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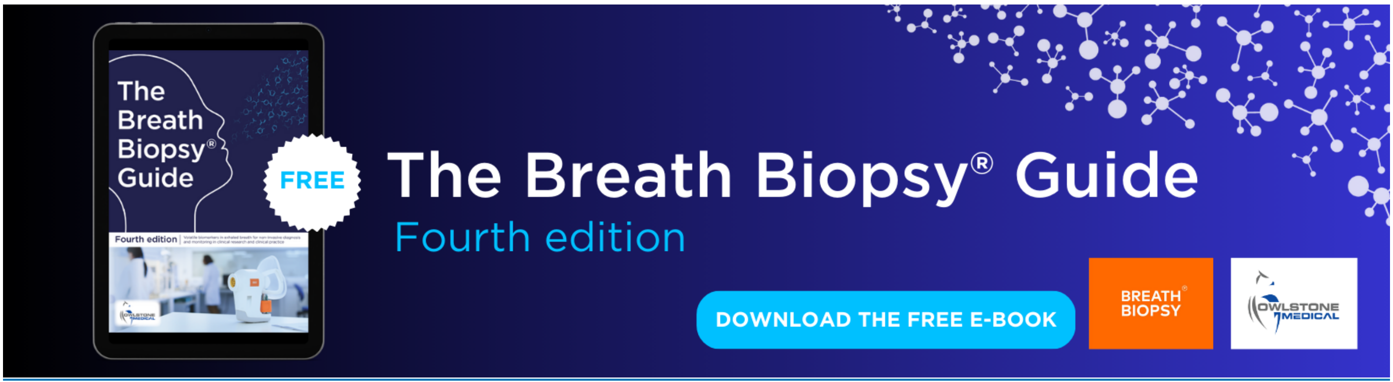

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Partial costs of global climate change adaptation for the supply of raw industrial and municipal water: a methodology and application

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Abstract
Despite growing recognition of the importance of climate change adaptation, few global estimates of the costs involved are available for the water supply sector. We present a methodology for estimating partial global and regional adaptation costs for raw industrial and domestic water supply, for a limited number of adaptation strategies, and apply the method using results of two climate models. In this paper, adaptation costs are defined as those for providing enough raw water to meet future industrial and municipal water demand, based on country-level demand projections to 2050. We first estimate costs for a baseline scenario excluding climate change, and then additional climate change adaptation costs. Increased demand is assumed to be met through a combination of increased reservoir yield and alternative backstop measures. Under such controversial measures, we project global adaptation costs of \$12 bn p.a., with 83–90% in developing countries; the highest costs are in Sub-Saharan Africa. Globally, adaptation costs are low compared to baseline costs (\$73 bn p.a.), which supports the notion of mainstreaming climate change adaptation into broader policy aims. The method provides a tool for estimating broad costs at the global and regional scale; such information is of key importance in international negotiations.

Keywords: adaptation, climate change, costs, global, hydrology, reservoirs, water supply

S Online supplementary data available from stacks.iop.org/ERL/5/044011/mmedia

1. Introduction

Impacts of climate change on the hydrological cycle are already evident, and these are expected to intensify over the 21st century. There is growing interest in the assessment of those impacts on water supply and shortage (e.g., Bates *et al* 2008, Kummu *et al* 2010). The availability of water will increase in some parts of the world, and decrease in others, whilst water demand is expected to increase greatly in most parts of the world (Kundzewicz *et al* 2007). It is therefore essential to develop adaptation measures to moderate the impacts and realize the opportunities associated with climate change.

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Studies estimating the costs of climate change in the industrial and municipal water supply sector remain limited, especially at the regional and global scale (Adger *et al* 2007, Kuik *et al* 2008), even though such information is of key importance in international negotiations. At the local, national, and river basin scales, several attempts have been made (e.g., Dore and Burton 2001, Kirshen *et al* 2006, EEA 2007, Vergara *et al* 2007), although these are skewed toward developed countries. To our knowledge, the only global assessment is that of Kirshen (2007), which estimated costs of additional water infrastructure needed by 2030 to provide sufficient water supply for over 200 countries. The results suggest total costs of \$531 bn to[5] 2030, due to both socioeconomic and climatic changes. This assessment was modified by UNFCCC (2007), in which worldwide adaptation costs to 2030 were estimated for two scenarios of the Intergovernmental Panel on Climate Change (IPCC 2000); ca. \$639–797 bn. It was assumed that 25% of these costs are specifically related to climate change; hence global climate change adaptation costs were estimated at \$9–11 bn p.a.

We present a methodology for estimating a subset of global climate change adaptation costs related to the supply of raw industrial and municipal water. We apply the method for two simulations of future climate change, and discuss several remaining challenges. The work builds on that of Kirshen (2007) in several ways: (a) cost estimates of reservoir storage are more detailed by incorporating storage-yield curves; (b) costs are first estimated for a socioeconomic baseline without climate change, in order to derive an improved delineation between climate related and non-related costs; and (c) the time-horizon of our study (to 2050) is longer.

2. Methods

In this study, adaptation costs are defined as the costs of the technical aspects of providing enough raw water to meet future industrial and municipal water demand, based on country-level demand projections to 2050. In brief, hydrological models were used to project changes in water availability between present day and 2050, and national statistics were used to project changes in water demand. Adaptation measures were then implemented in the models to assess the level of adaptation required to ensure that all demand can be met, and the costs of these measures were estimated. Increased demand was assumed to be met through reservoir yield by increasing surface reservoir storage capacity with two exceptions: (a) the average cost of supplying water from reservoir yield exceeds \$0.30 m^{-3}; and/or (b) reliance on additional reservoir yield increases withdrawals to more than 80% of runoff. In these cases, supply was assumed to be met through a combination of alternative backstop measures (recycling, rainwater harvesting, desalination) at an average cost of \$0.30 m^{-3}.[6] This represents only a rough estimate of the average costs of these measures globally (e.g. Sutherland and Fenn 2000, Hughes *et al* 2010); future studies would benefit from estimating the separate contribution of each of these measures based on their own marginal costs. However, global datasets to allow such analyses are currently lacking. The second decision rule is a preliminary attempt to account for ecological flow requirements of rivers. Smakhtin and Toulouse (1998) showed that for a variety of rivers, 20–35% of annual flow is required to maintain 'good' conditions; our decision rule is based on the lower bound of this estimate.

