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Costs of adaptation to climate change impacts on freshwater systems: existing estimates and research gaps

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ABSTRACT: Information on the cost of adaptation in freshwater systems is necessary to better design strategies to face climate change and water management. We look at the existing estimates with the aim of identifying research gaps. Our analysis shows that case study-specific literature is scarce, fragmented, and not always methodologically transparent. At the same time, most existing global assessments are likely to represent underestimates and rely heavily on each other. We conclude that a clear conceptual framework is still missing. Remaining research gaps include addressing inter-sector linkages and estimations of other than only direct costs, in addition to addressing the issues of 'adaptation deficit' and 'residual damage'.

KEYWORDS: Adaptation, climate change, costs, freshwater systems.

JEL classification: Q54, A56.

Costes de adaptación a los impactos del cambio climático en sistemas hídricos: estimaciones existentes y retos para la investigación

RESUMEN: Tener información sobre los costes de adaptación en sistemas hídricos es necesario para un mejor diseño de estrategias de cambio climático y gestión hídrica. En este artículo se analizan las estimaciones existentes en la literatura con el fin de identificar los retos para la investigación. Nuestro análisis pone de manifiesto que la literatura focalizada en casos de estudio específicos es escasa, es fragmentaria y no siempre es transparente en cuanto a su metodología. Asimismo, las evaluaciones globales existentes representan probablemente una subestimación de los costes y además se trata de estimaciones interdependientes. Concluimos que falta desarrollar un marco conceptual para la estimación de los costes de adaptación y que la investigación futura debe preocuparse por el análisis de costes más allá de los costes directos y por las relaciones intersectoriales; así como por el 'déficit de adaptación' y el 'daño residual'.

PALABRAS CLAVES: Adaptación, cambio climático, costes, sistemas hídricos.

Clasificación JEL: Q54, A56.

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1. The impacts of climate change in freshwater systems

The impacts of climate change on freshwater systems are mainly due to the observed and projected increases in temperature, sea level rise and precipitation variability. This is predicted by the last IPCC assessment with a high to very high level of confidence (Kundzewicz *et al*., 2007). In recent years, numerous reports have provided various assessments of the potential impacts of climate change and socio-economic development on world water resources (e.g., Shiklomanov, 2000; Vörösmarty *et al*., 2000; Oki and Kanae, 2006; Arnell, 2004; Alcamo *et al*., 2007 and Shen *et al*., 2008).

An increase in the ratio of winter to annual flows, and possibly the reduction in low flows caused by decreased glacier extent or snow water storage, is also predicted (IPCC Climate Change, 2007). Sea-level rise will extend areas of salinisation of groundwater and estuaries, resulting in a decrease in freshwater availability for humans and ecosystems in coastal areas. Precipitation intensity and variability are projected to increase the risks of flooding and droughts in many areas of the world.

The effects of climate change in freshwater systems will exacerbate many forms of water pollution, and will impact on water system reliability and operating costs. Of all ecosystems, freshwater systems will have the highest proportion of species threatened with extinction due to climate change (Millennium Ecosystem Assessment 2005), via the warming of water, flow alteration and loss of aquatic habitat.

The potential effects of climate change on water systems are also expected to lead to changes in other water related sectors. For example: health (see Markandya and Chiabai, 2009) for a review on the evidence of the impacts of climate change in the health sector, including the increase of the transmission of water-borne infectious diseases due to unsafe water and sanitation conditions and decrease water accessibility); agriculture (Bates *et al*., 2008; Easterling *et al*., 2007; Kabat *et al*., 2003); (Kabat *et al*., 2003); industry, transport, and energy supply (Wilbanks *et al*., 2007); ecosystem services (Fischlin *et al*., 2007); fisheries (Easterling *et al*., 2007); FAO (2009); and forestry (Easterling *et al*., 2007). Climate change will also affect the management of water resources. Globally, water demand will grow in the coming decades, primarily due to population growth; but also climate change will result in a large increase of water demand for irrigation (Kundzewicz *et al*., 2007).

Climate change might also generate some positive impacts resulting from improved water availability in some areas. For example, increased annual runoff may produce benefits for a variety of in-stream and out-of-stream water users by increasing renewable water resources. But according to the IPCC Climate Change (2007) it is very likely that, although some areas are predicted to experience benefits that outweigh the costs in the short to medium term, globally the costs of climate change will be larger than the benefits (e.g., increased runoff can simultaneously generate harm by increasing flood risk).

Even if emissions of anthropogenic greenhouse gases were stabilized today, human-induced changes in climate will continue for many centuries. Therefore, in addition to mitigation, it is essential to develop adequate adaptation measures. There is still very scarce information on the costs of this adaptation. This information is particularly necessary to help designing effective responses to climate change in areas where freshwater systems are threatened or likely to be threatened in the future. The objective of this paper is to critically review existing assessments of the costs of adaptation to the effects of climate change in freshwater systems and to identify the main research gaps. As it will be discussed, some of the existing literature is in the form of case studies (an important number of them are reviewed in Ward *et al*., 2010a). Other is in the form of global assessments such as the ones produced by the World Bank (2006), the Stern report (Stern *et al*., 2006; Oxfam, 2007; UNDP, 2007 and the UNFCC, 2007).

