

Reply to referee comment by Dr. J. Ward.

### **A. Population and water: an important issue, but wickedly complex**

Under this section you have raised the following issues:

1. The complexity of national population dynamics has not been considered, with special regard to the sub-national spatial dynamics.
2. Water consumption and water availability both has to be considered, again at the sub-national scales.

You have raised the importance of addressing a more useful resolution for policy makers in terms of population dynamics and water availability both. It is very hard to disagree with you on this. Thank you very much for the comprehensive explanation of the practical need of such an assessment. We hope to extend our analysis further more to test in sub-national scales. However, the current paper aims at addressing the global level, as you have already noticed. The current output of the paper introduces population control policies as low-regret measures for adaptation to climate change. As for now, the greater input of this study is to socio-economic scenario modeling in climate projections, rather than to the local policy making.

1. As you have mentioned, the sub-national and inter-national migration patterns are very difficult to be incorporated in population projections, especially in the global study as it stands now. How migration will be affected by the population policies complicates this further. As a simplification of the problem, but not deviating out of the practical situation, we opted to consider actual trends of population growth rates resulted by policy interventions, by the way of an example, China. Even though we have not considered the ultimate age profiles of populations, the output population growth trends resulted by the population policies (for SC2 and SC3 scenarios) assumed were the actual trends seen in China as a result of their population control programs during the past three decades. However, for the no-policy population scenario (SC1), consideration was only given for the national growth rates.

Of course in a case study we would be able to explore the population dynamics, in a way that the results would be more useful for the local policy makers.

2. Of course without considering water transfers between grids (resolution 0.5°) and nations, in the means of liquid water as well as goods (virtual water transfers) it is not possible to create a justifiable view of the potential future vulnerabilities of water. Analyzing how the natural condition of water availability (our current analysis) is affected by the consumption patterns, water transfer agreements between nations/ basins and virtual water transfers is the next step in our research. However, again assumptions on the future scenarios of these have to be done with caution. As you have mentioned, this kind of a comprehensive study will be very attractive at a finer scale.

### **B. Methodology section lacking**

1. An exponential growth rate of 2.5% using as a threshold is questionable.

Of course the threshold chosen to apply the population policies is a high growth rate. However, we did not intend to say that below 2.5% are **low** population growth rates. Unfortunately, there is a misuse of wording in the phrase “**low** population growth rates” (p. 9244, line 11). It should be “**lower** population growth rates”. This will be corrected in the final manuscript (Manuscript text altered in p.9244, lines 10 and 11). As the population policies in the study are not meant to serving only climate change adaptation, the countries selected for policy application are the ones with other documented benefits of population control such as economic development, and improvement of the quality of life, finally leading to sustainable life styles.

In this regard, another attempt was made to apply the population reduction policies differently. The environmental foot-print (Rees and Wackernagel, 1996), which speaks of a country’s self-sufficiency in terms of resources was considered along with the 2.5% population growth rate (the conditions applied were: population growth rate of 2010 >2.5% and national ecological deficit (ecologically productive land of a country- ecological foot print of that country ≤0). However, this didn’t result in much of a difference. Almost all countries satisfying population growth rate >2.5% were having negative environmental foot-prints, except for five countries (out of 24 countries which had population growth rates larger than 2.5% in 2010). Therefore, only the population growth rates were considered as a condition to apply policies.

## 2. Consideration should be given to globally different policy scenarios

First of all, it should be noted that the policy applied population scenarios (SC2 and SC3) look at two different things.

- SC2 looks at the hypothetical situation: what if the countries with higher population growth rates applied population reduction policy?
- SC3 looks at the situation: what will happen to the reduction of population by the population reduction policies, if the developed countries choose to stop the shrinking of population effectively (by any means: let it be migration as you have mentioned, child incentives, child raising support etc) at a global level?

Secondly, our results do not imply that the world is locked at a population of 13 billion or more. It just implies that we have opted to test a high population scenario, and its regionally applied variations. The global view of these population scenarios are given, only to look at the global impact of the scenarios. Of course, the SC3 scenario does not change the world from that of SC2, nor it affects the per capita water availability in the SC3-only policy (keeping the population growth at 0%) countries according to our analysis.

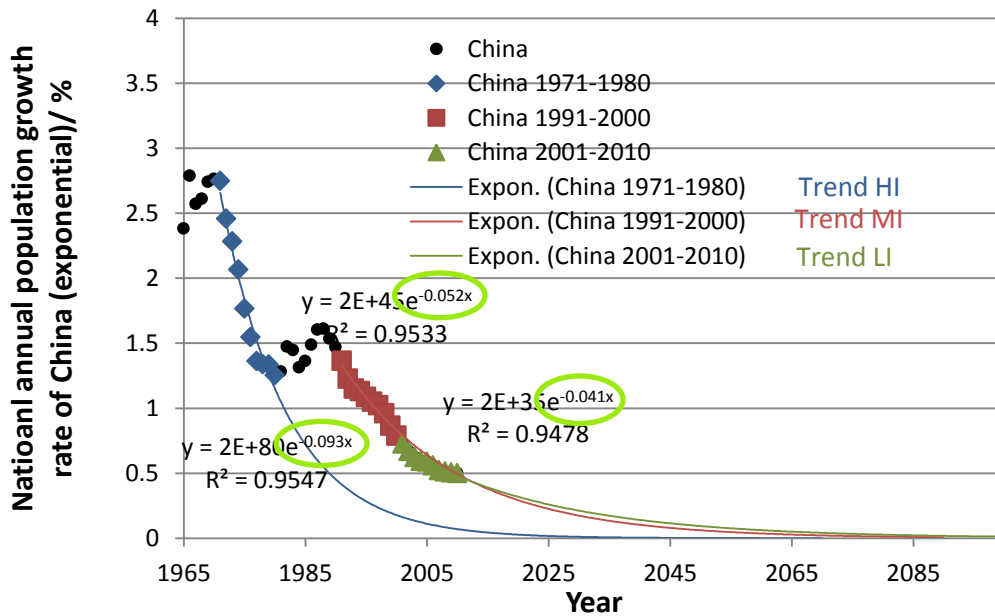
What we have tried by our population policy scenarios (**Fig. 1** in the manuscript) is to test the impact of the regional policy decisions to the global level, and not trying hard to obtain three different globes. On the other hand, if someone applies population policy to only some countries (or regional), and hopes to see an entirely different world (in terms of population) could the applied population policies be realistic at all?