All analyses were carried out for the following scenarios:

- Socioeconomic baseline (Baseline): accounts for changes in water demand to 2050 (section 2.2).
- Baseline and climate change (B&CC): assumes the changes in water demand under the baseline, and accounts for changes in water availability due to climate change (section 2.2).
- Climate change only (CC): difference between Baseline and B&CC scenario.

The baseline scenario assumes that, without climate change, future demand is met. Since present day demand is not yet met, baseline costs cover both the elimination of any development deficit, and the consequences of socioeconomic development without climate change. This allows us to separate adaptation to climate change from the effects of economic development.

In our approach, we only assessed a specific subset of adaptation costs in the water supply sector; here we describe several key sectoral costs that are not included, though the list is not exhaustive. Adaptation costs in the agricultural sector are not considered, although agricultural irrigation accounts for 90% of global consumptive water use (Shiklomanov and Rodda 2003). Furthermore, costs associated with relocating water infrastructure affected by sea-level rise are not assessed, although these can be substantial (Heberger *et al* 2009). Moreover, we only estimated costs of raw water supply, and not costs associated with infrastructure for transporting water from sources to consumption points. Additional adaptation costs due to changes in water quality are not considered, although it should be noted that climate change is expected to worsen many forms of water pollution (Kundzewicz *et al* 2007). Moreover, we only examined the direct construction, implementation, and O&M costs associated with the adaptation measures considered. All adaptation measures entail other costs, both direct and indirect. Furthermore, we did not consider the possible direct and indirect economic benefits of adaptation measures. As such, the study does not provide an economic cost–benefit analysis, but an assessment of the construction, implementation, and O&M costs of this limited set of adaptation strategies.

The adaptation measures considered are technical, and represent just a few of the many measures available, since few cost estimates are available for so-called 'soft' measures at the global scale (Gleick 2003, Kundzewicz *et al* 2007). This does not mean that we consider the former options preferable to 'soft' options. An analysis for water utility infrastructure in OECD countries by Hughes *et al* (2010) found that total costs of adaptation can be substantially reduced by using economic incentives designed to hold total water demand

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[5] All costs given in USD2005, unless otherwise stated.

[6] The average desalination cost is higher than this, but it yields the equivalent of treated water so one must deduct the average cost of water treatment to obtain the average cost of raw water (Hughes *et al* 2010).

