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# Rareté de l'eau et relations interbassins en Méditerranée sous changements globaux. Développement et application d'un modèle hydroéconomique à large échelle

Noémie Neverre

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Par

**Noémie Neverre**

Rareté de l'eau et relations interbassins en Méditerranée sous changements globaux  
Développement et application d'un modèle hydroéconomique à large échelle

**Thèse présentée et soutenue à Nogent sur Marne, le 17 septembre 2015 :**

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WATER SCARCITY AND INTER-BASIN INTERACTIONS  
UNDER GLOBAL CHANGES  
A large-scale hydroeconomic model applied to the  
Mediterranean region

RARETÉ DE L'EAU ET RELATIONS INTERBASSINS EN  
MÉDITERRANÉE SOUS CHANGEMENTS GLOBAUX  
Développement et application d'un modèle  
hydroéconomique à large échelle

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# SUMMARY

Global socioeconomic and climatic changes will increase the pressure on water resources in the Mediterranean region in the next decades. This thesis contemplates the question of how heterogeneously distributed water constraints might foster inter-basin interactions. To do so, it is necessary to assess localised water scarcity in terms of both water quantities and economic values, in a framework combining a river basin level modelling with an extended geographic coverage. The methodological approach used is generic hydroeconomic modelling.

The first part of the thesis is dedicated to the projection and valuation of water demands. For the domestic sector, the approach is to build three-part inverse demand functions, calibrated at the country scale, taking into account structural change. For the agricultural sector, the economic benefits of irrigation water are calculated based on a yield comparison approach between rainfed and irrigated crops.

The second part concentrates on the supply-side of the hydroeconomic model. Operating rules of the reservoirs and water allocation between demands are determined based on the maximisation of water benefits over time and space. A parameterisation-simulation-optimisation approach is used, with hedging parameters and branch allocation parameters optimisation. The model is applied to Algeria, at the 2050 horizon.

The last part explores how this hydroeconomic model could be used to investigate inter-basin issues. In a context of heterogeneous water availability between basins, water dependent activities could relocate from water scarce areas to less constrained locations. The last chapter of the thesis suggests looking at the impacts of water scarcity on economic activities location and population migration in an economic geography framework.



# RÉSUMÉ

Les changements globaux, socio-économiques et climatiques, vont très probablement accroître les tensions sur les ressources en eau dans la région méditerranéenne dans les prochaines décennies. Dans un contexte de contraintes en eau inégalement distribuées géographiquement, des interactions entre bassins pourraient se développer. Par exemple, les activités dépendantes de l'eau pourraient quitter les zones où l'eau est rare pour rejoindre des endroits où elle est plus abondante. Pour étudier cette question, il est intéressant d'évaluer les contraintes en eau localisées, en termes de quantité d'eau et de valeur économique, en combinant une modélisation à l'échelle du bassin à une couverture géographique étendue. Cette thèse mobilise comme cadre méthodologique celui de la modélisation hydroéconomique générique.

La première partie de la thèse est consacrée à la projection et à la valorisation des demandes en eau. Pour le secteur domestique, des fonctions de demande inverse en trois parties sont construites, en tenant compte des changements structurels, et sont calibrées à l'échelle des pays. Pour le secteur agricole, le calcul de la valeur économique de l'eau d'irrigation repose sur une méthode de comparaison de rendements entre les cultures pluviales et irriguées.

La deuxième partie se concentre sur l'aspect approvisionnement en eau du modèle hydroéconomique. Pour modéliser la gestion des réservoirs, une approche économique est utilisée, fondée sur la maximisation inter-usages et inter-temporelle des bénéfices liés à l'eau. Afin de déterminer les règles d'allocation, une approche "paramétrage-simulation-optimisation" est utilisée, avec des paramètres prudentiels et des paramètres de répartition entre les branches. Le modèle est appliqué à l'Algérie, à l'horizon 2050.

La dernière partie de la thèse suggère de s'intéresser aux impacts du manque d'eau sur la localisation des activités économiques et les migrations de population qui s'ensuivent, en se plaçant dans le cadre théorique de l'économie géographique et en utilisant le modèle hydroéconomique développé dans la thèse.





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# INTRODUCTION

Global changes are expected to challenge the sustainability of water resources. Impacts of climate change on the hydrological cycle will add to non-climatic drivers of change such as demographic growth, economic development, land use changes, urbanisation etc. [Cisneros et al., 2014].

The issue is particularly acute in the Mediterranean region. On the one hand there is strong consistency in projections of reduced freshwater availability in the Mediterranean region due to reduced rainfall and increased evaporation, and droughts are projected to become longer and more frequent [Cisneros et al., 2014]. On the other hand, demand is expected to increase with economic development and demographic growth (Figures 1 and 2), especially in countries of the southern and eastern Mediterranean rims (map in Figure 3).

The Mediterranean is already a vulnerable area. More than half of the world's "water-poor" population is located in the region, which concentrates 7.3% of the world's population for only 3% of its water resources [Margat and Treyer, 2004].

Across the Mediterranean basin water supply and demand are characterised by an important spatial and temporal heterogeneity, related to the socioeconomic and hydroclimatic conditions. Demand is often higher in the summer months, when supply is lower. Potential total usable water resources vary from 113 m<sup>3</sup>/capita/year in Libya to almost 7000 m<sup>3</sup>/capita/year in Greece. The sustainability of water resources is variable, with some resources being non-renewable. Total water use can represent less than 20% of the available renewable resources (e.g. Greece, France, Turkey) but it reaches 954% of renewable resources in Libya [Iglesias et al., 2007]. Water demand is also very variable. Among countries with the lowest use, some are constrained by the lack of supply (e.g. less than 250 m<sup>3</sup>/capita/year in Malta or Algeria), while others use little water because they have little irrigated agriculture (e.g. Croatia). In southern countries where irrigation is important (e.g. Egypt, Libya, Syria, Spain), water use per capita is the highest (over 1000 m<sup>3</sup>/capita/year in Egypt). At the basin level, situations can be even more contrasted [Margat and Treyer, 2004]. These heterogeneities could be accentuated or modified in the future through global changes.

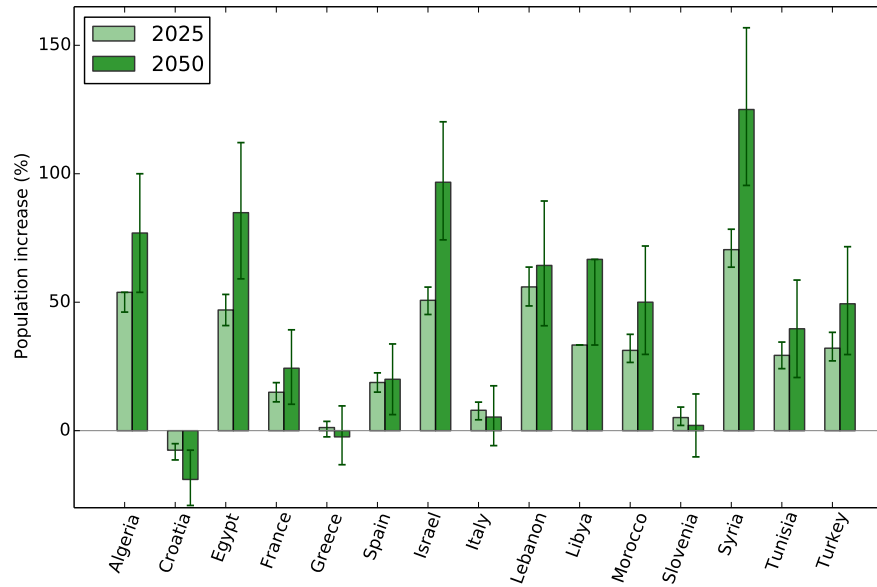


Figure 1: Population increase between 2000 and 2025/2050 in the main Mediterranean countries, according to UN projections [UN, 2009]. Bars represent the “Medium variant”, and error bars represent the “Low variant” and “High variant”.

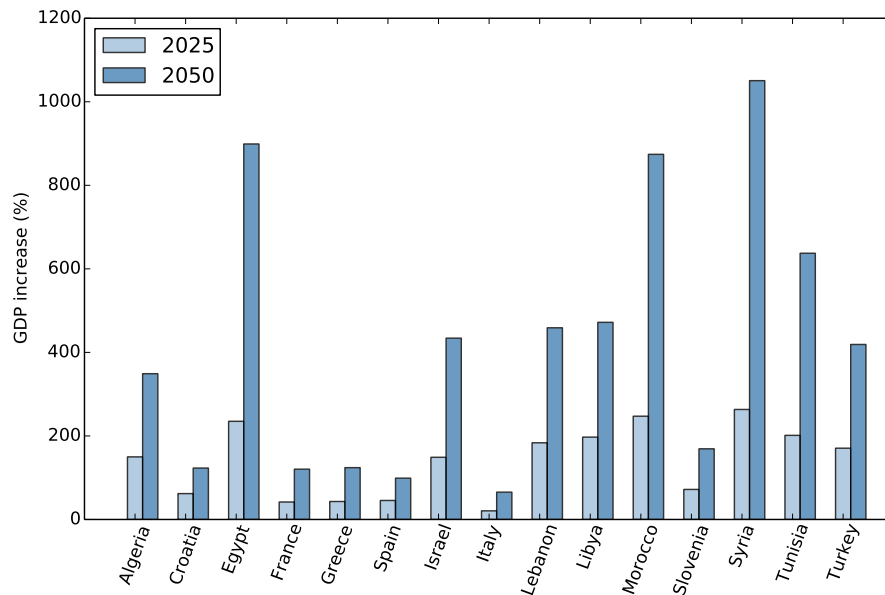


Figure 2: Gross Domestic Product increase between 2000 and 2025/2050 in the main Mediterranean countries, according to OECD projections under the Shared Socioeconomic Pathway No.2 (Source: SSP database).



Figure 3: Countries of the Mediterranean basin

Water is an important factor of production for several sectors, agriculture in particular, and it is essential for human consumption. Spatially contrasted situations, with some basins more affected by water scarcity than others, could foster water related interactions between basins such as water transfers, virtual water trade, activity relocation, or migration. When facing water scarcity, people or activities could choose to relocate to a region where water is available. Changes in water availability could generate decreases in agricultural productivity, which could in turn exacerbate urban migration [Hallegatte et al., 2008].

Such inter-basin interactions could particularly arise in the Mediterranean. The region already engages in virtual water trade, the biggest net importer countries being Italy, Egypt, Spain and Algeria, mostly through crops trade. On the opposite, France is the biggest net exporter, through crops and livestock production exports [Margat and Treyer, 2004]. The region also has a history of migrations between rims [de Haas, 2011].

These multi-basins issues are not often taken into account in policy making. Water scarcity is mostly contemplated from the basin scale, which is the usual water management level, with the perspective of reducing the demand-supply gap. The traditional response to tensions on water resources in the Mediterranean region has been to increase supply, by mobilising new resources (dams, groundwater, and more recently desalination) to meet the populations' growing needs. As water resources become increasingly scarce, demand management policies are developed to limit losses and wastage in the use of the resource (through hydroeconomic equipment for instance).



However, it would also be pertinent to consider the issue from a broader perspective, in which the mobility of demand (population or water-using activities) and supply (through transfers or virtual water) and the interrelations between basins are possible. This perspective is not common in the literature.

To anticipate these potential inter-basin interactions, it is necessary to anticipate localised water scarcity issues. Assessing the quantities of water involved and the associated economic costs for human activities is a prerequisite for understanding how inter-basin interactions may be fostered.

This thesis contemplates the question of how heterogeneously distributed water constraints might foster inter-basin interactions in the Mediterranean region in the next decades, in particular in terms of economic activities and population mobility. For this, a proper representation of localised water constraints is needed.

The first objective of this thesis is thus to build a framework that can anticipate these localised water constraints.

This framework should project and compare future water supply and demand in each basin. Because of the nature of water's specificities, this is a complex task. Surface water resources are mobile, and water availability downstream depends on upstream withdrawals. Some water uses are non-consumptive and generate return flows, while others consume all the water withdrawn. Demand and supply are variable in time and space, and they depend on various variables: climate, physical geography, socioeconomic conditions, etc. Water can be stored in reservoirs, which have an important impact on water fluxes [Biemans et al., 2011, Haddeland et al., 2013]. The Mediterranean region in particular is well equipped with dams. Water management infrastructures were developed to regulate the variable flows, and distribute water to the demands when needed. At the beginning of the 21<sup>st</sup> century, 1200 large dams (reservoirs of more than 10 million cubic meters) were in operation in Mediterranean countries, with 500 in the Mediterranean basin itself [Margat and Treyer, 2004].

The developed framework needs to adequately represent water management infrastructures, and how they allocate the available water between the different uses in time and space. Water management policies are increasingly encouraged to consider water as an economic good [ICWE, 1992]. Water basin management requires being able to measure the economic benefits associated with water uses, and the changes in benefits associated with a change in water allocation or availability. In hydroeconomic models, water is allocated based on the economic benefits it generates. Hydroeconomic models address allocation between competing uses as well as inter-temporal allocation. The economically optimal allocation is the one that maximises

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the aggregated economic value of the water used [Harou et al., 2009]. Knowing the economic benefits associated with water use also makes it possible to estimate the potential direct economic losses associated with water shortage. Although economic rules are not often used in practice, water valuation could be used as a proxy for allocation policies in the absence of precise information on the priorities set between the different demands in the different basins. A hydroeconomic model could give localised water constraints in terms of quantities and in terms of direct costs for human activities.

The main challenge is that the framework must maintain a double focus: a large-scale coverage, and a representation of spatial heterogeneity at the river basin level. Indeed, on the one hand a large-scale coverage allows for the representation of interactions between basins with heterogeneous profiles; it also enables to address global changes and their impacts on water resources. On the other hand, water resources are managed at the river basin scale, and, depending on the river basin's characteristics, the local impacts of global changes might be different.

The extended geographic coverage will make it more complex to gather data to represent basin-scale characteristics: sectorial demands, water infrastructure, etc. It will also make it difficult to take into account water value. Because markets are absent or inefficient for the water sector, it is not possible to directly observe the economic value of water. It is necessary to develop alternative non-market valuation techniques to reveal and estimate water's value [Young, 2005]. These methods are data intensive, and difficult to implement on a large scale.

The approach developed in this thesis is generic hydroeconomic modelling: it aims at representing basin-scale heterogeneities as precisely as possible, while using only globally-available data, and keeping the model simple in order to limit computation time. It builds on the ODDYCCEIA framework [Nassopoulos, 2012], which was developed to study imbalances between water supply and irrigation water demand under climate change in the Mediterranean region.

The second objective of the thesis is to examine how the representation of localised water constraints could then be used to investigate their indirect impacts on economic activities and populations. While an overall reduction in water availability would constrain all activities, contrasted situations between basins raise the more subtle question of interactions between basins, in particular changes in activities and population locations. Localised constraints on the resource could unsettle the organisation of human activities.

To study this question, a framework representing the interactions between water constraints and the organisation of the economy is needed. For instance, New Economic Geography studies the spatial organisation of the economy and represents why activities and people locate in one area or an-

other, depending on economic factors. It explicitly incorporates production factors location and mobility into a general equilibrium approach. Water could be included in this type of context, as a factor of production for water-dependent sectors and as a consumption good for populations. Constraints on the water factor availability could be provided by the generic hydroeconomic modelling framework. They would impact the economic activities and modify localisation choices. Relocations would in turn impact localised water demands and values, modifying localised water constraints.

The thesis first focuses on assessing localised water scarcity constraints and their direct economic costs, through the development of a large-scale hydroeconomic model. A first part is dedicated to the development of the demand side of the model. Chapter 1 focuses on projecting domestic demands and values, at country scale. Chapter 2 projects both domestic and irrigation potential demands and benefits; these projections are located in the different basins, and associated with reservoirs. A second part concentrates on the supply side of the model: Chapter 3 presents the reconstruction of reservoirs-demands networks, and the operation of water management infrastructures.

The last part of the thesis contemplates using this large-scale hydroeconomic model to explore the indirect impacts of localised water constraints on economic activities location and population migration. Chapter 4 reviews literature on climate change induced migration, and Chapter 5 proposes to investigate climate change induced migration through the lens of water availability constraints, based on a New Economic Geography formalism.

Appendix A proposes an overview of concepts and methods for water valuation, useful for readers who are not familiar with economic concepts.

## Part I

# DEMAND SIDE: PROJECTING LOCALISED WATER DEMANDS AND VALUES



## Chapter 1

# Projecting and valuing domestic water use at regional scale: a generic method applied to the Mediterranean at the 2060 horizon

This chapter focuses on the demand-side of the water scarcity assessment, in particular on the domestic sector. It projects domestic demands and values at country scale. These demands will then be distributed between basins (Chapter 2).

The chapter reproduces the contents of the following article: “Neverre, N. and P. Dumas (in press) Projecting and valuing domestic water use at regional scale: a generic method applied to the Mediterranean at the 2060 horizon. *Water Resources and Economics*.”

### Abstract

The present work focuses on the demand side of future water scarcity assessment, and more precisely on domestic water demand. It proposes a quantitative projection of domestic water demand, combined with an original estimation of the economic benefit of water at large scale. The general method consists of building economic demand functions taking into account the impact of the level of equipment, proxied by economic development. The cost and price of water are assumed to grow with economic development.

The methodology was applied to the Mediterranean region, at the 2060 horizon. Our results show the evolution of water demand and value, measured by surplus, over time. As long as GDP per capita and water price remain low, demand per capita increases along with economic development, and surplus per capita increases with demand. As demand approaches saturation, the combined negative effects

of water cost and price increase on surplus grow stronger, and surplus per capita begins to decrease.

The developed methodology is meant to be used for large-scale hydroeconomic modelling, in particular for regions with heterogeneous levels of development and low data-availability.

*Keywords* Domestic water demand, Water value, Projection, Hydroeconomic modelling, Mediterranean

## 1.1 Introduction

Pressure on water resources is a major issue in the Mediterranean region. More than half of the world's "water-poor" population is located in the region, which concentrates 7.3% of the world's population for only 3% of its water resources [Margat and Treyer, 2004]. Global changes are expected to exacerbate this pressure on resources in the following decades: on the one hand water demand will increase with demographic growth and economic development, while on the other hand climate change is predicted to reduce water availability and intensify droughts around the Mediterranean [Barros et al., 2014].

Spatially contrasted situations, with some basins more affected by water scarcity than others, could foster water related interactions between basins such as water transfers, activity relocations and, indirectly, migrations. Such interactions could particularly arise in the case of the Mediterranean, which has a history of exchanges and migrations between rims [de Haas, 2011].

In such a context, it is important to anticipate future water scarcity issues and identify basins at risk, in order to inform management strategies and policies. Traditionally, water management policies focused on adapting supply to demand, by mobilizing new water resources. But as resources become increasingly scarce and costly, policy makers have developed demand side management aiming at reducing water wastage.

In the present work we concentrate on the demand side of the water scarcity issue, and more precisely on domestic water demand. Irrigation is the largest water use sector in the Mediterranean, representing 63% of total water use [Margat and Treyer, 2004], and its projection is a research field of interest [Döll and Siebert, 2002]. However, its share in total water use is decreasing [Margat and Treyer, 2004]. Moreover, domestic demand, while accounting for a lower share of demand, is critical in terms of needs. Indeed, irrigation needs can be adjusted to some extent by virtual water trade, water scarce areas having the possibility of importing food rather than producing it themselves [Allan, 1997]. Domestic needs cannot be adjusted in that way. In addition, domestic uses such as consumption, food preparation and hygiene are essential to human life.

Some projections of domestic water use in Mediterranean countries exist, but they are not homogeneous between countries in terms of time horizons,

methods and scenarios. In most cases they rely on simple trend prolongations [Margat and Treyer, 2004]. When looking at the whole region, a global projection methodology applicable to the different countries, taking into account sociodemographic changes to come and simulating comparable scenarios across countries, is pertinent.

Generic global scale modelling of domestic water use is covered extensively in the literature [Alcamo et al., 2003b, Alcamo et al., 2007, Shen et al., 2008, Hanasaki et al., 2013a, Ward et al., 2010]. The general principle is to model and project a unitary water use intensity per capita, that is to be multiplied by the projected number of inhabitants. In the WaterGAP methodology [Alcamo et al., 2003a], the per capita water use intensity is modelled to evolve with the level of economic development (relationship statistically estimated at country scale) and decrease over time with technological improvement (represented by a fixed rate of improvement). In the Total Runoff Integrating Pathways (TRIP) model, future levels of domestic water use per capita in developing countries have been modelled either to converge towards that of present developed countries as economic growth continues [Shen et al., 2008, Hayashi et al., 2013], or independent of economic growth [Hanasaki et al., 2013a]. Other authors consider the impact of additional factors: Hughes et al. [Hughes et al., 2010] statistically estimate municipal water use per capita as a function of climatic variables and GDP per capita; Ward et al. [Ward et al., 2010] estimate municipal water demand as a function of GDP per capita and urbanisation rate, taking into account regional dummies and country characteristics as fixed effects.

While evaluating water quantities at stake is essential, it is also relevant to have an idea of the economic benefits associated with water uses and the potential economic losses associated with water shortage. Economic valuation can be an indication on how to manage at best the available resource and allocate it between competitive uses when water is scarce. In hydroeconomic models, instead of considering water demands as fixed requirements, water is allocated to its different uses based on the economic benefits it generates: the economically optimal allocation is the one that maximises the aggregated economic value of the water used [Harou et al., 2009].

However, economic valuation of domestic water, as well as methods to project changes in water value, is absent from the large-scale literature. Because markets are absent or inefficient for the water sector, it is not possible to observe directly the economic value of water. It is necessary to develop alternative non-market valuation techniques to reveal and estimate water's value [Young, 2005]. For the domestic sector, water is valued using willingness to pay and deriving economic surplus from econometric estimations of price-elasticity and demand functions [Young, 2005]. Such a method requires much data, which could be among the reasons explaining why hydroeconomic models have been developed mainly at an infra-national geographical scale [Harou et al., 2009].



To account for changes in both demands and economic benefits, in a region with heterogeneous data-availability, we develop an original generic method. We build an economic demand function, analogous to the demand function modelling approach used in hydroeconomic models of smaller scale [Medellín-Azuara et al., 2008], which enables water valuation. In order to take into account the link between water use and economic development, a methodology similar to WaterGap [Alcamo et al., 2003a] is used.

This paper first describes the methodology developed to build generic demand functions that project both quantities and economic values of future domestic water demands at large scale and at a time horizon enabling to picture global changes (cf. diagram in 1.A). Then it proposes an application to countries of the Mediterranean rim, from Western and Eastern Europe, Middle East and North Africa (cf. map of Mediterranean countries in 1.B).

## 1.2 Building generic demand functions taking into account structural change

### 1.2.1 Overview

Our approach is to build simple three-part inverse demand functions (Figure 1.1), in which the willingness to pay for water decreases with quantity [Harou et al., 2009]. Each part of the demand function corresponds to a different category of use. The first category corresponds to basic water requirements for consumption, food and hygiene, which are very highly valued (e.g. hand washing). The second category corresponds to intermediate needs, including additional hygiene (regular laundry, showers, etc.), less valued than uses of the first category. The last category corresponds to least-valued supplementary consumption, such as further indoor uses (e.g. leisure bath) or outdoor uses (lawn watering, pool, fountain, etc.).

To build a demand function for each country, we determine the bounds of the demand blocks corresponding to these three categories: their respective volume limits (noted  $Q$ ) and the marginal willingness to pay (noted  $V$ ) for those volumes.

Hence, the first step of the methodology is to determine the volume limits of the demand blocks, taking into account that demand will be impacted by economic development processes. The second step is to determine the willingness to pay for water at those volumes of reference, in order to value water. This second step also makes it possible to take into account the possible impact of water price on demand.

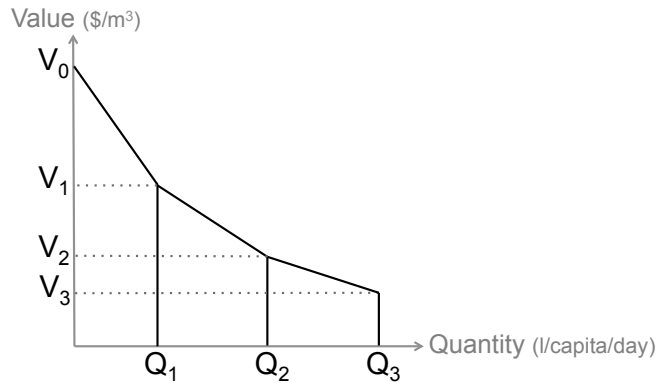


Figure 1.1: General structure of the three-part inverse demand function (with volumes  $Q$  and willingness to pay  $V$ )

### 1.2.2 Volumes of the demand blocks: taking into account structural change

Following Alcamo et al. [Alcamo et al., 2003a] and their “structural change” modelling, we want to take into account that average domestic water demand per capita grows along with economic development, proxied by GDP per capita, in order to take into account equipment effects. Indeed, as their income increases households get more water-using appliances (washing machines, dishwasher, etc.) and use more water; eventually they reach equipment saturation and water use stabilises whilst income continues to grow. To take into account structural change, we consider that the volumes of the blocks of our demand function evolve over time following economic development.

We assume that only non-essential uses are sensitive to this equipment effect, so we consider that the volume of the first block of our demand function is fixed. Following Gleick [Gleick, 1996] and Howard and Bartram [Howard and Bartram, 2003] (Table 1.1), we set the volume limit of the first demand block to 50 l/c/d, which meets needs for consumption, food and personal hygiene.

The volumes of the second and third demand blocks are assumed to evolve with the level of GDP per capita, with a saturation, drawing a sigmoid curve (Figure 1.2). When GDP per capita is low, water demand is composed of only basic uses and intermediate uses (categories 1 and 2); intermediate uses grow with economic development. Then, as GDP per capita further increases, third category uses appear and the third demand block grows along with the intermediate demand block. Eventually, demand reaches saturation and stabilises.

To determine the total demand ( $Q_{tot}$ ) structural change curve, we use

Table 1.1: Domestic water supply levels of reference, in litres per capita per day (l/c/d). The figures 50 l/c/d and 100 l/c/d are used in the demand function.

Water supply (l/c/d)	Description	Author
100	Fair level of domestic supply	Falkenmark and Lindh (1993)
50	Recommended basic water requirements Drinking water : 5 l/c/d Sanitation services : 20 l/c/d Bathing : 15 l/c/d Cooking and kitchen : 10 l/c/d	Gleick (1996)
20	Basic access - high level of health concern Consumption : should be assured Hygiene : hand-washing and basic food hygiene possible; laundry and bathing difficult to assure	Howard and Bartram (2003)
50	Intermediate access - low level of health concern Consumption : assured Hygiene : all basic personal and food hygiene assured; laundry and bathing should also be assured	
100	Optimal access - very low level of health concern Consumption : all needs met Hygiene : all needs should be met	

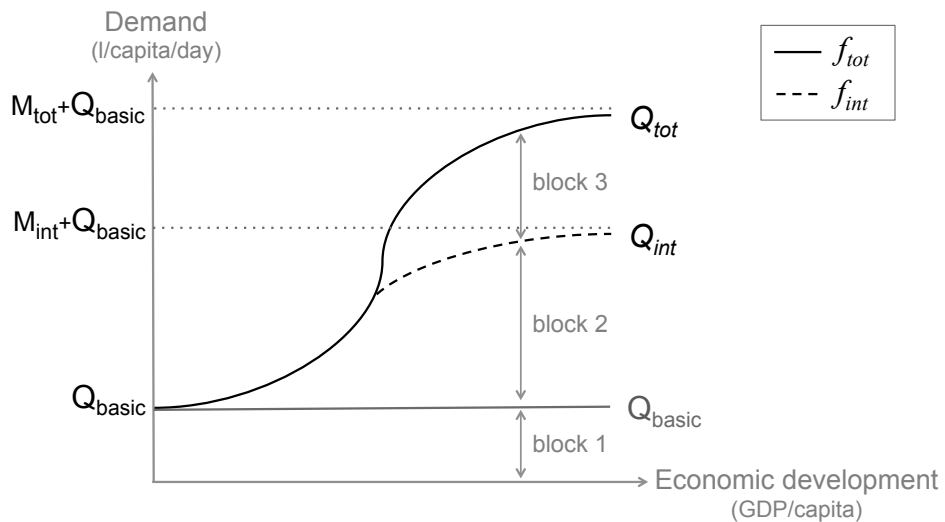


Figure 1.2: Evolution of domestic water demand with economic development: "structural change" modelling (with volumes  $Q_{basic}$ ,  $Q_{int}$  and  $Q_{tot}$ )

the sigmoid function  $f_{tot}$ :

$$Q_{tot} = f_{tot}(GDP) = m_{tot} + M_{tot} \cdot [1 - \exp(-\gamma_{tot} \cdot GDP^2)]$$

The function  $f_{tot}$  is defined by three parameters: the minimum demand ( $m_{tot}$ ), the maximum additional demand ( $M_{tot}$ ) and the curve parameter ( $\gamma_{tot}$ );  $GDP$  stands for average GDP per capita. Parameter  $m_{tot}$  is set to match basic needs:  $m_{tot} = Q_{basic} = 50$  l/c/d. The two remaining parameters of  $f_{tot}$  are to be statistically estimated at country scale using GDP, population and domestic water demand data (Section 1.3.1).

Then, to distinguish between second-block and third-block volumes, we introduce the following sigmoid curve  $f_{int}$ :

$$f_{int}(GDP) = m_{int} + M_{int} \cdot [1 - \exp(-\gamma_{int} \cdot GDP^2)]$$

This curve  $f_{int}$  is defined only starting from its intersection with  $f_{tot}$ , noted  $(GDP^*, Q^*)$ . Before this wealth level  $GDP^*$ , demand of the third category is null; after, intermediate demand is:  $Q_{int} = f_{int}(GDP)$ , and demand of the third category is:  $Q_{tot} - Q_{int}$  (Figure 1.2).

Parameters of  $f_{int}$  are completely determined without need for a statistical estimation. First, we set:  $m_{int} = Q_{basic} = 50$  l/c/d. Then  $M_{int}$  is set so as to match the reference figures of a "fair level of domestic supply" from the literature [Falkenmark and Lindh, 1993, Howard and Bartram, 2003]:  $M_{int} + m_{int} = 100$  l/c/d (Table 1.1). Finally, we constrain  $f_{int}$  by setting its inflection point so as to belong to the curve  $f_{tot}$ , which determines  $\gamma_{int}$ .

Once structural change curves parameters are calibrated for a chosen country, the volumes of the blocks of its demand function can be determined for a given year depending on the level of GDP per capita (Figure 1.2).

### 1.2.3 Willingness to pay for water along the demand function

Once the volumes of water demand are determined, we estimate the willingness to pay (WTP) for water along the demand function. The following section describes how we determine the WTP at the lower and upper bound volumes of each category (i.e. 1<sup>st</sup>, 50<sup>th</sup> and 100<sup>th</sup> l/c/d, and maximum potential demand), then interpolate linearly.