## 3. Are the policy scenarios macroscopic or microscopic? Are they realistic?

The applied population policies are macroscopic (Not considering population dynamics or the age profiles in each country, but assumed as a resulted reduced national population growth rate), even though the reduced national population growth rates were derived from a practical example, China. Therefore, the practical validity of the assumptions remains consistent. We have explained the method under the paragraph starting from p. 9243, line 18. The following account explains it further.

The assumption on the population reduction policy scenario SC2 is the outcome of the policies, assumed as a reduced national growth rate of a country. However, the reduced growth rates are unique for each country with policy applied, and those are not arbitrary assumptions.

China has a history of more than 3 decades of population control policies. The trends of population growth rates which could be expected out of such a population reduction policy were assumed to be similar to that of China, at various stages of population transition (**Fig.2** in the manuscript). However, the effectiveness of such policies in practice, and therefore the expected outcome of such policies were assumed to be increasing with the economic ability of a country. I.e. Countries with high economic capacity will gain stronger reductions in the population growth rate than poorer countries by the same policy. Three categories of economic capacity were assumed (high income - HI, middle income – MI and low income – LI, by World Bank, 2012 definitions). Therefore, three unique trends of reduction in the population growth rate were assumed (**Fig. a** below).



**Fig. a** The trends in the reduction of population growth rates assumed to be resulted in by the population reduction policy scenario SC2 (applied from 2011 to 2100). However, acknowledging the fact that the constant in the equations ( $A$  in the equations of type  $y = A.e^{bx}$ ) is a unique value for each country, only the exponential trends ( $bx$ ) were applied for the countries. ( $x$  is the year since the start of the transition period)

4. Technically, the policy application to countries with the use of the threshold 2.5% doesn't seem uniform.

The countries for the policy to be applied were selected by considering the population growth rates of countries in the year 2010. Since, from 2011 until 2025 are projections, the averages were not considered. Only the most recent population growth rates (2010) were considered.

### C. Climate scenarios

1. Detailed justification of simply averaging the four GCM derived data

(Manuscript text edited at p.9244 lines 19, 20. Citations and references added: Christensen et al., 2007, Wang et al., 2004, Cook and Vizzy, 2006, Chiew et al., 2009)

All GCMs have regional biases in estimating the present/ past climates. While most of the models share the incapability of reproducing the Sahelian (West Africa) dry climate (Christensen et al., 2007) and of areas with complex relief (such as Tibet) (Christensen et al., 2007) with reasonable accuracy, many of them show regionally unique weaknesses in modeling the present/ past climates in other regions. Moreover, most of the countries where the application of population reduction policies was necessary (**Fig.3 (c)** in the manuscript) are in fact African countries. Of the 4 GCMs considered (CCSM3, MIROC3.2, (MRI) CGCM2.3.2 and UKMO model) in this study, strong biases exist in the following regions due to weaknesses in their physics. These affect the future projections in those regions as well, even though there's no way of quantifying the future biases.

*In West Africa (Sahelian region):* CCSM3 does not perform well (Kamga et al., 2005) and both CCSM3 and UKMO do not generate the West African monsoon (Cook and Vizzy, 2006). MIROC3.2 and CGCM2.3.2 do generate the West African monsoon and do model a drier climate, still the accuracy is low (Cook and Vizzy, 2006).

*In South Asia:* CCSM3 is characterized with low variation of annual precipitation (Christensen et al., 2007, Wang et al., 2004) and temperature cycles (Christensen et al., 2007). CGCM2.3.2 over-estimates the monsoonal precipitation (Wang et al., 2004) and under-estimates the total annual precipitation cycle (Christensen et al., 2007), the annual temperature cycle is modeled quite well compared to observations (Christensen et al., 2007). UKMO model under-estimates the annual precipitation cycle, while showing a higher variation of the annual temperatures (Christensen et al., 2007). However, MIROC3.2 shows good agreement in both annual cycles of precipitation and temperature, with a slight over-estimation at peaks (Christensen et al., 2007).

*Southeast Asia:* Both CCSM3 and CGCM2.3.2 are characterized with high under-estimation and a low variation of monsoonal rainfall (Wang et al., 2004).

*Australia:* The only GCM which models the South-Eastern Australian rainfall is the UKMO model (Chiew et al., 2009) from the 4 GCMs used, while other three models show low spatial correlation and low variation of annual rainfall over the region, with low agreement on the rainfall trends (Chiew et al., 2009).

Runoff generated by GCMs should also be affected by the above shortcomings. As our current study is at the global level, considering the above facts, utilization of a single GCM cannot be justified. Therefore, the discharge data produced using the outputs of the utilized 4 GCMs; CCSM3, MIROC3.2, (MRI) CGCM2.3.2 and UKMO model were averaged, to reduce the effects of the regional biases of these GCMs to our study. Averaging over GCMs is a very simple but, common, scientific method for global level studies utilizing GCM data (Christensen et al., 2007).

2. Nexus between the declining energy availability with economic growth and with the rising population should be considered as a factor driving any future scenarios.

The no-policy population scenario utilized in our study is similar to the high population projection of the latest population prospects 2010 revision. This UN high projection is a slight upward revision of the high projection (all projections show upward shifts) of the population prospects 2008 version (please compare **Figure 1** and **Table 1.1** of World Population Prospects 2010 revision (United Nations, 2011) and its 2008 revision (United Nations, 2009). The reasons behind these upward revisions has been the recent downward trend of the HIV/AIDS prevalence in the Third World countries based on population surveys and the slow fertility decline seen in Sub Saharan Africa than previously expected (Lee, 2011). The projections have been based on the past fertility trends seen in each country as well (United Nations, 2011). However, the UN projections do not hint on the restrictions on economic development and therefore on population growth, in the foreseeable future because of the scarcity of fossil fuel resources. On the grounds of your argument, the changes should be visible in those surveys; At least they should hint on the probable changes by now.