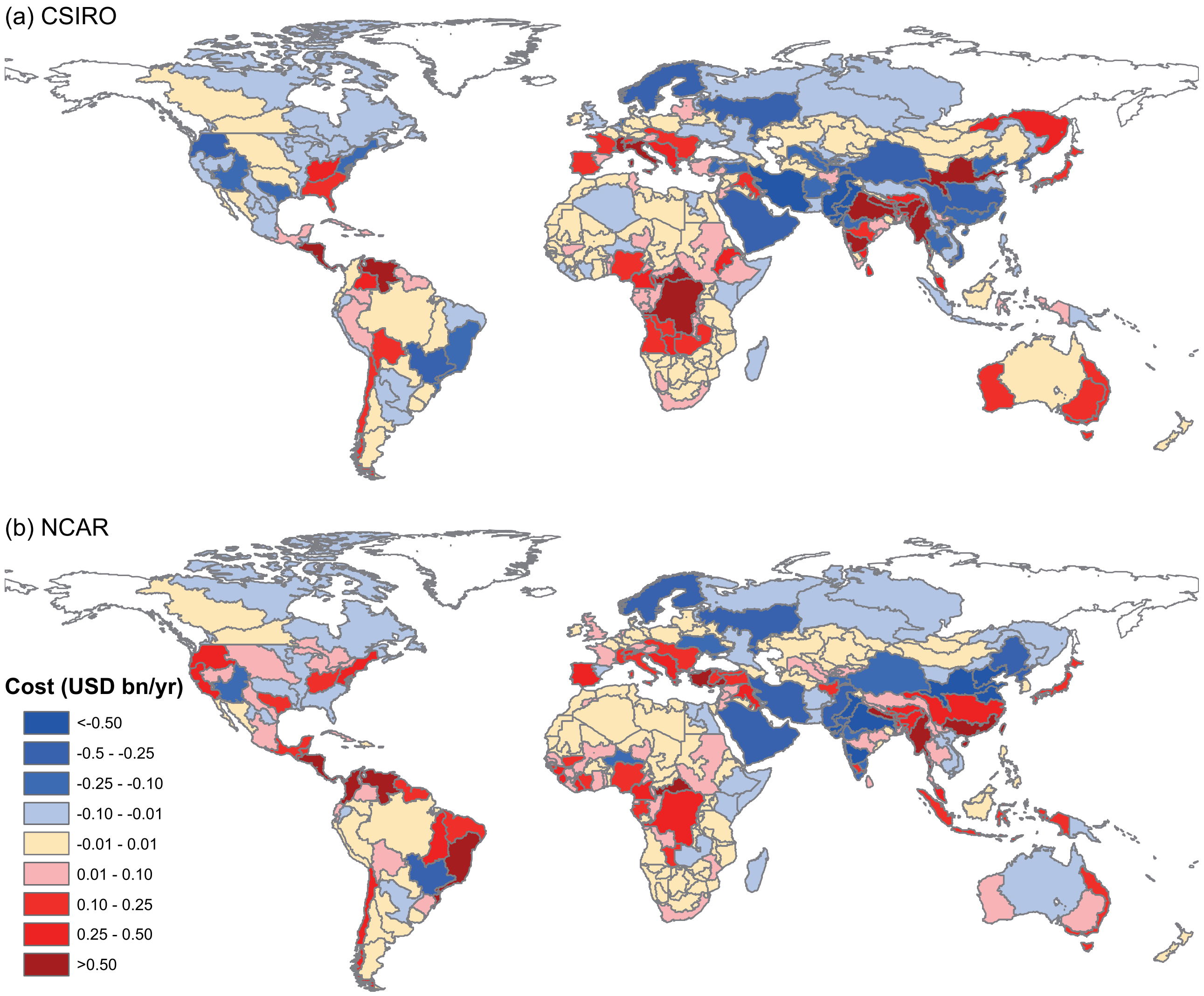


Figure 1. Average annual climate change adaptation costs ($ bn p.a.) per FPU in the industrial and municipal water supply sectors. Negative costs (shown in blue) refer to avoided costs as a result of climate change.

constant. Hence, our analysis should be understood as an upper bound on reasonable adaptation costs. The method is specifically designed for estimating costs at the global and/or (sub-) continental scale, and is not suitable for local or basin-scale assessments.

2.1. Geographical and temporal scale

All analyses were carried out at the scale of food producing units (FPUs) of IFPRI (International Food Policy Research Institute) and IWMI (International Water Management Institute). These divide the world into 281 sub-basins (figure 1), representing hybrids between river basins and economic regions (Cai and Rosegrant 2002, Rosegrant *et al* 2002, De Fraiture 2007). Cost estimates were then aggregated to the country level, and then to seven regions, namely the six development regions of the World Bank (East Asia and Pacific (EAP); Europe and Central Asia (ECA); Latin America and Caribbean (LAC); Middle East and North Africa (MNA); South Asia (SAS); and Sub-Saharan Africa (SSA)), with countries not belonging to these regions being classed as ‘high income’.

Climate change impact projections were carried out for three periods: baseline (1961–1990), 2030, and 2050 (2030 and 2050 actually refer to 2025–2035 and 2045–2055 respectively). The required adaptation measures were determined firstly for 2030, and then for 2050, and implemented linearly in the intervening years.

2.2. Socioeconomic and climate change scenarios

Projections of urban water demand were taken from Hughes *et al* (2010). These were derived from econometric equations using: (a) UN medium fertility projections for population (2008 revision) and urbanization (2006 revision); (b) average growth rates in GDP per person from five integrated economic assessment models for climate change; and (c) 2005 data for GDP per person at purchasing power parity. The projection of world GDP in real terms corresponds closely to the A2 SRES scenario. Separate equations were estimated for abstraction for industrial and municipal purposes using FAO and World Bank data for a panel of countries over time. The dependent variables are the logs of abstraction per person. The independent variables in the municipal use equation include log(% urbanization) and a quadratic in log(GDP per person) plus regional dummies and country characteristics as fixed effects. The quadratic term implies that municipal use peaks at an income of about $15 000 per capita in 2005 PPP and falls thereafter ($R^2 = 0.98$, $n = 366$, 15 df). The independent variables in the industrial use equation include a quadratic in log(GDP per person) and log(population) (but not urbanization), plus regional dummies and countries characteristics. In this case, peak use per person occurs at an income of about $12 500 per capita in 2005 ($R^2 = 0.96, n = 334$, 21 df). Water prices are not included as independent variable in the demand equations, since suitable price variables cannot be obtained for a sufficient number of countries. In practice, this means that prices are proxied by country characteristics, while the projections are based on a constant level of real prices. The analysis for OECD countries cited above examined what would happen if prices were used to hold water abstraction constant given reasonable price elasticities of demand for municipal and industrial users. The use of water pricing to influence water demand can reduce adaptation costs quite substantially, but developing countries have so far been very reluctant to adopt such policies.

The water cycle was assessed using the rainfall–runoff model CLIRUN-II (Strzepek and McCluskey 2010), run on a monthly time-step at a resolution of 0.5° × 0.5°. The model was used to simulate time-series of monthly runoff for the baseline, 2030, and 2050. The baseline simulations were carried out using input climate data from the CRU TS2.1 dataset (Mitchell and Jones 2005). Future climate time-series were taken from two GCM simulations, carried out for the Fourth Assessment Report (AR4) of IPCC (IPCC 2007) using SRES emissions scenario A2, since this corresponds most closely to the economic assumptions underpinning the demand projections. The GCMs used are NCAR_CCSM3 and CSIRO_MK3, hereinafter referred to as NCAR and CSIRO respectively.

2.3. Assessing the costs of additional reservoir capacity

Estimates of current reservoir storage per FPU were taken from the World Register of Dams (ICOLD 1998). Additional capacity required in each future scenario was calculated using storage-yield curves, which show the storage capacity needed to provide a given yield. Basin yield is a measure of the annually reliable water supply of a basin (figure 2).

Storage-yield curves were established per FPU, using monthly values, based on a modified version (Wiberg and Strzepek 2005) of the sequent peak algorithm approach (Thomas and Fiering 1963), whereby:

$$S_t = \begin{cases} R_t + E_{t-1} - P_{t-1} - Q_t + S_{t-1} & \text{if possible} \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

where S is reservoir storage capacity, R is release, E is evaporation above reservoir, P is precipitation above reservoir, Q is inflow, and t is current time period. Monthly time-series of inflow and net evaporation were derived from CLIRUN-II.