This paper is organized as follows: in the next section (Section 2) we discuss adaptation in the context of freshwater systems. Section 3 reviews the current evidence of the cost of adaptation in the literature and Section 4 discusses research gaps and key elements for a conceptual framework. Concluding remarks are presented in Section 5.

2. Adaptation measures

Public policy in response to climate change was initially dominated by the discussions on mitigation (Swart and Raes, 2007). When adaptation was discussed, it was mainly in the context of developing countries, due to their greater vulnerability to impacts (Schipper, 2006). In other contexts, adaptation remained a 'taboo' subject, feared to undermine the prospects for mitigation policies (Schipper, 2006; Pielke *et al.,* 2007; Gagnon-Lebrun and Agrawala, 2007).

Adaptation was only fully recognised internationally as a legitimate problem for public policy when scientific evidence began to suggest that some climate change was unavoidable (Rayner and Jordan, 2010) and it was progressively widely accepted that even if emissions of greenhouse gases were stabilized today, human-induced changes in climate will continue for many centuries. Therefore, adaptation is now increasingly regarded as an inevitable part of the response to climate change. Regarding specifically the water sector, current water management practices and infrastructures are very likely to be inadequate to reduce the impacts on water supply reliability, flood risk, health, energy and aquatic ecosystems, and therefore, adaptation will be needed. The IPCC Third Assessment Report constituted a landmark in this respect (Klein and MacIver, 1999) and, throughout the following decade, the need for adaptation gradually came to be recognised as a policy objective among industrialised and industrialising countries alike (Rayner and Jordan, 2010).

Adaptation is defined by IPCC as the "adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities" (IPCC Climate Change, 2007). In the case of freshwater, as the precipitation variability is very likely to increase, appropriate infrastructure investments and changes in water and land use management will be needed, as water infrastructures, use patterns, and institutions have developed in the context of current conditions (Conway, 2005).

Most of the adaptation measures reported in literature for freshwater is planned adaptation. By planned adaptation it is understood "the result of a deliberate policy decision based on an awareness that conditions have changed or are about to change and that action is required to return to, maintain, or achieve a desired state" (IPCC TAR Climate Change, 2001); on contrast to autonomous adaptation, which occurs spontaneously among individuals "triggered by ecological changes in natural systems and by market or welfare changes in human systems" [1].

The adaptation measures can be preventive and reactive. By preventive we mean those actions taken in order to avoid the damage due to climate change (e.g., to avoid restrictions in water supply, to avoid the rivers to overflow, but also advisory measures to prevent the damage in case the rivers do overflow, such as education and training campaigns). By reactive we mean those actions carried out to deal with the damage once it has occurred (e.g., salvation and evacuation of people in case of flooding). For an estimation of the costs, one could argue that this second type of measures, the reactive, does not correspond to the costs of adaptation but to the costs of the impact of climate change. In fact, from our review of the literature concerning the water sector, reactive measures are almost not mentioned as adaptation policies. Only the EEA Report (European Environmental Agency, 2007) discusses examples of adaptation to drought and glacier retreat in developing countries which include re-creation of employment options after drought, capacity building of local authorities and assistance to small subsistence farmers.

It should be mentioned that there is not an unique classification of measures and what can be considered as to be part of one category is, in some cases, subject to debate. Table 1 present one suggestion of classification, which is discussed next.

[1] Note that other classification criteria for adaptation measures are also used in the literature, e.g., soft *vs* hard (i.e. implying infrastructure construction); long-term *vs* short-term; technical *vs* legal and behavioural, (EEA, 2007).

TABLE 1

Adaptation measures for water related impacts of climate change

Type of Impact	Adaptation measure
General decrease in water availability and increase of the risk of drought	**Preventive**
	Promotion of changes in water demand and efficiency of water use: Establishing pricing and market mechanisms Promoting shift water within and between sectors (e.g., agriculture to urban) and sharing/rationing Programs for increasing efficiency (irrigation, industry and households) Leakage management Awareness rising (information and education campaigns and communication) **Action in water supply**: Increase reservoir capacity Increase groundwater pumping Rainwater harvesting Desalinization Reuse of municipal wastewater
	Reactive measures
	Emergency plans Re-creation of employment options after drought Assistance to population and economic sectors (e.g., assistance to small subsistence farmers) Adoption of insurance schemes
Increase of the risk of inland flooding	**Preventive**
	Sustainable urban drainage systems Watershed restoration (restoring and managing appropriate vegetation) Implementing floodplains and wetlands Promoting terracing Enhancing infiltration (e.g., permeable paths and parking lots) Implementing early warning systems and Forecasting Flood defence infrastructures (dams, control reservoirs, diversions, etc.) Flood-proofing installations Restriction of land use in floodplains Land use change Population relocation out of floodplains Awareness rising
	Reactive
	Emergency and evacuation plans Assistance and treatment of injured people Adoption of insurance schemes

Source: Modified and enlarged from European Environmental Agency (EEA, 2007).