Surely fossil fuel resources are the primary or the secondary source of energy for the Middle East and for the developing countries, where our policy scenarios are applied. Also this fossil fuel dependency will prevail longer for these countries. However, we see two sides in the argument of fossil fuel scarcity: a limitation for development as well as an imperative to change country's energy policy towards sustainability. The effect of energy sector to population change will be a combination of both; not only of the fossil fuel scarcity.

Nevertheless, we understand and we agree with you. The energy- population change link is very important to be discussed in climate change discussions. Thank you very much for the idea. It will be very useful for the future development of our research.

#### **D. Water stress indicator is overly simplistic**

1. Water stress indicator is too simple and the assumption of the discharge out of a grid cell is the potentially available water for the use by the population in the same grid cell is questionable in terms of the reality.

Falkenmark water stress indicator has its merits and demerits as any other indicator. Its thresholds refer to the requirements indicated for the household, agricultural, industrial, energy sectors and the needs of the environment as well (Rijsberman, 2006). It therefore, provides a basis for distinguishing between climate and human induced water scarcity.

The demerits could be: the use of annual averages masking the scarcity information at smaller scales, the simple thresholds omit variations in water demand among countries resulted by culture, lifestyle, climate etc.

However, if one considers only household, agricultural and industrial sectors even the analysis is incomplete. This is a reason for looking at the potential water availability (the discharge out of a grid) rather than the water use for the grid. Performing a comprehensive analysis considering all the household, agricultural, industrial, energy sectors and the environment requirements is only possible with a considerable amount of assumptions on the missing data of various countries. However, the uncertainty introduced by these assumptions will deviate our results away from the actual conditions considerably, making it indistinguishable from the current analysis. Again I would like to emphasize on the current status of this study, even though acknowledging the benefits of such a comprehensive analysis on a smaller scale; our per capita water availability compared against Falkenmark thresholds shows a country-wide picture rather than a city/irrigation scheme status. The only reason we couldn't consider (not that it was ignored) the ground water availability is the unavailability of such a global level data set. Of course now the region-wide groundwater data availability is improving in regions such as Europe.

2. These factors which significantly affect water stress at local scale should be explored at least qualitatively: political, economic and social factors / conflicts preventing the development and maintenance of water storage, treatment and distribution infrastructure
2. Local heterogeneity of both water resources and population (i.e. variations at a smaller scale than the regional scale at which the per-capita runoff was assessed – perhaps most of the water falls on the wrong side of the mountain range and flows out to sea, and most of the population occurs on the other side)
3. Lack of accuracy in the runoff data itself
4. Populations' reliance on water resources other than runoff, such as groundwater, which may be depleting faster than the recharge rate, and/or may be declining in quality (e.g. saltwater intrusion)

The current paper explores the water stress situations in a country. This study is only a part of my PhD thesis. Our study expands into exploring the heterogeneity of water resources and population in terms of inequality of water resources within a country. The methodology considers not only the water availability considering any water allocations by the existing water sharing agreements, but also the groundwater dependency of countries, the economic capacity, and finally, links the physical water availability and the inequality to the risks of water conflicts. However, this comprehensiveness in the analysis and of the data cannot be achieved at a finer scale such as the utilized 0.5 degree gridded scale in a global study, as you have mentioned. The full analysis will be published in a separate paper. However, few lines were added under the conclusions in this regard. (Manuscript edited at p. 9250, line 2)

The details of accuracy of the runoff data and of the discharge data provided in research done by our data producers are discussed here and will be added to the manuscript under description of data. (Manuscript edited at p. 9244, line 18. Citation and reference added: Oki et al., 1999)

The accuracy of runoff/ discharge data



Most of the Land Surface Models (LSMs) tend to underestimate runoff in higher latitudes (Oki et al., 1999), because of the insufficiency of the forcing data and also partly of the shortcomings of the physics considered in the LSMs (Oki et al., 2001). Oki et al (2001) finds their runoff estimates to be smaller approximately by a 20% compared to the previous studies (**Table 1**). Also, the regions with river discharge observations tend to have higher simulated annual runoff, than the regions without discharge observations (Oki et al., 1995). Also, for precipitation forcing, when the precipitation gauge density is less than 30-50 / 10<sup>6</sup> km<sup>2</sup> (Oki et al., 1999), the accuracy of runoff estimates out of LSMs may not be realistic. However, for precipitation gauge densities more than this threshold, the LSM output runoff does not depend on the precipitation gauge densities any longer. Routing runoff using Total Runoff Integrating Pathways (TRIP – routed by TRIP same as the data used in our research) improves seasonal cycle of river discharge, enhancing the correspondence with the observed discharge. However, the accuracy of simulated discharge depends on the accuracy of the forcing data.

**Table 1** Continental runoff (km<sup>3</sup> year<sup>-1</sup>)

| Region        | WMO (1997)   | Vorosmarty et al. (2000) | Oki et al. (2001) |
|---------------|--------------|--------------------------|-------------------|
| Africa        | 4050         | 4520                     | 3616              |
| Asia          | 13510        | 13700                    | 9385              |
| Europe        | 2900         | 2770                     | 2191              |
| Oceania       | 2404         | 714                      | 1680              |
| North America | 7890         | 5890                     | 3824              |
| South America | 12030        | 11700                    | 8789              |
| <b>Total</b>  | <b>42784</b> | <b>39394</b>             | <b>29485</b>      |

Source: Oki et al., 2001

3. [The consideration of the balance of import and export of virtual water is also important factor in deciding how water-stressed a region actually is.](#)

Although our research has performed an analysis in the 0.5° grid scale, it looks at the situation in the country level. At this time, we cannot look at the city/ agricultural region disparities, as we are performing the same analysis for the whole world. However, it is our hope to extend our analysis to consider virtual water fluxes in the future. Then we will have to consider national/ international trade data as well, to suit our scale of analysis.