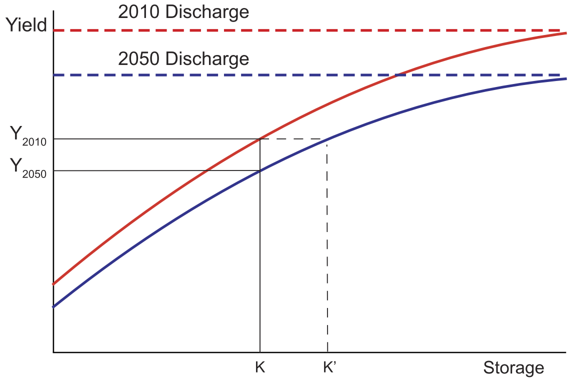


Figure 2. Example of a typical storage-yield curve for a hypothetical basin. Due to climate change, the discharge in the year 2050 is lower than in 2010, and therefore the storage-yield curve is lower (diminishing returns of yield for the same level of storage). The points Y_{2010} and Y_{2050} show the basin yield for storage capacity K in the years 2010 and 2050 respectively. The distance K–K′ shows the additional storage requirement needed to compensate for the loss in basin yield between 2010 and 2050 due to climate change. Based on World Bank (2009).

To estimate the costs of an additional unit of reservoir storage capacity, we used relationships between mean basin slope and cost per cubic metre for 11 size classes of reservoirs, based on Löf and Hardison (1966) and Wollman and Bonem (1971). The latter studies developed storage–cost relationships for 11 size classes and ten physiographic zones in the USA; we updated these to USD2005 values. As the spectrum of these zones encompasses many of the physiographic zones elsewhere in the world, and because the main factor explaining cost differences is the slope (Strzepek 2010), we assumed these relative cost structures to be similar around the globe (e.g., Wiberg and Strzepek 2005). Relationships between slope and construction costs per cubic metre for each size class, derived by Strzepek (2010) (supplementary data table 1 available at stacks.iop.org/ERL/5/044011/mmedia), were used to estimate construction costs per FPU, applying construction index multipliers (based on civil engineering construction costs) from Compass International Consultants Inc. (2009) to account for differences in construction costs between FPUs. We validated the method against a database of construction costs for 85 reservoirs around the world that we developed from published literature (Merrow and Shangraw (1990), World Bank (1996), Aylward *et al* (2001) and references therein; and World Bank project performance assessment reports, implementation completion and results reports, performance audit reports, and project completion reports).

We assumed reservoir O&M costs of 2% of construction costs per annum; (Palmieri *et al* 2001, WCD 2000). There is no global database of the size class distribution of planned future reservoirs. Therefore, our best estimate assumes that future construction will follow the same size distribution as the 20th century; sensitivity analysis on this assumption is carried out in section 4.

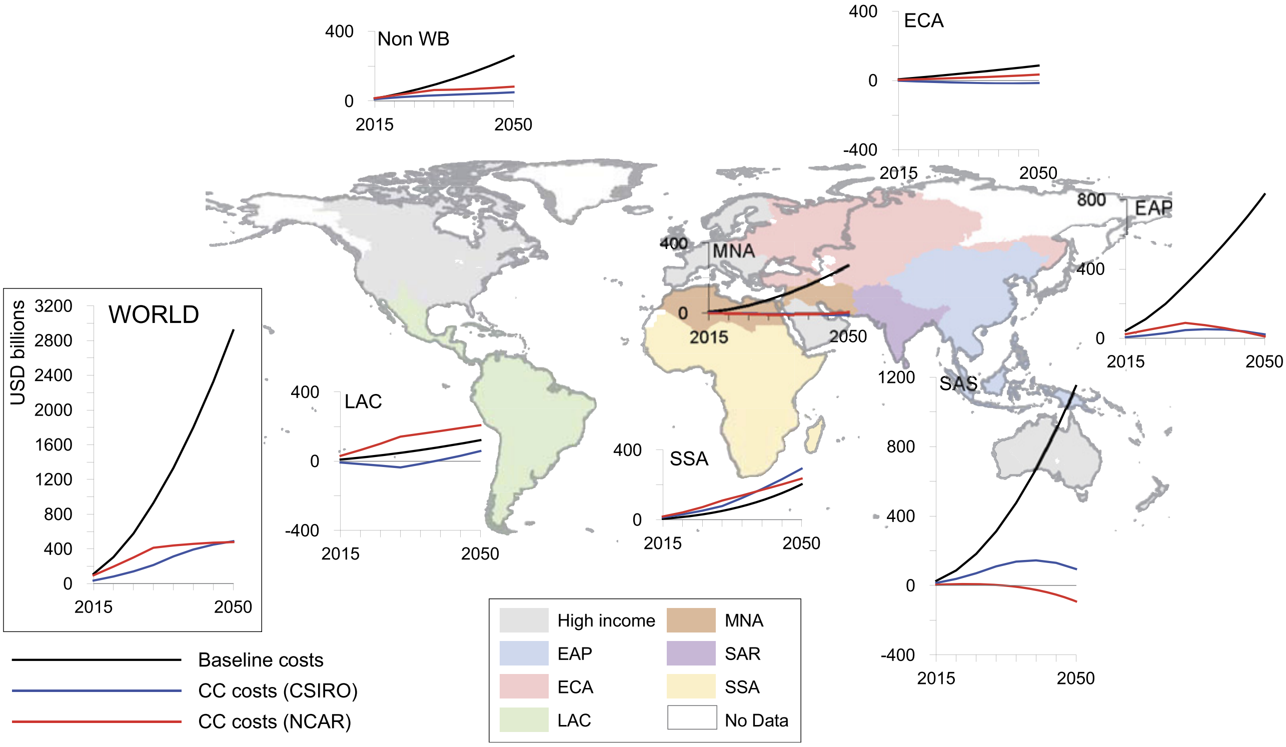


Figure 3. Cumulative adaptation costs (in $2005 bn) in the industrial and municipal water supply sectors for the period 2010–2050. The results are aggregated and displayed for the World Bank development regions (East Asia and Pacific (EAP); Europe and Central Asia (ECA); Latin America and Caribbean (LAC); Middle East and North Africa (MNA); South Asia (SAS); and Sub-Saharan Africa (SSA)), and for countries not belonging to one of these regions (high income).