We collected econometric studies, located in the Mediterranean region or in Europe, that estimate the response of domestic water demand to price. Studies that provided both estimated price elasticities and observed levels of price and demand were used to calculate the marginal willingness to pay for water along the demand curve for each study, following the point-expansion method [Harou et al., 2009]. Demand values were adjusted for some studies [Arbués and Villanúa, 2006, Frondel and Messner, 2008, García-valiñas, 2005, Martínez-Espiñeira, 2002, Martínez-Espiñeira, 2003, Martins and Fortunato,

2005] to include collective uses, based on the assumption that collective uses represent 25% of total municipal uses, the remainder corresponding to residential uses. For one of the studies [Nauges and Thomas, 2000] the number of persons per household was assumed to be 2.57, which was the average 1990 household size in France at the time of the study (data from the French National Institute of Statistics and Economic Studies).

Some studies [Arbués and Villanúa, 2006, Martínez-Espiñeira, 2002, Martínez-Espiñeira, 2003, Martins and Fortunato, 2005] displayed very low prices (0.49-0.86  $\$/_{2005}/\text{m}^3$ ), associated with very low demands (104-157 l/c/d). One study [García-valiñas, 2005] on the contrary displayed a very high demand (369 l/c/d) for a higher price (1.64  $\$/_{2005}/\text{m}^3$ ). Some studies performed the econometric estimation with a linear structural form [García-valiñas, 2005, Martínez-Espiñeira, 2002, Martínez-Espiñeira, 2003, Martins and Fortunato, 2005], others with a log-log structural form (i.e. constant price-elasticity) [Arbués and Villanúa, 2006, Frondel and Messner, 2008, Nauges and Thomas, 2000, Schleich and Hillenbrand, 2009]. The linear studies led to low slopes, with a very low WTP for water for the first litre consumed (1.59-4.98  $\$/\text{m}^3$ ), and WTP in the [0.57  $\$/\text{m}^3$ ; 4.09  $\$/\text{m}^3$ ] range for the 100<sup>th</sup> l/c/d [García-valiñas, 2005, Martínez-Espiñeira, 2002, Martínez-Espiñeira, 2003, Martins and Fortunato, 2005].

For low demand levels, the linear structural forms are likely to underestimate water values since estimates are much lower than prices actually paid for (e.g. bottled water, which can reach 300  $\$/\text{m}^3$  or higher). Moreover, such low values do not agree with the notion that water is essential [Arbués et al., 2003]. Values given by log-log structural forms are higher, but the econometric estimations were performed in conditions where observed demands were higher than 100 l/c/d. For low demand levels, i.e. the 1<sup>st</sup> and 50<sup>th</sup> l/c/d, which are far from the observations range of the estimations, we chose not to rely on econometric estimates of WTP for water and made simple assumptions (Table 1.3).

For the 100<sup>th</sup> l/c/d, values given by the linear form are much lower than values obtained with log-log structural form. Even though there is no strong evidence that the values given by the linear form are incorrect, we assumed that values were too low at this demand level. Therefore, we chose to rely only on the marginal WTP for water calculated from studies using a log-log structural form. Three studies remained, after we chose not to use the results derived from Arbués and Villanúa [Arbués and Villanúa, 2006], for which a high observed demand combined with a low price-elasticity implies a steeper slope and much higher values than the other studies (Figure 1.3 and Table 1.2). Demand consists of total domestic demand (i.e. residential uses and collective uses).

The marginal WTP for the 100<sup>th</sup> l/c/d ranges from 10.46 to 17.64  $\$/\text{m}^3$ , with a 25% variation range around the average of 14. We assume that the WTP for the 100<sup>th</sup> l/c/d is 14  $\$/\text{m}^3$ . Because the error range of this

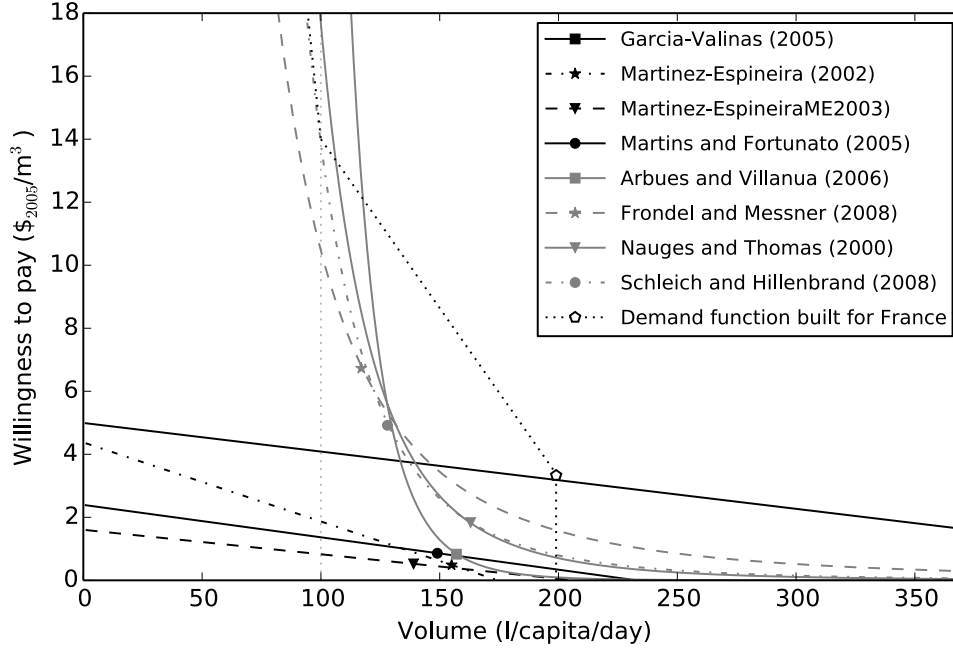


Figure 1.3: Marginal willingness to pay along the demand curve, calculated from the results of various econometric studies. In grey: econometric estimations using a log-log structural form, in black: linear structural form. Markers indicate the average observed levels of demand and price for each study. The dotted curve represents the demand function built for France, the pentagonal marker indicates the point of maximum potential demand calibrated for France and current water price in France.

parameter is high, it is included in the sensitivity analysis performed in Section 1.4.

For the upper bound of the third block, we use available data on current water price. Combining observed quantity and observed price could give us a point of the demand curve. However, if equipment limits demand, there is some rationing and the point of observed demand does not correspond to the consumption level where willingness to pay equals price and consumer's marginal surplus becomes null. To estimate this level of demand, unconstrained by equipment, we use the maximum potential demand  $Q_{basic} + M_{tot}$ , i.e. the plateau of the structural change function  $f_{tot}$ . Hence we use  $Q_{basic} + M_{tot}$  and  $P_{t=0}$  as a reference point of the demand curve, where  $P_{t=0}$  is the current water price, determined by the authors from available data (Table 1.5 and Section 1.3.2). This point constitutes the upper bound of the third category demand block (Table 1.3). Then, for a given year, the third block actually ends when reaching  $Q_{tot}$ , i.e. the actual total

Table 1.2: Marginal willingness to pay (WTP) for the 100<sup>th</sup> litre per capita per day (1/c/d), calculated from the results of four econometric studies

Reference	Location	Observed demand (1/c/d)	Observed price (US\$ <sub>2005</sub> /m <sup>3</sup> )	Estimated price-elasticity	Marginal WTP for 100 <sup>th</sup> 1/c/d (US\$ <sub>2005</sub> /m <sup>3</sup> )
Nauges and Thomas (2000)	France	163	1.83	-0.215	17.64
Arbués and Villanúa (2006)	Spain	157	0.83	-0.108	54.25
Frondel and Messner (2008)	Germany	117	6.73	-0.365	10.46
Schleich and Hillenbrand (2009)	Germany	128	4.92	-0.242	13.85

Table 1.3: Marginal willingness to pay (WTP) at the bounds of the blocks of the three-parts demand function, with LB: lower bound, UB: upper bound.

Point of reference	Volume 1/capita/day	Marginal WTP US\$ <sub>2005</sub> /m <sup>3</sup>	Justification
LB block 1	1 <sup>st</sup>	300	Average price of bottled water
UB block 1: $Q_{basic}$	50 <sup>th</sup>	50	Assumption
UB block 2: $Q_{basic} + M_{int}$	100 <sup>th</sup>	14	Adapted from literature (Section 1.2.3)
UB block 3: $Q_{basic} + M_{tot}$	country specific	$P_{t=0}$	Point of maximum potential demand if equipment was not limiting

demand for the level of GDP per capita of the considered year, as demand is constrained by revenue and domestic equipment (Figure 1.4).

Table 1.3 summarises the figures used to define the WTP for water at the bounds of the blocks of our three-part inverse demand function. Once the WTP for water at the volume points of reference of the three categories of demand has been determined, a linear interpolation is used to build the demand function. The linear form is chosen for its simplicity, in absence of data justifying another shape.

In this way, we build a domestic demand function for each country, whose parameters take into account the impact of economic development on demand. The structure of that final demand function is pictured in Figure 1.4, where  $Q_{int}$  and  $Q_{tot}$  are being redetermined for each year following projected GDP per capita. The total economic value of the water used can be derived from this demand function, depending on the cost of water, the price of water and the level of satisfaction of the demand: it consists of consumers' surplus plus the water utility's revenue (1.C). Water utility's revenue can be

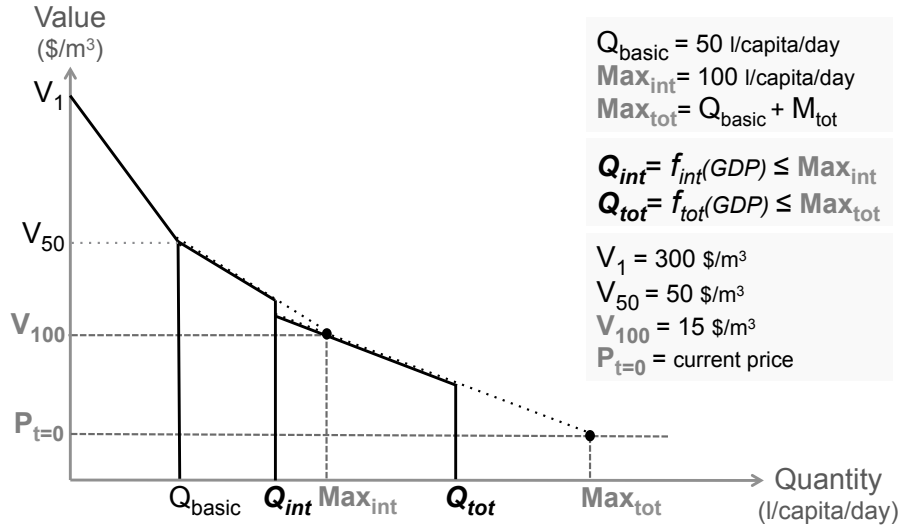


Figure 1.4: Structure of the final three-parts inverse demand function and its points of reference (volumes  $Q$  and values  $V$ ).  $Q_{basic}$  is set to 50 l/capita/day, whereas  $Q_{int}$  and  $Q_{tot}$  depend on the level of GDP per capita on the considered year.  $Q_{int}$  and  $Q_{tot}$  grow with GDP per capita with a saturation, their maximum value are respectively  $Max_{int}$  and  $Max_{tot}$ .  $Max_{int}$  is set to 100 l/capita/day, whereas  $Max_{tot}$  is calibrated at country scale.

negative if price is lower than cost.

A sensitivity analysis is later carried out to assess the impact of the different assumptions (Section 1.4).

### 1.3 Application to the Mediterranean region

The first step is to calibrate structural change curves for each country. Then, for a given year  $t$  and level of GDP per capita  $GDP_t$ , potential intermediate and total demands can be determined and used to define the volumes of the blocks of the three-part demand function for year  $t$  (Figure 1.4). Finally, actual demand for year  $t$  can be determined depending on the price of water  $P_t$ .

#### 1.3.1 Calibration of structural change curves for the Mediterranean countries

Structural change curves parameters ( $M$  and  $\gamma$ , Cf. Section 1.2.2) were calibrated for countries of the Mediterranean rim based on data available at a regional scale. Historical water demands were determined using water withdrawal data at country level from the Mediterranean Information System on



Environment and Development database (SIMEDD [Plan Bleu, 2012]) and water withdrawal to water demand ratios (i.e. water networks' efficiency) from Margat and Treyer [Margat and Treyer, 2004]. Population data were taken from UNO, GDP data from World Bank. All GDP figures are expressed in purchasing power parity terms, in US\$<sub>2005</sub>.

Data was available to calibrate the structural change curves for six countries (France, Italy, Israel, Malta, Slovenia, Spain). For the other countries, historical GDP per capita is low and data is concentrated in the lower part of the sigmoid, so the plateau of the curve cannot be estimated. In such case, assumptions based on available data and assumptions on country similarities<sup>1</sup> need to be made. For Montenegro, we used the plateau calibrated on Greece. For the remaining countries, in absence of a suitable country of reference, we set the maximum additional demand parameter ( $M_{tot}$ ) and pricing ( $P_{t=0}$ ) to the average value in countries where it could be estimated, and calibrated only the curve parameter ( $\gamma_{tot}$ ). For Montenegro, we did not have sufficient data to fit the curve parameter either, so we used the curve parameter calibrated on Greece.

Results of the calibration of the  $M_{tot}$  parameter and resulting maximum potential demands for each country are presented in Table 1.4. The plateau level is the lowest in Malta and France, and the highest in Spain and Italy. Goodness of fit between country data and the obtained calibrated function is evaluated with Willmott index of agreement in its original form [Willmott, 1981], which is suitable for sigmoid curves. For France, the curve fits well visually (1.D), but in this specific case the Willmott index is not an appropriate indicator of goodness of fit because historical consumption has already reached the plateau and observations are flat (instead of being of a sigmoid form), so the sum of squares of the regression (SSR) is null.

In our methodology the projection variable is demand, leaving the possibility of making various assumptions about the evolution of network efficiency when determining the corresponding withdrawal. To be able to compare our calibration results with those of the WaterGAP methodology applied to European countries [Flörke and Alcamo, 2004], we converted our demand figures into withdrawals under the assumption that demand to withdrawal ratios remain equal to current ratios (average current ratios, adapted from Margat and Treyer [Margat and Treyer, 2004], cf. Table 1.6). For Spain and Slovenia, our results are very similar to Flörke and Alcamo [Flörke and Alcamo, 2004] findings, with less than 10% of difference in maximum potential withdrawals, whereas for France and Italy we obtain substantially lower results (-65 to -85%). Flörke and Alcamo [Flörke and Alcamo, 2004] perform their structural change calibration using adjusted data: they offset past improvements in water use efficiency by applying a fixed annual technological

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<sup>1</sup>Maximum potential demands should reflect cultural effects, along with other factors influencing domestic water demand (climate, household characteristics, etc.).

Table 1.4: Calibrated maximum potential demand for the different countries (where  $\text{m}^3/\text{c}/\text{y}$ : cubic metre per capita per year; and  $\text{l}/\text{c}/\text{d}$ : litre per capita per day)

Country	$M_{tot}$ parameter ( $\text{m}^3/\text{c}/\text{y}$ )	Maximum potential demand		Willmott index of agreement
		( $\text{m}^3/\text{c}/\text{y}$ )	( $\text{l}/\text{c}/\text{d}$ )	
France	54.52	72.77	199	0.00
Israel	71.79	90.04	247	0.41
Italy	92.11	110.36	302	0.63
Malta	54.49	72.74	199	0.65
Slovenia	82.08	100.33	275	0.44
Spain	91.26	109.51	300	0.83
<i>Others</i> <sup>a</sup>	77.58	95.83	263	-

<sup>a</sup> Albania, Algeria, Bosnia, Croatia, Cyprus, Egypt, Greece, Lebanon, Libya, Morocco, Syria, Tunisia, Turkey, Montenegro

change rate. The adjusted data they use are therefore higher than historical data, which can explain the differences with our results for France and Italy. For Malta, Flörke and Alcamo [Flörke and Alcamo, 2004] obtained a very low plateau (about two times lower than ours), which could be because their data do not take into account desalinated water.

### 1.3.2 Projection scenarios

The calibrated three-part demand curves were used for the projection and valuation of domestic water demands in the Mediterranean countries, as a function of economic development and water price. Since demands are mostly higher than the upper bound of the second block (100  $\text{l}/\text{c}/\text{d}$ ), for simplification we used the average value of water per block instead of the variable marginal value in the first two blocks of the demand functions when calculating consumer's surplus. This could lead to an underestimation of consumer's surplus when demand is lower than 100  $\text{l}/\text{c}/\text{d}$  (Morocco before year 2010, Bosnia before 2015, Tunisia before 2020, Algeria until 2050 under the reference scenario).

Projection and valuation of future domestic water demands at the 2060 horizon were performed under contrasted scenarios of economic development and population growth. For economic development scenarios, we used GDP projections of the five Shared Socioeconomic Pathways (SSPs) [Rozenberg et al., 2014] available in the SSP Database (version 0.9.3). For population projections, we used four UNO scenarios: the medium, low and high variants, and the constant fertility variant. The medium population variant combined with the SSP2 economic scenario is used as the reference scenario.

The cost of water was assumed to evolve over time as countries develop and invest in water infrastructures. Current cost level in France was cho-

sen as a target cost of reference, because we consider it to be representative of a mature domestic water distribution and sewerage service, with a cost-recovery ratio close to one. We assume that, as far as conventional water resources are concerned, water costs mainly consist of distribution and sewerage costs and do not differ greatly between countries (this assumption is relaxed in Section 1.3.4). Cost evolution was hence represented as follows: in every country water cost increases over time and converges towards the current cost level in France, following the evolution of GDP per capita. It is not allowed to decrease if GDP per capita drops. Water cost reaches the target cost level when GDP per capita reaches the current level of GDP per capita in France.

For Malta, the particular context of the water sector implies a very high cost of water due to intensive desalination: 62% of the water used came from desalination in 1998-1999 [Margat and Treyer, 2004]. For Croatia, the current cost of water is also above the target cost level. Therefore, no further increase in water cost was projected for Malta and Croatia.

The cost-recovery ratio was assumed to converge towards one as GDP per capita grows, reaching one when GDP per capita reaches the current level of GDP per capita in France. The price of water changes over time, resulting from the combination of cost evolution and cost-recovery evolution.

Current water prices and costs in each country were not directly available, they had to be reconstructed using available data on water costs or prices from Margat and Treyer [Margat and Treyer, 2004], OECD [OECD, 2010] and International Benchmarking Network for Water and Sanitation Utilities database (IBNET [International Benchmarking Network for Water and Sanitation Utilities, 2013]), cost-recovery ratios from Margat and Treyer [Margat and Treyer, 2004], Euro-Mediterranean Water Information System database (EMWIS [Euro-Mediterranean Water Information System, 2013]) and IBNET, and sewerage coverage ratios from EMWIS and IBNET. Domestic water prices and costs are estimated with two different methods: using available data on prices and costs, or reconstructing costs based on the most robust data and sewerage coverage rates. Then the maximal value given by these two methods is selected, to avoid unrealistically low values.

For the first method, in a first step data on water prices and costs are deflated. When possible, missing costs are determined using the cost/price ratio in each country. If this information is not available, the water volumes weighted average Mediterranean cost/price ratio is used (using SIMEDD data for year 2000 water volumes). The obtained values are then multiplied by a 1.3 factor to take into account additional costs (other than operational costs). The 1.3 figure originates from data on France from Margat and Treyer [Margat and Treyer, 2004]. Robust water costs data are available for four countries (France, Greece, Italy and Spain), the minimum estimated costs are observed for Italy (2.17\$/m<sup>3</sup>). This minimum cost accounts for both water services and sanitation services, each representing 50% of this cost.

Table 1.5: Reconstructed current costs and prices of domestic water in Mediterranean countries (around year 2000)

Country	Cost (US\$2005/m <sup>3</sup> )	Price (US\$2005/m <sup>3</sup> )	Years of available data
Albania	1.79	0.93	<2004, 2011
Algeria	2.01	0.41	<2004, 2010
Bosnia and Herzegovina	1.68	0.93	2007
Croatia	4.33	2.55	<2004
Cyprus	2.62	1.33	1989, <2004
Egypt	1.63	0.16	1989, <2004, 2010
France	3.33	3.33	<2004, <2010
Greece	2.22	1.31	<2004, <2010
Israel	2.15	0.95	<2004, <2010
Italy	2.17	1.4	1994, <2004, <2010
Lebanon	2.05	1.2	1989, <2004
Libyan Arab Jamahiriya	1.84	0.09	1997, <2004
Morocco	2.05	1.04	1989, <2004
Malta	10.58	2.08	<2004
Montenegro	1.65	0.93	2012
Slovenia	2.81	1.66	<2004
Spain	2.75	1.62	<2004, <2010
Syrian Arab Republic	2.83	0.91	1989, <2004
Tunisia	1.9	0.91	1989, 1996, <2004, 2010
Turkey	2.1	1.17	<2004, 2008

We use this value as a basis to calculate minimum costs for all the other countries in the second method.

For the second method, we estimate a minimal domestic water cost depending on the sewerage coverage rate. For countries where robust water costs data are not available, we assume that water distribution services costs are  $2.17/2$   $\$/m^3$  (i.e. half of the minimum total cost among countries with robust data). We then add sanitation costs, which vary from 0 to  $2.17/2$   $\$/m^3$ , depending on the sewerage coverage rate.

Final cost and price data used are displayed in Table 1.5.

### 1.3.3 Projection results

Results of projected water demand per capita are presented in Figure 1.5 for a selection of countries and in Table 1.6. Developed countries have mostly reached demand saturation: demand per capita does not increase in France, Israel and Malta, and it increases by only 2.1% to 9.7% in Spain between 2000 and 2060 under the different scenarios. In contrast, demand per capita grows sharply in developing countries, at a pace depending on socioeconomic drivers. In Egypt, domestic water demand per capita is of  $45.36$   $m^3/c/y$  in 2000, and it grows rapidly and reaches potential demand around 2030-2035 (Figure 1.5(a)). In Morocco and Algeria, initial demand is lower (respec-

tively 29.97 and 21.70 m<sup>3</sup>/c/y in 2000); whereas it grows rapidly in Morocco, reaching potential demand around 2035-2040, it grows more slowly in Algeria where GDP per capita evolves at a slower pace, and maximum potential demand is not yet reached in 2060 under the reference scenario.

An overshoot effect is perceptible for Egypt and Morocco (Figure 1.5(a)) after 2040, as the growth of demand per capita is counterbalanced by increases in water price (with an order of magnitude of -6.3% in demand in 2060 due to price increase). This impact of price on demand is also visible for Israel and for Spain (respectively -10.9% and -8.9% in 2060).

While GDP per capita and water price remain low, demand per capita increases with economic development, and surplus per capita increases with demand. Eventually, when GDP per capita and price reach a certain level, demand per capita begins to saturate and decrease, which impacts surplus negatively. In parallel, as the country develops the cost of water increases, which also impacts surplus negatively. As a result, surplus per capita begins to decrease sooner than demand per capita. The negative net effect on surplus is visible for Egypt, Israel, Morocco, Spain and Turkey (Figure 1.5(b)).

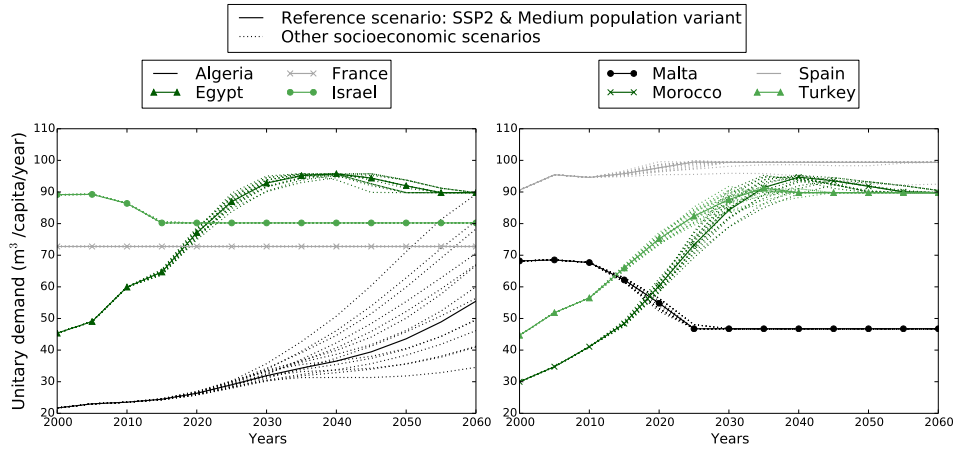
Malta is a particular case. The cost of water is the highest among Mediterranean countries: 10.58 \$<sub>2005</sub>/m<sup>3</sup> compared with an average cost of 2.77 \$<sub>2005</sub>/m<sup>3</sup> in the other countries. Surplus is particularly low due to this high cost of water. The impact of price on demand per capita is more pronounced for Malta (-35.7% in 2060) than for other countries, as the price of water converges towards a higher cost.

Total demand at country scale is the result of demand per capita evolution and population growth. In some countries, such as Turkey and Egypt, the combination of a strong population growth and increase in individual water demand leads to a rapid rise of total water demand: +170% for Turkey and +210% for Egypt between 2000 and 2030, under the reference scenario (Figure 1.5(c)). In other countries, such as Algeria, demand per capita remains limited by revenue constraints and so, despite a high population increase, total demand does not grow that sharply in the first decades: +110% between 2000 and 2030 under the reference scenario. By 2060, total demand could almost triple under the reference scenario: +186% in Turkey, +273% in Egypt, and +286% in Algeria (compared with year 2000).

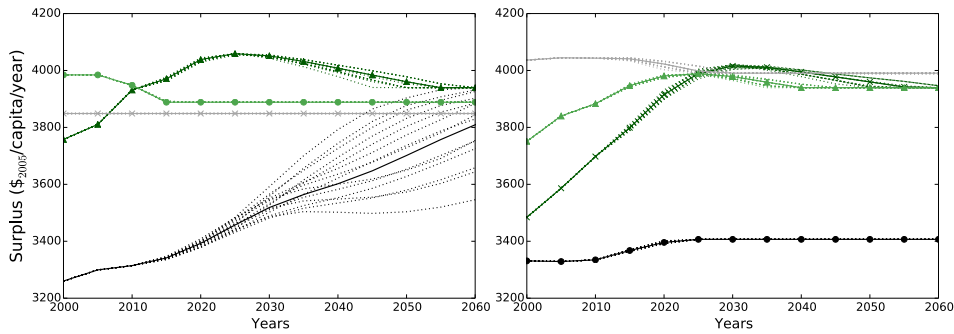
We compared our results with domestic water use projections in Mediterranean countries available in the literature (1.E). Globally our projections fall in the range of existing figures, which can be wide for non-OECD countries.

### 1.3.4 Simulation of a strong cost increase scenario

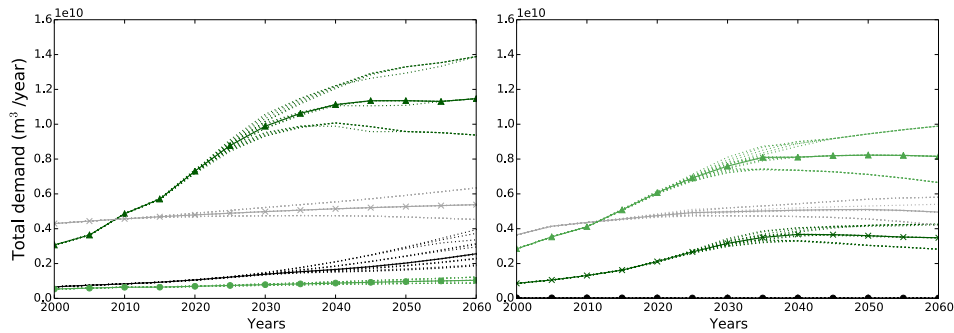
Under the standard price evolution modelled in Section 1.3.3 (Malta not included), the effect of price increase leads to a decrease in demand of up to 10.9% in 2060. These results were obtained under the assumption that



(a) Demand per capita



(b) Surplus per capita (consumer surplus + water utility revenue)



(c) Total domestic water demand at country scale

Figure 1.5: Projection of water demand and value over time for different socioeconomic scenarios (reference scenario with a solid line, others with dotted lines), for a selection of countries.

Table 1.6: Projected domestic demands in Mediterranean countries for years 2010, 2025 and 2050, for the reference socioeconomic scenario

Country	Total demand (km <sup>3</sup> /y)			Demand per capita (m <sup>3</sup> /c/y)			Demand to withdrawal ratios (%) <sup>a</sup>
	2010	2025	2050	2010	2025	2050	
Albania	0.30	0.32	0.28	93.49	95.72	93.21	45
Algeria	0.83	1.22	2.03	23.52	29.04	43.57	50
Bosnia and Herzegovina	0.13	0.21	0.27	35.63	59.01	89.79	40
Croatia	0.31	0.35	0.33	69.97	83.3	84.73	67.5
Cyprus	0.07	0.08	0.12	61.54	64.57	86.39	77
Egypt	4.86	8.78	11.35	59.93	86.96	91.96	52.5
France	4.57	4.89	5.27	72.77	72.77	72.77	70
Greece	0.81	0.91	1.05	71.6	78.45	89.79	66.5
Israel	0.64	0.74	0.96	86.39	80.22	80.22	81.5
Italy	6.21	6.05	5.86	102.64	98.99	98.99	73
Lebanon	0.34	0.44	0.42	80.68	94.44	89.79	65
Libya	0.55	0.7	0.79	87.06	93.94	89.79	75
Malta	0.03	0.02	0.02	67.69	46.74	46.74	65
Montenegro	0.02	0.03	0.05	32.74	44.38	74.59	63
Morocco	1.31	2.67	3.6	41.07	73.28	91.81	78.5
Slovenia	0.17	0.19	0.18	85.44	91.64	91.64	67.5
Spain	4.36	4.92	5.1	94.61	99.47	99.38	70
Syria	1.25	2.33	3.05	61.18	89.56	92.24	72.5
Tunisia	0.33	0.61	1.14	31.58	51.29	89.79	69
Turkey	4.11	6.92	8.23	56.5	82.37	89.79	50

<sup>a</sup> Adapted from Margat and Treyer (2004)

the cost of water will converge towards the current cost in France. But if the resource is too scarce and cannot meet the growing demand, some countries might need to mobilise alternative water supply sources, that are more costly. Taking into account demand sensitivity to price is useful for simulating stronger price increase scenarios.

As an illustration, another price evolution scenario was simulated for a selection of countries: a strong increase in the cost of water, due to the need to resort to non-conventional water resources such as desalination. In this scenario, desalination is introduced in 2020 and its share in total water production increases progressively so as to reach 25% of water demand in 2050 in Algeria, 50% in Tunisia and 100% in Libya. Such desalination rates are consistent with the fact that over 80% of current water withdrawals come from non-sustainable resources in Libya, over 30% in Algeria and over 20% in Tunisia [Margat and Treyer, 2004].

The cost of desalinated water is assumed to be  $10.58\$_{2005}/\text{m}^3$ , which is the current cost of water in Malta<sup>2</sup>. Similar to the standard price evolution scenario, the cost-recovery ratio is assumed to increase over time, converging towards one.

Impacts of this desalination scenario on demand evolution and surpluses are presented in Figure 1.6, projections are performed under the reference socioeconomic scenario (SSP2 and medium variant for population).