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This discussion paper is/has been under review for the journal Hydrology and Earth System Sciences (HESS). Please refer to the corresponding final paper in HESS if available.

# The effects of country-level population policy for enhancing adaptation to climate change

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Received: 1 May 2012 – Accepted: 18 July 2012 – Published: 3 August 2012

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Published by Copernicus Publications on behalf of the European Geosciences Union.

HESSD

9, 9239–9256, 2012

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## Abstract

The effectiveness of population policy scenarios in reducing the combined impacts of population change and climate change on water resources is explored. One no-policy scenario and two scenarios with population policy assumptions are employed in combination with water availability under the SRES scenarios A1b, B1 and A2 for the impact analysis. The population data used are from the World Bank. The river discharges per grid of horizontal resolution  $0.5^\circ$  are obtained from the Total Runoff Integrating Pathways (TRIP) of the University of Tokyo, Japan. Unlike the population scenarios utilized in the SRES emission scenarios and the newest Representative Concentration Pathways, the scenarios employed in this research are based, even after 2050, on country-level rather than regional growth assumptions.

Our analysis implies that in combination with a more heterogeneous pattern of population changes across the world, a more convergent, environmentally friendly emissions scenario, such as B1, can result in a high-impact climate scenario, similar to A2, for the already water-stressed low latitudes. However, the effect of population change supersedes the changes in the climate scenarios. In 2100, Africa, Middle-East and parts of Asia are in extreme water-stress under all scenarios.

For countries with high population momentum, the population policy scenario with fertility-reduction assumptions gained a maximum of 6.1 times the water availability in Niger and 5.3 times that in Uganda compared with the no-policy scenario. Most of these countries are in Sub-Saharan Africa. These countries represent 24.5% of the global population in the no-policy scenario and the scenario with fertility-reduction assumptions reduces it to 8.7% by 2100. This scenario is also effective at reducing the area under extreme water stress in these countries. However, the policy scenario with assumptions of population stabilization at the replacement fertility rate increases the water stress in high-latitude countries. Nevertheless, the impact is low due to the high per capita water availability in the region. This research is expected to widen the

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understanding of the combined impacts of climate change in the future and of the strategies needed to enhance the space for adaptation.

## 1 Introduction

Global water resource assessments project grim futures, with increased water stress in many parts of the world (Vorosmarty et al., 2000; Arnel, 2004). Therefore, adaptation to global climate and population changes is a need of the time. Population policy (Das Gupta et al., 2011; United Nations, 2011b) and climate policy interventions (Clarke et al., 2009; Moss et al., 2010), early warning systems, effective risk communication between decision makers and citizens, sustainable land management and ecosystem management and restoration (IPCC, 2012) are among the adaptation measures with high potential benefits. However, few studies have specifically quantified the effects of changes in population (Curtis et al., 2011; IPCC, 2012). Nevertheless, societal development trends play significant roles in climate change adaptation compared with specific climate policies (Vorosmarty et al., 2000; Van Vuuren et al., 2010). Furthermore, the global population projections utilized in the new Representative Concentration Pathways (RCPs) and other emissions scenarios (IPCC, 2000; EMF-22 cited in Van Vuuren et al., 2010; Riahi et al., 2011) have uniform regional growth assumptions after the year 2050 (Arnel, 2004; Van Vuuren et al., 2010; Riahi et al., 2011). Therefore, their use in climate impact assessments (Arnel, 2004; Shen et al., 2008) masks vulnerabilities at finer scales.

Most of these studies (IPCC, 2000; Arnel, 2004; Riahi et al., 2011) employ either the United Nations population projections or those of the International Institute of Applied Systems Analysis (IIASA). The projected global populations in 2100 vary significantly among the various projections. The EMF-22 scenarios utilize a population projection of eight to ten billion in 2100 (cited in Van Vuuren et al., 2010), whereas the recent RCP population projections vary from approximately eight to twelve billion (Van Vuuren et al., 2010; Riahi et al., 2011). However, the 2100 population projections used in the

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previous SRES scenarios (IPCC, 2000) vary from seven billion under the A1 and B1 storylines to fifteen billion under the A2 storyline (IPCC, 2000). Although more recent literature provides more downward projections for 2100 (Van Vuuren and O'Neill, 2006), the most recent World Population Prospects 2010 revision provides a different picture, with slight upward revisions of its 2008 version. The high variant projects a global population of 15.8 billion, whereas the medium and low variants project values of 10.1 and 6.2 billion, respectively (United Nations, 2011a). The reasons for this upward shift are the confirmed evidence of the decreasing prevalence of HIV/AIDS among the Third World populations and the slow progress of the fertility decline in Sub-Saharan Africa than the previous expectations (Lee, 2011). Even though the UN low projection (United Nations, 2011a) gives a declining global population in the second half of the century, the National Research Council (NRC, 2000) has found only a one-in-one-thousand probability that the global population would decline from 2030–2050, in contrast to the UN low scenario (Lee, 2011). However, the UN and IIASA scenarios explicitly assume that the population growth will not change course due to feedback from negative environmental or climate change impacts (Lee, 2011). Therefore, to address these needs, we explore the impacts of a global population projection that results in a total global population similar to that of the UN high population projection (United Nations, 2011a) in 2100, resulted by country level growth assumptions even after 2050. The effectiveness of population control policies adopted by a few countries to reduce the combined impacts of population and climate changes globally and regionally is also explored, by the means of two other major population scenarios that assume country level population policy. The climate change impact addressed here is the potential decrease in per capita water resources. However, the benefit of population control in achieving sustainability is well established in literature (Koutsoyiannis et al., 2009). Here, population policies are tested as low-regret measures to reduce the effects of combined population and climate changes.