Regarding decreased water availability, a distinction is made between demand-side and supply-side measures. Supply-side options generally involve increases in storage capacities or abstraction and can generate further environmental impacts (Bates *et al.,* 2008). It should be noted that some supply-side options may also be inconsistent with climate change mitigation measures because they involve high energy consumption, such as desalination (Ward *et al.,* 2010b).

Risk management measures/policies, such as adopting insurance schemes, have a preventive nature in the sense that are taken as a *precautionary* action. However, adopting an insurance scheme will not prevent the damaging event from happening, but will simply compensate for the damage once it has happened. Therefore, it can be considered that this measure only takes effect after the damaging event, and that is why we have placed it among the reactive measures. But we acknowledge that other interpretations are possible.

Also, some of these measures can be considered as autonomous when carried out spontaneously by people (e.g., population movements out of floodplains, adopting flood insurance schemes, change in irrigation systems and introduction of "home-made" water harvesting infrastructures).

3. The costs of adaptation in freshwater systems: a review of the literature

Adaptation to the impacts of climate change will entail social and economic costs to many different sectors (from freshwater systems to agricultural systems, forest, coastal areas, etc.), which are in general difficult to determine. Significant progress has been done for the assessment of the costs of the impacts of climate change (Kundzewicz *et al.,* 2007; Stern *et al*., 2006), but much less evidence has been gathered relating to the costs of adaptation to those impacts. This might be partly related to the lesser level of attention that adaptation received in the past in comparison to mitigation, as discussed previously.

At the same time, and in addition to uncertainties about the impacts of future climate in general, there are other compounding factors, including socio demographic, societal and economic developments that make the estimation of the costs of adaptation particularly difficult. Also, this kind of studies suffers from more general problems such as: the scale issue (the gap between the assessments of adaptation strategies at the local level and the national or even global level); rate and speed of climate change and adaptation (most of the studies use a comparative state framework for assessment and not a dynamic transient framework); discount rate, uncertainty and the problems associated with the valuation of non-market values.

In this context, how much adaptation costs is a particularly under-researched area. Estimates of the costs of adaptation are required, at the national level, for designing effective adaptation strategies, and at the international level, for identifying the financial flows needed for an effective international response to climate change see (Copenhagen Accord, 2009).

While the above is true for all sectors affected by climate change, it is of particular relevance in the case of freshwater systems, on which humans, livelihoods and species depend critically. Besides the mentioned difficulties, costs estimates for the water sector are hampered by the uncertainty regarding how changes in water availability will be allocated across various types of water users. Even more important, is the fact that water adaptation is very highly determined by the socio-economic and demographic scenarios under which it is evaluated. Water scarcity is driven both by demand-driven scarcity (water stress) and population-driven scarcity (water shortage) (Falkenmark *et al*., 2007). (Kummu *et al.,* 2010) analysed the trend in water shortage over the past 2000 years, obtaining that the effects of changes in population on water shortage over this time period are roughly four times as important as changes in water availability due to long-term climatic change. Kummu *et al*.'s study illustrates the importance of the socio-economic scenarios used and the effects that this can have in the estimation of the costs of adaptation.

Additionally, quite often the estimates of the costs of adaptation in freshwater system are difficult to differentiate from overall adaptation costs or from the costs of adaptation to other very interlinked sectors, such as health and agriculture.

Next we report on existing studies that have been carried out for the assessment of costs of adaptation regarding the water sector. The added value of this review is that it specifically focuses on the costs of adaptation to climate change, separately to the costs of the impacts. Two different approaches can be distinguished. On the one hand, there are costs estimations of specific case studies at the river basin or national level. On the other hand, there are top-down approaches in which general estimations at large spatial scales (regional or even worldwide) are produced.

3.1. Case studies

At the local, national and river basin level, the geographical distribution of research is skewed towards developed countries, although examples do exist in developing countries (Ward *et al.,* 2010b). Next we describe a number of case studies specifically looking at the costs of adaptation in freshwater systems. We do not claim this review to be fully exhaustive, but significantly comprehensive.

Table 2 presents a summary of the reviewed studies, including information on the aim of the study, the study site and the scale of analysis (e.g., national level, river basin level, etc.) and the temporal scale and costs estimates. Figures in the table are expressed in billion of US dollars, but it should be noticed that the figures correspond to different temporal frames depending on the study. Time frames are specified in the table and three types of cost types have been identified according to the time scale: i) annual costs, ii) total costs up to the specified horizon, and iii) total costs over the number of years considered in the study. Brief information on the methodological approach, when specified in the study, is also provided. The studies have been organized in developed and developing countries (and then by year of publication).