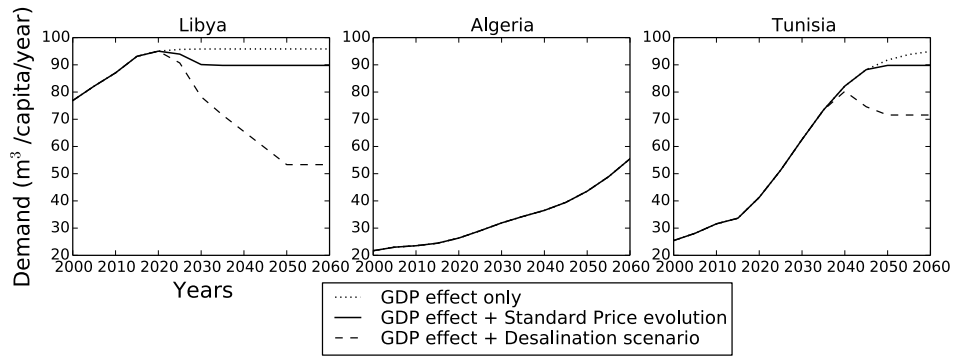
In Algeria, the simulated price evolution scenarios do not impact demand. Indeed, in Algeria, the evolution of demand per capita is constrained by the low level of economic development, and does not reach  $36.5 \text{ m}^3/\text{c}/\text{y}$  until the end of the considered time horizon. Therefore, the willingness to pay for the last unit consumed is still high. In addition, cost recovery ratio stays low, so the increase in price is limited. Thus, in Algeria the revenue-effect remains stronger, even with the desalination scenario (Figure 1.6). Cost still has an impact on total economic surplus since the increase in water cost lowers water utility's revenue.

For Libya and Tunisia, where the growth of GDP per capita boosts demand per capita in the next decades, the price effect decreases demands by 6.3% and 5.4% respectively in 2060 under the standard price evolution scenario. The price effect becomes more important under the implemented desalination scenario, with decreases in demands of respectively 44.36% and 24.61% for Libya and Tunisia in 2060. This illustrates how a change in water price could affect demand.

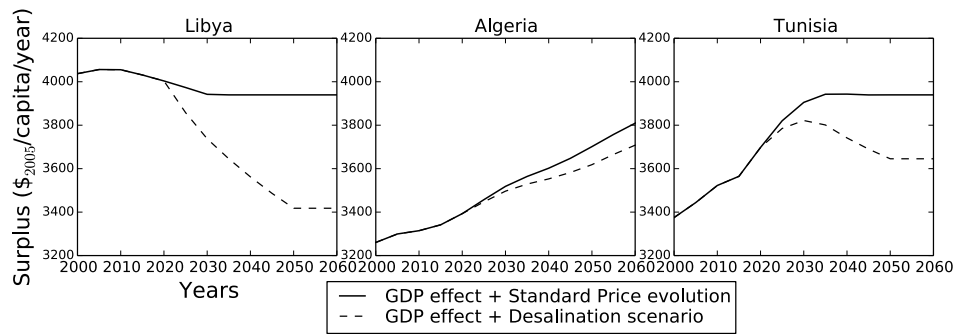
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<sup>2</sup>Costs could however become more important in the future, evolving with the cost of energy.





(a) Demand per capita



(b) Surplus per capita

Figure 1.6: Impact of the “desalination increase scenario” on demand and surplus projections in Libya, Algeria and Tunisia (with reference socio-economic scenario)

## 1.4 Sensitivity analysis

In the developed methodology, a number of elements could not be determined with available data and had to be considered as exogenous. A sensitivity analysis was performed to explore the impacts of the assumptions made about the value of those parameters: volume of first block ( $Q_{basic}$ ), parameter for maximum volume of second block ( $M_{int}$ ), parameter for maximum potential demand ( $M_{tot}$ ) for concerned countries, marginal value of the 100<sup>th</sup> l/c/d ( $V_{int}$ ) and current price of water ( $P_{t=0}$ ). In the analysis the parameters range of variation is [-50%, +100%] for parameters  $M_{tot}$ ,  $V_{int}$  and  $P_{t=0}$ . Parameter  $Q_{basic}$  varies from -60% to +40%: the lower bound corresponds to 20 l/c/d (Table 1.1), the upper bound variation is constrained so that  $Q_{basic}$  remains lower than the upper bound of the second block. Then the upper bound of the second block varies from -20% to +40%, which corresponds to a variation range of [-78%, +136%] of the  $M_{int}$  parameter.

The sensitivity of projected demands to  $M_{tot}$  parameter was checked for the countries where it could not be calibrated (countries with a low current level of GDP per capita, Cf. Section 1.3.1 and Table 1.4) and was unsurprisingly found to be determinant when countries approach the demand plateau (Figure 1.7). Projection scenarios would hence need to be readjusted when there is more precise data or scenarios on maximum potential demand in those developing countries of the Mediterranean. The model is more robust to the other parameters settings (Figure 1.7). Under the reference socioeconomic scenario, the impact of the combined variations of  $Q_{basic}$ ,  $M_{int}$ ,  $V_{int}$  and  $P_{t=0}$  parameters on demand per capita in 2060 in the different countries is an average [-38%, +23%] range of variation around the mean.

Regarding the projection of the economic value of water, the most important parameter is  $Q_{basic}$  (Figure 1.7). This result is not surprising since water is very highly valued in the first block of the demand function. Under the reference socioeconomic scenario, the combined variations of  $Q_{basic}$ ,  $M_{int}$ ,  $V_{int}$  and  $P_{t=0}$  parameters lead to an average variation around the mean of [-16%, +31%] in surplus per capita in 2060 in the different countries.

## 1.5 Discussion and conclusion

The presented methodology can project the combined impact of economic development and water price on future domestic water demands, in terms of both quantity and economic benefits.

The method was applied to a region with heterogenous levels of development. The decision to use the same generic methodology for both developed and developing countries is debatable. We found that it was not possible to fully calibrate the structural change curves used to build the final demand function, for a number of countries past data alone did not enable to de-

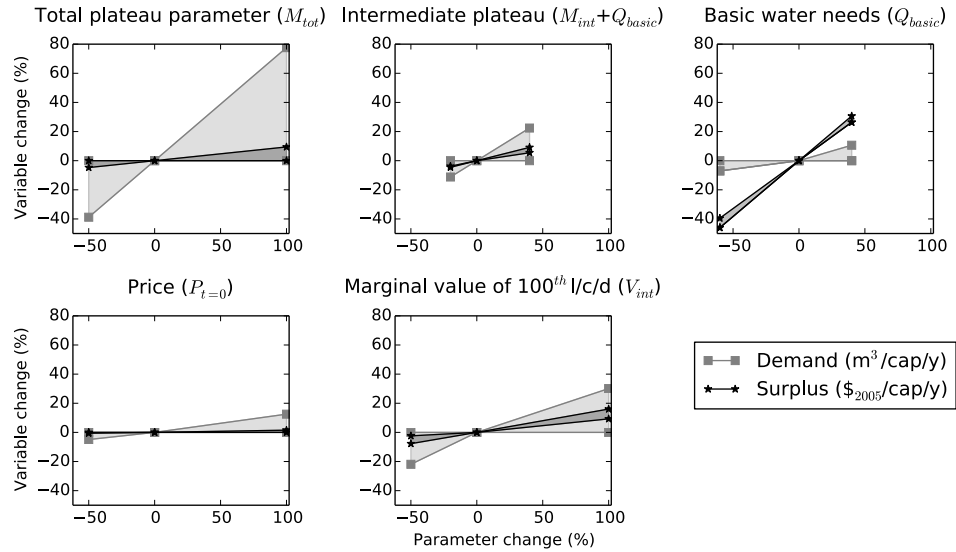


Figure 1.7: Sensitivity of demand and surplus projections to the variation of five parameters, for year 2060 under the reference scenario, in the Mediterranean countries. The grey area represents the range of variation between countries.

termine the level of demand saturation. Still, the methodology enables to capture some socioeconomic determinants of the rate of change, via the calibration of the slope parameter of the structural change curves. In addition, when some countries are expected to catch up with some others, it makes sense to use a method suitable for different stages of the same evolution process. Indeed, some countries are still at the beginning of the process, some mid-way and some already at the end. It is very likely that developing countries will undergo structural change, shifting from demand being constrained by equipment and revenue to demand being constrained by water costs, so we try to represent how this may happen even if there is currently no data to fully calibrate the process.

A number of parameters could not be determined with the available data, and were considered to be exogenous (Section 1.3.1). For instance, the levels of demand saturation for most countries converge towards the exogenously fixed average calibrated plateau. On the one hand this points out a limitation of the methodology which, although generic, is not able to capture all features with globally available data. On the other hand such exogenous parameters arise from the incomplete knowledge of future conditions, and can enable the simulation of different exploratory scenarios. It is possible to readjust scenarios when new data or more precise scenarios about the exogenous elements of the methodology become available.

Other parameters were determined using ad hoc assumptions (e.g. willingness to pay for the 100<sup>th</sup> and the 50<sup>th</sup> 1/c/d). Better evidence could improve parameter determination in the future. In the Mediterranean, the sensitivity analysis showed that a variation of [-50%,+100%] in WTP for the 100<sup>th</sup> 1/c/d led to a variation of [-22%,+30%] in demand per capita (Section 1.4).

Our demand projection approach does not explicitly account for technological change, nor does it consider evolutions in cultural effects. The level of demand saturation could indeed evolve over time with technological change improving water efficiency, although a rebound effect could lead to an increase in per capita demand. Water price increase could be an incentive to invest in less water-intensive devices. However, we did not specifically model technical change. First, it is difficult to distinguish the effect of technological progress from the effect of revenue and price evolution. Indeed, the adoption of more technologically efficient water appliances by a household should somehow be conditioned by the level of GDP per capita, which constrains the purchase of a new appliance (the technology must be available but also affordable). Second, though technological change would be expected to have an effect it is not visible in the data we used for the application of the methodology to the Mediterranean: for now the available data do not show a decrease in per capita domestic water intensity even in countries which have already reached demand saturation. Thus, unlike Alcamo et al. [Alcamo et al., 2003a], we do not correct data for technological change before estimating the parameters of the sigmoid structural change curve. In fact, the sigmoid curve we estimate accounts for both structural change effects and embedded technological change effects (which may have slowed down demand increase), as a function of GDP per capita. In particular, once a country has reached the demand plateau there is no further technological change, unlike in the WaterGAP modelling [Alcamo et al., 2003a].

Technological change and cultural changes could however become more important in the future. Though data from developed countries can give us an idea of the current value of the demand saturation plateau, future pathways are not easily predictable. Demand evolution parameters are estimated with historical data, and their validity to represent future evolutions is uncertain [Hanasaki et al., 2013a], breaks in trend could arise.

In conclusion, given the scale of the study and the scarce globally available data, especially for countries from the eastern and southern Mediterranean rims, a generic method seems appropriate. Despite identified limitations for the least-developed countries, it has the merit of offering a comprehensive estimation of future domestic water demands and values in the region. Since the methodology is generic and not too data intensive, it can be easily transposed to other large-scale regions of applications, in particular developing regions where little reliable data are available. Assumptions on costs and costs evolution, and on source of missing parameters need to be

made on a per country basis, depending on available data.

The novelty of the method lies in its taking into account of the economic value of water in a large scale projection framework. It makes it possible to evaluate impacts of water scarcity in terms of welfare, measured by surplus losses. The method can simulate the impacts of different price evolution scenarios. Projection results showed that price increase can limit water demands (Section 1.3.4), which illustrates the potential of incentive water pricing policies. This result is interesting in view of demand-side water management, since limiting water abstractions instead of developing water supply infrastructure could reduce the burden of adaptation to climate change [Hughes et al., 2010].

This work's large scale, both geographical and temporal, is suitable to study the impacts of global socioeconomic and hydroclimatic changes on the water sector and consider potential interactions between sub-basins. Some models compare water availability and water abstraction on a large scale [Hanasaki et al., 2013a, Biemans et al., 2011], not taking into account the value of water. Our work opens up the possibility of using water values in this type of framework, to assess water uses' economic benefits and model water allocation between competitive uses.

## Appendices

### 1.A Overview of the methodology

Cf. Figure 1.8

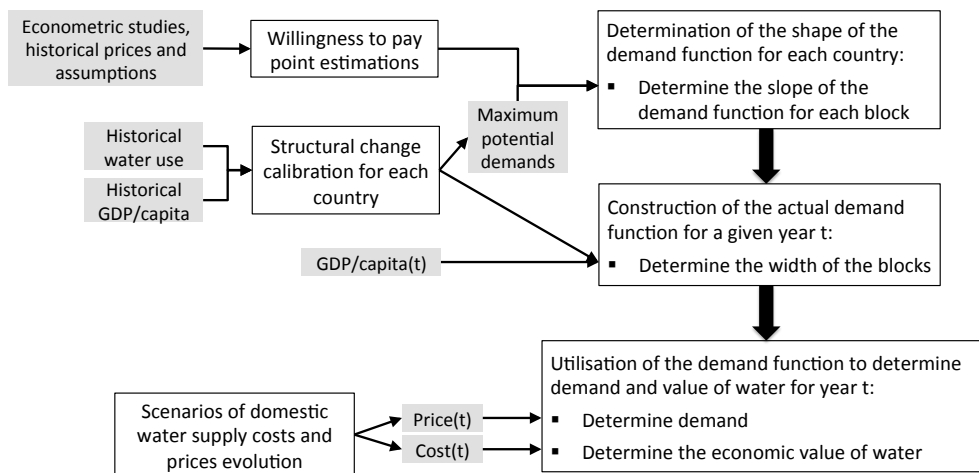


Figure 1.8: Main steps of the generic methodology developed to project and value domestic water demands

### 1.B Map of the Mediterranean basin

Cf. Figure 1.9

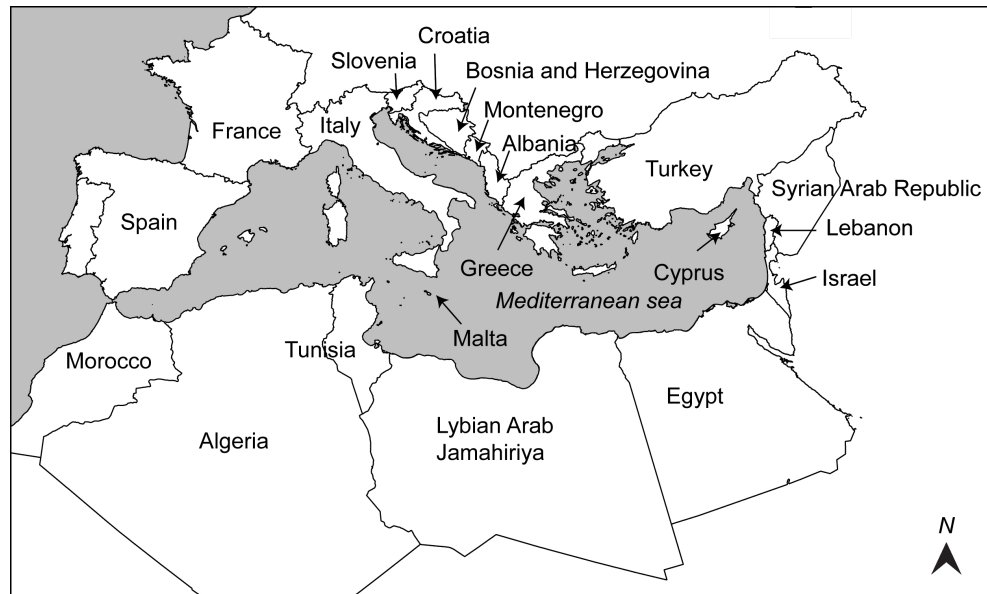


Figure 1.9: Countries of the Mediterranean basin

### 1.C Domestic water demand function and the economic value of water

Cf. Figure 1.10

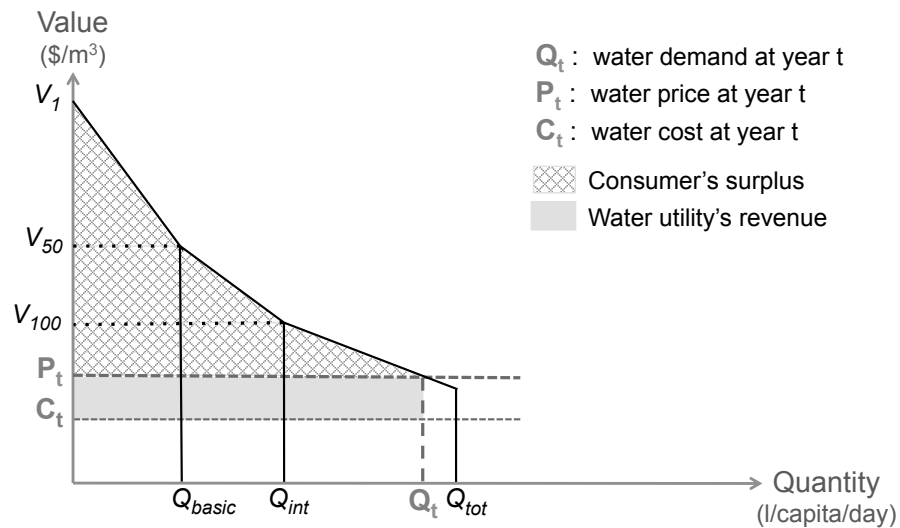


Figure 1.10: Total economic value of water: consumer's surplus and water utility's revenue

## 1.D Calibration of the structural change curve for France

Cf. Figure 1.11

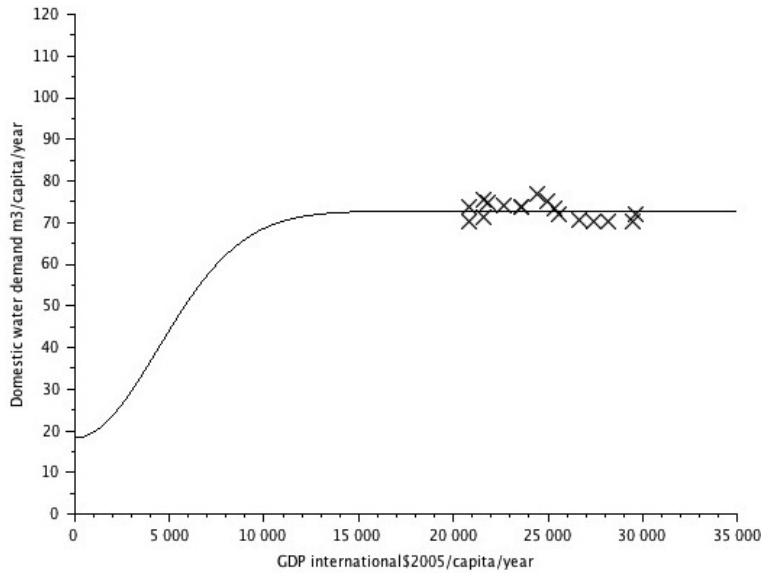


Figure 1.11: Calibration of the structural change curve for France, based on historical domestic demand and GDP per capita.

## 1.E Comparison with previous domestic water use projection attempts in the Mediterranean region

We compare our results with domestic water use projections in Mediterranean countries available in the literature: figures from various sources displayed in Margat and Vallée [Margat and Vallée, 1999] and Margat and Treyer [Margat and Treyer, 2004] and results of the WaterGAP model applied to European countries from Flörke and Alcamo [Flörke and Alcamo, 2004].

The elements of comparison, available for four years of reference, are displayed in Figure 1.12, Table 1.8 and 1.7, along with our results for the reference socio-economic scenario. Globally our projections fall in the range of existing figures, which can be wide for some countries (Algeria, Egypt, Libya, Syria, Turkey).

In some countries demand increase is more rapid with our methodology and projected demand is high in 2025 (Lebanon, Tunisia, Syria, Morocco, Egypt) compared with the literature range. The difference tends to reduce



afterwards, with lower projections for 2030 with our methodology (Algeria, France, Morocco, Tunisia, Italy). This pattern - higher projections for 2025, but closer to or below literature range in 2030 - is probably due to the sigmoid structural form we used for structural change modelling (steep curve followed by a saturation), whereas most Mediterranean projections from national planning are based upon trend prolongation [Margat and Treyer, 2004]. In addition, our modelling of price impact tends to reduce demand per capita once GDP per capita reaches high levels.

Still, for some countries our projections for year 2030 fall above literature range (Egypt, Malta and Spain, cf. Figure 1.12 and Table 1.7). However, for Malta and Spain there is only one study providing projections to 2030. Prolongating the trends of the other studies would lead to higher demands than projected by our methodology. For Egypt, the literature range is very wide (-39% to +39%) which denotes a high level of uncertainty.

Table 1.7: Projection of total domestic water use at country scale, comparison with elements from the literature for four years of reference (km<sup>3</sup>/year)

Country	Projected withdrawals*				Range of results from the literature			
	2000	2010	2025	2030	2000	2010	2025	2030
Albania	0.52	0.67	0.7	0.7		0.8-0.83	0.8	
Algeria	1.33	1.67	2.44	2.77		1.87-4.1	2.4-7.26	3.38-6.72
Bosnia	0.25	0.33	0.53	0.61		0.4	0.4	
Croatia	0.36	0.46	0.52	0.54		0.9	0.78-0.8	
Cyprus	0.07	0.09	0.11	0.12	0.08-0.1	0.1	0.094-0.104	
Egypt	5.85	9.26	16.71	18.83		4.0-9.0	3.1-6.3	7.1-16
France	6.14	6.53	6.99	7.12	9.097	5.8-10	6-9.6	8.256-8.356
Greece	1.02	1.22	1.37	1.45	1.343	0.9-1.5	1-1.83	1.495-1.5
Israel	0.66	0.79	0.91	0.97		0.77-0.86	1.15-1.4	
Italy	8.07	8.51	8.29	8.25	12.098	7.2-7.6	4.85-7	12.018-12.688
Lebanon	0.34	0.52	0.67	0.67		0.33-0.55	0.48-0.64	0.63-0.98
Libya	0.54	0.74	0.93	0.93		0.55-1.01	1.28-1.93	1.06-2.54
Malta	0.04	0.04	0.03	0.03	0.022	0.04	0.04	0.015-0.017
Morocco	1.1	1.67	3.4	4.03		1.4-2.9	1.5-1.97	5.34-6.54
Slovenia	0.21	0.26	0.28	0.28	0.268	0.3	0.3	0.154-0.17
Spain	5.21	6.23	7.03	7.1	6.255	5-6.28	5.2-7	4.655
Syria	1.08	1.72	3.21	3.61		1.29-2.1	1.26-3	1.26-3.04
Tunisia	0.35	0.48	0.89	1.11		0.37-0.63	0.5-0.65	1.1-1.67
Turkey	5.69	8.22	13.84	15.19	4.346	7.15-17.8	8.6-23.6	5.862-11.656

\* Our demand projection results were converted into withdrawals using demand to withdrawal ratios adapted from Margat and Treyer (2004).

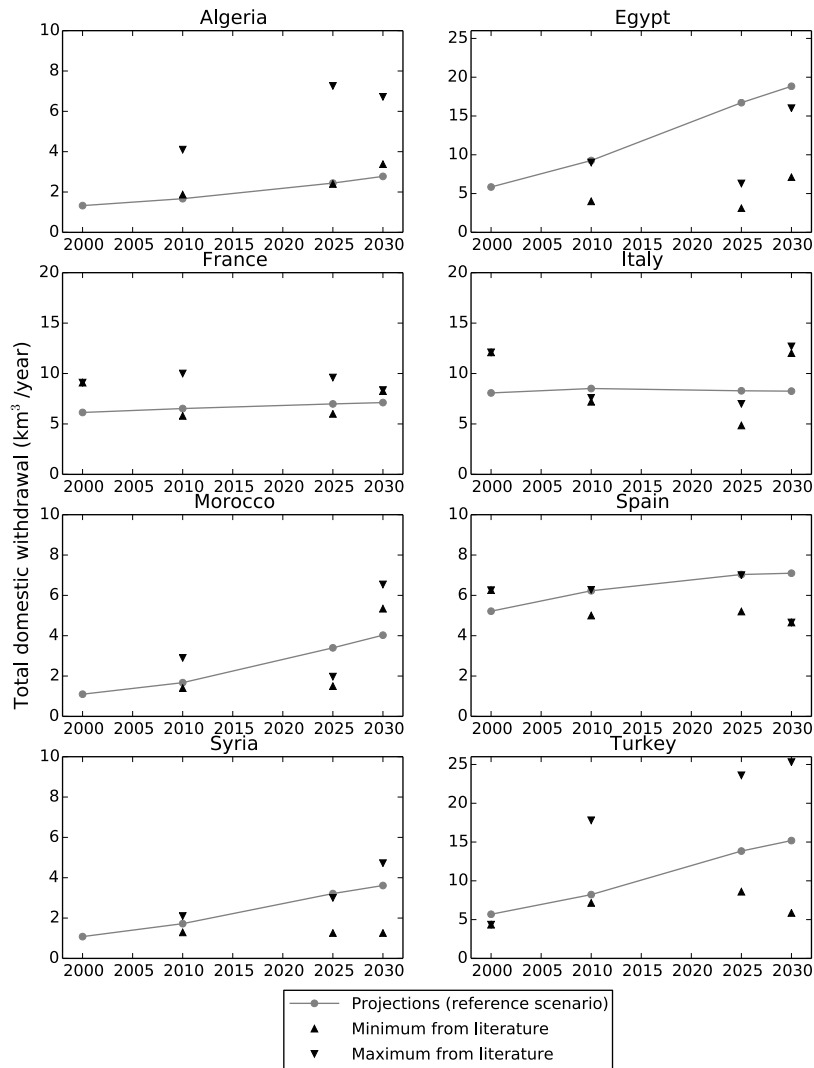


Figure 1.12: Domestic water withdrawal projections (with reference socio-economic scenario) compared to the literature, for Mediterranean countries with the highest levels of domestic withdrawal

Table 1.8: Projections of total domestic water use at country scale for four years of reference: elements from the literature ( $\text{km}^3/\text{year}$ )

Year	2000			2010			2025			2030			
	Source	FA <sup>a</sup>	AI <sup>b</sup>	NP <sup>c</sup>	PB <sup>d</sup>	MV <sup>e</sup>	AI <sup>b</sup>	NP <sup>c</sup>	PB <sup>d</sup>	MV <sup>e</sup>	FA <sup>a</sup>	AI <sup>b</sup>	NP <sup>c</sup>
Albania				0.83	0.83	0.83			0.8	0.80			
Algeria		1.87-3.58		2.0-3.26	2	4.10	4.86-7.26	3.1-4.9	2.4	6.05		3.38-6.72	
Bosnia				0.4	0.4				0.4				
Croatia				0.9	0.9			0.78	0.8				
Cyprus	0.103			0.09	0.08	0.10			0.1	0.10	0.094-0.104		
Egypt		4.0-9.0		4.5	5	5.00	4.3-6.3	3.1	6	6.00		7.1-16	
France	9.097			10	5.8	7.90		8.03	6	9.60	8.256-8.356		
Greece	1.343				0.9	1.50		1.83	1	1.80	1.495-1.5		
Israel				0.77	0.86	0.77		1.3-1.4	1.15	1.40			
Italy	12.098				7.2	7.60		4.85	7	5.20	12.018-12.688		
Lebanon		0.33-0.55			0.4	0.40	0.48-0.64		0.52	0.52		0.63-0.98	0.72
Libya		0.55		0.708-1.01	0.71	1.00	1.49-1.93	1.24-1.76	1.28	1.76		1.06-2.54	
Malta	0.022				0.04	0.04			0.04	0.04	0.015-0.017		
Morocco		1.97-2.9		1.59	1.4	1.60	1.5-1.97		1.9	1.57		5.34-6.54	
Slovenia	0.268				0.3				0.3		0.154-0.17		
Spain	6.255				5	6.28			5.2	7.00			
Syria		1.29-1.62		2.1	1.4	2.10	1.26-1.94		2	3.00		1.26-3.04	4.72
Tunisia		0.57		0.37-0.63	0.41	0.42	0.57-0.65		0.5	0.53		1.1-1.67	0.53-0.55
Turkey	4.346			7.15	7.15	17.80			8.6	23.60	5.862-11.656		25.3

<sup>a</sup> Flörke and Alcamo (2004), range of results of 4 scenarios simulated with WaterGAP

<sup>b</sup> Arab Institutions, in Margat and Treyer (2004)

<sup>c</sup> National planification documents, in Margat and Treyer (2004)

<sup>d</sup> Plan Bleu (2002), moderate trend scenario, in Margat and Treyer (2004)

<sup>e</sup> National planning documents completed with various sources, moderate trend scenario, in Margat and Vallée (1999)

## Chapter 2

# Projecting basin-scale distributed irrigation and domestic water demands and values: a generic method for large-scale modeling

This chapter projects localised water demands. For the irrigation sector, demands are projected in terms of quantity and economic benefits. For the domestic sector, projections from Chapter 1 are used. Demands and values of both sectors are spatially distributed. They will be used to determine allocation rules and compared with available water supply in Chapter 3.

The chapter reproduces the contents of the following article: “Neverre, N. and P. Dumas. Projecting basin-scale distributed irrigation and domestic water demands and values: a generic method for large-scale modeling. *In revision at Water Economics and Policy.*”

### Abstract

This paper presents a methodology to project irrigation and domestic water demands on regional to global scale, in terms of both quantity and economic value. Projections are distributed at the water basin scale.

Irrigation water demand is projected under climate change. It is simply computed as the difference between crop potential evapotranspiration for the different stages of the growing season and available precipitation. Irrigation water economic value is based on a yield comparison approach between rainfed and irrigated crops using average yields.

For the domestic sector, we project the combined effects of demographic growth, economic development and water cost evolution on future demands. The method consists in building three-part inverse demand functions where volume limits of

the blocks evolve with the level of GDP per capita. The value of water along the demand curve is determined from price-elasticity, price and demand data from the literature, using the point-expansion method, and from water cost data.

This generic methodology can be easily applied to large-scale regions, in particular developing regions where little reliable data is available. As an illustration, it is applied to Algeria, at the 2050 horizon, for demands associated to reservoirs. Our results show that domestic demand becomes a major water consumption sector.

The methodology is meant to be integrated into large-scale hydroeconomic models, to determine inter-sectorial and inter-temporal water allocation based on economic valuation.

*Keywords* Water demand projection, Water value, Large-scale modeling, Domestic water demand, Irrigation water demand

## 2.1 Introduction

Water resources are already under pressure in some regions of the world, and are facing increasing pressures caused by global socioeconomic and environmental changes. This issue is particularly acute in the Mediterranean, where demographic and economic growths are expected to increase water demands in the next decades, while climate change is predicted to affect negatively water supply [Barros et al., 2014]. In this context, there is a need for water resources assessments, to anticipate future scarcity issues.

It would be relevant for those assessments to maintain a double focus: a large-scale coverage, and a representation of spatial heterogeneity at the river basin level. Indeed, on the one hand a large-scale coverage allows for the representation of interactions between basins with heterogeneous profiles (water transfers, virtual water trade etc.); it also enables to address global changes and their impacts on water resources [Alcamo et al., 2003a, Hadde-land et al., 2011, Hanasaki et al., 2013a, Hanasaki et al., 2013b, Strzepek et al., 2013]. On the other hand, water resources are managed at the river basin scale, and, depending on the river basin's characteristics, the local impacts of global changes might be different.