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## 2 Methodology

### 2.1 Population scenarios used

A scenario that projects the global population to be 15.7 billion in 2100 (SC1, Fig. 1a) was employed without any assumptions regarding additional population control policies directed at tackling climate change for any country. This scenario closely agrees with the UN's high population projection (United Nations, 2011a) of 15.8 billion in 2100. However, only the decadal trends in the historical annual population growth rate (1961–2010) data (World Bank, 2012) at the regional level (for the countries in the three World Bank income categories: high, middle and low income) were explored to derive the future trends. Although the concurrent scenarios used in climate research utilize regionally uniform population growth rates (Arnel, 2004; Van Vuuren et al., 2010) after 2050, this study assumes regional trends in the annual population growth rate. Distinctive trends were derived regionally for trends in the annual population growth rate in the high-, middle- and low-income countries (World Bank, 2012). The year 2010 was taken as the base year for population projections, whereas the base year for this analysis was assumed to be 2000. Therefore, every scenario considered follows the World Bank (2012) country populations until 2010.

The population policy scenarios are applied only for selected countries (Fig. 1b). SC2, which focuses on fertility-reduction programs, is applied only for countries with population growth rates greater than 2.50% in 2010 (the average population growth rate for heavily indebted poor countries in 2010 is 2.56% and for Sub-Saharan Africa only is 2.49%; World Bank, 2012). SC1 assumes an above-replacement-level fertility for these countries even until 2100, and it is the SC2 (or SC3) population policies that reduce them to near-replacement fertility (or replacement fertility in SC3). Trends in the population growth rate similar to that of China at various stages of transition (Fig. 2) were applied to these countries based on their income category (World Bank, 2012). The effectiveness of the fertility-reduction programs was assumed to decrease with decreasing income of the country. China is a country with more than 30 yr of experience

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in fertility-reduction policies in the form of family planning programs in combination with other incentive and disincentive programs (Peng, 2011). Although, its “one-child policy” is open to limitless critique, the same policy has been more flexible in rural China (Peng, 2011). Therefore, it is a good example of policy-driven population growth trends. SC3 assumes that by the time the countries reach the replacement fertility level, they have policies to keep the populations stabilized at that level, apart from the assumptions in SC2.

However, the global impacts of scenarios SC2 and SC3 do not differ greatly according to Fig. 1. Even the no-policy scenario, SC1, assumes that populations will reach near-replacement fertility levels for the countries with low population growth rates ( $<2.5\%$  in 2010) by 2100, simulating small, above-zero population growth.

## 2.2 Future water availability scenarios used

Water availability due to climate change was considered under emissions scenarios A1b, B1 and A2. However, only renewable water resources were considered for the analysis. The discharges per grid of horizontal resolution  $0.5^\circ$  from the Total Runoff Integrating Pathways (TRIP-1) of the University of Tokyo were assumed to be the potentially available water for use in the respective grids. Validation of the TRIP data can be found in Oki et al. (1998, 2001). The data were averaged over four climate models, CCSM3, MIROC3.2, CGCM2.3.2 and UKMO, for each climate scenario to reduce regional biases. The year 2000 was selected as the base year for the analysis. The per capita water resources ( $m^3 yr^{-1}$ ) were calculated for all combinations of the population and climate scenarios.

Although the underlying population scenario utilized for the SRES A2 projects 15.1 billion people in 2100, similar to the population scenario employed in this study (15.7 billion in 2100), the other two projections are lower (IPCC, 2000; Arnel, 2004). Therefore, the climate scenarios were selected to represent the SRES high and low projection storylines (15.1 and 7.0 billion). However, as in the EMF-22 scenarios

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(Clarke et al., 2009, cited in Van Vuuren et al., 2010), no relationship was assumed between the climate scenarios and the population scenarios.

### 3 Results and discussion

#### 3.1 The combined impact of climate change and population change on water availability

The impacts of population change under scenarios SC1, SC2 and SC3 for the water availability scenarios A1b, B1 and A2 were explored. Global per capita water availability ( $\text{m}^3 \text{yr}^{-1}$ ) was calculated for grids with a horizontal resolution of  $0.5^\circ$  for the base year 2000 and for the years 2025, 2050 and 2100. Falkenmark's (1992) water stress indicator was employed in the analysis. This indicator defines three levels of water stress: an annual per capita water availability of  $0\text{--}500 \text{m}^3 \text{yr}^{-1}$  is extreme stress,  $500\text{--}1000 \text{m}^3 \text{yr}^{-1}$  is high stress and  $1000\text{--}1700 \text{m}^3 \text{yr}^{-1}$  is moderate stress (cited in Arnel, 2004). In addition, an upper transition zone of  $1700\text{--}5000 \text{m}^3 \text{yr}^{-1}$  was defined to clearly show the climate-population interactions in the middle to upper latitudes. The country-level population scenarios were disaggregated to the  $0.5^\circ$  grid level using population counts per grid data for the year 2000 (corrected for the UN estimates) from the Centre for International Earth Science Information Network (CIESIN, 2010).

Figure 3 shows the per capita water availability from the combined effects of population and climate changes under the three climate scenarios in 2100 and how the population policy scenarios are beneficial or detrimental to regions addressing the impacts of climate and population changes. Figure 3a compares the effect of the no-policy population scenario (SC1) under the three climate scenarios A1b, B1 and A2 in the year 2100. Although A2 is expected to be the worst-case scenario (Arnel, 2004; Shen et al., 2008), in this case B1 in combination with the SC1 scenario (15.7 billion in 2100) also shows impacts similar to A2 for the already water-stressed lower latitudes. However, the B1 scenario, which has the same SRES population projection as in A1b (7.0 billion

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in 2100), shows a comparatively higher impact on the per capita water resources than A1b. This result implies that, opposed to the assumptions made in the SRES scenarios after 2050 (Arnel, 2004; Van Vuuren et al., 2010; Riahi et al., 2011), if combined with a more scattered pattern of population change across the world, a more convergent, environmentally friendly emissions scenario can result in a high-impact climate scenario. This effect is explained in detail in Sect. 3.2. The magnitude and the regions negatively affected ( $< 0.8$ , Fig. 3b) by the combined climate change and population change, differ among the three climate change scenarios. However, all the three climate scenarios agree with the extremely negative impacts to water availability ( $< 0.5$  times water availability in 2000, Fig. 3b) in the African continent, the Middle-East, Australia and in some parts of Asia. Therefore, the applied fertility reduction scenario (SC2) addresses the projected extreme water availabilities.