Regarding developed countries, we find several studies for The Netherlands. Kuik (2007) discusses a cost-benefit analysis of the "Room for the River Program". The project implies a major change in the Dutch approach to face river flooding: river cross sections are widened by situating the dikes further away from the river, or by lowering the river forelands (i.e. giving more space to the river). The author carries out a cost-benefit analysis of this adaptation to increased river flood risk, including, as innovative features, both economic growth and climate change induced increases in river discharge[2]. The results of the study indicated that optimal flood defence investments would reduce climate-induced flood damage from € 39.90 billion to €1.1 billion over the 21th century at a relatively modest cost of around € 5.1 billion ($ 7.2 billion) (modest in comparison to flood defence investment that were made in the 20th early 21st century)[3].

(Van Ierland *et al.,* 2006) carry out a similar study, reporting a present value of adaptation cost to the Rhine river flooding of € 1.2 billion, including maintenance, and € 0.8 billion for the river Meuse ($ 1.07 – 1.14 billion respectively). This study is discussed in the wider context of the scientific assessment and policy analysis of climate change adaptation in the Netherlands. The work is aimed at collecting existing and new information on adaptation options in that country on the basis of an existing inventory of vulnerability of human and natural systems to climate change Van Ierland *et al.,* 2001). The information from 2001 is reviewed, and to the extent of what is available, authors provide quantitative estimates of incremental costs and benefits in agriculture, ecosystems, water, transport and energy (incremental costs and benefits refer to those that are attributable to the adaptation measure only and will not occur if the adaptation measure is not implemented). Societal costs of providing more space for the lower stretches of Rhine and Meuse, which are calculated through the optimization of the net present value of flood defence, include: i) loss of strictly economically exploitable land; and ii) loss of certain valuable habitats and species confined to the less river-influenced parts of the floodplain, less space for riverine woodland or other rough vegetation types hampering the flow capacity.

Also in The Netherlands is the study by (Aerts *et al.,* 2009) on the estimation of the costs of adaptation to riverine and coastal impacts. The study, based on investments on protective infrastructures, results in costs ranging from 13 to over a hundred billion US dollars by 2100.

The Climate's Long-term impacts in Metro Boston, the CLIMB project (Kirshen *et al.,* 2008), conducted from 1994 to 2004, explored the potential changes in infrastructure systems and services in Metropolitan Boston, in response to climate change and socioeconomic and technological developments. The emphasis of the CLIMB project was on the integration of climate change and demographics on infrastructures and on examining those impacts with a common framework. The research also identified a number of possible adaptations to climate change. The only adaptation options for which the authors estimated the costs were bridge scour and water quality. The methodological approach was the standard engineering cost data.

Also in the US, we find two studies addressing adaptation in California: (Zhu *et al.,* 2007) look at urban flood control systems in the Metropolitan area of the Lower American River and Medellin-Azuara *et al.* (2007), who examine economically optimal operation changes at the state level. Both studies apply economic engineering optimization programming models, but use different time frames.

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2 The details of the application of the model are given in Dutch in Eijgenraam (2005). Insights on some of the input used for the models are in English in Eijgenraam (2006).

3 The total cost of € 5.1 billion is reduced to €1.5 billion if the costs of the catching up of the dikes to the optimal height are not considered as part of the adaptation process.

Also using economic optimization models (and 'rule of thumb') is the study by Dore and Burton (2001) who analyze adaptation cost in social infrastructures including water utilities in Canada. This study works at the level of ecoclimatic zones, providing with different estimations for different areas, ranging from $ 0.006 billion in Halifax up to $ 9.3 billion in Toronto over the next 100 years.

In the United Kingdom, the study commissioned by the Environmental Agency (IFC and International RPA, 2007) estimate the potential costs of adaptation for the water industry in England and Wales, based on the literature, on $1.78 billion per year.

Turning now to studies in developing countries, Callaway *et al*. (2006) report a study on the cost and benefits of adaptation in the water management sector in the Berg River basin, in South Africa. Adaptation measures investigated include the establishment of an efficient water market and an increase in water storage capacity through the construction of a dam. The costs of adaptation include: the cost of operating reservoirs, delivering water to municipal consumers and farms, pumping, long-term (investments) and short-term (variable) costs for the farms and capital cost of the dam. However, it is not clear how do they actually calculate these costs. Also they do not include transaction costs associated with water markets and the costs of urban water works and waste treatment costs, due to lack of data. Total costs are actually not reported in the available reference.

Kirshen *et al.* (2005) use generalized costs functions for obtaining the unit costs of water storage to estimate the costs of additional storage and groundwater development necessary to maintain water supply yields in the Huang Ho River Basin in China, reaching an estimate of $ 0.5 billion per year up to 2050.

Muller (2007) and the more recent Gosh *et al.* (2011) use very simple approach based on unit costs of existing infrastructures and programs applied to 'rule of thumb' (non-simulated) predictions of water supply needs and river flooding in India in the case of Gosh *et al.* (2011).

