the stressed class due to climate change by 2025 in the A1 world, but if population totals are reduced by 10% 585 m people move into the stressed class: most of these would already have been stressed with the original population totals). A similar effect can be seen when population is increased. More watersheds are already in the stressed category than with the original population totals, and cannot therefore move into the stressed class if runoff decreases: they are already there.

Notwithstanding these subtleties, Table 14 shows that relatively small differences in population can have large percentage effects on the numbers of people affected by climate change: a 10% variation in population can lead to a range in the numbers of people with an increase or decrease in water stress of between 15% and 20% (Tables 15 and 16).

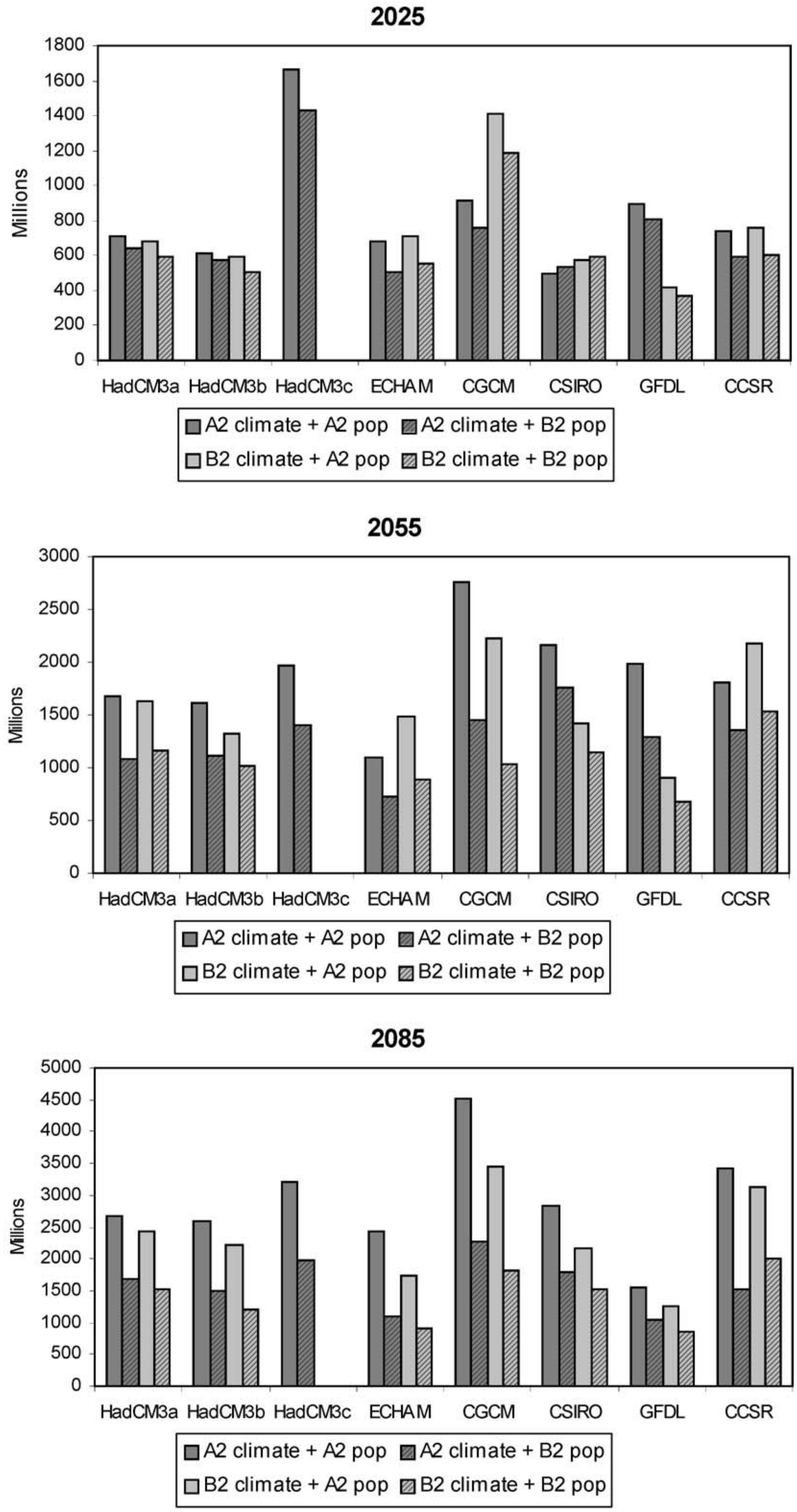

Fig. 8. Comparative effect of emissions scenario, climate model and population scenario on number of people with increase in water-stress. For each climate model, the first two bars show the A2 climate simulation with the A2 and B2 populations, and the last two bars show the B2 climate simulation with the A2 and B2 populations.