It should be noted that the relative costs of dam construction may increase because existing dams and reservoirs are likely to have used many of the most cost-effective locations. Furthermore, we did not account for effects of sedimentation on storage capacity, since there are no databases describing regional rates of this phenomenon. This will lead to an underestimation of costs, since either: (a) more capacity will be needed to replace lost capacity; (b) more supply will have to be met through alternative measures; and/or (c) expensive dredging activities will be necessary.

3. Results

Cumulative baseline and adaptation costs over the period 2010–2050 are shown in figure 3. Globally, these estimates imply that the average adaptation costs over this period are \$12.2 bn p.a. (CSIRO) or \$12.0 bn p.a. (NCAR), of which 90%/83% (CSIRO/NCAR) relate to World Bank countries. However, global baseline costs (\$73.0 bn p.a.) are high compared to the climate change adaptation costs. Of the baseline costs, 91% are incurred in World Bank countries. For completeness, we show adaptation costs per FPU in figure 1. However, results at this scale should not be used to identify costs for specific locations, because analyses at this scale require more localized data and consideration of local and regional socioeconomic conditions, policies, and geography.

The highest baseline costs are in South Asia (SAS) (\$28.7 bn p.a.), where projected water demand increases by >200% by 2050 (figure 4). The growth in the baseline cost curve is exponential; in comparison, adaptation costs are low. Over the period 2030–2050, both simulations show negative adaptation costs in this region; this is because many parts of the region are projected to become drier until 2030 and wetter thereafter. The next highest baseline costs are in East Asia (EAP) (\$20.8 bn p.a.), due to large increases in demand (figure 4); adaptation costs here are low (\$0.6 bn p.a., CSIRO/\$0.3 bn p.a., NCAR).

There are two regions in which projected adaptation costs are greater than baseline costs, namely Sub-Saharan Africa (SSA) (both GCMs) and Latin America (LAC) (NCAR only). The main cause of the high adaptation costs in SSA is the projected drying of western Central Africa (figure 5). For LAC (under NCAR) the increase in adaptation costs is mainly due to increased costs in eastern Brazil (figure 1) due to projected increased seasonal and interannual rainfall variability.

In table 1 we show average annual baseline and adaptation costs (2010–2050) as a percentage of projected mean regional GDP, whereby the highest baseline costs are in the SAS region. For SSA, the region where adaptation costs are highest in absolute terms, this is more prominent as a percentage of GDP. For high income countries the costs are very low in GDP terms (baseline and climate change).

In this study, adaptation costs consist of a component derived from reservoir storage construction, and a component derived from alternative backstop measures. In figure 6 we show these cost components individually per region (and globally).

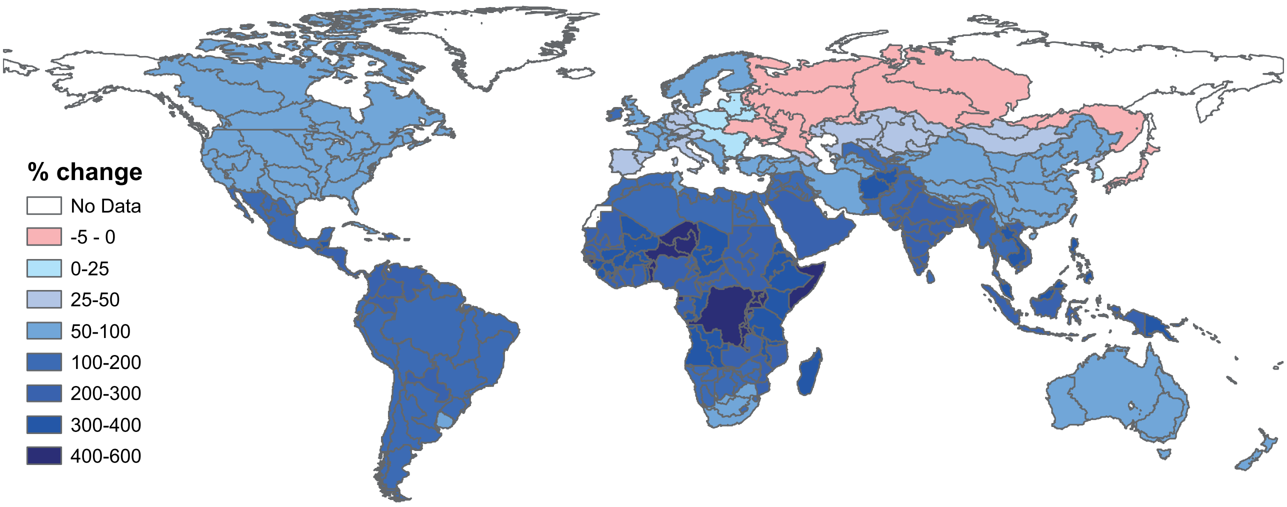
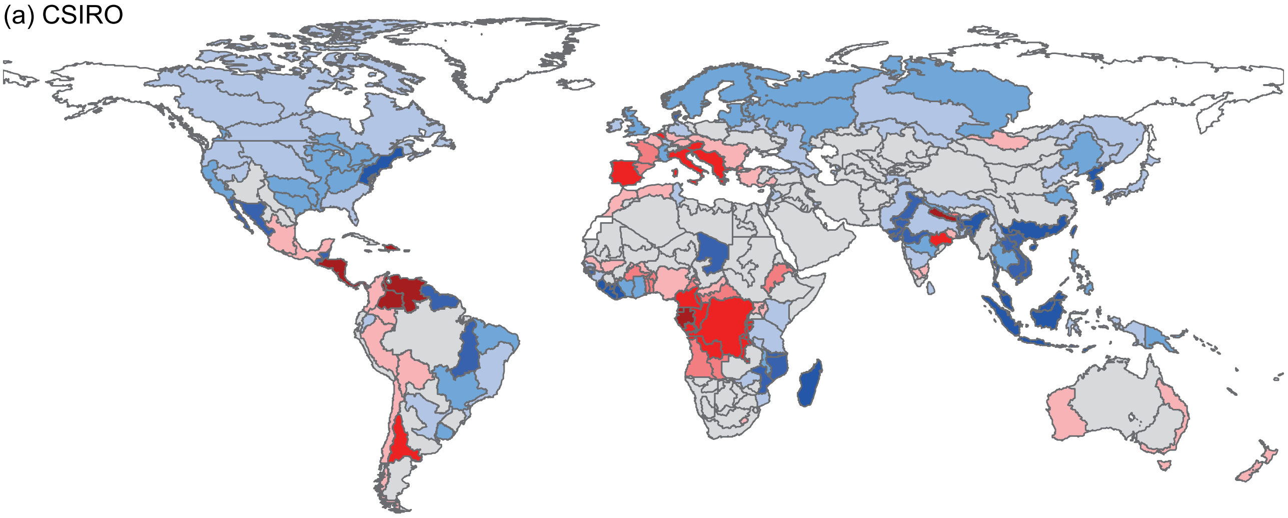