Figure 3c and d show the gain or loss that could occur under the fertility-reduction policy scenario SC2 and the effects if it is combined with population stabilization at replacement fertility (scenario SC3), respectively. The scenario SC2 gives the highest gain (Fig. 3c), with 6.1 times the water resources per capita in Niger, compared with SC1, with the second-highest gain of 5.3 times in Uganda. Niger and Uganda are the countries with the highest momentum for future population increase in Sub-Saharan Africa. In 2100, these two countries represent 12.5% of the total population in the region. The fertility-reduction policy scenario SC2 reduces this figure to 4.5%. The countries with fertility-reduction policies (SC2 – Fig. 3c) represent 24.5% of the global population in 2100 under the no-policy (SC1) scenario. Under SC2, this figure is reduced to 8.7%. However, the benefits of SC2 far outweigh the losses due to population stabilization at replacement fertility (SC3). A decrease in the annual per capita water availability of half (0.5) can be more detrimental than a twofold increase (Arnel, 2004), especially for regions with moderate to high water stress (annual per capita water  $< 1700 \text{ m}^3 \text{ yr}^{-1}$ ). However, the countries negatively affected by population stabilization at replacement fertility in SC3 are all high-latitude countries, including Russia and Eastern European countries with low water stress (annual per capita water  $> 1700 \text{ m}^3 \text{ yr}^{-1}$ ).

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If the population policies were combined together with the technological advancements in water resource management gained until present (Koutsoyiannis, 2011), the effectiveness in reducing extreme water stress could be much higher.

### 3.2 Effectiveness of the population policy in reducing the impacts of climate change and population change in the selected countries

The combined population and climate changes increase water stress steadily in the countries where the population growth rates are high ( $> 2.5\%$ ) under the no-policy (SC1) scenario.

However, all three climate scenarios, A1b, B1 and A2, exhibit similar impacts on increased water-stressed areas in these countries (Fig. 4). In the extreme ( $0\text{--}500\text{ m}^3\text{ yr}^{-1}$ ) and high ( $500\text{--}1000\text{ m}^3\text{ yr}^{-1}$ ) water stress categories, the highest impact is given by the A2 scenario in 2100. The other two scenarios follow. As seen in Fig. 3a, by 2100 (after 2050) the B1 scenario sometimes gives a higher impact (Fig. 4b and d), whereas A1b surpasses B1 at other times. The most important outcome is that the effect of population change supersedes the changes in climate scenarios.

Being the regions (Fig. 3c) where 24.5% of the population is concentrated in 2100, fertility-reduction programs could be considered a low-regret measure to address climate change impacts on water resources. However, a comparison of the reductions in the water-stressed area show that SC2 and SC3 have parallel reduction paths, in contrast to the  $0\text{--}500\text{ m}^3\text{ yr}^{-1}$  extreme water stress category, where SC2 is more effective at reducing the impact under the climate scenarios A2 and B1. This result occurs because most of the grids in the  $0\text{--}500\text{ m}^3\text{ yr}^{-1}$  stress category are in the lower latitudes, where only fertility-reduction policies (SC2) are applied. However, the SC3 applied areas under each stress category are higher than even the no-policy scenario areas simply because the SC3 region is larger than the SC2 region (Fig. 3d).

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### 3.3 The population policy and fertility-reduction programs to date

Although this study assumes the effects of population policies of a certain nature, identifying the types of population policies that will result in this form of benefit for a certain country is beyond the scope of the current study. However, a brief review of the existing policies that exhibit a greater potential for fertility decrease is provided here.

Among the various population policies employed to date, two emerge as the most effective in facilitating fertility decline: improving access to family planning services and educating the high-priority groups consisting of young women and mothers (O’Neil et al., 2001; Bongaarts and Sinding, 2011; Lutz and Samir, 2011, United Nations, 2011b).

For the programs to be successful, improving access to contraceptive methods should accompany education programs, especially to eliminate the exaggerated fear of side effects, and family counseling services, to reduce opposition from spouses (Bongaarts and Sinding, 2011). In fact, this approach has proven to be highly effective even in the most traditional societies (Bongaarts and Sinding, 2011). Women with higher levels of education have a lower desired fertility (O’Neil et al., 2001; United Nations, 2011b). Therefore, government spending on women’s education is an indirect but highly effective strategy for achieving fertility decline. Providing incentives for women to join the labor force, as implemented by Japan (Samuel, 1966) and by China (Peng, 2011), also gives incentives to women to lower their desired fertility. However, governments are reluctant to interfere openly (O’Neil et al., 2001) with the fundamental reproductive rights of couples and individuals (United Nations, 2011b). Nevertheless, setting a higher minimum marriage age (United Nations, 2011b), which increases the mother’s age at first birth, and China’s “one-child policy” (Peng, 2011) could be considered instances in which governments intervened in the fertility decisions of individuals.

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## 4 Conclusions

The effectiveness of population policy scenarios in reducing combined population change and climate change impacts was explored. The impact considered was increasing water stress, measured by the Falkenmark water stress index. Water resource availability under three climate scenarios, A1b, B1 and A2, was considered along with a population scenario projected at 15.7 billion in 2100. Two other population scenarios evaluated the strength of the fertility-reduction policy (SC2) and its combination with population stabilization with replacement fertility (SC3) to reduce climate change impacts. Unlike the population growth scenarios utilized in climate research, which use regionally uniform population growth rates after 2050, the scenarios in this study assume trends in the population growth rates regionally, even after 2050.

For countries with high water stress (annual per capita water < 1700 m<sup>3</sup> yr<sup>-1</sup>), the climate change effects are far outpaced by the population change effects. The fertility-reduction policy scenario assumes policy only for a number of countries with high population growth rates. Most of these countries belong to Sub-Saharan Africa. These countries represent 24.5 % of the global population in 2100, a value that is reduced to 8.7 % under the scenario with fertility-reduction policy assumptions, SC2. SC2 reduces water stress in these countries significantly, although it is most effective at relieving the extremely water-stressed (annual per capita water < 500 m<sup>3</sup> yr<sup>-1</sup>) regions. However, the SC3 policy scenario increases the stress for Russia and for a few Eastern European countries, in addition to the benefits given by the SC2 assumptions. Nevertheless, the two scenarios do not differ greatly on a global scale.