Besides, it would also be relevant to consider both water quantities and water values. Indeed, water management policies are increasingly incited to consider water as an economic good [ICWE, 1992]. Water basin management requires to be able to measure the economic benefits associated with water uses, and the changes in benefits associated with a change in water allocation or availability. Economic valuation can provide valuable information on how to manage at best the available water. Hydroeconomic models address the issues of water allocation between competing uses as well as intertemporal allocation. Water is allocated between its different uses based on the economic benefits they generate, the objective being to maximize the expected aggregated economic value of the water used [Harou et al., 2009].

With this in mind, our objective is to project future water demands and their economic values to 2050, in a framework combining a river basin level

modeling with an extended geographic coverage. In the present paper we focus on two main sectors of water use: the agricultural sector, and the domestic sector. Irrigation is the major water consumption sector in many regions of the world; in the Mediterranean basin it represents 65% of total water use, and up to 80% in its southern rim [Margat and Treyer, 2004]. Since livestock water use is much smaller than irrigation water use [Alcamo et al., 2007, Hanasaki et al., 2013a], in the present paper we consider only irrigation water needs. Domestic demand is the second largest consumption sector of the Mediterranean basin, representing 13% of total water use; moreover, it is critical in terms of needs, and its share in total demand is increasing.

A number of studies have addressed the issue of water demand projection at large scale: [Döll and Siebert, 2002, Biemans et al., 2011], for irrigation water, [Ward et al., 2010] for municipal and industrial water, [Alcamo et al., 2003a, Hanasaki et al., 2013a, Strzepek et al., 2013] for both agricultural and non-agricultural sectors. For agricultural water demand, two different approaches coexist: one based on statistical projections of irrigated areas at the country scale [Shen et al., 2008], and another based on the modeling of crops biophysical water needs [Döll and Siebert, 2002, Alcamo et al., 2003a, Alcamo et al., 2007, Strzepek et al., 2013, Hanasaki et al., 2013a]. For the domestic sector, existing projections are mainly based on statistical approaches at country scale, in which demand evolves with GDP per capita as the country develops. Demand can either be directly estimated as a function of population and GDP per capita [Hughes et al., 2010, Ward et al., 2010], or domestic water use intensity per capita is estimated as a function of GDP per capita [Alcamo et al., 2003a, Shen et al., 2008] and is then multiplied by the projected population. Other country-dependent variables (e.g. climatic variables) can also be included in the estimations.

However, the issue of water value has yet to be addressed by the large-scale literature. Determining the value of water in its different uses is complex and requires non-market valuation methods, as described by [Young, 2005]. For producers' uses, such as agricultural demand, where water is an intermediary good, the main valuation method is the residual method. It consists in isolating the marginal contribution of water to the total value of the final good produced: knowing the value of the output, values of all inputs other than water are subtracted, and what remains is the residual value of water. For consumers' uses, such as domestic demand, where water is a final good, the most frequently used approach is statistical. It consists in econometrically estimating demand functions, and deriving consumers' surplus. Such methods are very data intensive. Large-scale data availability is low and implementing methods as precise as what can be done at the water basin scale proves difficult at large scale. This could be one of the reasons why hydroeconomic models have mostly been developed at infra-national scales [Harou et al., 2009].

To fill this need, this paper presents a methodology designed to project

both water demands and values under global changes, and suitable for a large-scale region with heterogeneous data availability such as the Mediterranean. The methodology is thus generic, and easily transposable to other large-scale regions of application. It is meant to be integrated into the ODDYCCEIA<sup>1</sup> water-modeling framework ([Portoghese et al., 2013], section 9.4), to form a generic large-scale hydroeconomic model.

We model irrigation water demand using a biophysical approach, following [Döll and Siebert, 2002]. For irrigation water valuation, we propose a simple method derived from the residual method, using only globally available data. For the domestic sector, we develop a generic method in which an approach similar to WaterGAP's [Alcamo et al., 2003a, Alcamo et al., 2007] is incorporated into a simple demand function estimation framework, enabling to project both demands and values. Demands are located and associated to reservoirs and water basins using the ODDYCCEIA methodology [Portoghese et al., 2013]. Therefore, only demands that could be satisfied by large reservoirs are taken into account.

As an illustration, the methodology is applied to Algeria, covering fifteen basins, at the 2050 horizon.

## 2.2 Methodology

Future demands and values are projected at the 2050 horizon; year 2000 is considered as the year of reference for historical conditions. The methodology described below projects on-site potential demands. To obtain corresponding potential water withdrawals, potential demands would have to be multiplied by efficiency ratios, to account for distribution losses.

### 2.2.1 Irrigation demand projection

Irrigation demand projection follows the methodology of ODDYCCEIA model [Portoghese et al., 2013].

Historical irrigated areas are determined from globally available data on irrigated areas and crops [Siebert et al., 2005], and crop mixes in the different irrigation perimeters are taken from Agro-MAPS database [FAO, 2005]. Future crops surfaces and types are assumed to be the same as in historical conditions (year 2000): we do not model changes in crop types distribution nor in areas equipped for irrigation.

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<sup>1</sup>ODDYCCEIA is the name of the framework. The abbreviation stands for Optimal Dam Dimensioning Yield and Climate Change Economic Impact Assessment. The acronym does not necessarily match the current use of the framework. It was coined for the [Nassopoulos et al., 2012] paper, dedicated to cost benefit analysis and robust decision making for dam dimensioning adaptation under uncertain climate change. The ODDYCCEIA framework was also used to analyze imbalances between water supply and irrigation demand in the Mediterranean basin under climate change [Portoghese et al., 2013].

Irrigation requirements are defined as the deficit between the potential crop evapotranspiration and the effective precipitation. Effective precipitation is computed following [Döll et al., 2003]. Crop evapotranspiration is computed for the different stages of the growing season using [Allen et al., 1998] method. [AQUASTAT Program, 2007] is used for crop calendars, and growth phases are assumed to remain of the same duration in the future. The reference evapotranspiration ( $ET_0$ ) is computed following the Hargreaves method. Then crop evapotranspiration ( $ET_c$ ) is determined using crop coefficients ( $K_c$ ) values from [Allen et al., 1998]:  $ET_c = ET_0 \cdot K_c$ .

For each crop  $c$  localised in perimeter  $l$  and for each month  $m$ , the monthly irrigation water demand  $W_{c,l,m}$  is:

$$W_{c,l,m} = \left[ \sum_{\phi} (d_{\phi,m} \cdot ET_{0g} \cdot K_{c\phi,c}) - P_{effg} \right] \cdot A_c$$

with  $d_{\phi,m}$  the number of days of each growth stage  $\phi$  in month  $m$ ,  $ET_0$  the daily reference evapotranspiration,  $P_{eff}$  the monthly effective precipitation,  $g$  the nearest climatology grid point,  $K_{c\phi,c}$  the crop coefficient for phase  $\phi$  and crop  $c$ , and  $A_c$  the crop area.

Future irrigation needs are affected by climate change. Climatic data are taken from the Centre National de Recherches Météorologiques (CNRM) climatic model [Dubois et al., 2012] outputs, using the A1B IPCC-SRES emission scenario.

Sixteen types of crops are differentiated in the ODDYCCEIA methodology: cotton, fodder, fruits, maize, oil-seed, oil-tree, potatoes, pulses, rice, rubber, sorghum, sugar beet, sugarcane, tobacco, vegetables and wheat.

## 2.2.2 Irrigation water value

### Yield comparison approach

We estimate irrigation water value based on a “yield comparison approach” [Turner, 2004], a simple approach derived from the residual method [Young, 2005], in which respective costs and benefits of rainfed and irrigated production are compared. For a given crop in a given location, the additional profits made possible by irrigation are compared to its additional costs, and the value of water consists in the additional net benefits associated with the use of water.

We compute the value of water for each ODDYCCEIA crop type, in each irrigation perimeter location (i.e. at the  $0.5^\circ$  per  $0.5^\circ$  grid cell scale), as follows:

$$V = (B_{ir} - B_{r.f})/W$$

Where  $V$  is the volumetric value of irrigation water (in US\$/m<sup>3</sup>).  $B_{ir}$  is the net benefit obtained by the irrigated production of a given crop in a given



location (in US\$/ha), and  $B_{rf}$  is the net benefit that would be obtained if this crop was rainfed.  $W$  is the quantity of water used for irrigating the crop in this irrigation perimeter (in m<sup>3</sup>/ha).  $V$  can be negative if the additional profits generated by irrigation do not offset its additional costs. In this case, rainfed production is preferable to irrigated production.

We assume that, for a given crop in a given location, production costs (fertilizers, labor etc.) are identical<sup>2</sup> for an irrigated or a rainfed crop, and that the only difference in costs between rainfed and irrigated production comes from the cost of irrigation (investment, operation and maintenance costs). This enables us to compute the value of water despite the lack of data on agricultural production costs. It gives a simple expression of the value of water:

$$V = ((Y_{ir} - Y_{rf}) \cdot P - C_{ir})/W$$

Where  $Y_{ir}$  and  $Y_{rf}$  are irrigated and rainfed crop yields (in tons/ha),  $P$  is the price of the crop (in US\$/ton),  $C_{ir}$  is the cost of irrigation (in US\$/ha) and  $W$  is the quantity of water used for irrigation (in m<sup>3</sup>/ha). The following paragraphs describe how the different terms of this expression are computed.

Irrigation needs ( $W$ ) are estimated following the methodology described in Section 2.2.1. In this methodology, irrigated crops are assumed to be irrigated to the potential.

### Prices and costs

Crops prices ( $P$ ) are taken from country scale FAOSTAT data [FAOSTAT, 2013], for a representative crop for each ODDYCCEIA crop type. We assume that the price of an irrigated and a rainfed crop is identical. Unfortunately, data is not always available for every year and assumptions may have to be made on a country basis. For the application to Algerian basins, we selected a representative year among those for which data is available (Appendix 2.A). For one crop type, sugar beet, price is not directly available in FAOSTAT data. It has to be reconstructed based on the price of raw sugar from Pink Sheet data [World Bank, 2013]. Authors' calculations are described in Appendix 2.B.

Precise and localized data on irrigation costs ( $C_{ir}$ ) are not available at global scale. Therefore, assumptions have to be made depending on the region of application of the model. For Algeria we estimate irrigation costs as follows. Irrigation costs consist of investment costs plus operation and maintenance costs. We assume that investment costs represent 150 US\$/ha/year, which is the average cost for irrigation projects in Algeria,

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<sup>2</sup>We assume that both the irrigated and the rainfed crop receive the same quantity of inputs, even if inputs do not have the same efficiency. We also assume that the difference in harvest costs due to the difference in yields is low compared with total cost per hectare.

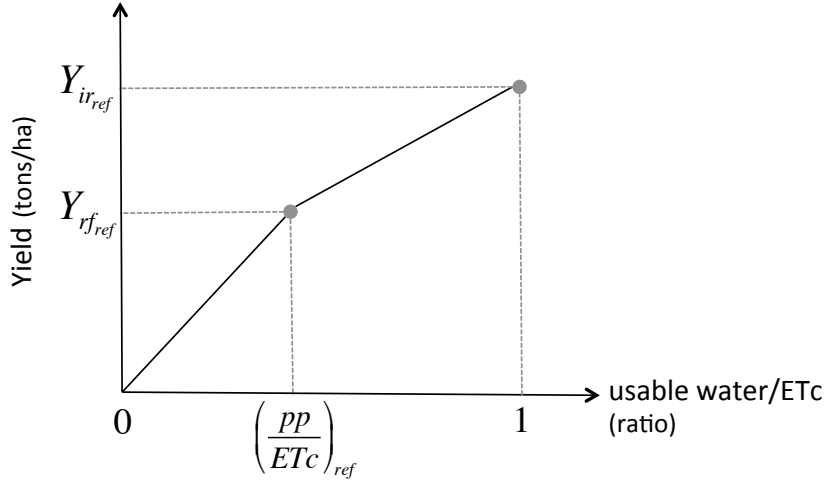


Figure 2.1: Modeling crop yield as a function of available water to ETc ratio.  $Y_{ir_{ref}}$  and  $Y_{rf_{ref}}$  are irrigated and rainfed crop yields of reference (in tons/ha),  $ETc$  is the crop evapotranspiration,  $pp$  the effective precipitation. Irrigated crops are considered to be irrigated to the potential so, with  $W$  the quantity of irrigation water, by construction  $(pp + W)/ETc$  is always equal to one.

calculated based on [Inocencio et al., 2007] with a 5% interest rate and a thirty years lifetime of the equipment. Data on operation and maintenance costs is very heterogeneous. Based on reports and working papers on irrigation costs in African countries [Perry, 1996, SNC-Lavalin International Inc., 2010, Takeshima et al., 2013], operation and maintenance costs are assumed to represent 150 US\$/ha/year on average.

### Yield function

In order to determine irrigated and rainfed yields ( $Y_{ir}$  and  $Y_{rf}$ ) in future hydro-climatic conditions, we model yield as a simple function of usable water and ETc.

The simple piecewise linear yield function (Figure 2.1) is calibrated for each crop type in each location by means of these two points of reference: the couples (yield of reference, usable water to ETc ratio of reference), for rainfed and irrigated crops. Hence, for each crop type in each irrigation perimeter location, we have to determine *i*) historical usable water-to-ETc ratios, and *ii*) historical rainfed and irrigated yields.

For rainfed crops, historical precipitation-to-ETc ratios are computed at the  $0.5^\circ$  per  $0.5^\circ$  spatial resolution, based on average precipitation and ETc outputs of the CNRM climatic model [Dubois et al., 2012] calculated over fifty past climatic years. For irrigated crops, by construction, usable water-

to-ETc ratio is always equal to one (Figure 2.1).

Lund-Potsdam-Jena managed Land (LPJmL) [Bondeau et al., 2007] provides data on potential and actual yields for rainfed and irrigated crops, at the  $0.5^\circ$  per  $0.5^\circ$  spatial resolution, on a global scale. This data is available only for a certain number of crop types. Therefore, we use two different methodologies to reconstruct crops yields of reference, depending on crop types.

For ODDYCCEIA crop categories matching LPJmL crop types (Table 2.4), we use LPJmL data. First, data are corrected for inconsistencies<sup>3</sup>. Then, to make sure that the difference in yield between irrigated and rainfed crops is due only to the water used, and not to differences in inputs or soil quality, we do not use actual irrigated yields from LPJmL. Instead, we use potential irrigated yields, corrected by the same actual-to-potential yield gap ratio as the one observed for rainfed yields. Yield gap ratios between potential and actual rainfed yields are very variable between crops and grid cells. In order to reduce possibly unrealistic heterogeneities, we define both irrigated and rainfed yields of reference as LPJmL potential yields scaled by the average actual-to-potential yield gap ratio. The average yield gap ratio is computed across all rainfed crops at the country scale. Finally, for each crop in each location the yields of reference are calculated as:  $Y_{ref,rf} = Y_{pot,rf} \cdot \bar{r}_{Y_{gap}}$ , and  $Y_{ref,ir} = Y_{pot,ir} \cdot \bar{r}_{Y_{gap}}$ , where  $\bar{r}_{Y_{gap}}$  is the average yield gap ratio between potential and actual yields, and  $Y_{ref}$  and  $Y_{pot}$  are yields of reference and potential yields for rainfed (*rf*) or irrigated (*ir*) crops.

For the other crop categories, data on localized yields is not available. Therefore, we use data on national production and area per crop from [FAO-STAT, 2013], which we aggregate to match our crop categories (Appendix 2.C), and we make a simple assumption on yield ratios in order to reconstitute irrigated and rainfed yields. We suppose that a country's total agricultural production for a crop type is:

$$Q_{tot} = Q_{rf,tot} + Q_{ir,tot} = \bar{Y}_{rf} \cdot S_{rf,tot} + \sum_{cells} (Y_{ir,cell} \cdot S_{ir,cell})$$

Where  $Q_{tot}$  is the total quantity produced (in tons),  $Q_{rf,tot}$  and  $Q_{ir,tot}$  are total rainfed and irrigated productions (in tons),  $S_{rf,tot}$  is the total rainfed area (in ha) and  $\bar{Y}_{rf}$  is the mean rainfed yield (in tons/ha) in the country.  $S_{ir,cell}$  and  $Y_{ir,cell}$  are the irrigated area and the irrigated yield in each grid cell of  $0.5^\circ$  per  $0.5^\circ$ . Then, we assume that in every grid cell:

$$Y_{(ir,cell)} = \bar{Y}_{rf} \cdot ETc_{cell}/pp_{cell}$$

---

<sup>3</sup>For a given crop in a given grid cell, if potential yield is inferior to actual yield (for both rainfed and irrigated crops) or if potential irrigated yield is inferior to potential rainfed yield, data are corrected so that both yields are equal to the highest value.

Where  $pp_{cell}$  and  $ET_{c_{cell}}$  are historical precipitation and ETc in the considered grid cell, calculated over fifty past climatic years. And:

$$\bar{Y}_{rf} = Q_{tot} / (S_{rf,tot} + \sum_{cells} (ET_{c_{cell}} / pp_{cell} \cdot S_{ir,cell}))$$

In this way we can determine an average historical rainfed yield and a localized historical irrigated yield per crop type.

Yield data sources used for each ODDYCCEIA crop category and crop types equivalences are displayed in Appendix 2.A and Appendix 2.C.

Once the simple yield function calibrated with the two points of reference, future yields can be easily computed for each crop type in each grid cell, as a function of future hydro-climatic conditions (Figure 2.1): rainfed yield will be a function of future effective precipitation-to-ETc ratio, whereas irrigated yield will always match the potential irrigated yield since by construction the quantity of water used for irrigation is computed as the deficit between precipitation and ETc. To take into account future yield increases associated to an increased use of other inputs, we add a yield change multiplier. Its value is taken from [Alexandratos et al., 2012] data, for corresponding crop types in Algeria at the 2050 horizon (Appendix 2.A).

As with the residual method, the methodology results in the estimation of average values. For each crop in each location we obtain a past value of irrigation water based on historical yields and climatic conditions, and a future value of irrigation water based on future climatic conditions and yield change multipliers, computed over fifty climatic years.

### 2.2.3 Projection and valuation of municipal water demand

#### Building demand functions

For the domestic sector, the value of water is usually evaluated using econometrically estimated demand functions at the basin scale [Arbués et al., 2003]. Given the low data availability when working at a large scale, we developed a framework to build generic demand functions [Neverre and Dumas, 2015].

Our approach is to build simple three-part inverse demand functions (Figure 2.2): the first part consists of basic water requirements for consumption and hygiene, which are very highly valued (e.g. drinking water); then the second part consists of additional hygiene and less essential uses, which are less valued than those of the first part (e.g. regular laundry); finally the third part consists of further indoor uses and outdoor uses which are the least valued (e.g. lawn watering).

Then, we allow for the structure of our demand function to evolve over time, in order to take into account the effect of economic development on demand (Figure 2.2). As GDP per capita increases, households get more water

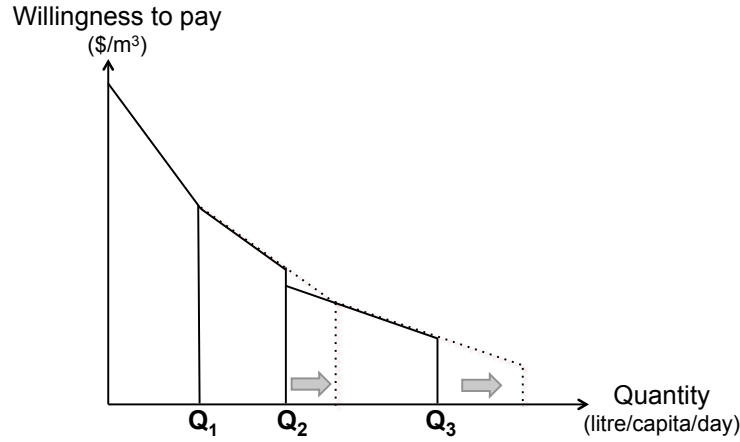


Figure 2.2: Domestic water demand function: economic development effect.  $Q_1$ ,  $Q_2$  and  $Q_3$  are the volume limits of the three demand parts. The gray arrows represent the effect of economic development, which leads to larger demand by expanding the width of the blocks.

using appliances (e.g. washing machines) and demand more water, until they eventually reach equipment saturation and water demand stabilizes even if income continues to grow. This economic development effect was modeled in the WaterGAP model [Alcamo et al., 2003a]. We use a similar methodology, but incorporate it into our economic demand function framework: the size of the blocks of the demand function are scaled by economic development. The width of the second and third blocks grow with the level of GDP per capita, as illustrated in Figure 2.2. We assume that basic needs are not affected by this equipment effect, and the width of the first block is assumed fixed and based on literature [Howard and Bartram, 2003, Gleick, 1996].

Willingness to pay is estimated for some demand points of reference, based on econometric studies [Nauges and Thomas, 2000, Schleich and Hillenbrand, 2009, Frondel and Messner, 2008] and price data (domestic water prices, bottled water prices), then interpolated linearly to form the slopes of the blocks.

Demand can be projected for a given year  $t$  following these steps: first, determine  $Q_{int}$  and  $Q_{tot}$  depending on the level of GDP per capita on year  $t$ . This enables to build the economic demand function for that year  $t$ . Second, project price for year  $t$ , and determine the level of demand for that level of price based on the economic demand function (Figure 2.3). Then the value of water can be computed: it consists of the economic surplus, i.e. the difference between willingness to pay and the actual cost of water, (Figure 2.3).

The domestic demand functions we model account for both household uses, and commercial and collective uses.

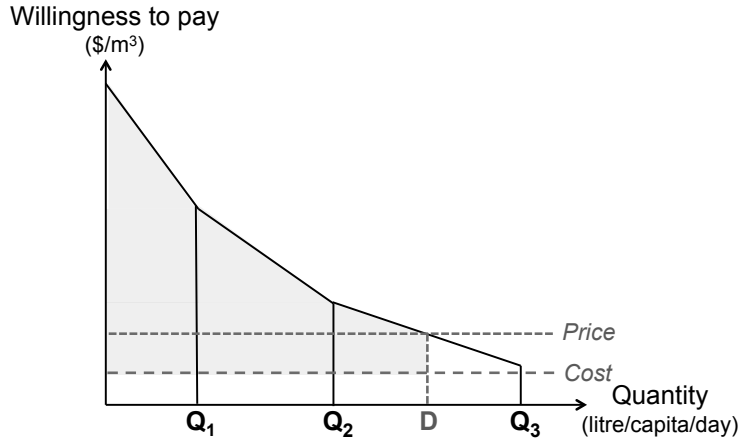


Figure 2.3: Domestic water demand function: surplus.  $D$  is the level of demand corresponding to the level of price. The gray-colored area under the curve represents total economic surplus.

### Spatial distribution

Current urban areas localization and population distribution are taken from the Global Rural-Urban Mapping Project (GRUMP) database [Center for International Earth Science Information Network (CIESIN) et al., 2004]. We assume that the localization of future urban areas remains the same as in 2000, and that future population growth is homogeneously distributed among existing locations (the population ratio of each city over the total population remains unchanged).

#### 2.2.4 Demand-reservoir-basin association

Agricultural demands and values are computed at a thirty minutes spatial resolution, and then aggregated at the basin scale. Domestic demands and values are computed at national scale, and then distributed at the basin scale. The basin-scale distribution of demands is performed as follows.

To associate demands with basin, we first associate reservoirs to basins and then demands to reservoirs. Reservoirs are located using [AQUASTAT Program, 2007]. Associations of demands to reservoirs are not known at a country or regional level. To reconstruct reservoir-demand links, we use a method based on topological constraints with a penalization of distance covered and altitude difference of ascending moves, along the supply-demand path. Water balance constraint on the network mean annual supply and consumptive demand are also taken into account while minimizing the total cost of associations [Portoghese et al., 2013]. Demands associated to a reservoir can potentially be situated in an adjacent basin.

## 2.3 Application to Algeria

### 2.3.1 Scenarios

Crops future water needs, yields and water values were determined for each crop type in each irrigation perimeter, depending on average future climatic conditions from fifty future climatic years of CNRM model outputs, for the A1B IPCC-SRES emission scenario. Irrigation water value was computed under two different scenarios of future crops prices evolution: either crops prices remained equal to present prices, or crops prices increased in the future. The price increase scenario follows Nexus Land Use model [Souty et al., 2012] outputs for a baseline scenario [Brunelle et al., 2015], as described in Appendix 2.D.

Domestic water demand projection was performed for various socioeconomic scenarios: five Shared Socioeconomic Pathways [Rozenberg et al., 2014] for GDP evolution, combined with three population projection scenarios from the UN ([UN, 2009] - low, medium and high variants). Water cost and water price were assumed to increase over time along with the following scenario ([Neverre and Dumas, 2015]): the cost of water increases with GDP per capita, towards the cost of a mature water distribution and sewerage service (current cost level in France was chosen as a representative target cost of reference); cost-recovery ratio converges towards one as GDP per capita grows. Water cost reaches the target cost level and cost-recovery ratio reaches one when GDP per capita reaches the reference level of GDP per capita in France.

### 2.3.2 Results

The area of application covers fifteen basins (Figure 2.4). Among these, one is an “internal drainage” basin (basin 1), which does not outflow to the sea and corresponds mostly to desert; the remainders are coastal basins (basins 2 to 15). Results of projected demands and values are presented in Table 2.1 for an overview of all fifteen basins, and in Figure 2.5 and Figure 2.6 for a closer look at the respective values of domestic and irrigation water in two representative basins.

Looking at the region as a whole, results show that both domestic demand and irrigation demand increase in the future. Domestic demand becomes a major consumption sector at the 2050 horizon. Its share in total demand (domestic demand plus potential irrigation demand) increases from 16% in historical conditions to 35-45% in 2050, depending on socioeconomic scenarios (Table 2.1). Indeed, domestic demand increase could range from +200% to +358% by 2050, while irrigation demand is modeled to increase by 8% under future climatic conditions (A1B SRES scenario) with constant irrigated areas.

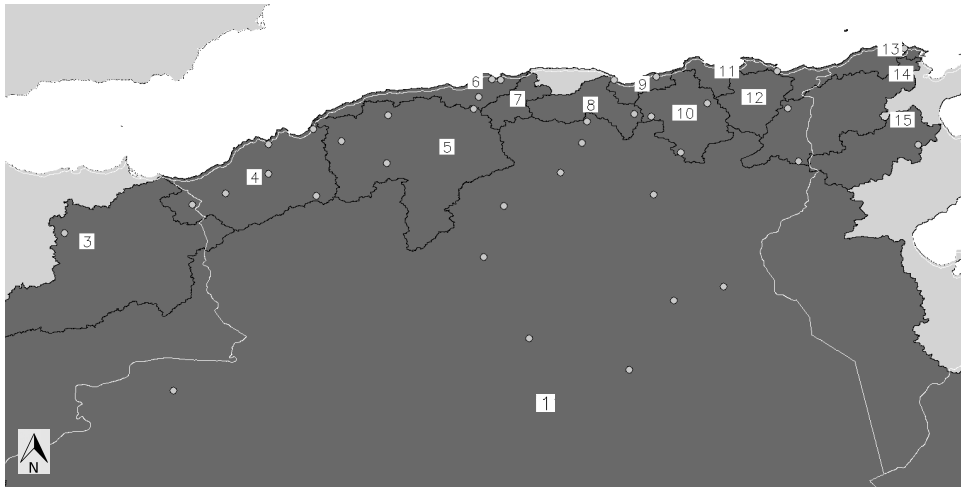


Figure 2.4: Map of Algerian basins, labeled 1 to 15. Basins borders are in black, and Algerian borders in white. The Mediterranean Sea is the white area. White dots represent cities of more than 100,000 inhabitants. Basin 2 is a basin located in western Algeria, that flows mostly through Morocco to the Atlantic Ocean and is out of the scope of this map.

Results are contrasted between the two different types of basins. This contrast is illustrated with projection results for basins 1 and 4 (Figure 2.5 and Figure 2.6). Basin 1 is a very large basin, located in the arid part of Algeria. Runoff is infiltrated and evaporated, and the basin does not outflow to the sea. Basins 4 is one of the smaller basins located in the coastal part of Algeria. They are both cross-border basins (Figure 2.4).

Figure 2.5 and Figure 2.6 show annual sectorial water demands at the basin scale, ordered by decreasing value. The three-part structure of our domestic demand-function modeling framework is identifiable, with high valued basic uses, followed by less valued intermediate uses, and finally least-valued supplementary uses.

In basin 4 (Figure 2.5), total domestic demand (coming from both Algerian and Moroccan cities) outweighs irrigation demand in 2050. The value of irrigation water is very low compared with the value of domestic water. For Algerian demand, domestic water value is always higher than irrigation water value; for Moroccan demand, only some least-valued domestic uses have a value comparable to irrigation water value.

In basin 1 (Figure 2.6), future irrigation water needs remain much higher than total domestic demand. Irrigation water can have a very high value for some crops, comparable to values of second-block domestic demands (or even first-block domestic demands, in some exceptional cases). A reason may be that in this arid zone crop production is null without irrigation, while with irrigation there is no limitation by radiation. In this basin, water



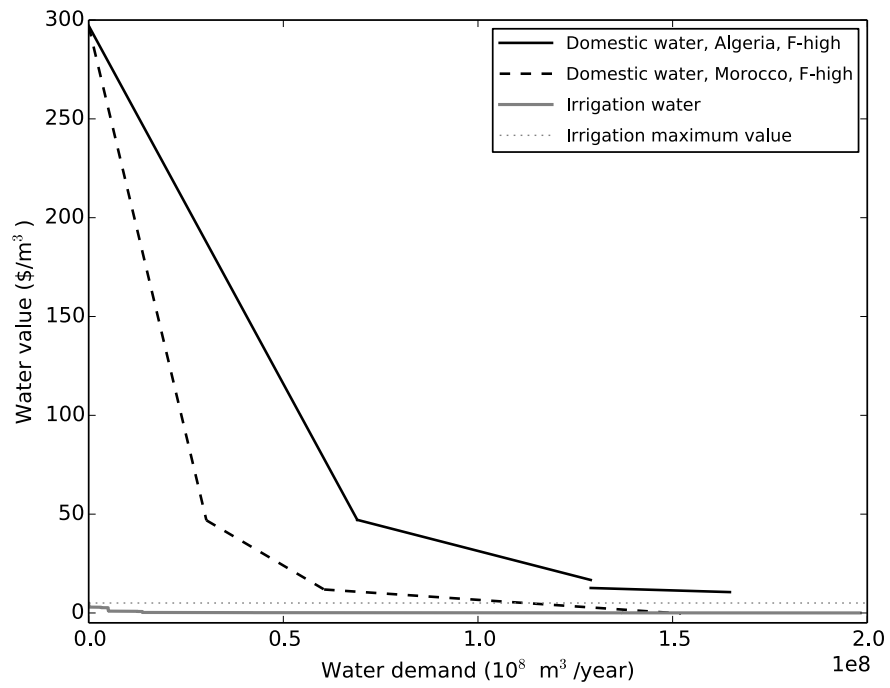


Figure 2.5: Projected domestic and irrigation demands in Basin 4, for year 2050, under the following scenarios: F-med (i.e. medium population variant and SSP2) for domestic demand, and F-0 (i.e. no price increase) for agricultural demand.