Figure 4. Percentage change in industrial and municipal water demand per FPU between 1961–1990 and 2050.

(a) CSIRO



(b) NCAR

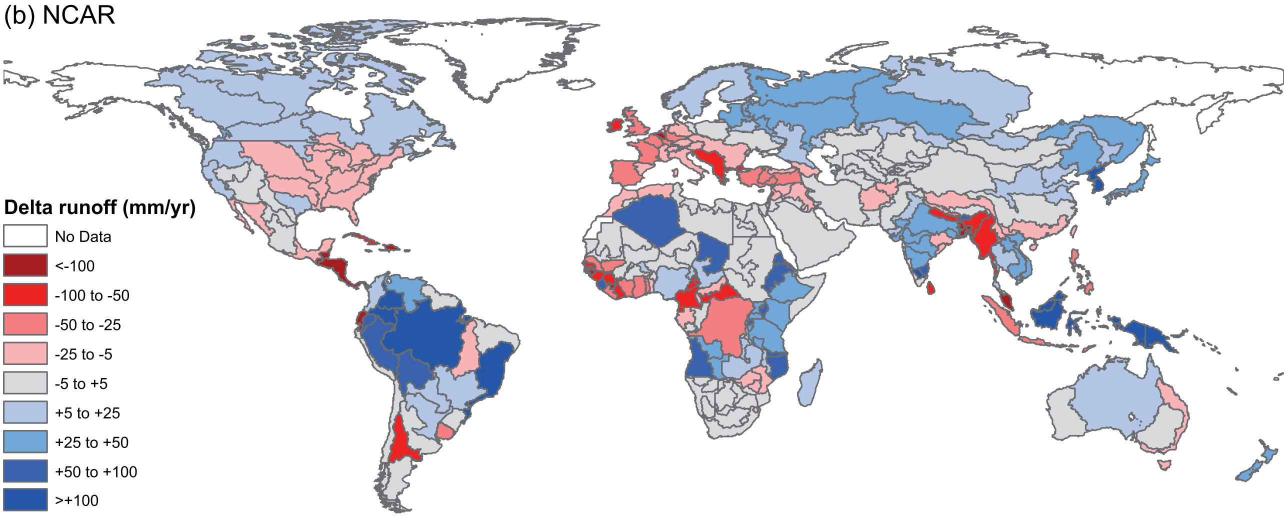


Figure 5. Change in mean annual runoff (in millimetre) per FPU between 1961–1990 and 2050 using the results of climate models: (a) CSIRO; and (b) NCAR.