TABLE 2

Case studies addressing the costs of adaptation in freshwater system

Source	Aim of the study	Site/Country	Spatial Scale	Temporal Scale	Costs estimates $ billion*	Methodological approach
Developed countries						
Aerts *et al*. (2009)	Estimation of the costs of adaptation to riverine and coastal flooding	The Netherlands	Country	2100	12.75 – 113.75 (by)	Investments on protective infrastructures
Kirshen *et al*. (2008)	Exploration of potential changes in infrastructure systems and services, in response to climate change and socioeconomic and technological developments	Boston, USA	Metropolitan area	2100	6 - 94 (by)	Engineering cost data for infrastructures
Kuik (2007); Eijgenraam (2005, 2006)	Cost-Benefit Analysis of the Room for the River Program	The Netherlands	River Basin	100 years	7.26 (over)	Optimization of net present value of flood defence infrastructures
Zhu *et al*. (2007)	Assessment of long term performance of urban flood control systems	Lower American River, California, USA	Metropolitan area of floodplain	150	0.093 (over)	Economic engineering optimization. Dynamic programming model
ICF International and RPA (2007)	Assessment of potential costs of climate change adaptation for the water industry, including: water quality impacts; stormwater management and see level rise	England and Wales	National level	30-40 years range	1.78 (p.a.)	Scaling up from small published case studies in the literature
Medellin-Azuara *et al*. (2007)	Examination of economically optimal operational changes and adaptations for water supply system	California, USA	State wide	2050	0.490 (p.a.)	Economic-engineering optimization model(CALVIN, http://cee.engr.ucdavis.edu/faculty/lund/CALVIN/)
Van Ierland *et al*. (2006)	Cost-Benefit analysis of river flood protection	The Netherlands	River Basin level	2100	1.70 (river Rhine) – 1.14 (river Mause)	Optimization of net present value of flood defence infrastructures
Dore and Burton (2001)	Estimation of adaptation costs of climate change for social infrastructure (water utilities reported here)	Canada	Ecoclimatic zone	100 years	(over)	General circulation models used to predict climate change Optimization model and 'rule of thumb'
			Toronto		0.684-9.3	
			Niagara		0.008–0.025	
			Halifax		0.006	

TABLE 2 (continued)

Case studies addressing the costs of adaptation in freshwater system

Source	Aim of the study	Site/Country	Spatial Scale	Temporal Scale	Costs estimates $ billion*	Methodological approach
Developing countries						
Gosh *et al*. (2011)	Estimation of the costs of adaptation to freshwater systems (water supply and inland flooding)	India	National level	2050	0.6 (p.a.)	Water supply: predictions of water deficit (based on population growth, water demand and decreased precipitation); multiplied by unit costs of existing water supply programs. Inland flooding: increased number of people at risk multiplied by unit costs of current flooding defence programs
Muller (2007)	Estimation of the costs of adapting urban water infrastructure (Urban water storage, wastewater treatment and electricity generation)	Sub-Saharan Africa	Regional	unclear	2-5 (p.a.)	Unit cost assumptions applied to estimated supply and demand changes under climate change
Callaway *et al*. (2007)	Development of a policy-planning model to evaluate measures for coping with water shortages	Berg River Basin, South Africa	River Basin	30 years	Not reported	Dynamic Spatial Equilibrium Model (dynamic, multiregional, nonlinear programming model)
Kirshen *et al*. (2005)	Estimation of the costs of changes in water supply in China under climate change	Huang Ho River Basin (China)	Rive Basin	2050	0.5 (p.a.)	Costs of additional storage and groundwater development necessary to maintain target yields estimated using generalised cost functions relating dollars to units of storage.

*Money amounts have been converted to US dollars ($) using current currency conversion rates. Cost coding: (p.a): per annum; (over): over the specified time frame; (by) by the specified time horizon.

Source: Own.

From the above review it can be observed that the literature on the costs of adaptation to the impacts of climate change in freshwater systems is fragmented and methodological approaches differ greatly. Engineering costs approaches and economic optimization models (sometimes combined with climatic circulation models) are more frequently used. But there is a significant amount of studies based on the adjustment of literature-based and 'rule of thumb' estimates. Very simplistic approaches (based on the multiplication of unit costs of existing infrastructures to non-simulated water deficits predictions) are also used. Additionally, it is difficult some times to assess the accuracy and reliability of the estimates, since the methodological approach is not always sufficiently reported in the studies.

In general, costs are estimated using very different methodologies subject to an important set of assumptions that have important effects on the final results. This, added to the inherent uncertainty underpinning the climatic models and predictions used to estimate the climate change impacts and the specificity inherent to adaptation, makes the studies difficult to compare and difficult to replicate elsewhere.

3.2. Global estimates

Estimates of the costs of adaptation to climate change across sectors at the global scale were not available until 2006. Since them, there have been several attempts to estimate the adaptation costs at the global level. Table 3 provides with a summary of their aims, their focus and scale of analysis, costs estimates and some key elements of the approach used and the assumptions made.