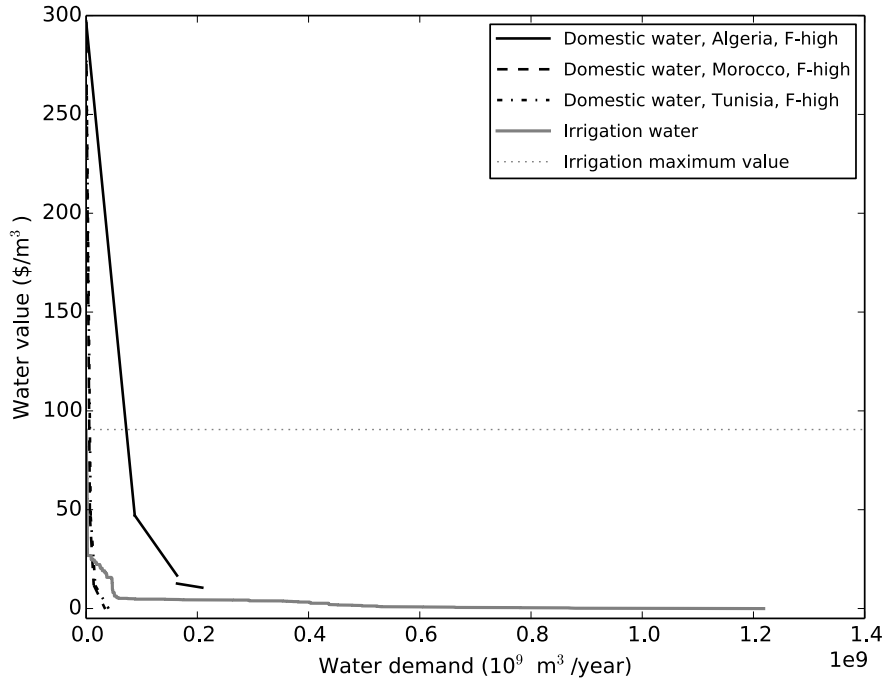


Figure 2.6: Projected domestic and irrigation demands in Basin 1, for year 2050, under the following scenarios: F-med (i.e. medium population variant and SSP2) for domestic demand, and F-0 (i.e. no price increase) for agricultural demand.

allocation based on economic criteria could favor some irrigation demands over non-essential domestic demands.

Population is predominantly distributed in the coastal water basins, where irrigation demand is lower than domestic demand (e.g. basin 4, where Oran, the second largest city of Algeria, is located). Irrigation demands are larger in less-populated areas (e.g. basin 1). The priority given to domestic needs over agriculture can impact the quantity of water allocated to irrigation within a basin, but it can also impact longer-term investments decisions, such as which areas to equip for irrigation, in which basins.

The impacts of different socioeconomic scenarios on future domestic demand are illustrated in Figure 2.7, compared with modeled historical domestic demand. In historical conditions, the third block of domestic demand is small (Morocco) or even inexistent (Algeria). As countries develop and equipment grows, this third-block demand increases. Our results for future projections show that the total quantity demanded is more sensitive to socioeconomic scenarios than is the value of water.

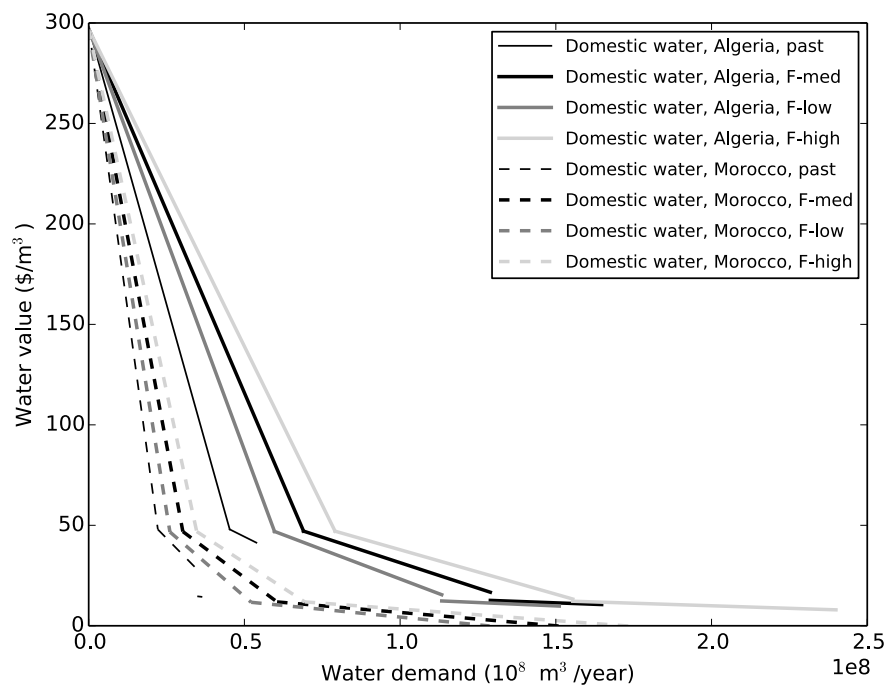


Figure 2.7: Projected domestic demand in basin 4, under historical conditions for year 2000, and under three socioeconomic scenarios for year 2050. Scenarios: F-med (i.e. medium population variant and SSP2), F-low (i.e. low population variant and SSP4) and F-high (i.e. high population variant and SSP5).

Table 2.1: Domestic and irrigation demands and values in Algerian basins. Comparison between modeled historical values and projections at the 2050 horizon under various scenarios. Scenarios for the future are, for the domestic sector: F-med: Medium population variant & SSP2; F-high: High population variant & SSP5; F-low: Low population variant & SSP4. For agriculture: F-0: no crop prices increase; F-1: baseline crop prices increase scenario.

Basin	Domestic sector					Irrigation sector							
	Total demand (million m <sup>3</sup> /year)		Total value of water (million US\$2005/year)			Total demand (10 <sup>6</sup> m <sup>3</sup> /year)		Total value of water (10 <sup>6</sup> US\$2005/year)					
	Historical	F-med	F-low	F-high	Historical	F-med	F-low	F-high	Historical	F-0 & F-1	Historical	F-0	F-1
1	85.1	283.8	255.9	390.0	12,355.8	21,005.4	18,276.6	24,792.7	1,177.2	1,218.3	2,026.5	3,115.7	11,915.2
2	10.4	43.3	36.6	49.7	1,206.2	1,866.3	1,602.7	2,141.2	170.1	180.6	5.4	13.9	89.6
3	11.7	48.8	41.3	56.1	1,360.6	2,105.3	1,807.9	2,415.4	87.7	97.7	2.1	9.8	69.0
4	90.3	316.9	279.8	414.8	12,330.7	20,555.2	17,826.3	24,137.8	173.5	197.6	18.4	42.6	227.1
5	57.4	175.5	161.0	255.7	8,620.2	14,910.6	12,990.6	17,698.2	202.6	239.8	16.0	44.9	258.7
6	112.0	342.5	314.2	498.9	16,821.9	29,097.1	25,350.4	34,537.0	117.1	130.1	13.9	31.4	161.5
7	12.9	39.6	36.3	57.7	1,944.8	3,364.0	2,930.8	3,992.9	18.7	20.2	3.1	6.0	26.8
8	15.5	47.3	43.4	68.9	2,323.3	4,018.7	3,501.2	4,770.0	32.5	35.7	1.7	6.2	33.1
9	7.3	22.4	20.6	32.7	1,102.1	1,906.4	1,660.9	2,262.8	2.1	2.2	0.1	0.3	1.6
10	21.8	66.6	61.1	97.0	3,271.1	5,658.0	4,929.4	6,715.8	10.2	12.2	0.5	2.4	14.5
11	9.2	28.2	25.9	41.1	1,384.7	2,395.2	2,086.8	2,843.0	2.3	2.6	0.5	0.9	4.3
12	29.2	89.3	81.9	130.1	4,385.6	7,585.9	6,609.1	9,004.1	39.5	45.3	9.7	18.2	81.7
13	13.2	60.1	52.4	69.8	1,769.9	2,795.5	2,427.9	3,205.9	29.4	33.8	9.0	17.2	76.7
14	17.9	77.2	67.7	92.5	2,458.1	3,951.5	3,434.0	4,563.3	259.8	298.5	54.0	103.5	459.2
15	5.5	26.1	22.7	29.8	733.2	1,144.9	993.9	1,306.8	285.6	306.6	44.7	81.4	348.6
All	499.4	1,667.6	1,500.8	2,284.8	72,068.3	122,359.9	106,428.5	144,386.9	2,608.2	2,821.4	2,205.5	3,494.5	13,767.6

## 2.4 Discussion and conclusions

The developed methodology enables to project the combined impacts of population growth, economic development and water costs on future domestic water demands, and the impact of climate change on future irrigation water demands, in terms of both quantity and economic benefits.

The methodology projects demands, not withdrawals. In Algeria, the historical demand-to-withdrawal ratio, accounting for distribution losses, is of 50% for both irrigation and domestic water [Margat and Treyer, 2004]. Domestic sector efficiency is about 78.5% and 69% for Moroccan and Tunisian demands in cross-border basins. These efficiency ratios may evolve in the future.

We compared the demands we modeled for historical conditions to historical data gathered by SIMEDD [Plan Bleu, 2012]. In Algeria, historical irrigation withdrawals range from 1.8 to 4 km<sup>3</sup>/year, for the years 2000 to 2002. Our modeled historical demand for Algeria<sup>4</sup> is 19 km<sup>3</sup>/year, which represents a withdrawal of 38 km<sup>3</sup>/year. Three reasons can explain why potential demand could be much larger than actual irrigation. First, not all areas equipped for irrigation do actually irrigate. [Benmouffok, 2004] notes that for Algerian big irrigation perimeters (“grands périmètres irrigués”) irrigated areas represent only about 25% of areas equipped for irrigation. Second, we model irrigation needs required to irrigate to the potential. In reality, crops are not irrigated to the potential because demand is constrained by available water and also because crops can tolerate some level of water constraint. Third, some irrigation perimeters rely on groundwater, especially Saharan basins where there is pumping of fossil groundwater.

Our results show that the domestic sector becomes an important sector of water consumption in 2050, catching up with the irrigation sector. This trend is similar to [Alcamo et al., 2007] results, which is not surprising since we rely on similar assumptions (e.g. we do not model increases in irrigated areas).

With our methodology, irrigation needs increase by 8% under climate change (A1B scenario) in Algeria. The assumption of constant irrigated area could prove to be wrong in 2050. However, at the present time many areas equipped for irrigation are not actually irrigated, and the increase in irrigated areas is constrained by water availability. Increasing irrigation areas would require infrastructure investments, which could be possible in Algeria although the country is already well covered by reservoirs.

[Aylward et al., 2010] gathered water value estimations from various studies, in various countries, for the different sectors. Those estimations show that on average domestic water uses have higher values than irrigation uses. However, there is a large variability between results obtained in the differ-

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<sup>4</sup>Within Algerian frontiers, excluding foreign water demands in cross-border basins.

ent studies, which were carried out in different countries and with various methodologies. For the agricultural sector in Africa, the value of water ranges from 0 to 2 US\$/m<sup>3</sup>. In Algerian basins, a large part of our projected irrigation values falls within that range, but we also have some irrigation uses with higher values.

In our methodology, data on crop mixes are currently taken from Agromaps, which leads to an overestimation of areas of irrigated wheat as we do not select crops that are most likely to be irrigated. In our basins of application, there should be more irrigated vegetables and fruits, and less irrigated wheat. The consequence of this discrepancy could be an underestimation of the total value of irrigation water, since vegetable and fruits tend to be more water limited and high value-added crops. In future works, we could use crop mixes data from MIRCA2000 [Portmann et al., 2010].

In general, water values are very different between uses, the highest being domestic water values. With our results for Algeria, value estimations come close to simple ranking rules between uses, such as what is implemented by [Strzepek et al., 2013]. If total demand cannot be met, they allocate water between the different uses based on absolute priorities: the domestic and industrial sectors are the first to satisfy, then come irrigation and livestock uses. For Tunisia and Morocco, the projected increase in GDP per capita leads to a demand for domestic water extending to low-value uses (Figure 2.5 and Figure 2.6). For such uses, trade-offs with irrigation uses are possible. It must also be noted that a correct valuation of water is important for intertemporal prudential allocation rules, to measure correctly the expected water value.

In light of the global coverage, but also lack of precision at the local level, our methodology is meant to represent local impacts of global changes, by bringing together global and local approaches from the literature. It is however not suitable to build a detailed representation for operational purposes.

In a next step, this demand modeling methodology shall be integrated into the ODDYCCEIA water model framework [Portoghese et al., 2013], in order to build a generic hydroeconomic model bringing together demand and supply sides. The modular and generic nature of the framework, which only requires globally available data, makes it suitable to apply to diverse regions, in particular to developing regions with low data-availability. This model could be applied to the study of any issue requiring a wide area, such as virtual water trade, evolution of the energy sector water use, or activities and population relocalizations due to water supply reduction or water demand value changes.

## Appendices

### 2.A List of crop types in Algeria and data sources for each crop type

Cf. Table 2.2.

### 2.B Computation of the price of sugar beet

Sugar is extracted from sugar beet. In the process, sugar can be obtained directly from the refining of the beet, and then some additional sugar can be obtained from further processing the molasses (refining byproducts). Therefore, we compute the price of sugar beet as follows:

$$P_{SugarBeet} = P_{RawSugar} \cdot (r_{sugar} + (r_{molasses} \cdot \tau_{sucrose} \cdot \pi_{sucrose} \cdot y_{sucrose}))$$

Where  $P_{RawSugar}$  is the price of raw sugar (in US\$/ton),  $r_{sugar}$  and  $r_{molasses}$  are the weight ratios of sugar and molasses available in sugar beet,  $\tau_{sucrose}$  is the ratio of sucrose in molasses,  $\pi_{sucrose}$  is the purity of sucrose in molasses, and  $y_{sucrose}$  is the reachable sucrose yield ratio from molasses. Data sources and values are displayed in Table 2.3.

This price does not take into account transformation costs, nor sugar beet pulp coproduct. Overall, it is probably an overestimation of the sugar beet price.

Table 2.3: Data used for the computation of sugar beet price

Technical parameters		Value	Data source
$r_{sugar}$	Sugar weight ratio in sugar beet	0.14	FAO (1996)
$r_{molasses}$	Molasses weight ratio in sugar beet	0.035	
$\tau_{sucrose}$	Ratio of sucrose in molasses	0.5	Broughton (1983)
$\pi_{sucrose}$	Purity of sucrose in molasses	0.995	
$y_{sucrose}$	Sucrose extraction yield ratio from molasses	0.965	

### 2.C ODDYCCEIA crop categories: LPJmL crop types equivalents, and aggregation of FAO crop types

Cf. Table 2.4

Table 2.4: LPJmL and FAO crop types and ODDYCCEIA crop categories (nes: not elsewhere specified)

ODDYCCEIA crop categories	LPJmL crops
Maize	Maize
Pulses	Field pea
Rice	Rice
Sorghum	Millet
Sugar beet	Sugar beet
Wheat	Wheat
ODDYCCEIA crop categories	FAOSTAT crops
Fruits	Fruits, nes <sup>*</sup> ; Citrus, nes; Apples; Apricots; Cherries; Figs; Grapes; Oranges; Peaches and nectarines; Pears; Plums and sloes; Quinces; Sour cherries; Tangerines, mandarins, clem.; Dates; Grapefruit (inc. pomelos); Stone fruit, nes; Lemons and limes; Bananas; Plantains; Citrus fruit, nes; Kiwi fruit; Avocados; Persimmons; Mangoes, mangosteens, guavas; Papayas; Pineapples; Tea; Lemons and Limes; Grapefruit and Pomelos; Peaches and Nectarines; Peaches and nectarines; Berries nes; Fruit, tropical fresh nes; Plums; Tang.Mand.Clement.Satsma; Cloves, Whole+Stems; Cloves; Citrus Fruit nes; Fruit Fresh nes; Gooseberries; Raspberries; Blueberries; Cranberries; Coffee, green; Coffee, Green; Cocoa beans; Cocoa Beans; Coconuts; Kolanuts; Maté; Arecanuts; Vanilla; Pome fruit, nes
Oil-tree	Olive; Almonds, with shell; Carobs; Hazelnuts, with shell; Olives; Walnuts, with shell; Pistachios; Chestnuts; Nuts, nes; Almonds; Walnuts; Hazelnuts (Filberts); Oil palm fruit; Oil Palm Fruit; Karite Nuts (Sheanuts); Cashew nuts, with shell; Cashewapple; Cashew Nuts; Brazil nuts, with shell
Potatoes	Sweet potatoes; Roots and Tubers, nes; Yams; Cassava
Tobacco	Tobacco, unmanufactured; Tobacco Leaves
Vegetables	Cabbages and other brassicas; Carrots and turnips; Cauliflowers and broccoli; Chicory roots; Chillies and peppers, green; Chillies and peppers, dry; Cucumbers and gherkins; Garlic; Lettuce and chicory; Onions; Onions, dry; Onions (inc. shallots), green; Onions+Shallots, Green; Onions, Dry; Pepper,White/Long/Black; Pepper (Piper spp.); Pumpkins, squash and gourds; Eggplants (aubergines); Strawberries; Tomatoes; Vegetables fresh nes; Watermelons; Other melons (inc.cantaloupes); Artichokes; Asparagus; Spinach; Anise, badian, fennel, corian.; Okra; Cabbages; Eggplants; Cucumbers and Gherkins; Cauliflower; Carrots; Lettuce; Pumpkins, Squash, Gourds; Melonseed; Cantaloupes&other Melons; Chillies&Peppers, Green; Spices, nes; Currants; Peppermint; Ginger; Mushrooms and truffles; Nutmeg, mace and cardamoms; Cinnamon (canella); Pimento, Allspice

\* not elsewhere specified



## 2.D Scenario of future crops prices increase

Increased crops prices for year 2050 are taken from Nexus Land Use (NLU) model [Souty et al., 2012] outputs, following the scenario described below [Brunelle et al., 2015]. The main scenario variables are the following: food and biofuel consumption, evolution of forest areas, prices of other agricultural inputs. When possible, they are set to reproduce as closely as possible the values provided by [Alexandratos et al., 2012].

Food availability given by the FAO is corrected to include animal fat and exclude fisheries products. In 2050, the NLU average food availability amounts to 3727 kcal/capita/day in the OECD countries and the CIS and to 3092 kcal/capita/day in the other countries. With a population growing according to the median scenario projected by the United Nations [UN, 2009], this leads to a global increase in food consumption by 57% over the 2005-2050 period (+1.0% per year).

The biofuel scenario is deduced from the world use of crops for biofuels provided by [Alexandratos et al., 2012]. The biofuel production grows from 4 million-tons equivalent of petroleum (Mtep) in 2005 to around 64 Mtep in 2020, and remains constant thereafter. Only first generation biofuels are considered.

In these simulations, the demand for calories is supposed to be inelastic to prices. From this point of view, the results used here can be considered as an upper bound since the possible reduction in food or biofuel demand, due to higher food prices may indeed mitigate the impact on land-use of higher fertilizer price. However, given the weak elasticity of food demand to price<sup>5</sup>, this effect is thought to be small.

The deforestation rate is exogenously set according to the observed trends over the period 2001-2010 [FAO, 2010], assuming that reforestation that occurs in some regions (such as in the US or China) ceases after 2020. The evolution of total agricultural areas (pasture and cropland area) is directly deduced from reforestation/deforestation rates.

The evolution of fertilizer price is econometrically related with the evolution of oil and gas prices. This equation is estimated over the 1971-2011 period based on World Bank data [World Bank, 2013]. For future projections, oil and gas prices from the Imacim-R model [Bibas and Méjean, 2014] are used, assuming no climate policy.

Results are available for twelve geographical regions: USA, Canada, Europe, OECD Pacific, Former Soviet Union, China, India, Brazil, Middle-East, Africa, rest of Asia, rest of Latin America. The scenario described above leads to a +3.20% average annual crops price increase rate worldwide, and +2.75% in Africa.

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<sup>5</sup>Biofuel demand is also considered to be weakly price elastic as it is largely driven by national mandates.

Table 2.2: Data sources for Algerian crop types

ODDYCCEIA	Yield	Future yield change	Price
Crop type	LPJmL (Bondeau et al., 2007) or FAOSTAT data (FAO, 2013)	Alexandratos and Bruinsma (2012) data	FAOSTAT data (FAO, 2013)
Fruits	FAOSTAT, aggregation	Oranges, Mandarines	Oranges (2005)
Maize	LPJmL, Maize	Maize	Maize (1995)
Oil-tree	FAOSTAT, aggregation	Olives	Olives (1995)
Potatoes	FAOSTAT, aggregation	Potatoes	Potatoes (2005)
Pulses	LPJmL, Field pea	Pulses	Peas, green (2004)
Rice	LPJmL, Rice	Rice	Rice, paddy (1992)
Sorghum	LPJmL, Millet	Sorghum	Sorghum (1995)
Sugar beet	LPJmL, Sugar beet	Roots and tuber	Authors' computation
Tobacco	FAOSTAT, aggregation	Tobacco	Tobacco, unmanufactured (1995)
Vegetables	FAOSTAT, aggregation	Tomatoes	Tomatoes (2005)
Wheat	LPJmL, Wheat	Wheat	Wheat (2005)



## Part II

# SUPPLY SIDE: OPERATION OF THE RESERVOIRS' SYSTEM



## Chapter 3

# Benefits of economic criteria for water scarcity management under global changes

In order to assess localised water constraints, this chapter compares localised water demands (Chapter 2) to water supply. It presents the reconstruction of reservoirs-demands networks, and the operation of water management infrastructures.

### 3.1 Introduction

Climate change, demographic growth and economic development are expected to impact the water supply-demand balance and exacerbate water scarcity issues in the Mediterranean region in the next decades. In this context, there is a need for water resources assessments to anticipate future water scarcity issues and their economic impacts. For water using sectors, water shortages mean unrealised benefits.

The Mediterranean region is well equipped with dams [Margat and Treyer, 2004]. Man made reservoirs have an important impact on water fluxes [Biemans et al., 2011, Haddeland et al., 2013]. They help regulate climatic variability in time and space, to distribute water when needed by demands. Moreover, when water is scarce reservoirs can help increase the water benefits, by allocating the available water to the most valuable uses. In hydroeconomic models, water allocation between competitive uses is based on the economic benefits they generate [Harou et al., 2009], and reservoirs can be managed with the objective of maximising the total economic benefits generated by water uses. Although economic rules are not often used in practice, water valuation could be used as a proxy for allocation policies, in the absence of precise information on the priorities set between the different demands in the different basins.

Taking into account the economic value of water enables not only to allocate water to the most valuable uses, but also to estimate the direct costs of water scarcity, in terms of unrealised economic benefits. To do so, a first step is to measure the benefits of water in its different uses, i.e. to determine the economic value of water [Young, 2005]. Then assessing the missing quantity of water gives the corresponding unrealised economic benefits. Knowing water value in its different uses, it is possible to manage the available water so as to minimise the economic costs of scarcity.

In this work, we examine if reservoir operation rules designed to maximise the economic benefits of the allocated water can help reduce the costs of future water scarcity under global changes in the Mediterranean.

Water resources assessments can be carried out at various spatial levels, from the catchment level to the global scale, with different levels of complexity for the water management infrastructure representation.

At the river basin scale, reservoirs can be represented as a network, with a nodal structure, and managed in a coordinated way. Some river basin level assessments cover extended geographic areas, as does the CALVIN model in California [Medellín-Azuara et al., 2008]. But such models are developed for a specific basin or area, and use detailed data that are not generic. Some tools are developed to be flexible, and easily implemented to different basins, for instance the Water Evaluation And Planning system (WEAP) [Stockholm Environment Institute, 2011], but they also have high data requirements. In general, local scale approaches require a lot of data, which is not available at a large scale, and they are not applicable to regions where data is scarce.

In the global scale literature, the representation of reservoirs networks is challenging. Some studies do not represent reservoirs. The water resources assessment can be grid-based, without flow routing [Arnell, 2004]. Some grid-based studies consider grid cell “storages”, which are linked through flow routing [Oki et al., 2001]. Other assessments take into account reservoirs, either without specific operation rules [Döll et al., 2003], or with reservoirs operating individually with generic rules [Hanasaki et al., 2008, Ward et al., 2010], or with optimised individual operation rules [Haddeland et al., 2007]. In general, global scale studies lack to consider the nodal structure of reservoirs systems and the possibility of coordinated operation of reservoirs for a better supply-demand balance.

The economic dimension is taken into account at the river basin scale [Medellín-Azuara et al., 2008, Pulido-Velazquez et al., 2008]. Many basin-scale hydroeconomic models were developed [Harou et al., 2009]. However, in the large-scale literature approaches are mostly quantitative [Alcamo et al., 2007, Hanasaki et al., 2013a, Hanasaki et al., 2013b, Schewe et al., 2013, Strzepek et al., 2013]. Some large-scale studies incorporate an economic assessment, by considering the costs of water infrastructure adaptation to climate change [Hughes et al., 2010, Ward et al., 2010] necessary to meet projected demands. Some approaches introduce priorities between water

uses, for instance [Strzepek et al., 2013] use ranking rules (absolute priorities) between uses: domestic and industrial uses are the first in priority, then come irrigation and livestock uses. But water valuation [Young, 2005] is absent from the large-scale literature.

In order to investigate water scarcity issues in the Mediterranean under global changes, and the benefits of reservoirs management rules based on economic criteria, we use generic hydroeconomic modelling. We develop a model able to compare future water supply and demand on a large scale, while representing river basin heterogeneity. It takes into account man-made reservoirs and their coordinated operation, which relies on an evaluation of water economic benefits in the different water using sectors.

This paper first presents the methods for demand and supply projection, and for the reconstruction of the water network and the operation of the reservoirs systems. The framework is then applied to Algeria, at the 2050 horizon.

## 3.2 Projection of future inflows and demands

### 3.2.1 Runoff and flow accumulation

On the supply side, we evaluate the impacts of climate change on water availability, following the ODDYCCEIA methodology [Portoghese et al., 2013].

Water inflows to the reservoirs are computed at the monthly time step. Each reservoir's inflow corresponds to the summed runoff over the reservoir's upstream sub-basin, similarly to [Islam et al., 2005]. The sub-basin flow-accumulation area of each reservoir is determined based on a Digital Elevation Model [HYDRO1k, 2009]. Runoff data are taken from the CNRM climatic model outputs per grid cell [Dubois et al., 2012], for the A1B scenario.

### 3.2.2 Projecting water demands and values

On the demand side, we focus on the two main sectors of water use: irrigation, which represents 65% of water uses in the Mediterranean basin and 58% in Algeria, and the domestic sector, which accounts for 13% of water uses in the Mediterranean basin and 27% in Algeria [Margat and Treyer, 2004]. Irrigation and domestic demands are projected in terms of both quantity and economic value.

#### Irrigation sector

Irrigation water demand is projected under climate change (A1B scenario), for twelve different types of crops, at the 0.5° spatial resolution.



Globally available data on irrigated areas and crops are combined in order to determine irrigated crops localisation. Then, crops irrigation requirements are computed as the difference between potential crop evapotranspiration (ET<sub>c</sub>) and usable precipitation, for the different stages of the growing season, following the Allen method [Allen et al., 1998], as in ODDYCCEIA [Portoghese et al., 2013].

The economic value of irrigation water is calculated using a yield comparison approach between rainfed and irrigated crops: additional profits made possible by irrigation are compared to its additional costs, and the value of water consists of the additional value added associated with the use of water. In order to estimate irrigated and rainfed yields under future hydro-climatic conditions, we model yield as a simple function of usable precipitation and ETP.

Further details on the methodology are available in Appendix 3.B.

### Domestic sector

We project the combined effects of demographic growth, economic development and water cost evolution on future domestic demands. Our methodology is to build three-part inverse demand functions, at the country scale [Neverre and Dumas, 2015]. The economic value of domestic water is defined as the economic surplus (i.e. difference between the marginal willingness to pay for water and the cost of water along the demand curve). Further details on the methodology are available in Appendix 3.A.

Projected demands are then spatially distributed. Current urban areas localisation and population distribution are taken from the GRUMP database [Center for International Earth Science Information Network (CIESIN) et al., 2004]. We assume that the location of future urban areas remains the same as present, and that future population growth is homogeneously distributed among existing locations (the population ratio of each city over the total population remains unchanged).

## 3.3 Reconstruction of the network

Information on the physical links between reservoirs and demands are not available at large scale, the network has to be reconstructed.

### 3.3.1 Demand-reservoir association

Reservoirs are located using Aquastat [AQUASTAT Program, 2007], and the reservoir network is reconstructed by defining upstream-downstream reservoir links.

A generic methodology was developed for the determination of demand-reservoir links [Portoghese et al., 2013]. Links are reconstructed based on a

topological cost constraint, with a penalisation of distance covered and uphill moves along the potential supply-demand paths. The paths start from the stream that flows down from the reservoir, not from the reservoir itself. For a reservoir  $r$  and a demand  $i$ , the cost of the  $r, i$  link is:

$$cost_{r,i} = \min_{path} \left( d_{r,i}^{path} + 10^4 \cdot H_{r,i}^{path} \right) \quad (3.1)$$

with  $d_{r,i}^{path}$  the distance covered along a supply-demand path and  $H_{r,i}^{path}$  the altitude differential of uphill movements along the path. A penalty coefficient of  $10^4$  is attributed to uphill movements, implying that going up one meter is  $10^4$  times more costly than covering one meter horizontally. The path corresponding to the minimum cost is the supply-demand path for this reservoir-demand couple  $r, i$ . Each demand is associated to only one reservoir.

### 3.3.2 Order of the demands on a stream

Water demands are not entirely consumptive (Table 3.1), they generate return flows that may help satisfy downstream demands. In order to take into account return flows, it is necessary to know the order of the demands' water intakes on the stream.

Table 3.1: Consumptive rates for different water uses (source: Margat and Treyer, 2004)

Sector	Consumptive rate
Collectivities	15 %
Agriculture	80 %
Industry	5 %
Power plants	1,5 %

First, we determine the point of intersection between the final supply-demand path and the stream. This is the potential location of the demand's inlet.

Demands located close to the stream are likely to have their own water intake. However, demands located far from the stream are likely to share common supply infrastructure (pipes, channels, aqueducts, etc.), and share a common water intake on the stream. Therefore, in a second step, we group potential inlets based on the average topological cost of the supply-demand paths for the considered stream. We assume that if the conveyance of water does not necessitate uphill moves of more than 10 meters, then water intakes can be numerous, and we do not regroup them. They can be located as close as 1 km from each other, which is the resolution of the Digital Elevation Model. If the supply-demand path requires uphill moves higher

than 160 meters (or covers distances longer than 1600 km), water intakes are grouped so that they cannot be located closer than 21 km from each other. In between, the spacing between water intakes increases proportionally to the topological cost, by steps of 5 km.