Table 13
People living in water-stressed watersheds in the absence of climate change: "drought runoff" used as indicator of resources

	Millions of people			As % of total population		
	A1/B1	A2	B2	A1/B1	A2	B2
Water-stressed watersheds have drought runoff less than 1700 m^3/capita/year						
1995		3310			58	
2025	5039	5912	5185	64	69	65
2055	5867	8746	6685	68	75	71
2085	4685	10908	7277	60	77	72
Water-stressed watersheds have drought runoff less than 1000 m^3/capita/year						
1995		2228			39	
2025	3749	4406	3910	48	51	49
2055	4419	7191	5041	51	62	53
2085	3901	9449	5601	50	67	55

Compare with Table 5.

Table 14
Numbers of people (millions) with an increase and decrease in water stress: "drought runoff" used as indicator of resources: HadCM3 scenarios only

	A1	A2	B1	B2
Increase in stress				
2025	1474	1026–2023	763	816–1234
2055	152	2102–2629	1491	1483–1698
2085	1787	3837–4295	1530	1708–2057
Decrease in stress				
2025	957	448–2211	1967	1903–2210
2055	2928	3360–4788	2700	2758–3314
2085	2354	5130–5902	2198	3117–3707

Water-stressed watersheds have drought runoff less than 1000 m^3/capita/year.
Compare with Table 10.

Table 15
Effect of uncertainty ($\pm 10\%$) in population totals on number of people living in water-stressed watersheds: percentage difference from core values (Table 5)

	A1/B1	A2	B2
2025	−16 to 17	−17 to 15	−14 to 17
2055	−15 to 19	−18 to 27	−16 to 16
2085	−30 to 21	−14 to 14	−13 to 22

Stress threshold = 1000 m^3/capita/year.

8. Conclusions

8.1. Caveats

There are caveats associated with all four components of the study—the definition of climate change scenarios, the estimation of future resource availability, the estimation of future populations, and the estimation of the implications of climate change for water stress.

The key caveats associated with the climate change scenarios are that: (i) they are based on few climate models (HadCM3, ECHAM4, CGCM2 and CSIRO Mark 2, GFDL_R30 and CCSR/NIES2), (ii) they represent just the change in monthly mean climate and (iii) for all but two of the emissions scenarios run with HadCM3 there are just one repetition, making it difficult to separate the effects of climatic variability from those of climate change (although the similarity in the spatial pattern of change in climate under each emissions scenario suggests that the signals in the scenarios are primarily those due to climate change).

The key limitation to the estimation of future resources (described in more detail in Arnell, 2003) is that both current and future runoff are based on simulations, not observations: any bias in the simulation model will, therefore, lead to bias in the estimated amount of resources available. It is likely that the model overestimates the amount of runoff available in dry areas, and underestimates in areas with significant snowfall, in $0.5 \times 0.5°$ cells with large variations in topography, and cells draining receding glaciers. Other limitations relate to the use of average annual runoff and the 10-year return period minimum annual runoff as indicators of resource availability. Resources availability in some catchments may be determined more by the seasonal variability in resource than by the total annual volume.

For each SRES storyline there is just one population projection. The watershed population estimates were driven by estimates of future national population (just one for each storyline) downscaled to the $0.5 \times 0.5°$ resolution, with two key assumptions. The first is that beyond 2050 population in every country in a region changes at the same regional rate, and the second is that every grid cell within a country grows at the same rate. The second assumption is less important than the first

Table 16
Effect of uncertainty (±10%) in population totals on number of people in water-stressed watersheds with increase or decrease in stress: percentage difference from core values (Tables 9 and 10)

	A1	A2			B1	B2	
		a	b	c		a	b
Become stressed							
2025	59 to 0	28 to 24	34 to 28	−3 to 13	30 to 0	−22 to −18	−38 to 40
2055	−28 to 5	−41 to −40	−13 to 0	61 to −23	−34 to −18	27 to 105	70 to 55
2085	−15 to 55	5 to 17	−5 to 37	2 to 115	−29 to 7	−37 to 2	−8 to 28
Increase in stress							
2025	−14 to 20	−15 to 20	−21 to 15	−17 to 12	−21 to 19	−25 to 20	−30 to 26
2055	−17 to 15	−27 to 7	−17 to 18	−7 to 15	−19 to 9	−18 to 24	−15 to 19
2085	−12 to 29	−14 to 13	−15 to 18	−14 to 28	−15 to 16	−23 to 11	−15 to 18
Stop being stressed							
2025	726 to 11	−18 to −76	−16 to −81	840 to 18	−15 to −82	512 to 30	−7 to −80
2055	12 to 23	−39 to 94	−21 to −9	47 to 349	−11 to 17	−10 to −68	−14 to −70
2085	−44 to −1	111 to −20	−5 to 6	325 to 28	−69 to 33	253 to 36	14 to 47
Decrease in stress							
2025	60 to 13	−15 to 13	−14 to 9	−12 to 11	−12 to 11	−11 to 12	−12 to 14
2055	−16 to 18	−18 to 25	−18 to 28	−11 to 34	−15 to 15	−12 to 18	−12 to 18
2085	−41 to 23	−11 to 13	−12 to 13	−8 to 16	−43 to 22	−12 to 21	−12 to 26