The climate scenario B1, in combination with a population scenario with a heterogeneous pattern of population growth opposed to the regional growth assumptions in the current climate scenarios, outpaces the impacts from the A1b scenario in the regions with high water stress. However, the effects of population growth supersede the changes in the climate scenarios.

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For the population scenarios utilized, population growth was assumed uniform across a country. Furthermore, future migration trends were disregarded. These factors were considered, the impact assessment would be more informative at a finer scale.

Population policies were proved highly effective at facilitating adaptation to the combined impacts of population change and climate change in the countries with the highest population momentum in the future, including Uganda, Niger and Nigeria. Even though the effects of the fertility-reduction policies were assumed to be similar to those of China during its population transitions, female education and increased access to contraceptive methods are accepted as more effective and attractive strategies for lowering fertility rates.

**Supplementary material related to this article is available online at:**  
**<http://www.hydrol-earth-syst-sci-discuss.net/9/9239/2012/hessd-9-9239-2012-supplement.zip>**

*Acknowledgements.* The authors thank the Environment Research and Technology Development Fund (S-8) of the Ministry of Environment, Japan, and the Ministry of Education, Culture, Sports, Science and Technology, Japan, for their assistance in this research.

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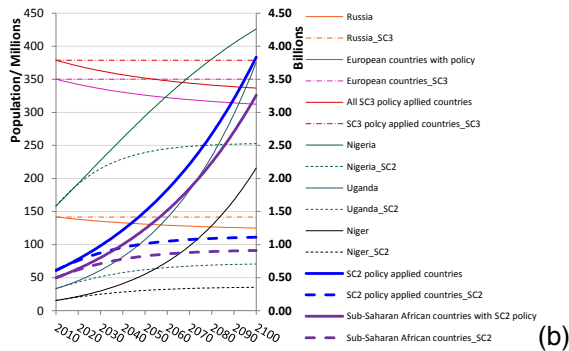
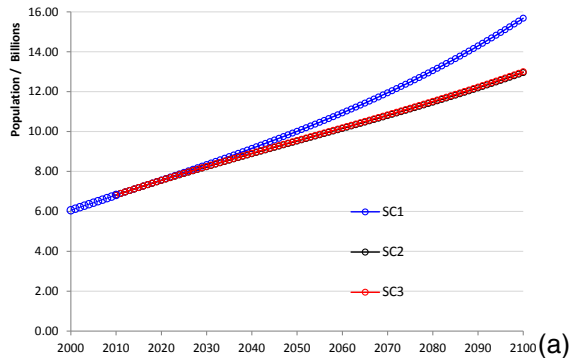
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**Fig. 1. (a)** The population policy scenarios utilized in the study. SC1 does not assume any population policy to reduce climate change impacts. SC2 applies fertility-reduction policies to countries where the annual population growth rate in 2010 exceeds 2.5%. SC3 additionally assumes that by the time the countries reach the replacement fertility rates, there will be no policy to keep populations stabilized at zero growth. **(b)** The regional population growth for the countries where the SC2 (dotted line) and SC3 (center line) policies are applied. The solid lines show the populations under the no-policy scenario, SC1. For the thicker lines, please refer to the bold secondary vertical axis in billions.

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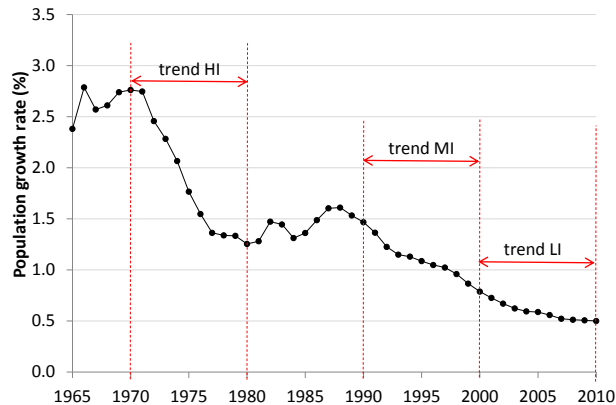
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**Fig. 2.** The historical annual population growth rates in China (data from World Bank, 2012). The exponential trends for the marked periods were assumed to be driven by the fertility-reduction policy trends: HI, MI and LI in the annual growth rate under scenarios SC2 and SC3 for the selected countries in the respective income categories of high income, middle income and low income (World Bank, 2012).