### 3.4 Operation of the reservoirs' system

Once the demand-reservoir network is reconstructed, the next step is to compute coordinated operating rules for the reservoirs system, taking into account available inflows and potential demands.

Multiple reservoirs systems operation has been extensively studied. Simulation models, which require the prior specification of operating rules [Oliveira and Loucks, 1997], can be used. Defining effective predefined operating rules is a challenge for complex multi-reservoirs systems, and at large scale it is not possible to use operator defined rules. A wide range of optimisation techniques exist [Labadie, 2004]; optimisation can be used to help define the parameters of operating rules, and combined simulation-optimisation approaches were developed [Rani and Moreira, 2009].

Our approach is to build something not too complex, which is not too data-intensive nor computationally-intensive. We use a parameterisation-simulation-optimisation (PSO) approach [Nalbantis and Koutsoyiannis, 1997, Koutsoyiannis and Economou, 2003], generalised to more complex reservoirs systems, and with prudential rules.

#### 3.4.1 Objective function

Operating rules of the system are based on the maximisation of water benefits, over time and space. The objective function is  $Max(B_{tot})$ , where:

$$B_{tot} = \sum_{t=1}^T \sum_{r=1}^R \sum_{n=1}^{N_r} D_{n,t} \cdot v_{n,t} \quad (3.2)$$

$T$  is the number of time periods,  $R$  is the number of reservoirs in the network (i.e. also the number of streams), and  $N_r$  the number of demands on the stream just downstream of reservoir  $r$ .  $D$  is the satisfied demand, and  $v_{n,t}$  is the value of water for demand  $n$  on month  $t$  (per unit of water).

This objective affects the water management rules on two levels: *i*) the allocation of water between demands on one stream, *ii*) the coordinated management of the whole reservoirs' system.

#### 3.4.2 Water allocation between demands on one stream

In order to reduce computation time, we group demands based on their valorisation of water. First, given total yearly demand on the stream, we

define a number of value classes. The larger the demand, the more the classes: for each additional 10 million m<sup>3</sup> (i.e. roughly the annual water use of a city of 100 thousand inhabitants), we consider one more class. We then determine the value bounds of the classes so that the total cumulated water benefits in each class is identical. Finally, for each inlet, we group demands pertaining to the same value class, and compute the monthly total demand and average value of this aggregated demand. This is done separately for irrigation and domestic demands. Water is then allocated considering these aggregated demands.

For each month, given a release  $I_0$  for the stream (released from the upstream reservoirs' system), we determine the satisfied demands  $D_n$  ( $n \in (1, \dots, N)$ ) under the objective:

$$\text{Max} \sum_{n=1}^N D_n v_n \quad (3.3)$$

Subject to the following continuity constraints, where  $l$  indexes inlets, and inlet  $l + 1$  is downstream from inlet  $l$ :

$$I_l = I_{l-1} - \sum_{n_l=1}^{N_l} \gamma_{n_l} D_{n_l} ; \quad \sum_{n_l=1}^{N_l} D_{n_l} \leq \min \left( \sum_{n \text{ in } l} M_{n_l}, I_{l-1} \right) \quad (3.4)$$

$N_l$  is the number of demands located on inlet  $l$ .  $M_{n_l}$  is the potential demand,  $\gamma_{n_l}$  the consumptive ratio,  $v_{n_l}$  the water value, and  $D_{n_l}$  the satisfied demand.  $I_0$  is the inflow entering the stream,  $I_l$  is the inflow downstream inlet  $l$ .

We suppose that return flows from a demand located on inlet  $l$  are available for downstream demands at inlet  $l + 1$ , without considering any decrease in quality.

The water allocation method within a stream gives priority to the high value uses and little consumptive uses.

### 3.4.3 Building coordinated operating rules for the reservoirs' system

For each stream of the network, at each time step, the operating rules of the reservoirs answer two questions: *i*) how much water to release from the upstream storage system for the demands of this stream, *ii*) how to distribute this release between the different reservoirs of the upstream system. In order to manage water at best, these operation decisions should be coordinated, for all reservoirs of the network.

#### A parameterisation-simulation-optimisation approach

We use a PSO approach to set up operating rules, with two parameters for each node ( $\alpha$  and  $\beta$ ) to parameterise choice between upstream branches

[Nalbantis and Koutsoyiannis, 1997] and prudential rules, as described below. Parameters are optimised using a genetic algorithm [Hinçal et al., 2011]. This heuristic programming method may help avoid to get stuck in local optimums [Labadie, 2004].

### Determining how much water to release for a given stream

We want to give priority to the satisfaction of demands with high valorisations of water and low consumptive rates. Thus, it can be preferable not to satisfy entirely a demand, if it enables the satisfaction of demands of a higher value, which can be located on another stream downstream, or occurring at a later time-period.

To take into account these spatial and temporal trade-offs, we introduce prudential parameters. A hedging rule [Draper and Lund, 2004] is used, to determine how much water to release for the demands of a stream, and how much water to retain for potential higher value uses. To avoid increasing computation time, and avoid overfitting, we use a one-point hedging rule [Draper and Lund, 2004], as illustrated in Figure 3.1.

First, we determine what minimum release would be necessary to satisfy all demands of the stream. This is the target release  $T$ . In a second step, we determine actual release, based on the hedging parameter for the stream ( $\alpha$ ). Under a standard operating policy (SOP), the storage system would release water depending on the quantity available and the target release  $T$ : if the available water quantity is lower than  $T$ , all available water is released; if more than  $T$  is available, the quantity  $T$  is released; if there is more water available than  $T$  plus what can be stored, the excess water is spilled and release consists of  $T$  plus the spill (Figure 3.1). Under the hedging rule, when the available water quantity is lower than the trigger volume  $V_{lim}$ , there is some rationing: release is lower than under the SOP, following the slope  $\alpha$  (with  $\alpha \leq 1$ ).

### Distributing release between reservoirs of the upstream storage system

For reservoirs in series, a rule proposed by [Lund and Guzman, 1999] is used. When satisfying a demand, water is first extracted from the most downstream reservoir, then progressively from the upstream reservoirs. The objective is to leave the water as upstream as possible, where it will be available for a wider geographical area.

For reservoirs in parallel, we have to decide from which branch to withdraw the water allocated to the downstream demand. The parametric rule of [Nalbantis and Koutsoyiannis, 1997] is used. A  $\beta_r$  parameter is defined for each reservoir  $r$  upstream of an node. With  $N$  upstream reservoirs:  $\sum_{r=1}^N \beta_r = 1$ . The  $\beta$  parameters determine the distribution of the empty

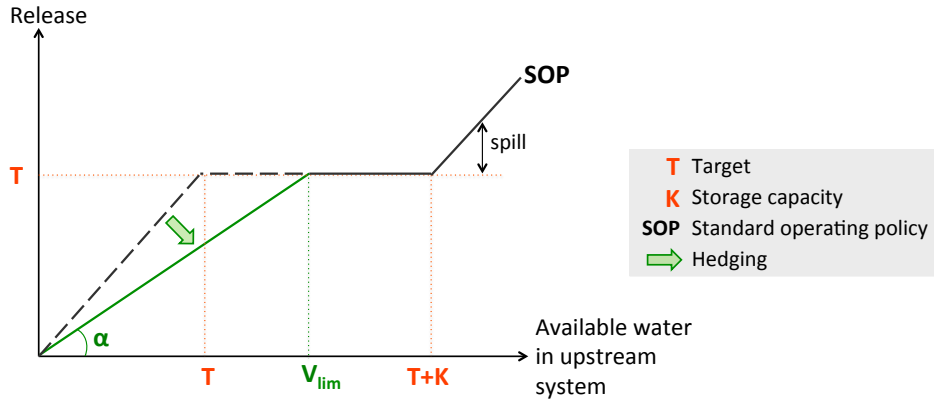


Figure 3.1: One-point hedging: one prudential parameter per reservoir ( $\alpha$ ), rationing is initiated when the stored volume is lower than  $V_{lim}$

storage space amongst the reservoirs in parallel, as a function of their respective storage capacities and common downstream demand [Portoghese et al., 2013] (Appendix 3.C).

### Tree traversal

The coordination of operations throughout the demand-reservoir network is implemented using tree traversal, instead of a system of constraints. Two traversals interlock: one progresses downstream, to compute the water release for the demands of each stream; the other one progresses upstream, to distribute this release between reservoirs of the upstream storage system (Appendix 3.D).

## 3.5 Application to Algeria

As an illustration, the methodology is applied to Algeria. Future demand and supply are projected at the 2050 horizon. Year 2000 is the year of reference for the historical period. The model is run for fifty climatic years, centered around the year of reference: 1975-2025 for the historical period, and 2025-2075 for the future period.

### 3.5.1 Scenarios

**Demand projection** We project domestic demand under the Medium variant population scenario of UNO [UN, 2009], and SSP2 [Rozenberg et al., 2014] GDP evolution scenario. Domestic water cost is assumed to converge towards the cost of water in France, which is used as a proxy for the cost of water in a mature domestic water distribution and sewerage service. Cost-

recovery ratio is assumed to converge towards one, following GDP per capita evolution [Neverre and Dumas, 2015].

Irrigation demands and values are projected under the assumption that crops growing period are of fixed length, and with no evolution of crops prices in the future.

The demand projection methods (Section 3.2.2) estimate on-site demands. To get corresponding withdrawals, we have to take into account distribution losses. Efficiency ratios are based on [Margat and Treyer, 2004]. For Algeria, both irrigation and domestic sectors have a demand to withdrawal ratio of 50%. We assume that these ratios remain unchanged in the future.

**Supply** When runoff exceeds the reservoir’s storage capacity, the excess water is spilled. Runoff and demands are computed at a monthly time step. The spill can be handled in two different ways. On the one hand, we can compute the spill at the beginning of each month, before computing demand satisfaction. In this case, spilled water that is not collected by downstream reservoirs is lost, it does not help satisfy demands. This is a pessimistic scenario, compatible with heavy concentrated rain. On the other hand, the spill can be computed while allocating water to the demands. In this way, all runoff participates in the satisfaction of demands. This is an optimistic scenario, compatible with well distributed precipitations during the month. Both scenarios are compared, they are noted “spB” when spill is computed before demand satisfaction, and “spA” when spill is computed along with demand satisfaction.

We also compare the results of two operating rules strategies. Under the option “V<sup>+</sup>H<sup>+</sup>”, demands are prioritised: the value of water in its different uses is taken into account (V<sup>+</sup>) and one-point hedging is implemented (H<sup>+</sup>). Under the option “V<sup>-</sup>H<sup>-</sup>”, the value of water is not taken into account (V<sup>-</sup>), and no hedging is implemented (H<sup>-</sup>).

### 3.5.2 Results

Results of satisfied demands and satisfied economic benefits are displayed in Table 3.2, under past and future conditions, under the V<sup>+</sup>H<sup>+</sup> operating rules option. Results are presented for each water network system (Figure 3.7). Knowing that we model potential demands, and that not all areas equipped for irrigation are actually irrigated [Benmouffok, 2004], we expect that the reservoirs may not be able to satisfy the whole demand.

The modelled historical rates of demand satisfaction seem pertinent for system 1186, which corresponds to a large basin and is the largest reservoirs’ system in Algeria, with 18 nodes (Figure 3.7). Results also seem appropriate for systems 20, 35, 1191 and 1192, which correspond to smaller coastal basins.

Modelled past demand satisfaction rates may be too high for systems 13 and 28 (small basins with only one reservoir).

For other water systems (systems 1170, 1171, 1178, 1181, 33, 1190, 9 and 1189), our results display very low demand satisfaction rates in historical conditions.

Systems 1170 and 1171 correspond to endorheic basins located in arid areas (Figure 3.7). It is not surprising that the modelled supply in the reservoirs system does not meet the modelled demand. Supply sources other than dams are used in these areas, notably the Saharan aquifer.

System 1178 is associated to the city of Oran, the second largest city in Algeria. However, Oran suffered from water deficits and had to resort to desalination as an alternative water supply source. This can explain the low demand satisfaction rate modelled for this reservoirs system.

Errors in reservoirs-demands network reconstruction can explain the demand-supply imbalance in the remaining problematic systems. In system 1181, the reservoirs are associated to demands from large irrigation perimeters in Morocco. These associations are probably erroneous, and the total demand associated to the system is too large. In system 33, the reservoir is associated to irrigation demands from the Mila province. However, the reservoir purpose is domestic supply, and Mila province irrigation perimeters are not supplied by reservoirs [Messahel et al., 2005]. System 1190 is also associated to irrigation perimeters, although it is reported to supply water only to cities [Ministère des Ressources en Eau Algérien, 2007]. Systems 9 and 1189 are located close to each other. There are multiple problems with the reservoirs-demands network reconstruction in this area. The two reservoirs of system 1189 are incorrectly located in the database we used [AQUASTAT Program, 2007], which can alter inflow computation and supply-demand paths computation. System 9 is associated to the city of Alger, the largest Algerian city, whereas Alger should be associated to closer and smaller dams, that are missing in the dams database used for the modelling [AQUASTAT Program, 2007]. There is also one reservoir missing in the Aquastat database, the Boukerdane reservoir, which should supply water to the irrigation perimeters of Sahel Algérois Ouest. The model associates these irrigation perimeters to the other reservoirs, and their associated demand is therefore higher than it should be. Reservoirs of system 9 are also erroneously associated to irrigation perimeters which rely on groundwater.

For most systems, the spill computation option has no impact (Table 3.2). For others, the “optimistic” spill option (SpA) increases demand satisfaction rate: +4.6-27% in past conditions for systems 1178, 1186, 1190 and 1192, and +2.2-5.5% in the endorheic systems 1170 and 1171.

Under future climatic and socioeconomic conditions, few basins (systems 35 and 1171) experience an improvement in the demand-supply balance. Their increase in satisfaction rates ranges from +3.5-12.6 % in demand satis-



Table 3.2: Satisfied demands, under the objective of economic value maximisation and using one-point hedging (option  $V^+H^+$ )

System	Satisfaction rate (%)							
	Demand (quantity)				Value			
	Past		Future		Past		Future	
	spA	spB	spA	spB	spA	spB	spA	spB
9	2.9	2.9	0.1	0.1	9.2	9.2	0.5	0.5
13	88.3	88.3	52.6	52.3	99.8	99.8	65.5	65.4
20	53.3	53.1	11.7	11.7	53.3	53.1	32.1	32.1
28	100.0	100.0	9.0	9.0	100.0	100.0	31.3	31.3
33	8.0	8.0	1.5	1.5	15.4	15.3	5.6	5.5
35	72.4	71.3	84.4	84.0	99.7	99.7	99.9	99.9
1170	4.9	0.8	3.5	0.3	10.2	4.7	6.5	1.5
1171	11.0	7.8	15.3	11.3	22.6	20.4	28.2	21.9
1178	13.5	7.1	5.3	0.9	15.2	6.9	6.5	0.7
1181	5.5	5.5	1.9	2.0	9.3	9.3	5.8	5.9
1186	40.5	34.4	21.9	15.2	48.9	43.3	29.2	22.1
1189	16.4	16.4	9.4	9.4	24.0	24.0	2.4	2.4
1190	11.1	5.4	8.1	0.3	12.2	7.6	6.7	0.7
1191	60.3	60.1	42.3	38.1	72.8	72.6	56.0	50.2
1192	31.8	12.3	17.5	0.5	60.0	33.0	28.6	2.6

faction, and +0.2-5.6% in terms of economic benefits satisfaction (Table 3.3). Most basins undergo a decrease in satisfaction rates under future conditions: up to -41.6% in demand satisfaction, and -34.4% in economic benefits satisfaction. System 28 is particularly affected, with a 91% decrease in demand satisfaction.

Table 3.4 illustrates the impacts of demand prioritisation. In terms of water quantities, demand satisfaction can be higher with prioritisation than without it (e.g. system 1191), probably because water is allocated to less consumptive uses that generate more return flows. Demand satisfaction can also be lower with prioritisation (e.g. system 1178 in past conditions), because when there is no hedging more water can be allocated to demands. The impact of demand prioritisation on economic value satisfaction rate is always positive: up to +27.1% in past conditions, and up to +22.5% in future conditions. For some systems (9, 33, 1170, 1189, 1190, 1191 and 1192), the positive impact of prioritisation is more pronounced under past conditions than under future conditions. For other systems on the contrary (systems 13, 20 and 28), the positive impact of prioritisation increases in the future, when these systems experience more pressure on the resource (Table 3.2). For the remaining systems, past and future benefits of prioritisation are comparable.

Table 3.3: Change in demand satisfaction between the past period and the future period, under the objective of economic value maximisation and using one-point hedging (option  $V^+H^+$ )

System	Change in satisfaction			
	satisfaction rate <sub>future</sub> - satisfaction rate <sub>past</sub> (in %)			
	Demand (quantity)		Value	
	spA	spB	spA	spB
9	-2.7	-2.7	-8.7	-8.7
13	-35.7	-36.0	-34.2	-34.4
20	-41.6	-41.4	-21.1	-21.0
28	-91.0	-91.0	-68.7	-68.7
33	-6.4	-6.5	-9.7	-9.8
35	11.9	12.6	0.2	0.3
1170	-1.4	-0.5	-3.7	-3.1
1171	4.3	3.5	5.6	1.6
1178	-8.3	-6.3	-8.7	-6.2
1181	-3.6	-3.5	-3.5	-3.4
1186	-18.5	-19.1	-19.8	-21.1
1189	-7.0	-7.0	-21.6	-21.6
1190	-3.0	-5.0	-5.5	-6.9
1191	-18.0	-22.0	-16.8	-22.4
1192	-14.4	-11.8	-31.3	-30.4

Table 3.4: Impact of demand prioritisation: difference in satisfaction with the option  $V^+H^+$ , compared to the results obtained with the option  $V^-H^-$

System	Difference in satisfaction							
	satisfaction rate <sub><math>V^+H^+</math></sub> - satisfaction rate <sub><math>V^-H^-</math></sub> (in %)							
	Demand (quantity)				Value			
	Past		Future		Past		Future	
spA	spB	spA	spB	spA	spB	spA	spB	
9	1.5	1.5	0.1	0.1	7.6	7.6	0.3	0.3
13	0.0	0.0	0.4	0.3	0.0	0.0	11.1	11.4
20	2.5	2.5	5.5	5.5	2.4	2.4	20.2	20.2
28	0.0	0.0	3.5	3.5	0.0	0.0	22.5	22.5
33	2.7	2.7	0.7	0.6	7.3	7.2	3.7	3.6
35	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1170	-1.4	0.1	-0.4	0.0	3.2	2.8	1.7	0.9
1171	0.1	0.2	-0.4	0.3	9.0	9.2	10.1	7.2
1178	-3.3	-0.4	1.6	-0.3	1.4	1.8	3.4	0.3
1181	-0.8	-0.8	0.2	0.3	4.1	4.1	4.3	4.4
1186	-0.1	-0.2	0.6	0.4	6.4	6.7	6.3	5.9
1189	1.6	1.6	0.7	0.7	16.6	16.6	1.7	1.7
1190	0.8	0.8	0.1	0.2	4.6	3.4	0.5	0.3
1191	2.0	1.9	0.8	1.5	11.3	11.2	6.4	6.0
1192	-5.3	4.6	8.4	-0.0	27.1	22.6	17.7	0.8

### 3.6 Discussion and conclusion

The developed methodology models domestic and irrigation water demands, as a function socioeconomic and climatic conditions. It reconstructs water infrastructure networks and compares potential withdrawals to available water supplies. Simple parametric operating rules are implemented to manage the reservoirs in a coordinated way, for a better valorisation of water.

Overall, our results show that the supply-demand imbalance will increase in most Algerian basins in the future, under the simulated socioeconomic and climate scenario.

Under future conditions, in some basins demand satisfaction (in terms of value) can be increased by up to 22.5% when using economic criteria to determine reservoirs operation rules. It suggests that global changes may be an incentive to use valuation in operating rules in these basins.

In other basins, the benefits of reservoirs management based on economic criteria are less pronounced. In this case, trade-offs could arise between implementing economic based operation policies or not. Implementing economic based priorities between uses may be complicated, costly, and involves acceptability issues. These difficulties should be compared to the expected gains in water benefits.

Our approach combines a large-scale coverage with a representation of heterogeneities at the river basin level (climate, water infrastructure, human activities, etc.). This double focus is useful to assess operating rules or policies effects on a multi-basins scale, as in the present paper. It would also be useful to investigate issues that occur on a large scale, for instance virtual water trade through markets of goods requiring water for their production. Being able to represent contrasted situations between basins, some suffering from water scarcity more than others, makes it possible to consider the water scarcity issue from a broader perspective than the usual water basin management level and consider possible interactions between basins. Modelling the economic benefits associated with water use, and the economic constraints associated with water shortage, is particularly important to address such inter-basin issues, to understand how interactions may be fostered.

The generic nature of the framework, necessary to maintain this double scale focus, has its limits. In particular, there can be non-negligible errors in reservoirs-demands network reconstruction when using only globally available data. Some degree of validation seems to be needed for a closer look at basin-scale results. The framework is not designed to provide a detailed representation of catchments for operational purposes, but rather to represent localised impacts of global changes, with an extended geographic coverage.

Validating the representation of reservoirs' operation policy would require data on naturalised and non-naturalised flows. Some data may be available for the Mediterranean [Ludwig et al., 2009], but their coverage, both in terms of years and locations, is far from complete. Some information on which

demands suffer restrictions would also be needed, but to our knowledge such data is not available. Besides, the purpose of the framework is not necessarily to reproduce observations. The operation rules built should perform better than uncontrolled flows, even if they do not match observations well. Since using explicitly economic value for water management is rare in practice, observations could also enable to evaluate if using water value as an allocation criteria is better than not to reproduce existing practices.

The framework could be used to evaluate different scenarios. In particular, different socioeconomic development paths or different scenarios of crops prices increase in the future may impact water values and the trade-offs between water uses. It could also be used to evaluate different water management policies. It is possible to assess the benefits of supply-side or demand-side adaptation policies: changes in dams (dimension, operation, construction, etc.), or the mobilisation of alternative water supply sources (e.g. desalination), changes in efficiency ratios (use of less water-intensive technologies, reduction of leaks in distribution networks, etc.), crop adaptations, etc.

Other sectors of water use could be taken into account, such as electricity production (cooling, hydropower) or environmental flows. The framework's large scale would be particularly pertinent to consider the electricity sector, since electricity markets are of a large scale. The relevance of using water for producing electricity and the relative benefits of different production technologies could be investigated, depending on the price of electricity. It would also be relevant to incorporate groundwater into the framework. Some areas rely on groundwater as a complementary or major water supply source. Groundwater management is often decentralised. An economic approach comparing water pumping costs to the economic benefits of the water demands could be used; the type of prioritisation and prudential rules we developed could also be generalised to aquifers.

Given its generic nature and low data requirements, the developed framework could be implemented in other regions concerned with water scarcity and its costs, or extended to a global coverage.

## Appendices

### 3.A Domestic water demand projection and valuation

Given the low data availability when working at a large scale, we developed a framework to build generic demand functions [Neverre and Dumas, 2015].

Our approach is to build simple three-part inverse demand functions (Figure 3.2): the first part consists of basic water requirements for consumption and hygiene, which are very highly valued (e.g. drinking water); then the second part consists of additional hygiene and less essential uses, which are less valued than those of the first part (e.g. regular laundry); finally the third part consists of further indoor uses and outdoor uses which are the least valued (e.g. lawn watering).

Then, we allow for the structure of our demand function to evolve over time, in order to take into account the effect of economic development on demand (Figure 3.2). As GDP per capita increases, households get more water using appliances (e.g. washing machines) and use more water, until they eventually reach equipment saturation and water use stabilises even if income continues to grow. This economic development effect was modelled in the WaterGAP model [Alcamo et al., 2003a]. We use a similar methodology, but incorporate it into our economic demand function framework. The size of the blocks of the demand function are scaled by economic development. The width of the second and third blocks grow with the level of GDP per capita, as illustrated in Figure 3.2. We assume that basic needs are not affected by this equipment effect, and the width of the first block is assumed fixed and based on literature [Howard and Bartram, 2003, Gleick, 1996].

Willingness to pay is estimated for some demand points of reference, based on econometric studies [Nauges and Thomas, 2000, Schleich and Hiltenbrand, 2009, Frondel and Messner, 2008] or price data (domestic water prices, bottled water prices), then interpolated linearly to form the slopes of the blocks.

Demand can be projected for a given year  $t$  following these steps: first, determine  $Q_{int}$  and  $Q_{tot}$  depending on the level of GDP per capita on year  $t$ . This enables to build the economic demand function for that year  $t$ . Second, project price for year  $t$ , and determine the level of demand for that level of price based on the economic demand function (Figure 3.3). Then the value of water can be computed: it consists of the economic surplus, i.e. the difference between willingness to pay and the actual cost of water, (Figure 3.3).

The domestic demand functions we model account for both household uses, and commercial and collective uses.

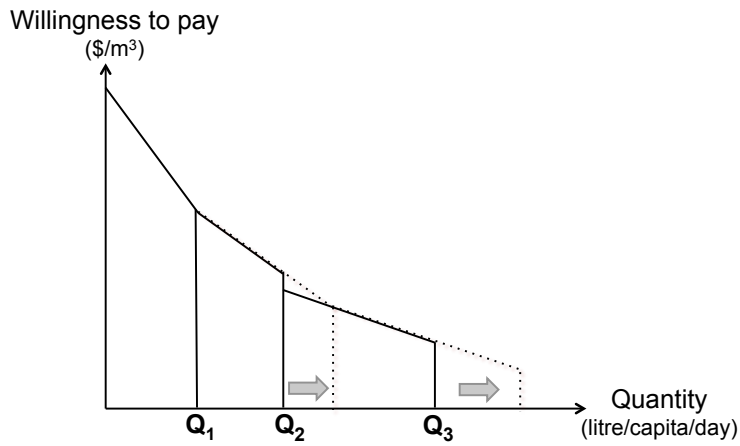


Figure 3.2: Domestic water demand function: economic development effect.  $Q_1$ ,  $Q_2$  and  $Q_3$  are the volume limits of the three demand parts. The grey arrows represent the effect of economic development, which leads to larger demand by expanding the width of the blocks.

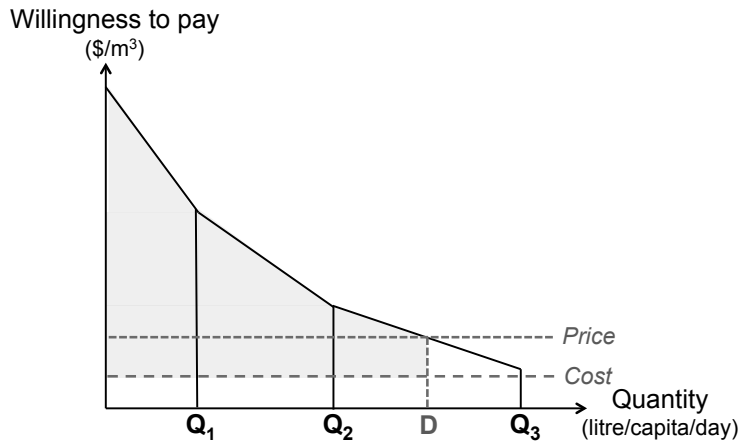


Figure 3.3: Domestic water demand function: surplus.  $D$  is the level of demand corresponding to the level of price. The grey-coloured area under the curve represents total economic surplus.

## 3.B Irrigation water demand projection and valuation

### Irrigation demand projection

Irrigation demand projection follows the methodology of ODDYCCEIA model [Portoghese et al., 2013], which analysed imbalances between water supply and irrigation demand in the Mediterranean basin under climate change.

Historical irrigated areas are determined from globally available data on irrigated areas and crops [Siebert et al., 2005], and crop mixes in the different irrigation perimeters are taken from Agro-MAPS database [FAO, 2005]. Future crops surfaces and types are assumed to be the same as in historical conditions (year 2000): we do not model changes in crop types distribution nor in areas equipped for irrigation.

Irrigation requirements are defined as the deficit between the potential crop evapotranspiration and the effective precipitation. Effective precipitation is computed following [Döll et al., 2003]. Crop evapotranspiration is computed for the different stages of the growing season using [Allen et al., 1998] method. [AQUASTAT Program, 2007] is used for crop calendars, and growth phases are assumed to remain of the same duration in the future. The reference evapotranspiration ( $ET_0$ ) is computed following the Hargreaves method. Then crop evapotranspiration ( $ET_c$ ) is determined using crop coefficients ( $K_c$ ) values from [Allen et al., 1998]:  $ET_c = ET_0 \cdot K_c$ .

Future irrigation needs are affected by climate change. Climatic data are taken from the CNRM climatic model [Dubois et al., 2012] outputs, using the A1B IPCC-SRES emission scenario.

Sixteen types of crops are differentiated in the ODDYCCEIA methodology: cotton, fodder, fruits, maize, oil-seed, oil-tree, potatoes, pulses, rice, rubber, sorghum, sugar beet, sugarcane, tobacco, vegetables and wheat.

Since livestock water use is much smaller than irrigation water use [Alcamo et al., 2007, Hanasaki et al., 2013a], in the present paper we consider only irrigation water needs.

### Irrigation water value

We estimate irrigation water value based on a “yield comparison approach” [Turner, 2004], a simple approach derived from the residual method [Young, 2005], in which respective costs and benefits of rainfed and irrigated production are compared. For a given crop in a given location, the additional profits made possible by irrigation are compared to its additional costs, and the value of water consists in the additional net benefits associated with the use of water.

We compute the value of water for each ODDYCCEIA crop type, in each

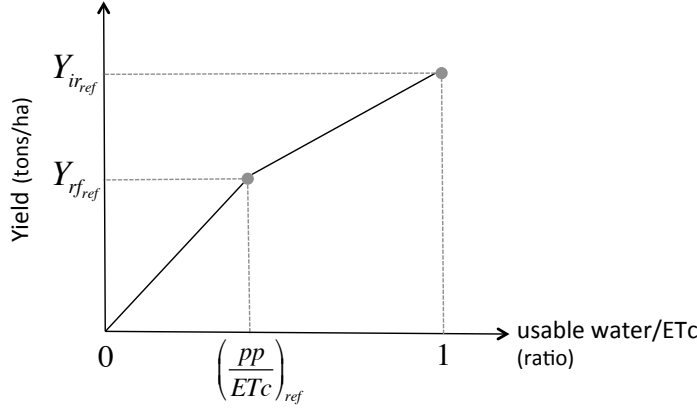


Figure 3.4: Modeling crop yield as a function of available water to ETc ratio.  $Y_{ir\_ref}$  and  $Y_{rf\_ref}$  are irrigated and rainfed crop yields of reference (in tons/ha),  $ETc$  is the crop evapotranspiration,  $pp$  the effective precipitation. Irrigated crops are considered to be irrigated to the potential so, with  $W$  the quantity of irrigation water, by construction  $(pp + W)/ETc$  is always equal to one.

irrigation perimeter location (i.e. at the  $0.5^\circ$  per  $0.5^\circ$  grid cell scale), as follows:

$$V = (B_{ir} - B_{rf})/W$$

Where  $V$  is the volumetric value of irrigation water (in US\$/m<sup>3</sup>).  $B_{ir}$  is the net benefit obtained by the irrigated production of a given crop in a given location (in US\$/ha), and  $B_{rf}$  is the net benefit that would be obtained if this crop was rainfed.  $W$  is the quantity of water used for irrigating the crop in this irrigation perimeter (in m<sup>3</sup>/ha).  $V$  can be negative if the additional profits generated by irrigation do not offset its additional costs. In this case, rainfed production is preferable to irrigated production.