Stress threshold = 1000 m^3/capita/year. HadCM3 scenarios only.
Note: a, b and c represent HadCM3 ensemble members.

when the gridded population is summed across each watershed.

The final set of caveats are associated with the use of threshold-based indicators of water stress. Small changes in climate or population can push some large and populous watersheds from one side of the threshold to the other (also leading to instances where the apparent effect of climate change is greater with smaller population totals). The use of different thresholds would lead to different quantitative indications of the effects of climate change, and may give a different impression of the geographical variability in climate change effects. This limitation is even more significant when indicators are applied at the national scale, because the units over which the indicators are generally much larger. Finally, the indicators used characterise availability of resources, not access to safe water or sanitation.

The net effect of all these caveats is that the numerical estimates of the implications of climate change on future water resources stresses are not to be taken too literally. Rather, the numbers in the tables can be used to indicate the relative effects of different emissions, climate and population scenarios.

Finally, and perhaps most importantly, the actual impact of the effects of climate change on water scarcity will depend on how water resources are managed in the future. This will vary between the SRES storylines, depending not only on economic prosperity but also attitudes towards environmental management and protection.

8.2. Key conclusions

The principle conclusions concerning the effects of climate change are:

(i) Climate change increases water resources stresses in some watersheds, but decreases them in others. If the absolute numbers of people living in water-stressed watersheds was taken as the indicator of water resources stress, then climate change would appear to reduce global water resources pressures because more watersheds move out of the stressed class than move into it. However, this gives a misleading indication of the effect of climate change, for two reasons. Firstly, the increases in runoff generally occur during high flow seasons, and may not alleviate dry season problems if this extra water is not stored: the extra water may lead to increased flooding, rather than reduced water resources stresses. Secondly, the watersheds that apparently benefit from a reduction in water resources stress are in limited, but populous, parts of the world, and largely confined to east and southern Asia: areas that see an increase in stress are more widely distributed. The pattern of the impact of climate change is broadly consistent between the climate models used to construct the climate change scenarios, with some differences in Asia.

(ii) The estimated impact of climate change on global water resources depends least on the rate of future emissions, and most on the climate model used to estimate changes in climate and the assumed future population. By the 2020s between 53 and 206 million people move into the water-stressed category, and between 374 and 1661 million people are projected to experience an increase in water stress. There is little difference between emissions scenarios and population assumptions, and most of the range derives from the use of different climate models. By the 2050s there is still little difference between emissions scenario, but the different population assumptions have a clear effect. Under the A2 population between 262 and 983 million people move into the water-stressed category, and between 1092 and 2761 million people have an increase in stress. Under the B2 population the ranges are 56–476 million and 670–1538 million respectively, and under the A1/B1 population are 261–280 million and 988–1136 (but based on just one climate model). A change in total population under a given population scenario of plus or minus 10%, for example, leads to changes in the numbers of people with increases or decreases in water stress of around 15–20%.

(iii) Areas with an increase in water resources stress include the watersheds around the Mediterranean, in central and southern Africa, Europe, central and southern America. Areas with an apparent decrease in water resources stress are concentrated in south and east Asia.

Acknowledgements

This research has been funded by the UK Department for the Environment, Food and Rural Affairs (DEFRA), contract EPG/1/1/70. Climate baseline data and climate change scenarios were provided through the Climate Impacts LINK project by Dr. David Viner of the Climatic Research Unit, University of East Anglia. The national population projections were provided by CIESIN, New York. Comments from the other members of the ''Fast Track'' group and the anonymous referees are gratefully appreciated.

References

Alcamo, J., Döll, P., Kaspar, F., Siebert, S., 1997. Global Change and Global Scenarios of Water Use and Availability: An Application of WaterGAP1.0. University of Kassel, Germany. 47pp + app.

Alcamo, J., Heinrichs, T., Rösch, T., 2000. World Water in 2025—Global Modeling and Scenario Analysis for the 21st Century. Report A0002, Center for Environmental Systems Research, University of Kassel, Kurt Wolters Strasse 3, Kassel 34109, Germany.