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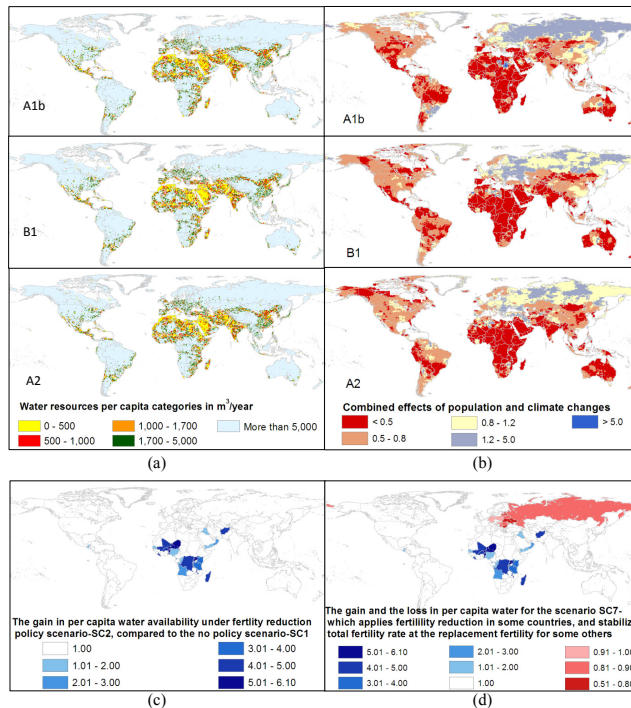
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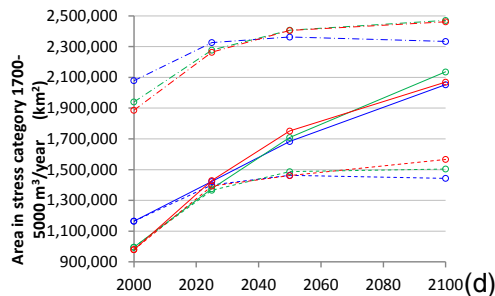
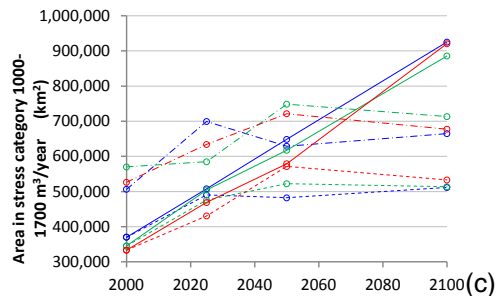
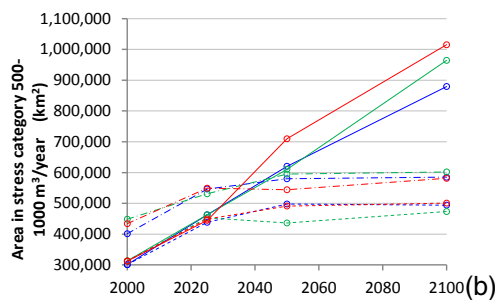
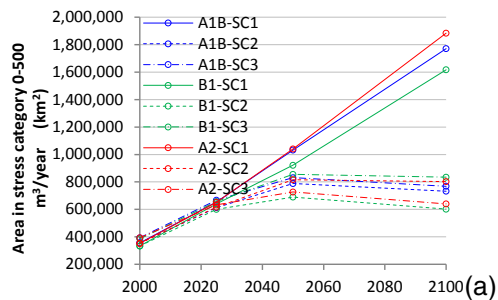


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**Fig. 3.** The combined impact of population change and climate change for the year 2100 and the effectiveness of the population policy scenarios in reducing the impacts. The horizontal resolution is  $0.5^\circ$ . **(a)** Per capita water availability ( $m^3 yr^{-1}$ ) in the world. The highest water stress categories are  $0-500 m^3 yr^{-1}$ ,  $500-1000 m^3 yr^{-1}$  and  $1000-1700 m^3 yr^{-1}$ , indicating countries where water stress is a major obstacle to human well-being and development or where water stress occurs regularly (Falkenmark et al., 1992). **(b)** The ratio of per capita water availability in  $0.5^\circ$  grids in 2100 to that in the base year 2000. The median class (yellow,  $0.8-1.2$ ) assumes a change of  $\pm 20\%$  from the per capita water availability of 2000. **(c)** The gain in the per capita water availability given by the fertility-reduction policy scenario SC2 as the ratio between the per capita water for SC2 to that of SC1. **(d)** The gain (blue) or loss (red) in scenario SC3, which applies fertility reduction in certain countries and stabilizes the total fertility rate at the replacement fertility in certain others, compared to SC1, with the ratio of per capita water between SC3 and SC1.



**Fig. 4.** The effectiveness of the population control policies (SC2 – fertility-reduction policy, SC3 – policy of population stabilization at replacement fertility) at reducing the area under water stress compared with the no-policy scenario, SC1. The figures consider only the countries for which the policies were applied (Fig. 3c for SC1 and SC2, Fig. 3d for SC3). The climate scenarios are indicated according to color: A1b-blue, B1-green and A2-red. The lines indicate the population scenarios under each climate scenario: SC1-continuous lines, SC2-dotted lines and SC3-center lines.

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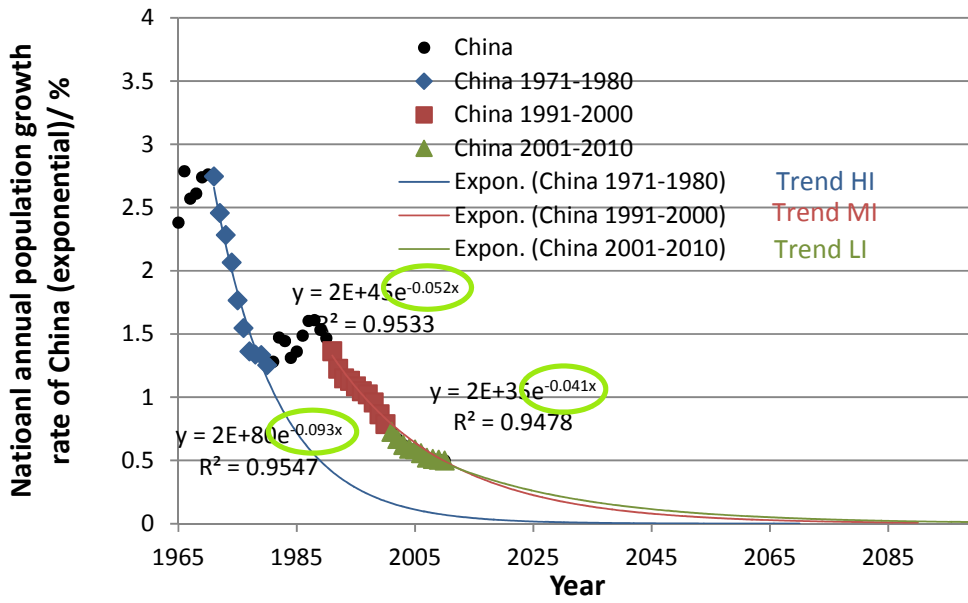
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**Fig. a** The trends in the reduction of population growth rates assumed to be resulted in by the population reduction policy scenario SC2 (applied from 2011 to 2100). However, acknowledging the fact that the constant in the equations (A in the equations of type  $y = A \cdot e^{bx}$ ) is a unique value for each country, only the exponential trends (bx) were applied for the countries. (x is the year since the start of the transition period)