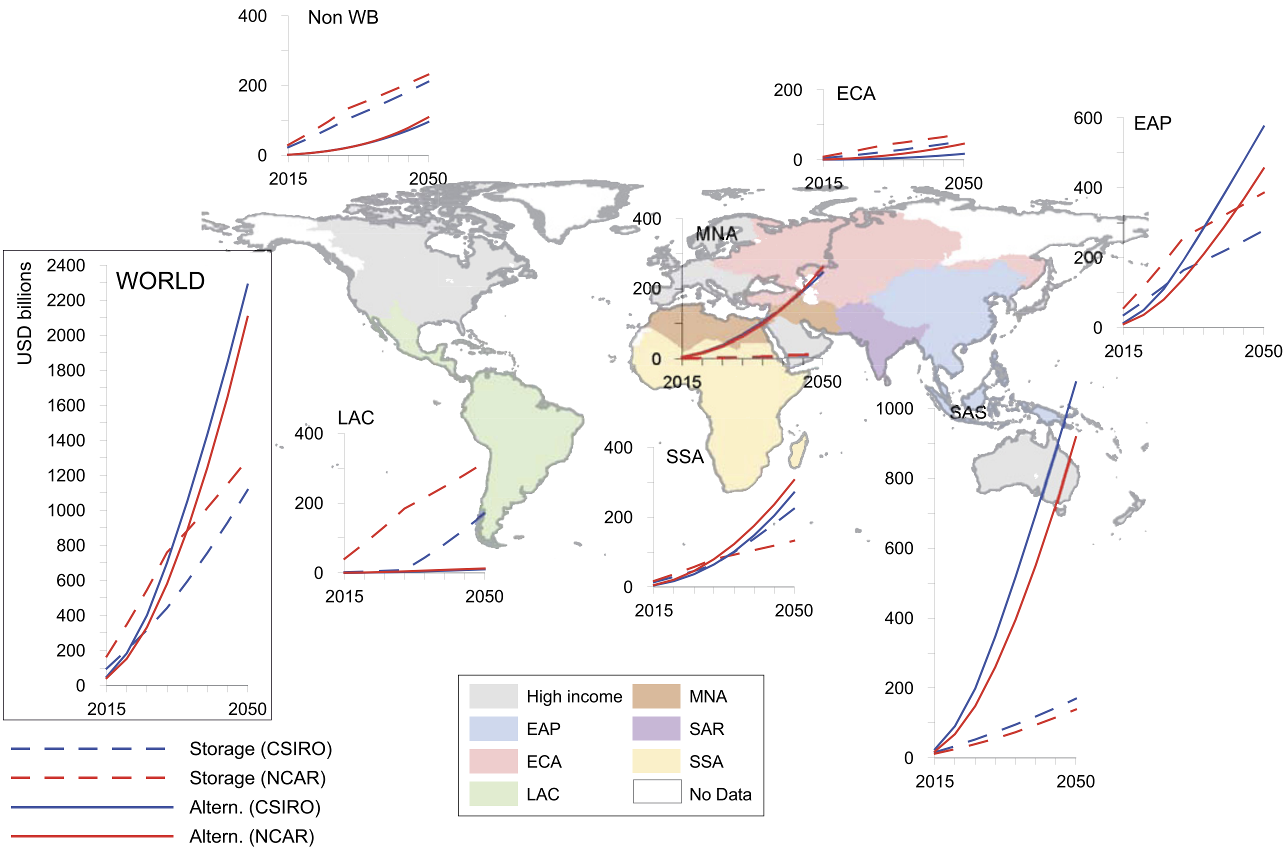


Figure 6. Cumulative costs (baseline and climate change adaptation) (in $2005 bns) in the industrial and municipal water supply sectors for the period 2010–2050. The dotted lines show the costs related to providing extra reservoir storage capacity, and the solid lines show the costs related to alternative adaptation measures. The results are aggregated and displayed for the World Bank development regions (East Asia and Pacific (EAP); Europe and Central Asia (ECA); Latin America and Caribbean (LAC); Middle East and North Africa (MNA); South Asia (SAS); and Sub-Saharan Africa (SSA)), and for countries not belonging to one of these regions (high income).

Table 1. Adaptation costs over the period 2010–2050 as percentages of total regional GDP. Where net adaptation costs are negative, no percentage is shown.

	EAP	ECA	LAC	MNA	SAS	SSA	High income	Global
	Costs as % of regional GDP							
Baseline	0.09	0.03	0.03	0.17	0.28	0.16	0.01	0.06
CSIRO	<0.01	0.01	0.05	—	—	0.19	<0.01	0.01
NCAR	<0.01	—	0.01	—	0.02	0.23	<0.01	0.01

Table 2. Total increase in reservoir storage capacity (km^3) between present and 2050 under the B and CC scenario for CSIRO and NCAR (best estimate).

	Increase in capacity (km^3)	
Region	CSIRO	NCAR
EAP	469	647
ECA	77	95
LAC	701	789
MNA	26	40
SAS	298	220
SSA	983	420
High income	426	591
Global	2981	2803

At the global level over the whole period, the cost of alternative backstop measures is considerably greater than the cost of expanding reservoir capacity. Nevertheless, the results suggest a large expansion of reservoir capacity compared to present (table 2). In the SAS region, where total costs (B&CC) are highest, the projected increase in capacity is relatively low (table 2), with most future investment directed towards alternative backstop measures. For EAP, the region with the second highest total costs, this difference is lower (figure 6), and in absolute terms the projected increase in reservoir capacity is higher (table 2). Relatively large increases in capacity are also projected for SSA and LAC; using the decision rules implemented here only a marginal amount of investment is projected in alternative backstop technologies in the latter region.

4. Discussion

Previous studies have shown that the developing world is particularly vulnerable to the impacts of climate change (Adger *et al* 2003, Huq and Reid 2004, IPCC 2007). The costs estimated in this paper for adaptation for raw industrial and municipal water supply are also greater for developing countries than for developed countries, both in absolute terms and as a percentage of GDP. In most regions, baseline costs far exceed adaptation costs. This supports the notion of mainstreaming climate change adaptation, and current and future climate vulnerability, into broader policy aims (e.g. Agrawala and Van Aalst 2005, Dasgupta and Baschieri 2010). The largest adaptation costs are projected in Sub-Saharan Africa, both in absolute terms and as a percentage of regional GDP.

So far, we have examined adaptation costs at the regional scale by summing positive and negative costs across all FPUs in that region, i.e. net costs. However, the argument could be made that when assessing 'costs' for a given region, it is meaningful to ignore those countries for which negative costs are found, since a compensatory transfer of funds is unlikely from a country with negative costs to a country facing actual costs. Hence, we also estimated gross costs per region, by first summing all costs at the FPU scale to the country level, and then setting negative costs to zero, before summing to the regional scale. These gross global adaptation costs are higher than the net costs, namely $22–23 bn p.a. However, we argue that such analyses should only be used across countries when all sectors affected by climate change are considered (e.g., World Bank 2010), since a given country may be affected positively and negatively by climate change in different sectors.