Alcamo, J., Döll, P., Heinrichs, T., Kaspar, F., Lehner, B., Rösch, T., Siebert, S., 2003. Global estimates of water withdrawals and availability under current and future business-as-usual conditions. Hydrological Sciences Journal 48, 339–348.

Arnell, N.W., 1999a. Climate change and global water resources. Global Environmental Change 9, S31–S49.

Arnell, N.W., 1999b. A simple water balance model for the simulation of streamflow over a large geographic domain. Journal of Hydrology 217, 314–335.

Arnell, N.W., 2003. Effect of IPCC SRES emissions scenarios on river runoff: a global perspective. Hydrology and Earth System Sciences, submitted for publication.

Arnell, N.W., Livermore, M.J.L., Kovats, S., Nicholls, R., Levy, P., et al., 2003. Socio-economic scenarios for climate change impacts assessments: characterising the SRES storylines. Global Environmental Change 14, 3–20.

Center for International Earth Science Information Network (CIESIN), 2000. Columbia University; International Food Policy Research Institute (IFPRI); and World Resources Institute (WRI). 2000. Gridded Population of the World (GPW), Version 2. Palisades, NY: CIESIN, Columbia University; available at http://sedac.ciesin.columbia.edu/plue/gpw.

Falkenmark, M., Lundquist, J., Widstrand, C., 1989. Macro-scale water scarcity requires micro-scale approaches: aspects of vulnerability in semi-arid development. Natural Resources Forum 13, 258–267.

Gaffin, S.R., Xing, X., Yetman, G., 2003. Downscaling and geo-spatial gridding of socio-economic projections from the IPCC Special Report on Emissions Scenarios (SRES), in press.

Gleick, P.H., 1998. The World's Water: The Biennial Report on Freshwater Resources 1998–1999. Island Press, San Francisco.

Gordon, C., Cooper, C., Senior, C., Banks, H., Gregory, J.M., Johns, T.C., Mitchell, J.F.B., Wood, R., 2000. The simulation of SST, sea-ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments. Climate Dynamics 16, 147–168.

IPCC, 2000. Emissions Scenarios. A Special Report of Working Group II of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

IPCC, 2001a. Climate Change 2001: The Scientific Basis. Contribution of Working Group 1 to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

IPCC, 2001b. Climate Change 2001: The Synthesis Report. Cambridge University Press, Cambridge.

Johns, T.C., Gregory, J.M., Ingram, W.J., Johnson, C.E., Jones, A., Lowe, J.A., Mitchell, J.F.B., Roberts, D.L., Sexton, D.M.H., Stevenson, D.S., Tett, S.F.B., Woodage, M.J., 2003. Anthropogenic climate change for 1860 to 2100 simulated with the HadCM3 model under up-dated emissions scenarios. Climate Dynamics 20, 583–612.

New, M., Hulme, M., Jones, P.D., 1999. Representing twentieth century space–time climate variability. Part 1: development of a 1961–1990 mean monthly terrestrial climatology. Journal of Climate 12, 829–856.

Raskin, P., Gleick, P., Kirshen, P., Pontius, G., Strzepek, K., 1997. Water Futures: Assessment of Long-range Patterns and Problems. Background Report for the Comprehensive Assessment of the Freshwater Resources of the World. Stockholm Environment Institute: Stockholm, 78pp.

Revenga, C., Brunner, J., Henninger, N., Kassem, K., Payne, N., 2000. Pilot Analysis of Global Ecosystems: Freshwater Ecosystems. World Resources Institute and Worldwatch Institute, Washington, DC.

Seckler, D., Amarasinghe, U., Molden, D., de Silva, R., Barker, R., 1998. World Water Demand and Supply, 1990 to 2025: Scenarios

and Issues. International Water Management Institute Research Report 19, Sri Lanka.
Seckler, D., Barker, R., Amarasinghe, U., 1999. Water scarcity in the twenty-first century. Water Resources Development 15, 29–42.
Shiklomanov, I.A., 1998. Assessment of Water Resources and Water Availability of the World. Background Report for the Comprehensive Assessment of the Freshwater Resources of the World. World Meteorological Organisation, Geneva.
UNEP, 1999. Global Environment Outlook 2000. Earthscan, London.
UNEP, 2001. Global Environment Outlook-3. Earthscan, London.
Vörösmarty, C.J., Green, P.J., Salisbury, J., Lammers, R.B., 2000. Global water resources: vulnerability from climate change and population growth. Science 289, 284–288.
World Meteorological Organisation, 1997. A comprehensive assessment of the freshwater resources of the world. WMO: Geneva.
World Resources Institute, 2000. World Resources 2000–2001. People and Ecosystems: The Fraying Web of Life. World Resources Institute, Washington.