In order to be able to determine irrigated and rainfed yields ( $Y_{ir}$  and  $Y_{rf}$ ) in future hydro-climatic conditions, we model yield as a simple function of usable water and ETc, as described in Figure 3.4.

The simple piecewise linear yield function is calibrated for each crop type by means of these two points of reference: the couples (yield of reference, usable water to ETc ratio of reference), for rainfed and irrigated crops. Hence, for each crop type in each irrigation perimeter location, we have to determine *i*) historical usable water-to-ETc ratios, and *ii*) historical rainfed and irrigated yields.

For rainfed crops, historical precipitation-to-ETc ratios are computed at the  $0.5^\circ$  per  $0.5^\circ$  spatial resolution, based on average precipitation and ETc outputs of the CNRM climatic model [Dubois et al., 2012] calculated over fifty past climatic years. For irrigated crops, by construction, usable water-to-ETc ratio is always equal to one.



For available crop types, historical yields of reference are based on localised potential irrigated and rainfed yields from LPJmL [Bondeau et al., 2007]. For other crops, they are based on data from FAOSTAT [FAOSTAT, 2013] and simple assumptions on yield ratios. We use data on the country scale average rainfed yield for each crop, and then assume that in each grid cell the average rainfed yield to potential yield ratio is equal to the precipitation to ETc ratio.

To take into account future yield increases associated to an increased use of other inputs, we add a yield change multiplier. Its value is taken from [Alexandratos et al., 2012] data, at the 2050 horizon.

As with the residual method, the methodology results in the estimation of average values. For each crop in each location we can obtain a past value of irrigation water based on historical yields and climatic conditions, and a future value of irrigation water based on future climatic conditions and yield change multipliers, computed over fifty climatic years.

### 3.C Distributing release between reservoirs in parallel

Here we consider a system of reservoirs formed by  $nl$  upstream reservoirs  $l$  in parallel and a direct downstream reservoir  $dp$ . First, the reservoir  $dp$  will cover, partly or totally, the downstream release. The residual release  $\Delta R_{dp,t}^0$  will be covered by upstream reservoirs using the parametric rule [Nalbantis and Koutsoyiannis, 1997]. The upstream system total final water volume is:

$$V_{dp,t}^{syst} = \sum_{l=1}^{nl} Vcur_{l,t}^0 - \Delta R_{dp,t}^0$$

The parametric rule is used to determine from which upstream reservoir water is extracted. The target volume  $S_{l,t}^{targ}$  of each upstream reservoir is:

$$S_{l,t}^{targ} = K_l + \beta_l \times \left( V_{dp,t}^{syst} - \sum_{l=1}^{nl} K_l \right) \quad (3.5)$$

These target volumes may not be consistent with constraints on volumes, i.e. volumes may be negative or exceed storage capacity. Hence, their corrected target volumes  $S_{l,t}^{targ,corr}$  are:

$$S_{l,t}^{targ,corr} = \begin{cases} K_l, & \text{if } S_{l,t}^{targ} > K_l, \\ 0, & \text{if } S_{l,t}^{targ} < 0, \\ S_{l,t}^{targ}, & \text{otherwise.} \end{cases} \quad (3.6)$$

Once these inconsistencies are corrected, the new target volumes may not add up to the system's volume  $V_{dp,t}^{syst}$ . Hence for the second change, a

correction coefficient is defined [Nalbantis and Koutsoyiannis, 1997]. The correction factor  $\phi_{dp,t}$  is computed as follows:

$$\phi_{dp,t} = \frac{(V_{dp,t}^{syst} - \sum_1^{nl} S_{l,t}^{targ,corr}) \times K_l}{\sum_1^{nl} S_{l,t}^{targ,corr} \times (K_l - S_{l,t}^{targ,corr})} \quad (3.7)$$

Based on the  $\phi_{dp,t}$  correction factor, new target volumes  $S_l^{targ,new}$  are computed as:

$$S_{l,t}^{targ,new} = S_{l,t}^{targ,corr} \times \left\{ 1 + \left[ \phi_{dp,t} \times \left( 1 - \left( \frac{S_{l,t}^{targ,corr}}{K_l} \right) \right) \right] \right\} \quad (3.8)$$

These two corrections have to be done repeatedly until the previous constraints are fulfilled.

$S_{l,t}^{targ,new}$  can be greater than the current volume  $Vcur_{l,t}^0$ . For the set  $R^g$  of upstream reservoirs for which this condition holds ( $R^g = \{r/S_{r,t}^{targ,new} > Vcur_{r,t}^0\}$ ), the final target volumes is set equal to their current volumes [Nassopoulos, 2012]. The residual release is covered by the set  $R^l$  of remaining upstream reservoirs which have target volumes lower than their current volumes ( $R^l = \{r/S_{r,t}^{targ,new} < Vcur_{r,t}^0\}$ ). Each one of these reservoirs contribution is set to be proportional to its current volume, and its final target volume will be  $\forall l \in R^l$ :

$$S_{l,t}^{targ,fin} = \frac{Vcur_{l,t}^0}{\sum_{r \in R^l} Vcur_{r,t}^0} \times \left( V_{dp,t}^{syst} - \sum_{r \in R^g} Vcur_{r,t}^0 \right) \quad (3.9)$$

### 3.D Tree traversals

The coordination of operations throughout the demand-reservoir network is implemented using tree traversal, instead of a system of constraints [Portoghese et al., 2013]. Two traversals interlock: one progresses downstream, the other one upstream.

For the traversal of the whole network, we start from the most upriver parts and progress downstream (Figure 3.5). This downstream traversal determines how much water is released for the demands of each stream, based on the hedging rule. Once a stream is processed, we move downstream, and the reservoirs of the upstream system already processed are aggregated into one reservoir. Going further down, the hedging rules are used for the satisfaction of the demands and the processed streams are aggregated, in the same way. This recursion continues until reaching the network root.

At the same time, the network is traversed upwards. Each time a demand has to be covered by an upstream reservoirs aggregate, we must determine

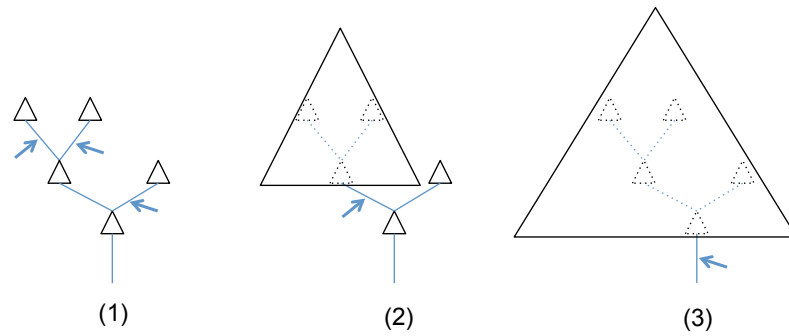


Figure 3.5: Satisfying demands of each stream: downwards tree traversal, with aggregations. (1) start with the most upriver streams, (2) aggregate upstream reservoirs' system when moving down, (3) repeat until reaching the root of the network.

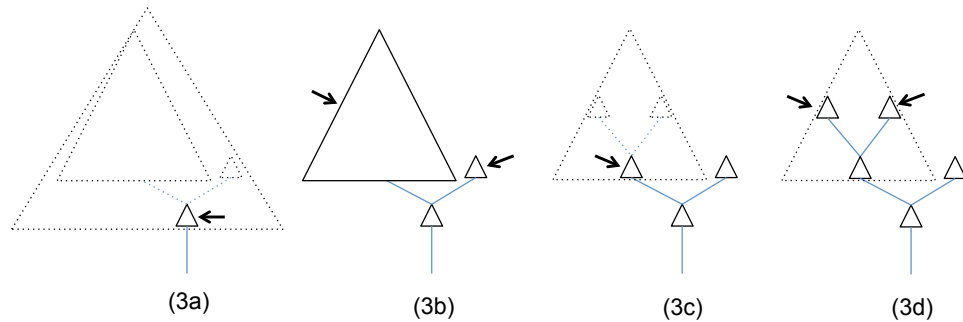


Figure 3.6: Distributing release between upstream reservoirs: upwards tree traversal, with disaggregations. Steps for case (3) of Figure 3.5

which reservoir of each upstream aggregate will contribute to the release. For this purpose, the rules to distribute release between reservoirs in series or in parallel are used, while progressing upwards (Figure 3.6). This recursion continues until reaching leaf reservoirs.

### 3.E Location of Algerian reservoirs systems

Cf. map in Figure 3.7.

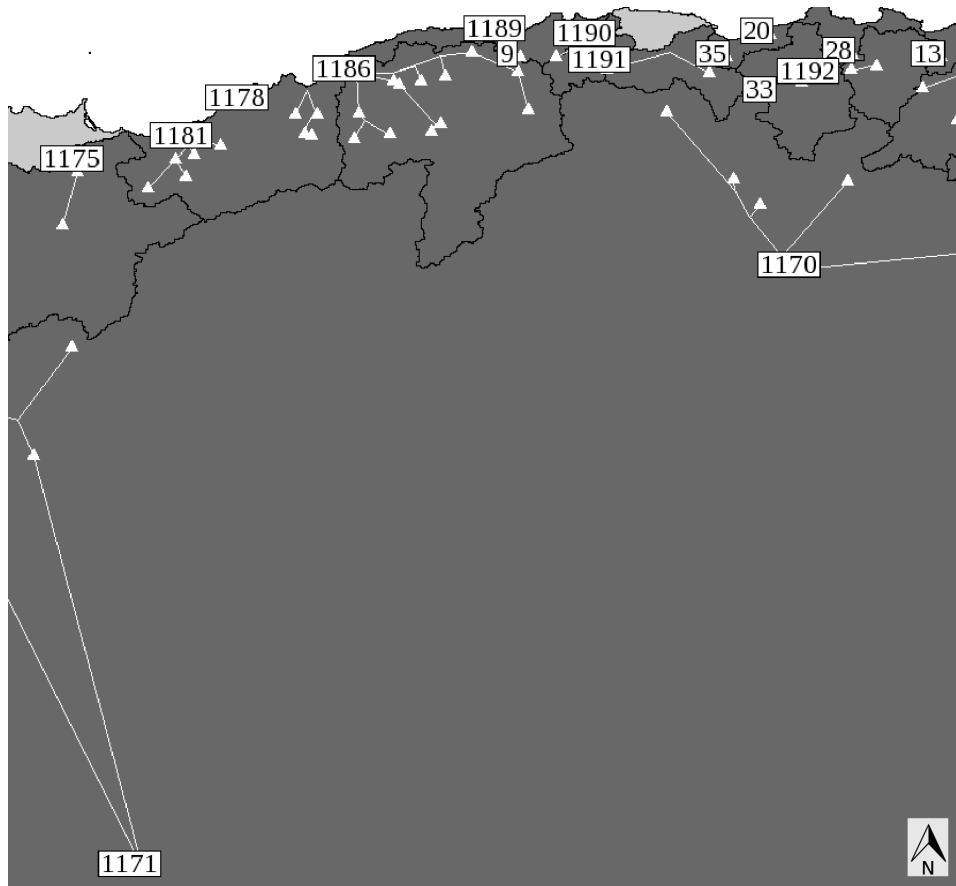


Figure 3.7: Map of Algerian reservoirs systems. The white area is the Mediterranean sea. Basins borders are in black. Light grey basins are basins without reservoirs. White triangles are reservoirs, and white lines are the upstream-downstream links between reservoirs. Numbered labels are located at the downstream root of each system.



## Part III

# TOWARDS USING LARGE SCALE HYDROECONOMIC MODELLING TO INVESTIGATE WATER SCARCITY INDUCED MOBILITIES



## Introduction

The traditional response to tensions on water resources in the Mediterranean has been to increase supply, by mobilising new resources (dams, groundwater, and more recently desalination) to meet populations' growing needs. However, water resources become increasingly scarce and it is increasingly difficult to secure water supply. Hence, demand management policies were gradually developed, to limit losses and wastage in the use of the resource (through hydroeconomic equipment for instance).

However, examining changes in economic activities intensity, or the possibility of economic activities relocation, related to pressures on water resources is not common in the literature. Yet, when facing water scarcity, an activity could choose to relocate to a region where water is available. A firm may find it advantageous not to invest in a region otherwise promising (e.g. in terms of labour costs), if it would require using water-efficient technologies that are more costly, and not necessarily available.

While an overall reduction in water availability would constrain all activities, contrasted situations between basins, with local constraints on water availability, raise the more subtle question of interactions between basins and changes in activities locations. Localised constraints on the resource could unsettle the organisation of economic activities.

This last part of the thesis proposes to consider this question of demand mobility: the evolution of water availability under global changes, in particular climate change, could lead to changes in the localisation of economic activities and migrations of workers.





## Chapter 4

# Climatic changes and migration

The issue of climate change's impacts on human migration, already raised by the Intergovernmental Panel on Climate Change (IPCC) in 1990, has aroused great attention in the recent years, with sometimes catastrophic scenarios being put forward.

This chapter reviews literature discussing how climate change is involved in migration processes, and to what extent. It first presents how climate change can affect migration and how it interacts with the other drivers of migration. It then presents the methods developed to represent, validate and quantify the impacts of climate change on migration and their results.

The scope of the chapter is wider than the sole water scarcity issue. Yet, the question is especially relevant with regard to water, as a particular environmental factor which is impacted by climate change and delivers impacts of climate change to society.

### 4.1 The drivers of migration and the role of the environment

Migration can take different forms, both in space and time. There can be external (or international) migration, with a displacement from one country to another, or internal migration within a country, such as urbanisation migration or local migration over a short distance. Migration can also be permanent or temporary, with a return to the original location in the short to long term, or even seasonal.

Initially, two main types of explanations were proposed to understand the migration phenomenon: the existence of unfavourable factors in the area of origin ("push factors") and favourable factors in the area of destination ("pull factors"). But these very simple concepts fail to account for the complexity of human movements and settlements, or to assess the role of global

environmental changes [Parnell and Walawege, 2011]. Thus a deeper understanding of the different processes involved and their interactions is needed.

#### 4.1.1 The drivers of migration: a combination of economic, demographic, sociological, political and environmental factors

[Black et al., 2011] propose an analytical framework to understand the impact of environmental change on the migration process. They identify five groups of factors affecting migration decisions:

- Economic factors: job opportunities, wages, prices etc.
- Political factors: discrimination, freedom, insecurity and conflict, land property rights etc.
- Social factors: education level, family obligations, cultural expectations and practices (inheritance, marriage) etc.
- Demographic factors: size and structure of the population, prevalence of diseases etc.
- Environmental factors: ecosystem services (soil productivity, food security, water availability), risk exposure etc.

It is the interaction between these five types of factors that determines whether migration will take place and how. The effect of the environment is dependent on the economic, political, social and demographic context. Therefore, it is important to understand the fundamental drivers of migration and to explore their interactions with global environmental changes, rather than considering these environmental changes only as an isolated factor [Parnell and Walawege, 2011]. Migration due to environmental change cannot be totally separated from the question of migration related to all the other factors, and it is rarely possible to identify migrants that are exclusively "environmental".

#### 4.1.2 Which dimensions of climate change can impact migration ?

Various dimensions of climate change can have an impact on the push factors of migration. We can distinguish, for example [Black et al., 2011]:

- rising sea level: risk of coastal flooding, erosion, salinisation etc.
- changes in frequency or intensity of tropical storms and cyclones
- changes in rainfall regimes: risk of flooding, low water availability, decline in agricultural productivity etc.

- temperature increase affecting agricultural productivity, ecosystem services etc.
- changes in atmospheric composition impacting agricultural productivity, aquatic ecosystems etc.

Most authors refer to two main forms of climatic changes: rapid changes, and slow and gradual processes. Rapid environmental changes, often in the form of natural disasters, are easy to identify and their impacts are immediately observable (floods, storms, landslides etc.). People have to leave the area for their safety, sometimes homes or livelihoods (equipment, crops etc.) are destroyed. In the case of progressive changes in environmental conditions (changes in rainfall variability, gradual degradation of ecosystems etc.), impacts are more difficult to observe and the influence on migration is more difficult to assess [Warner, 2011].

### 4.1.3 Direct and indirect impacts of environmental change

Environmental changes have the potential to directly affect the safety of a location (in the case of extreme events). But given the interactions between migratory factors, they can also affect migration indirectly, by impacting other fundamental drivers of migration, such as political factors (for instance through conflicts for resources) or economic factors [Black et al., 2011]. Thus, [Marchiori et al., 2011] identify two channels through which climate change can impact migration:

- the "amenity" channel: migration is related to environmental amenities, environmental changes have a direct impact on the quality of life;
- the "economic geography" channel: migration is related to economic geography effects, i.e. indirect impacts of climate, via income and urbanization.

[Lilleør and Van den Broeck, 2011] studied the theories of economic migration and identified two main economic factors of migration, related to income. The authors assumed that a person will migrate as a result of climate change (or increased climate variability) if it affects both factors:

- income differentials between region of origin and region of destination, in particular expected income differentials (taking into account the risk of unemployment etc.);
- income variability: in the case of a family, for example, the migration of one or more family members can help diversify the sources of income (with revenues having different causes of variability, e.g. weather related or not), to reduce the risks.

Climate change may indirectly impact migration decisions, for instance by reducing agricultural productivity or fisheries productivity, thus reducing household incomes, or by impacting the reliability of harvests and farm incomes. The data available shows that the poorest are also the most threatened by climate change. A decrease in income or in the reliability of income can become an economic driver of migration. On the other hand, it can also limit the ability of individuals and households to migrate, because the migration process is costly and requires resources [de Haas, 2011]. The effects of environmental changes may therefore be different depending on the characteristics of the impacted household or community [Black et al., 2011]. The presence of push factors of migration does not necessarily mean that migration will indeed take place. Therefore, the identification and quantification of migration phenomena related to climate changes appear to be a sensitive issue.

## 4.2 Empirical validation of the link between climate change and migration

Empirical studies examining the link between climate change and migration have addressed the issue from three different perspectives [Lilleør and Van den Broeck, 2011]:

First, a number of studies have looked at the impact of climate change on migration drivers. Economic drivers, including income related factors, are fundamental factors in the migration decision, as shown by numerous empirical analyses for both internal and international migration [Lilleør and Van den Broeck, 2011]. By using a standard mono-centric urban economy model [Brueckner, 1990] showed the importance of the income differential between rural and urban areas as a determinant of urban migration in developing countries. Thus, if climate change impacts these factors, it also will impact migration. An abundant literature shows that climate change and climate variability impact the income level and variability [Lilleør and Van den Broeck, 2011]. Statistical models of local to global scale analysing the impacts of climate change suggest that temperature and rainfall deficits have a negative impact on GDP (GDP being used as a proxy for income/wages).

Secondly, numerous studies have investigated the “direct” impact of climate change on migration. These studies establish a statistical link between climate variables (typically rainfall) and migration, and thereby estimate a reduced form model of the effect of climate change, where the channel through which it influences the migration is not specified (the effect can therefore operate through any type of migration driver). They show a negative correlation between rainfall and migration (internal and international, with greater effects on internal migration), even though they do not clearly identify what the causes are. The econometric study of [Barrios et al., 2006]

estimates the impact of rainfall and a set of other explanatory variables (GDP per capita, population density, etc.) on urbanisation. Their results validate the influence of climate in the urbanisation process in sub-Saharan Africa.

Finally, some studies attempt to study the impacts of climate change on migration through certain driving factors, but such studies are still scarce. [Barrios et al., 2006] proposed a theoretical analytical model of economic geography, modelling a rural agricultural sector and an urban manufacturing sector, and describing the impact of climate change (represented by rainfall) on agricultural productivity and therefore on agricultural employment and urbanisation migration. Similarly, [Marchiori et al., 2010] used a simplified model of economic geography to describe how climate change induces migration from rural to urban areas, and how this increased urbanisation then triggers international migration. Some empirical validation studies are presented in Table 4.1.

The work of [Marchiori et al., 2012] is the first analytical framework studying jointly internal and international migration. They highlight that climate anomalies strengthen the urbanisation process, which then has two contradictory effects. On the one hand, the influx of migrants reduces the wage level in the urban area, increasing the incentive for mobile urban workers to migrate abroad. On the other hand, given the role of agglomeration economies and their self-reinforcing nature<sup>1</sup>, such an increase in urbanisation constitutes a force of attraction for migrants, both internal and international. Therefore, urbanisation eventually mitigates the impact of climatic anomalies on international emigration.

In addition, the other drivers of migration affect the scale of the migration. For example, [Gray, 2009] conducted a statistical study based on survey data from the southern Ecuadorian Andes, and studied the effects of land property and environmental conditions on emigration to local, national or international locations. The results show that local and internal migration involves households without land (or with little land), while international migration involves households with substantial land. The determinants of migration are also different depending on the destination. For local migration, demographic and environmental factors are the main drivers. For international migration, the environmental conditions are less important while human capital (e.g. education level) is particularly important.

Empirical research shows that climate change does play a role in migration [Marchiori et al., 2011, Warner, 2011]. Environmental factors contribute to both internal and international migration [Marchiori et al., 2011], with a greater impact on internal migration [Gray, 2009, Gemenne, 2011]. The

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<sup>1</sup>“Snowball effect” of agglomeration economies: the larger the market (i.e. many consumers), the higher the profit of firms, the more new firms are attracted, the more job opportunities, the larger the market, and so on.

Table 4.1: Examples of empirical studies that confirm the link between climate change and migration

Study	Method	Intermediary variables	Type of migration	Location	Results
Barbieri et al (2010)	Integrated model population-economy-climate (economic model & simple model of migration rate)	Income and employment rate	Internal	North-East of Brazil	Climate change impacts the organization of the territory, creating employment and income conditions that affect the redistribution of economic activities and population.
Feng et al (2010)	Statistical, Estimation of the semi-elasticity of migration	Agricultural yields	International	Mexico	Significative impact of the effects of climate change on crop yields in Mexico on the rate of emigration to the United States.
Marchiori et al (2012)	Statistical, Estimation of three equations : i) net rate of migration, ii) GDP / capita, iii) urbanisation rate	Income level and urbanisation rate	Internal and international	Subsaharan Africa	Climatic anomalies amplify urbanization and emigration. Significant and robust effects of climate change on migration, both in terms of direct impact ("amenities" channel) linked to health risks, for example, and indirect impacts ("economic geography" channel).

influence of environmental factors works in interaction with the other factors of migration, in particular economic factors.

Different methodologies are used in the literature: statistical approaches (mainly on a global or regional level, sometimes more local, from survey data or time series, or multi-level analyses in rare cases), models of spatial vulnerability and, more recently, multi-agent modelling or "indirect" statistical approaches (via agricultural productivity for example). However, they do have some limitations.

Regarding statistical approaches (the most common approach), several limitations can be identified. For most of them ("reduced" statistical models), even if the link between rainfall and migration is validated by extensive research, the channel through which climate impacts migration is not identified. There is no information on what causes this statistical relationship. These studies do not provide information on how these impacts could be mitigated [Lilleør and Van den Broeck, 2011].

Furthermore, most studies do not control for endogeneities<sup>2</sup> affecting income or employment opportunities, which in turn affect incentives to migrate (except for some studies, e.g. [Feng et al., 2010]), which leads to biased results [Marchiori et al., 2011]. [Marchiori et al., 2012] seek to control endogeneities and enable the estimation of an indirect impact, estimating three equations simultaneously (migration, urbanisation and income).

Another shortcoming of conventional estimation methods is the inability to correct selection bias [Lilleør and Van den Broeck, 2011, Piguët, 2010]. Migrants and non-migrants can indeed be fundamentally different groups in nature (different level of education, for example). Thus, the relationship between two variables at the individual level may be different from the relationship between these same two variables at an aggregated level. We cannot generalise the findings of studies using individual data to the aggregated level ("atomistic" or "individualistic fallacy") and vice versa for studies based on global data, the conclusions can be untrue at the individual level ("ecological fallacy"). For instance, in the case of the impact of income differentials on migration, estimation methods are likely to overstate income gains associated with migration because they are not able to correct this selection bias [Lilleør and Van den Broeck, 2011].

Some studies try to avoid this bias by using time series (which however still faces the problem of lack of endogeneity control) or multi-level analysis, combining aggregate data and individual data, as [Gray, 2009]. However in the latter case the use of predefined spatial units (administrative units across which information is collected) is not necessarily adequate to represent the spatial distribution of the phenomenon studied [Piguët, 2010].

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<sup>2</sup>Explanatory variable omitted (especially because of lack of data), or simultaneity problem / reverse causality (one of the explanatory variables is determined simultaneously / partially caused by the explained variable).



Other methods often used (especially for the problem of rising sea levels) are the models of spatial vulnerability. They are based on the identification of areas or populations particularly vulnerable to the impacts of climate change, using geographic information systems combined with general circulation models and regional climate models, from which assumptions are made about the potential for population displacement. But these assumptions about the relationship between increasing exposure to climate change and increased migration potential (link "impacted-migrant") are rather simplistic [McLeman, 2011]; developing field research would help identify factors and interactions that transform vulnerability into actual migration.

Similarly, other methods that try to take into account the multifactorial dimension of migration are also confronted with the difficulty of the impacted-migrant link and the complexity of migratory behaviour. Approaches representing the indirect impact of climate change, through changes in agricultural yields and performance [Feng et al., 2010, Barbieri et al., 2010], are based on rather simple assumptions about migratory behaviour [McLeman, 2011]. Another methodology recently mobilised is multi agent modelling, which seeks to capture the migratory behaviour of individuals or specific population groups. For instance [Kniveton et al., 2011] built a multi-agent simulation model to study the role of environment on migration decisions in Burkina Faso with different climatic, socio-political, economic and demographic scenarios. Their model shows that the strongest international migration flows appear for dry climate scenarios. In terms of total migration, and for a constant socio-eco-political-demographic scenario, a dry climate generates more migration than a relatively humid climate. However, it is difficult to establish the behavioural rules necessary for the multi-agent modelling, in particular because the behaviours themselves may be uncommon in the field of climate change, since many stimuli consist of events which populations have never faced before [Piguet, 2010].

In general, [Piguet, 2010] regrets the poverty of the environmental variables used (which are generally limited to rainfall or the occurrence of natural disasters). The use of more elaborate indicators of climate change and environmental degradation would be relevant, in relation to the identification of key environmental variables involved in the migration process.

In conclusion, many empirical studies have validated the link between global environmental change and migration, in terms of direct and indirect impact, and internal and international migration. However, some methodological limitations exist and the results should be treated with caution regarding the numerical results; these studies provide estimates of potential trends of climate induced migration, rather than absolute predictions [McLeman, 2011].

### 4.3 The quantification issue

A critical review of existing estimates and future predictions of the global number of people displaced by environmental change was proposed by [Gemenne, 2011]. Regarding the slow, gradual environmental changes, the most quoted figures are those proposed by Myers in the years 1990 and 2000. Using the work of various researchers, he estimated that 25 million people were displaced in 1995 due to environmental change (drought, soil erosion, desertification, etc.). Various estimates from the literature are presented in Table 4.2, but these results are highly disputed in academic circles. Estimates of the number of people displaced due to extreme events are more robust and less controversial: 17 millions in 2009, 42 millions in 2010, mostly in Asia (Yenotani, 2011 Internal Displacement Monitoring Centre and the Norwegian Refugee Council, quoted by [Gemenne, 2011]). The different predictions of future migration range from 150 to 300 million people displaced by 2050 (Table 4.2), among which approximately 160 millions due to flooding and over 50 millions due to droughts, according to Myers.

As for regional studies, [Marchiori et al., 2012] estimate that 5 million people were displaced because of climatic anomalies in sub-Saharan Africa between 1960 and 2000 (0.3 per thousand persons), and their predictions suggest an additional displacement of 11.8 million people annually (in the case of medium-fertility scenario demographics of the United Nations) until 2100. In Mexico, [Feng et al., 2010] conducted a statistical study on the links between climate change, agricultural yields and migration to the United States (using the instrumental variable method, which takes into account the endogeneity of some explanatory variables). They estimate that a reduction of 10 % in yields would lead to the migration of an additional 2 % of the population. A projection attempt suggests that, if other factors held constant, climate change would cause the migration of 2 to 10 % (depending on the selected climate scenarios) of the current adult population by 2080, as a result of reduced agricultural productivity.

Thus, at the regional level some studies try to develop predictions of the number of future environmental migrants, in different countries and regions, but few studies are conducted at a more global level. At the moment, there is no consensus on the estimate of future global migration. All studies suffer serious bias: a tendency to use figures to generate awareness, and methodological limitations [Gemenne, 2011]. There is no commonly accepted or even truly satisfactory methodology. Estimations can rely on reviews of existing local scale studies (studies which can be using different methods, and focus on different migration types), or on the estimation of areas vulnerable to climate change. In particular, these methods face the limits presented in the following sections.

Table 4.2: Estimates and predictions of the overall number of migrants related to global environmental change - adapted from Genemne (2011)

Study	Estimation at the time of publication	Predictions for year 2010	Predictions for year 2050	Method (or sources)
Jacobson (1988), WorldWatch Institute	10 millions, including over 5 millions in Sub-Saharan Africa.	-	-	Based on the identification of risk areas and the number of internal migration (from all causes) in these regions.
INEP3 (El Hinawi 1985, Milan 2004)	30 millions	50 millions	-	Method not explained
Myers (1993 / 2002)	25 millions	-	150 / 200 millions	Based on various regional of country-scale works, some being from other authors.
Myers and Kent (1995)	25 millions	50 millions	212 millions	idem
Red Cross (2001)	More than the number of people displaced by war	-	-	Based on their field activities reports
UNU-EHS4 (Adam 2005, Renaud et al. 2007)	10 millions / year	50 millions	200 millions	Based on an interview of Pr Bogardi (director of UNU-EHS) in 2005
Stern (2007)	-	-	150 to 200 millions	Quoting the results of Myers
Christian Aid (2007)	25 millions	-	300 millions	Misquote of a fact sheet from UN-HCR5
Bierman and Boas (2010)	-	-	200 millions	Based on secondary sources

Table 4.3: Definitions and concepts of "environmental migrants" used by the main studies - adapted from Gemenne (2011)

Study	Definition of "environmental migrants"
UNEP (El-Hinnawi, 1985)	People who were forced to leave their traditional habitat, temporarily or permanently, because of a marked environmental disruption (natural and/or human-induced) that threatens their existence and/or seriously affect their quality of life.
Jacobson (1988)	People fleeing environmental decline.
Myers (2002)	People who can no longer have reliable livelihoods in their home region because of drought, soil erosion, desertification, deforestation, and other environmental problems, together with the problems of population pressures and profound poverty .