Our projections show a significant increase in global reservoir storage capacity between 2010 and 2050, by ca. 2800–3000 km^3. To put this in context, Chao *et al* (2008) estimate current global surface storage capacity to be ca. 8300 km^3. The main regions in which our simulations project future reservoir construction are SSA, LAC, and EAP. In the latter two regions, current capacity is relatively low (WCD 2000), which could mean that there is potential for new construction at a cost below the $0.30 backstop implemented here (i.e. additional capacity has a relatively large impact on yield). In the EAP region, recent years have indeed seen the commissioning of several large dams, especially in China. The IPCC states that new reservoirs are expected to be built in developing countries in the coming century (Bates *et al* 2008). However, addressing water supply issues by increasing reservoir storage is controversial; many stakeholders have strong feelings either for or against this strategy (WCD 2000). The decision of whether or not to build reservoirs is based on complex political, socioeconomic, and environmental factors. In this paper we limit ourselves to direct costs of reservoir construction and O&M. However, man-made reservoirs have many (indirect) impacts, particularly in environmental and social terms (Ward and Stanford 1979, Petts 1984, Poff *et al* 1997, WCD 2000, Poff and Hart 2002). Little information is available to assess these indirect costs (and benefits) at the global scale. Such assessments require case specific impact assessments and participatory decision-making processes. Our assessment should therefore be treated as an indication of adaptation costs assuming the limited number of technical measures described, rather than a recommendation to pursue such a policy everywhere.

Our estimates are based on the assumption that the size of future reservoir construction will follow the same size distribution as the 20th century; here we carry out simple sensitivity analysis on this assumption. The analyses were repeated assuming that all future reservoir build would be in the form of small dams (storage capacity <0.03 km^3) or large dams (storage capacity >12.3 km^3) (the smallest and largest size classes of Wollman and Bonem (1971)). Globally, the small dams scenario results in higher costs than the best estimate by a factor of 1.7, whilst the large dams scenario results in lower costs by a factor of 0.8–0.9. Hence, direct costs associated with our best estimate scenario are only slightly higher than those associated with the large dams scenario; it should also be noted that external costs associated with large dams are generally higher (WCD 2000). Moreover, these scenarios refer to heavy infrastructural dams, and do not consider alternative local small scale water storage structures. For example, in the Kitui district of Kenya, small sand dams are used to retain groundwater during the dry season. This avoids some of the negative costs of large infrastructural developments, and the capital costs are relatively low (Lasage *et al* 2008).

The absolute cost estimates should be treated with caution, but are indicative of the magnitude of the problem. Our adaptation cost estimates are of the same order of magnitude as those of UNFCCC (2007). As well as the methodological limitations described in section 2, several other limitations apply. The alternative backstop measures considered do not explicitly include demand-side adaptation, since the demand projections already account for some increase in efficiencies over time. However, there is substantial scope for economizing on water consumption (Gleick *et al* 2005, Zhou and Tol 2005, Cooley *et al* 2009, Srinivasan *et al* 2010). Also, we did not account for water trading between countries or efficient upstream–downstream transboundary user-agreements; in some cases, this could lead to more efficient water use. Such arrangements need to be negotiated and formalized between riparian states, and cannot be implemented in such global modelling exercises. Furthermore, we have only assessed adaptation costs for one SRES emissions scenario using the results of two GCMs, since the aim is to present the methodological framework. There are significant differences in adaptation costs for the two GCMs to 2030. To get a detailed insight into the size of the uncertainty, future research should assess impacts under a larger suite of emissions scenarios and GCMs. A key benefit of our approach is that it can easily be adapted to assimilate new information; for example spatially differentiated environmental flow claims can be implemented in the model chain, and cost estimates associated with reservoir construction and technologies can easily be adjusted.

5. Conclusions

Despite the growing recognition of the importance of climate change adaptation, and a flourishing literature on the impacts of climate change on the hydrological cycle, there are few global estimates of adaptation costs in the water supply sector. We describe a methodology for estimating a subset of the costs of raw industrial and municipal water supply at this scale. A key feature of our study is that baseline costs without climate change are first calculated, with adaptation costs being assessed in relation to these. Given the global nature of the method and data, the absolute cost estimates should be treated with caution, but are indicative of the magnitude of the problem. Another key feature is that new data and insights can easily be added and incorporated, including improved cost estimates of alternative water supply methods, as global and regional databases become available or are improved.

Based on simulations from two GCMs, we estimated adaptation costs over the period 2010–2050 at ca. \$12 bn p.a.; 83–90% of these costs are in developing countries. Globally, baseline costs (\$73 bn p.a.) far exceed adaptation costs. This supports the notion of mainstreaming climate change adaptation, and current and future climate vulnerability, into broader policy aims. The largest adaptation costs were simulated in Sub-Saharan Africa, both in absolute terms and as a percentage of regional GDP. In some river basins or countries, climate change will have a positive impact on water supply, leading to reduced costs compared to the baseline. However, on a global scale, and for the majority of regions, direct costs will outweigh direct avoided costs.

Our projections show a significant increase in global reservoir storage capacity over the period 2010–2050, by ca. 34–36% compared to present. Nevertheless, despite the fact that this study has mainly assessed physical adaptation options, the projected capital investments in alternative backstop measures are greater than those projected in the expansion of reservoir capacity.

This study does not provide a cost–benefit analysis of adaptation measures, nor does it include external costs (or benefits), but rather estimates a subset of the direct capital costs of adaptation for raw industrial and municipal water supply, based on a limited number of technical adaptation measures. Furthermore, the method has only been applied with climate data from two GCMs; further analyses with a larger suite of models and scenarios would give a first order estimate of the uncertainties in the cost estimates associated with uncertainties derived from climate models. Future research should also focus on developing methods and databases for incorporating, for instance, costs of soft measures, and of changes in water quality. Nevertheless, the method provides a useful tool for estimating broad adaptation costs at the global and regional scale.

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