The first available studies were commissioned by institutions such as the World Bank, Oxfam, UNDP, and in the Stern report. Agrawala and Frankhauser (2008) provide with an interesting discussion of several of them. It is worth noticing that they focus in developing countries and in the additional investments needed for coping with the effects of climate change. The methodological approach of the World Bank report (2006) is based on the cost of climate-proofing Foreign Direct Investment and Official Development Assistance flows. The subsequent reports heavily rely on these initial costs estimates, by just adding additional costs from different sources for example, from NGO projects in the case of the Oxfam report (2007), or poverty reduction programs, in the case of the UNDP report (2007).

TABLE 3

Global estimates of the costs of adaptation in freshwater systems

Source	Aim of the study	Focus	Spatial Scale	Temporal scale	Costs estimates US $ billion	Approach
World Bank (2006)	Review of existing financial instruments and explore the potential value of new financial instruments	Developing countries	All developing countries	2030	9-41 (p.a)	Cost of climate-proofing Foreign Direct Investment and Official Development Assistance flows
Stern *et al.* (2006)	Review of the economics of climate change	Developing countries	All developing countries	2030	4-37 (p.a.)	Based on an update of World Bank (2006) with slight modifications
Oxfam (2007)	Estimation of needs for adaptation	Developing countries	Regional and country level (some countries)	2030	>50 (p.a.)	Based on World Bank (2006), plus extrapolation of costs from National Adaptation Programmes of Action and NGO projects
UNDP (2007)	Part of Human Development Report 2007/2008	Developing countries	All developing countries	2016	86-109 (by)	Based on World Bank (2006), plus costing of Poverty Reduction Strategy targets, better disaster response
Kirshen (2007)	Analysis of existing and potential investment and financial flows international response to climate change	World	Nation	2030	11 (by)	Estimation of water supply and demand in the future, based on literature and assumptions
Ward *et al.* (2010a)	Examination of the costs of adaptation to climate change for industrial and municipal water supply and riverine protection	Developing countries	Food Production Units up-scaled to the six World Bank world regions	2050	13.3 – 16.9 net (over)	CLIRUN-II model for rainfall/runoff simulations. Fixed costs for reservoir capacity (0.30 $/m^3$) and riverine flood protection (50.000$/km^2 in urban areas and 8.000$/km^2 in agricultural land)

Source: Own.

In 2007 the United Nation Framework Convention on Climate Change (UNFCCC) produced a report based on a set of commissioned studies in the context of the Dialogue on Long-term Cooperative Action to Address Climate Change. The analysis assesses the order of magnitude of additional investment and financial flows that could be required in 2030 to adapt to the impacts of climate change in different sectors (including water) over and above the flows required to address needs related to the expected economic and population growth. In the context of this report and for the water sector, Kirshen (2007) looks at the adaptation options concerning exclusively water supply. The costs of the adaptation measures are calculated for two climate change scenarios (SRES B1 and RES A1b). The report considers increased reservoir storage and groundwater use, water reclamation, desalination and virtual water as adaptation measures. Virtual water as an adaptation mechanism refers to the minimization of the use of water in water-short areas by importing water consuming commodities (e.g., food, electric power) from areas or countries that have more water (Bouwer, 2000). Virtual water is increasingly being discussed in the context of adaptation to climate change, relating to drought and increased water-shortages in different parts of the world (some examples are Zhao, *et al.,* 2005) in China; El-Fadel and Maroun (2008) in the Middle East, Yang *et al.* (2007) in the Southern and Eastern Mediterranean countries, and Berrittella *et al.* (2007) for a worldwide general equilibrium model analysis).

The calculations by Kirshen (2007), which concern the whole world and are done at the national scale, are based on the estimation of water demand for domestic, industrial and irrigation for year 2000 and projections and adjustments from the literature for year 2050[4]. For the nations were it was estimated that there will not be sufficient excess of water, the maximum amount of reclaimed water was determined and allocated to meet, in order of priority, domestic, commercial, industrial and irrigation needs. If water was particularly scarce and the nation bordered an ocean or sea, then desalination was used to meet domestic and commercial needs. The report concludes that an additional investment in water supply infrastructure of $ 11 billion will be needed in 2030. Arnell (2009) considers this figure as an underestimate, as it does not include an allowance for costs of adapting in other aspects of water resources management, such as managing increased flood risk, maintaining water quality standards and supporting in-stream economic and environmental uses. Besides, the analysis only includes capital costs; it does not include operation and maintenance costs or wastewater management costs, indirect, transaction or opportunity costs. Also, the study is based on important assumptions and the unit of analysis is the *natio*n, which means that for large nations important regional hydrologic differences are masked. In addition, this unit assumes water can be transferred to the users across the country in a reasonable manner, also in large countries like China.

The UNFCCC estimates of adaptation cost are broadly in line with preceding studies published. As Parry *et al.* (2009) point out, since all these studies appear to support each other, the conclusion has sometimes been that there exists a comforting

[4] The report aims at estimating the financial flows needed for 2030. However, because the normal time horizon for water supply infrastructures is 50 years, the analysis was first done for 2050 and then adjusted to 2030.

convergen of evidence, but that would be misleading because they are not independent studies but borrow heavily from each other. Also they have not been tested by peer review in the scientific literature. Particularly concerning the UNFCCC report, it does not provide an estimate of the total costs of adaptation to the impacts of climate change. In any case, the estimates should be considered as conservative, because some activities that are likely need additional financial and investment flows have not been included.

The World Bank has recently released a new study on the economics of adaptation to climate change, which aim is to estimate the costs of adapting to climate change in developing countries over the period 2010-2050 (under the SRES A2 scenario) (World Bank, 2009). The overall objective of the study is to help decision makers in developing countries to better understand and assess the risks posed by climate change and to better design strategies to adapt to climate change. There is a particular section addressing the estimation of the adaptation costs in the industrial and municipal water supply sector and for riverine flood protection (Ward *et al.,* 2010a; Ward *et al*., 2010b). The annual costs of adaptation for developing countries is estimated for water supply in $ 13.3 – 16.9 (net costs); $ 20.2 – 22.8 (gross costs) billion, representing 0.03-0.04% of the world's GDP. The study shows that the burden of costs will be much higher in developing countries with large regional differences (e.g., Sub-Saharan Africa faces the highest costs).

Some of the limitations of the study, besides the inherent uncertainties related to climate change impacts and baseline socio-economics, include the fact that it only accounts for direct construction costs and operation and maintenance costs. Environmental and social costs are not estimated, demand-side adaptation is not costed (the estimations are based only on increase reservoir capacity) and impacts on water quality are not addressed, but at least it does represent and independent alternative to the ones produced on the basis of the original World Bank study in 2006.

It can be observed how the above studies in general rely heavily on the assumptions made regarding the expected water demand and other very clearly socio-demographic based assumptions. As mentioned before, and as illustrated by Kummu *et al.* (2010), the changes in population on water shortage have a greater effect that actually the changes in climate related water availability, pointing out at the crucial effects that assumptions made in this respect can have on the final estimates.

4. Research gaps

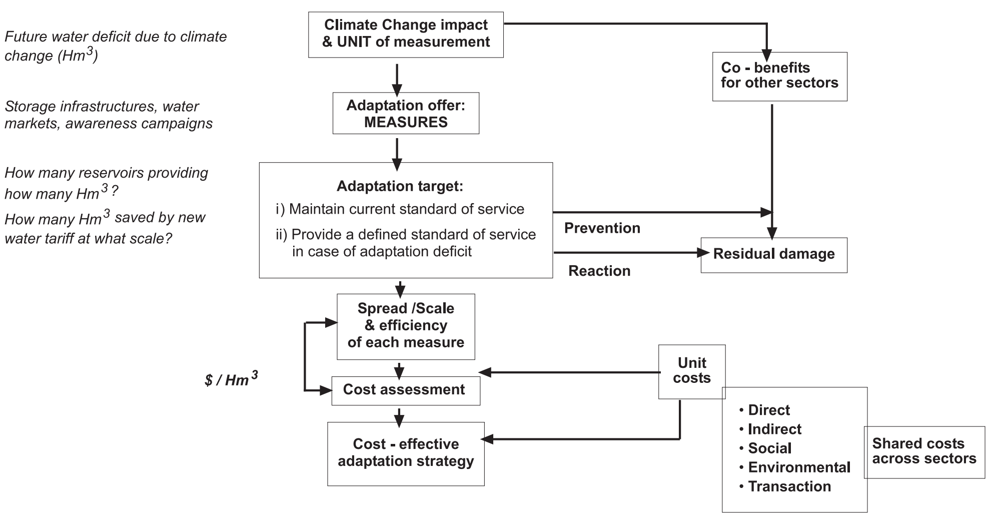
As comes out from the present review, there are currently relatively few studies on the estimation of the costs of adaptation to climate change in freshwater systems. Adaptation is very locally specific and as pointed out by Arnell (2009) in most cases there are multiple adaptation options which vary with local geographical, financial, institutional and socio-economic circumstances. Therefore, local case studies at the river basin level are difficult to replicate in other areas and extrapolation from a small number of case studies in a bottom-up approach could be very misleading.

On the other side, existing global approaches are highly interlinked, and the convergence of their results cannot be taken as a proof of their accuracy. Very important assumptions about the coverage needed from the different adaptation options are made and the current assessments generally do not respond to a cost-efficient approach but are mostly based on currently available data.

There are, therefore, a number of important research gaps that need to be addressed for a significant improvement of the estimation of the costs of adaptation to the impacts of climate change in freshwater systems. Many of those research gaps are at the methodological level, but more important is the fact that an overarching conceptual framework for the estimation is still missing. It is out of the scope of this paper to develop and test a conceptual model, but we do propose to discuss a number of key issues that we think are required as part of that conceptual model that serve here as way of pointing out key research gaps. For that purpose, elements of a conceptual framework are presented in a step-wise way in Graph 1 and discussed next.

GRAPH 1

Elements for a conceptual framework for the assessment of the costs of adaptation to climate change: the case of freshwater systems



Source: Own.

These key elements can be grouped in: i) pre-requisites for the estimation; ii) adaptation target and adaptation options and iii) the cost-effectiveness logic.

To start with, any assessment of the costs of adaptation should start by the definition of the climate change impact and the unit of measurement (eg. what is the expected future water deficit due to climate change, in Hm^3). Another pre-condition for the assessment is the identification of the 'adaptation offer', this is: which are the applicable adaptation measures?. This should be done on the basis of a previous definition of selection criteria. In many of the studies reviewed, very often only one measure was addressed or, when several were addressed, no previous definition of selecting criteria was discussed.

Other key issues relate to the definition of an adaptation target. The goals of adaptation are rarely stated explicitly (Adger *et al.,* 2009). Nevertheless, to be able to cost adaptation we need to know the spread and scale of each adaptation measure, which is determined not only by the expected impact, but also by how much adaptation are we aiming at and how efficient the measures are (eg., for costing the construction of dams, we need to know how many dams we need to build and how much water hm^3 is storaged by the dams). This leads to the need of addressing the following issues:

- The adaptation deficit: this is typically considered relevant for developing countries (Parry *et al.,* 2009). However, developed countries can also have an issue in relation to the adaptation deficit that might lead society and policymakers to consider the current standard of service as non-acceptable.
- The residual damage: if zero impact is not possible it is necessary to define how much residual damage can (wants) society assume. This will determine how much prevention and how much reaction are to be set up.

Additionally to the above, from an economic perspective, an efficient adaptation strategic should be based on the most cost-effective combination of measures to achieve a determined goal (i.e. the adaptation target). This probably implies an iterative process in which the economic analysis feeds back to the previous steps of selection of adaptation measures (e.g., reconsidering the use of supply side measures in favor of demand side measures) and the goal of adaptation (more prevention rather than reaction or vice-versa). Besides, two issues need to be addressed to complete the cost assessment:

- The inclusion of other than direct investment and operation cost. The approach used in the studies reviewed here is the direct costs of the measure (capital costs and sometimes maintenance and operation costs) and do not include indirect, environmental, transaction and opportunity costs.
- Co-benefits across sectors. The interlinkage between the water sector and other sectors, such as health and agriculture is such that the adaptation measures may overlap across them (e.g., measures for alleviating water supply deficiencies will have a direct impact on irrigation). As the adaptation benefits may spread across sectors, a discussion on how to input the costs of the measures to each of the sectors needs to be addressed, in order to avoid double counting. Moreover, certain adaptation measures will have

positive effects in several sectors at the same time. Estimates across sectors have been looked at separately (for example, this is the case of the UNFCC report, 2007), regardless of the potential effects of some of the measures in other sectors and providing added values at the global level. This is the case for instance of measures aimed at controlling water quality depletion, which will reduce the transmission of water-borne diseases as well as reducing the impacts on freshwater habitats. The costs of adaptation in the health sector could be significantly lower if measures for water quality depletion were implemented, or double counting could otherwise take place if measures were costed in the two sectors (water and health).

5. Conclusions

Freshwater systems will be significantly impacted by climate change, affecting a range of ecosystem services and human livelihood. Adaptation to these changes is going to be crucial for large parts of the world. Most of the adaptation in relation to freshwater systems is planned adaptation and includes a wide range of actions addressing securing water supply and river flooding, which also affect other sectors, like agriculture and health.

In this study, we have reviewed the existing estimates of the costs of adaptation to climate change in freshwater systems, finding not only that there is still scarce information on this respect, but also that the literature on existing case studies is fragmented, not always clear on the methodology used and is difficultly replicated elsewhere. Additionally, most global top-down existing assessments represent underestimatess and have not been tested by peer review in the economics literature.

There is still an important amount of work that needs to be done in order to overcome the current lack of reliable estimates of the adaptation costs. This needs to be done in parallel to the process of reducing the uncertainties in projections of the impacts of climate change on water resources. Many are the pending issues that still need to be addressed, but the crucial issue is the need for the development of a conceptual framework for determining how much adaptation is needed, feasible and efficient. Key elements for this conceptual framework have been discussed here and research gaps have been identified. This assessment can only be done accurately at the national or sub-national level, which requires a considerable amount of resources and time.

For informed decision-making, national governments need to know what financial resources are required for adaptation under different levels of impact reduction, which damages could be avoided through adaptation and what are the residual damages once adaptation occurs. Policy-makers require this information that should be introduced in the climate change strategy but also in the water planning process. For example, a priority in Europe should be the incorporation of the costs of adaptation to climate change in the forthcoming revision of the river basins plans under the prescriptions of the Water Framework Directive (WFD).

This information is particularly necessary in the case of developing countries to better design strategies to face climate change and estimate the additional investment and financial flows needed from the developed world regions, a major issue in the current and coming negotiations; but also to take part of the development of integrated water resources management (IWRM) programs.

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