#### 4.3.1 Identification of “environmental migrants”

First, there are no universally accepted concept and definition of “environmental migration” [Gemenne, 2011]. Thus, different studies use different terminologies and definitions, sometimes remaining vague [Lilleør and Van den Broeck, 2011], which makes it difficult to compare their results.

These definitions may or may not distinguish temporary and permanent migration, forced or voluntary, domestic or international, and involve very different environmental processes (ranging from volcanic eruption to progressive decline in environmental conditions), sometimes unrelated to climate change.

#### 4.3.2 Deterministic point of view

Furthermore, some studies (including those of Myers) are based on the number of people living in areas likely to be affected by environmental degradation, rather than on the number of people who could actually migrate. They do not look at the impacted-migrant link, assuming that all impacted people will migrate. In addition, they consider those who emigrated from an area affected by climate change relocated only because of climate change, and do not take into account the multi-causality of migration processes [Gemenne, 2011].

#### 4.3.3 Lack of data

A major difficulty is the availability of reliable data. Large-scale studies suffer from a lack of comprehensive data on population movements, especially movements linked to environmental factors [McLeman, 2011]. Researchers working at regional or local scales have been able to develop data sets including environmental information and information on populations (e.g. [Barbieri et al., 2010] for Brazil, [Feng et al., 2010] for Mexico), but these studies are

rather disparate (cf. problems of definition, and diversity of methods used) and their results cannot be extrapolated to a wider scale. It remains difficult to assess the overall number of migrants precisely. The absence of global mechanisms to collect the necessary data is problematic, and as most migration is internal rather than international it is even more difficult to identify and quantify [Gemenne, 2011].

In conclusion, the lack of a universal definition of “environmental migration”, the insufficient attention to the link between the presence of environmental factors of migration and the decision to migrate, and the lack of empirical data (difficulties exacerbated by the multi-causal nature of migration) make it difficult to evaluate precisely and rigorously the number of migrants. The different predictions - whose limits are known - have reported 150 to 300 million people displaced by 2050. In the absence of statistic information it is not possible to assess the accuracy of these predictions, and for now it seems difficult to provide more accurate data. These figures are sufficient to generate awareness, but they lack the robustness and precision necessary to design appropriate policies [Gemenne, 2011].

#### 4.4 What are the possible ways of improvement?

Attempts at quantifying the number of migrants generated by climate change are generally based on simple assumptions on the response of an individual to climatic changes, while empirical studies have shown that migration decisions are complex, both multi-causal and different depending on individual characteristics. The exploration of recent and/or new methods seem necessary (multi-agent modelling, multilevel analysis etc.). According to [Kniveton et al., 2011], modelling techniques are the only efficient way to simulate the migratory decision process. A few modelling approaches are presented in Table 4.4. Modelling climate change induced migration is still a recent enterprise and the promising research developments are i) the sophistication of models to take into account both a larger variety of explanatory variables and the multi-causality nature of migratory processes and ii) the incorporation of refined assumptions on behaviour. At the same time, it is necessary to deepen the understanding of the factors influencing migration, and the different types of migration responses in populations, studying in particular the influence of risk perception, networks, social capital etc. [McLeman, 2011]. Another fruitful research direction would be the introduction of hybrid modules "climate-migration", built around methodologies from both the migration domain and the environmental domain [Piguet, 2010].

Global models offering reliable predictions and relying on a good understanding of climate change induced migration patterns will not be available for some time. Progress will probably first come from regional or subregional works, for which data is more readily available [Gemenne, 2011, McLeman,

2011]. In order to progress in this direction, increased efforts for collecting and sharing reliable data on population displacements linked to environmental changes are highly desirable [Gemenne, 2011, Piguet, 2010, McLeman, 2011], particularly on a large scale. It is also necessary to use precise terminology, and to encourage the development of common definitions, particularly between different countries.

Furthermore, it would be interesting to address the issue of migration not as an isolated question, but together with the question of non migratory responses to climate change [Piguet, 2010]. Indeed, migration is an answer among others to environmental degradation. It may be a last resort option, but it can also be combined with in situ adaptation strategies at the family or community scale.

Finally, there is now a broad consensus on the likelihood of the impacts of environmental changes on migration in the future: the number of people displaced will increase with climate change, the climatic factor will add up to socio-economic, political and demographic factors [Tacoli, 2012]. Given the interdependence of the factors driving migration, it is expected that future environmental changes will not create new mass migration, but that they will rather amplify existing migration trends [McLeman, 2012, Black et al., 2011, Findlay, 2011].

The quantification of the phenomenon is more controversial. Predictions of the overall number of environmental migrants by 2050 are alarming, but not universally accepted, because they rely on less rigorous methodologies and lack empirical support. These difficulties can be explained, among others, by the lack of available data and the complexity of the multifactorial migration process. The improvement and sophistication of models, the development of data collection mechanisms on environmental migration, and the use of clear terminology are expected to provide more robust predictions, even if these predictions will probably be more local than global at first.

Table 4.4: Examples of climate change induced migration modelling

Study	Location	Structure of the economy	Sectors	Workers	Climatic variable	Internal migration	External migration
<i>Specific factors model</i>							
Barrios et al. (2006)	Sub-Saharan Africa	2 sectors	Agriculture, Manufacture	Workers are mobile between sectors.	Rainfall, which impacts effective land input.	✓	
<i>Event history model</i>							
Gray (2009)	Southern Equatorial Andes	1 region, and outside			Precipitation, harvest fluctuation	✓	✓
<i>General equilibrium, overlapping generations model</i>							
Marchiori and Schumacher (2011)	Theoretical	Two countries. Perfectly competitive world.	Firms in each region, with decreasing returns. Production is a function of capital, labor and a factor productivity.	Generations. Pare welfare.	Com- Temperature differential impacts the factor productivity. It depends on emissions at period $t$ and $t - 1$ , which depend on the stock of capital.		✓
<i>New Economic Geography model</i>							
Marchiori et al. (2010, 2012)	Sub-Saharan Africa	1 rural region, 1 urban region	Rural and urban sectors have decreasing returns in labor. There are Marshallian externalities on productivity in the urban sector.	Workers are mobile across locations and sectors. They compare their wages.	Theoretical model: climate change impact function, decreases the productivity of the rural sector. Statistical analysis: precipitation and temperature anomalies.	✓	✓

## Chapter 5

# Considering environmental migration through the lens of water availability constraints

The impact of climate change on migration is a growing concern. The literature on environmental migration shows a general agreement on the fact that migration will increase with climate change (Chapter 4). Three elements can be noted. First, until now the environmental variables used as indicators of climate change when looking at its impact on migration were generally basic (precipitation, occurrence of natural disasters), and developing more elaborate indicators would improve the understanding of the migration processes [Piguet, 2010]. Second, modelling tools seem promising to simulate the migration process [Kniveton et al., 2011], in particular the introduction of hybrid models bringing together methods from the environmental field and the migration field [Piguet, 2010]. Third, migration factors are multiple and interrelated. Economic and political factors are the main drivers, and environmental factors mostly play an indirect role [de Haas, 2011]. In the Mediterranean for instance, migration levels have fluctuated with labour demand between 1950 and 2010 [de Haas, 2011].

In this context, it seems relevant to look at environmental changes' indirect impacts on migration, via impacts on economic activities and their spatial organisation. For this purpose, we need to be able to represent why activities locate in an area or another, depending on economic criteria. An economic geography framework is suitable to model the spatial organisation of economic activities. It also seems relevant to account for climate change's role on migration via a tangible factor, which directly affects human activities and livelihoods. Water availability is such a factor. It delivers impacts of climate change to society [Cisneros et al., 2014]. Hence, this chapter proposes to couple ODDYCCEIA hydroeconomic model to an economic geography framework. The coupled framework makes it possible to consider the



interaction of economic and environmental factors as drivers of migration.

New Economic Geography (NEG) studies the spatial organisation of the economy. It developed from Krugman's seminal Core-Periphery model [Krugman, 1991], which integrates increasing returns and imperfect competition into a general equilibrium approach, and generates microeconomic foundations to spatial organisation driving forces. While international trade theory focuses on the trade of goods, assuming that production factors are not mobile, economic geography explicitly incorporates factors mobility, and agents localisation becomes endogenous.

The core notion is the co-existence of two types of forces: agglomeration forces, and dispersion forces. On the one hand there are economies of agglomeration such as technological externalities, e.g. knowledge spillovers, or pecuniary externalities, e.g. market effect. The market effect can be described as follows. Producers prefer locations with large markets, large availability of intermediate goods, and a pool of workers with varied skills. Workers prefer locations offering a wide range of products and services, and with a large pool of jobs. These agglomeration effects are self-reinforcing ("snowball effect", or circular causality). On the other hand there are dispersion forces: high land rents and congestion in the agglomerations, transportation costs, etc. The balance between these two types of forces determines the extent of agglomeration/dispersion and spatial disparities. NEG focuses in particular on the trade-off between increasing returns and transportation costs: firms arbitrate between concentration and market proximity.

Recently, a new field has been emerging: Environmental Economic Geography (EEG). It seeks to understand the interrelations between economic organisation and environmental aspects [Bridge, 2008]. EEG studies use economic geography methods and incorporate environmental factors such as pollution or biodiversity [Eppink and Withagen, 2009, Rauscher and Barbier, 2010], to look at reciprocal environmental and economic organisation outcomes.

So far, to the author's knowledge, few studies take into account a "water availability" factor when considering localisation choices. Constraints on water availability are complex to assess. They are spatially and temporally dependent. Water is stored where reservoirs are located, and water availability downstream depends on upstream withdrawals. Water availability depends on climatic variability, and on operating rules of water management infrastructures. We propose to account for such a factor by using ODD-YCCEIA, which can provide the necessary localised information on water availability (Chapter 3).

Coupling ODDYCCEIA to a NEG framework would make it possible to take into account the impacts of climate change (and global changes in general) on the economic sphere, via the water availability factor. In this way, it would be possible to assess not only the direct economic costs of water scarcity, but also its indirect impacts on economic activities and on

population’s location. In the long term, migration could be a means to development adaptation. [Barnett and Webber, 2010] argue that “there is considerable potential to harness migration to promote adaptation to climate change in both sending and host communities”.

This chapter pictures how the framework could be implemented.

## 5.1 Coupling ODDYCCEIA to an economic geography framework: overview

Figure 5.1 gives an overview of this coupling framework. ODDYCCEIA results on satisfied and unsatisfied localised water demands impact locations attractivity, and modify localisation choices. In turn, relocations impact localised demands and values, and modify water allocation rules. The coupled models give the final evolution of water constraints, and economic activities and population location.

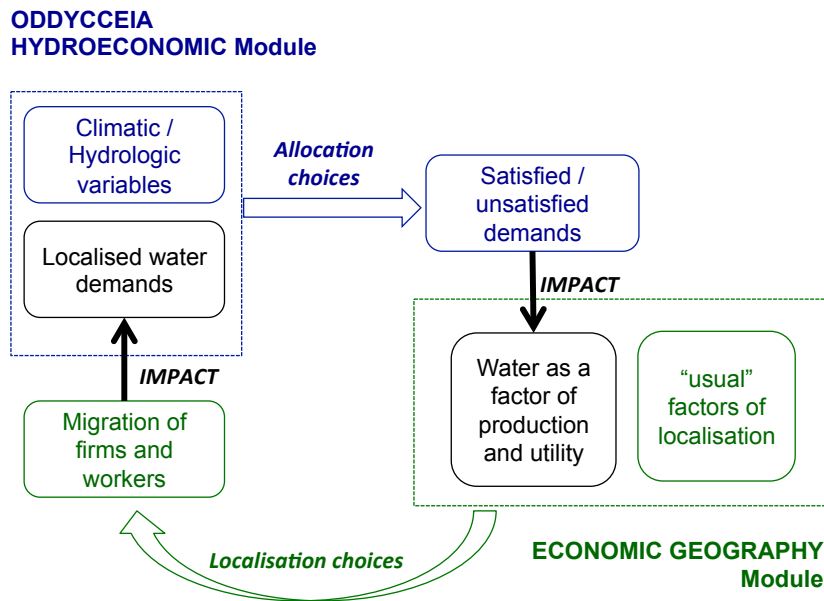


Figure 5.1: Coupling ODDYCCEIA to an economic geography model: overview

Figure 5.2 illustrates the main steps of this soft-coupling process. To begin with, a macroeconomic baseline is used to get the evolution of the economy at country scale, without taking into account the existence of water availability constraints. Modelling the impacts of the water availability constraint will thus give an evaluation of the deviation from the baseline due to this factor. This deviation from the baseline may consist of a different repartition of activities within a country, or even of a different evolution

of the total economic activity of the country. The macroeconomic baseline could be given by an integrated modelling assessment [Sassi et al., 2010, Leimbach et al., 2010, van der Mensbrugge, 1998].

The first step is to disaggregate the baseline situation between the different locations, and between water-dependent and non water-dependent sectors. This would enable to reconstruct a projection of localised water demands (Chapters 1, 2, 3).

In a second step, these localised water demands are compared with available water in the water management network, using ODDYCCEIA. ODDYCCEIA gives information on the quantity of water allocated to the different demands in the different locations, i.e. information on the localised water availability constraints.

In a third step, localised water availability constraints impact water dependent activities. Activities and populations relocate in order to maximise their utility, taking into account water availability constraints in the different locations. This gives a new projection of localised water demands and values. Steps two and three are then repeated.

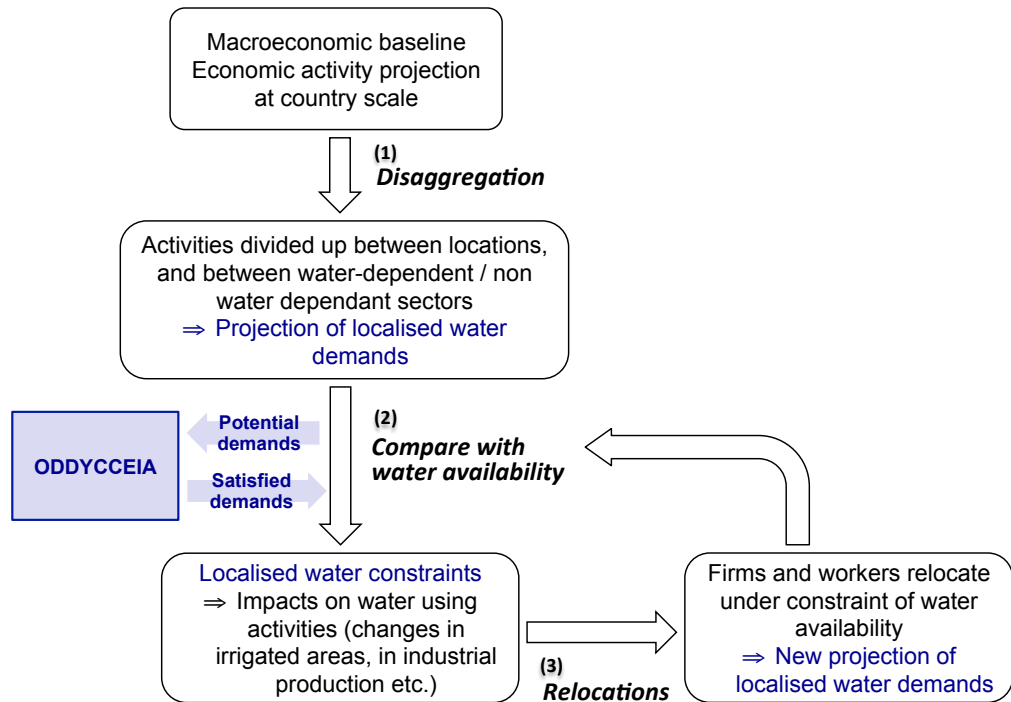


Figure 5.2: Coupling ODDYCCEIA to an economic geography model: main steps

## 5.2 Structure of the economic geography model

The objective is to build a very simple model, representing only the elements that are needed to investigate the issue of water scarcity related relocations. This simple model is based on Krugman's Core-Periphery model [Krugman, 1991]. Table 5.2 summarises the features of the proposed framework, and compares it to Krugman's Core-Periphery model. The notations used are recapitulated in Table 5.1.

### 5.2.1 Characteristics of the economy

We consider an economy entailing multiple regions. Each region can have two productive sectors: a rural (or agricultural) sector and an urban (or manufacturing and services) sector.

As in the standard approach [Krugman, 1991], these two consumer goods are produced:

- A homogenous agricultural good ( $A$ ), produced by the rural sector under constant returns, and traded under perfect competition.
- A differentiated manufactured and services good ( $M$ ) consisting of different varieties ( $M_k$ ), produced by the urban sector under increasing returns, and traded under monopolistic competition<sup>1</sup>.

In order to take into account water constraints on the economy, we add the following elements to the framework:

- A non-tradable good, water ( $W$ ), available in each region in a limited amount.
- The urban sector is subdivided into a water-dependent sub-sector, and a non water-dependent sub-sector.

### 5.2.2 Consumption

Workers and inhabitants are not distinguished between: in the following sections, the term “workers” accounts for both workers and associated inhabitants, i.e. all people living from the revenues of an economic activity (wages, revenues of capital or land). The workers are both input production factors and output consumers.

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<sup>1</sup>Increasing returns are necessary to explain the agglomeration of activities in a homogenous space. However, when firms experience increasing returns the assumption of perfect competition no longer holds. In order to analyse agglomeration processes, a framework combining increasing returns and imperfect competition is needed, within a general equilibrium structure. The basic New Economic Geography model has built on the monopolistic competition framework (Dixit-Stiglitz model [Dixit and Stiglitz, 1977]).

The economy employs a total mass  $L$  of mobile workers. Each region  $i$  employs  $L_i$  workers, divided between the agricultural sector, the water-dependant and the non water-dependent manufacturing sectors.

The individual utility of a representative consumer located in region  $i$  and working in sector  $s$  is defined as a function of the following variables and parameters:

$$U_{i,s} = f(A_{i,s}, \hat{M}_{i,s}, W_{i,s}; A_{min}, \Phi_{i,s})$$

Where  $A_{i,s}$  and  $W_{i,s}$  are the quantities of goods  $A$  and  $W$  consumed by a representative consumer of region  $i$  and sector  $s$ . Demand function for  $W$  would be fitted to our projected domestic water demand function (Chapter 1).  $\hat{M}_{i,s}$  is the CES aggregate of the consumption of all varieties of the manufactured good (produced both in the considered region and abroad):

$$\hat{M}_{i,s} = \left[ \sum_{k=1}^N (M_{k,i,s})^\sigma \right]^{\frac{1}{\sigma}}$$

$A_{min}$  is a parameter representing the minimum quantity of agricultural good necessary for consumption.  $\Phi_{i,s}$  is a location specific factor, accounting for local amenities of localisation (e.g. proximity to the sea, political factors). The structural form of the utility function could be a CES.

Given the prices  $p_{k,i}$ ,  $p_{A,i}$  and  $p_{W,i}$  of goods  $M_k$ ,  $A$  and  $W$ , and their revenue  $R_{i,s}$ , workers of sector  $s$  in region  $i$  are subject to the following budget constraint:

$$\sum_{k=1}^N (M_{k,i,s} p_{k,i}) + A_{i,s} p_{A,i} + W_{i,s} p_{W,i} = R_{i,s}$$

### 5.2.3 Rural sector

#### Production (good $A$ )

The agricultural good is a homogenous good, produced by the rural sector, under constants returns. Two technologies of production exist: rainfed agriculture (labelled  $A_r$ ) and irrigated agriculture (labelled  $A_w$ ), which presents a higher productivity than rainfed agriculture but is constrained by the amount of water available for agriculture in the region. In a given rural region the quantity produced ( $x$ ) on a surface area ( $h$ ) is:

$$x_{A_r} = \gamma_{A_r} h_{A_r} \text{ and } x_{A_w} = \gamma_{A_w} h_{A_w}$$

Where  $\gamma_{A_r}$  and  $\gamma_{A_w}$  are the weather dependent productivities.  $\gamma_{A_r}$  depends on weather conditions ( $\theta$ ),  $\gamma_{A_w}$  depends on both weather conditions and irrigation conditions ( $\delta$ ) and:  $\gamma_{A_r}(\theta) < \gamma_{A_w}(\theta, \delta)$ . Rainfed and irrigated

productivities are a piecewise linear function of available water to crop ETP ratio (Chapter 2).

The rural sector displays constant returns to labour, and the total number of rural workers  $L_A$  is:  $L_A = l_A h_A$ , where  $l_A$  is the number of workers per ha, and  $h_A$  is the total agricultural surface area. We assume that labour productivity per ha is identical for rainfed and irrigated production technologies.

### Water availability constraint on the rural sector

Total surface area  $H$  is divided between irrigated and rainfed production, depending on the amount of water available for agriculture (given by ODD-YCCEIA):

$$H = h_{A_r} + h_{A_w}$$

Where  $h_{A_w}$  is the irrigated area whose water demand is satisfied, and  $h_{A_r}$  corresponds to areas not equipped for irrigation, or whose water demand is not satisfied.

### Profits and revenues

In region  $i$  total profits ( $\Pi_{A_i}$ ) of the rural sector are:

$$\begin{aligned} \Pi_{A_i} &= \Pi_{A_{i,r}} + \Pi_{A_{i,w}} \\ &= p_{A_i}(x_{A_{i,r}} + x_{A_{i,w}}) - R_{A_i} L_{A_i} - c_i H_i - (v_{W_{A,i}} h_{A_{i,w}} + p_{W_{A,i}} W_{A,i}) \end{aligned}$$

Where  $p_{A_i}$  are the crops prices,  $c_i$  the inputs costs per ha (machinery, fertilisers, pesticides) and  $R_{A_i}$  the revenue of a rural worker.  $v_{W_{A,i}}$  are the irrigation cost per ha, and  $p_{W_{A,i}}$  the cost of water per m<sup>3</sup>,  $W_{A,i}$  being the total quantity of water used for irrigation. We assume that the crops prices, the inputs costs and the costs of labour are identical for rainfed and irrigated crops.

We assume that profits are distributed between the rural workers.  $\Pi_{A_i} = 0$  and a rural worker's revenue is:

$$R_{A_i} = \frac{p_{A_i}(x_{A_{i,r}} + x_{A_{i,w}}) - c_i H_i - (v_{W_{A,i}} h_{A_{i,w}} + p_{W_{A,i}} W_{A,i})}{L_{A_i}}$$

## 5.2.4 Urban sector

### Production (good $M$ )

The differentiated manufactured good is produced under increasing returns, with a single production factor: labour. As in the standard approach, each firm produces a single variety (labelled  $k$ ;  $k = (1, N)$ ). Therefore, the number of varieties produced in a region is equal to the number of firms located in that region.

In each region, two technologies of production exist:

- Technology  $w$ : productivity is high, but the production process requires water
- Technology  $r$ : productivity is lower, but the technology doesn't require water

In a region  $i$ ,  $n_{i,r}$  varieties are produced under the technology  $r$ , and  $n_{i,w}$  varieties are produced under the technology  $w$ . And in the economy:

$$\sum_i (n_{i,r} + n_{i,w}) = N$$

For a given variety (or representative firm)  $k$  produced in region  $i$ , according to the technology of production used ( $r$  or  $w$ ), the production function is:

$$L_{k,i,r} = \alpha_i + \beta_{i,r} x_{k,i,r}$$

or  $L_{k,i,w} = \alpha_i + \beta_{i,w} x_{k,i,w}$

With  $1/\beta_{i,w}$  and  $1/\beta_{i,r}$  the labour productivities in the water-dependent and the non water-dependent technologies, and:  $\beta_{i,r} > \beta_{i,w}$ . The fixed input quantity  $\alpha_i$  is assumed to be the same for both technologies in a given region, in the absence of information on capital intensity in the different sub-sectors (Section 5.3).

The total number of workers ( $L_{M_i}$ ) of the urban sector in region  $i$  is:

$$L_{M_i} = \sum_{k=1}^{n_{i,r}} (\alpha_i + \beta_{i,r} x_{k,i,r}) + \sum_{k=1}^{n_{i,w}} (\alpha_i + \beta_{i,w} x_{k,i,w})$$

And by symmetry between varieties produced under the same technology, in the same region:

$$L_{M_i} = (\alpha_i + \beta_{i,r} \bar{x}_{i,r}) \cdot n_{i,r} + (\alpha_i + \beta_{i,w} \bar{x}_{i,w}) \cdot n_{i,w}$$

### Water availability constraint on the manufacturing sector

In each region the production of good  $M$  is constrained by the amount of water available in the region for production ( $W_{M,i}$ ):

$$n_{i,w} \cdot \bar{x}_{i,w} \cdot w_M \leq W_{M,i}$$

Where  $w_M$  is the amount of water necessary to produce one unit of good  $M$  using technology  $w$ .

### Profits and revenues

For representative firms, profits are:

$$\begin{aligned} \Pi_{i,r} &= p_{i,r} \bar{x}_{i,r} - R_{i,r}(\alpha_i + \beta_{i,r} \bar{x}_{i,r}) \\ \text{or } \Pi_{i,w} &= p_{i,w} \bar{x}_{i,w} - R_{i,w}(\alpha_i + \beta_{i,w} \bar{x}_{i,w}) - p_{W_{M,i}} w_M \bar{x}_{i,w} \end{aligned}$$

With  $R_r$  and  $R_w$  the revenues of a worker in the manufacturing sector, depending on the technology of production, and  $p_{W_{M,i}}$  the price of water for the manufacturing sector.

In the chosen theoretical framework, free entry of firms implies  $\Pi = 0$ . Therefore, for a technology  $j$  in a region  $i$ , an urban worker's revenue is:

$$R_{i,j} = \frac{p_{i,j} \bar{x}_{i,j} - C_{i,j}}{\alpha_i + \beta_{i,j} \bar{x}_{i,j}}$$

Where the water costs  $C_{i,j}$  of the two technologies are:  $C_{i,w} = p_{W_{M,i}} w_M \bar{x}_{i,w}$  and  $C_{i,r} = 0$ .

### 5.2.5 Trade

The trade of the manufactured good is associated with an iceberg form of transportation cost ( $\tau > 1$ ) [Krugman, 1991]. When a certain quantity of good is shipped to another location, only a fraction  $1/\tau$  will arrive at the destination. Transportation costs are independent of the distance covered. The price of a variety  $k$  produced in region  $R(k)$  and consumed in region  $i$ <sup>2</sup> is then:

$$p_{k,i} = \tau \cdot p_{k,R(k)}$$

Agricultural goods could be traded without transportation costs, following [Krugman, 1991], or we could introduce transportation costs.

### 5.2.6 Equilibrium

As in usual approaches, firms maximise their profits, and free entry implies<sup>3</sup>  $\Pi = 0$ . Workers maximise their utility. They move across locations and sectors, towards those offering a higher level of utility, until the levels of utility equalise between locations and sectors.

Migration costs could be introduced, in particular to represent migration barriers between countries.

<sup>2</sup>Goods could also be traded via a pool, following [Grazi and Waisman, 2009].

<sup>3</sup>If firms in monopolistic competition are making profits, new firms have an incentive to enter the market. If they are incurring losses, firms have an incentive to exit the market. The equilibrium corresponds to firms having a null profit.



Table 5.1: Notations

Notation	Elements of the model
$A$	consumption of the homogenous agricultural good
$M_k$	consumption of a variety $k$ of the manufactured good $M$
$\hat{M}$	CES aggregate of the consumption of all varieties of the manufactured good
$W$	consumption of water
$p$	price of a good
$p_W$	price of water
$L$	mass of workers
$R$	revenue of a worker
$\Pi$	economic profits
$x_A$	quantity of agricultural good produced
$x$	quantity of manufactured good produced
$\bar{x}$	quantity produced for each variety of a given location is identical
$h$ or $H$	surface areas
$\gamma$	weather dependent agricultural productivity
$l$	labour intensity per ha
$c$ or $C$	costs
$v_W$	irrigation costs per ha
$n$ or $N$	number of firms
technology $w$	water-dependent production technology
technology $r$	non water-dependent production technology
$\alpha$	fixed input requirements
$1/\beta$	labour productivity
$w$	water intensity per unit produced
$\tau$	transportation costs

Table 5.2: Features of the New Economic Geography framework proposed to consider water availability constraints, and comparison with Krugman's seminal Core-Periphery model

Elements of the model	Krugman (1991)	Proposed framework
Number of regions	2	$I$
Goods	Differentiated manufactured good $M$ , and homogenous agricultural good $A$	A differentiated manufactured good $M$ , an homogenous agricultural good $A$ , and a non traded good $W$ (water)
Factors of production	2 types in each region: mobile workers, and non mobile peasants	Workers are mobile across regions and sectors
Production function	$M$ : increasing returns, $A$ : constant returns	$M$ : increasing returns, two technologies (water-dependent, non water-dependent), $A$ : constant returns, productivity depends on a water availability variable
Firm behaviour	Monopolistic competition. Free entry implies null profits.	Similar to Krugman (1991)
Utility function	Cobb-Douglas for $A$ and $M$ , where $M$ is a CES aggregate of varieties	Function of the consumption of goods $A$ , $M$ and $W$ , and a location-specific amenities factor
Transportation costs	$A$ : no costs, $M$ : iceberg costs	$A$ : possible costs, $M$ : iceberg costs, for export and import via a pool
Agglomeration factors	Increasing returns for $M$	Increasing returns for $M$
Dispersion factors	Peasants are not mobile, transportation costs	Minimum consumption of $A$ , transportation costs
Other localisation factors		Water availability constraints, location-specific amenities

### 5.3 Calibration

The model needs to be able to match the actual location of population within a country, and actual differences in production between countries or regions.

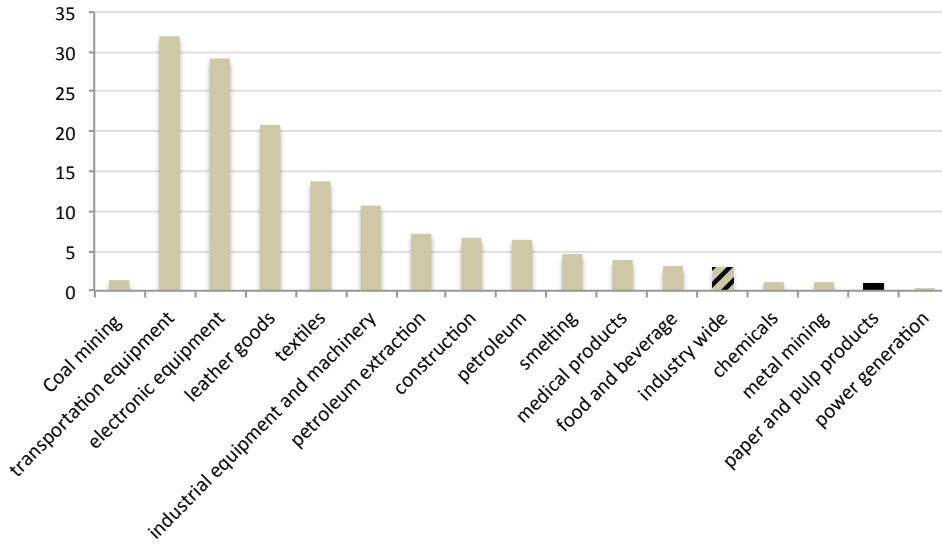
In particular, we need to divide the urban sector between water-dependent and non water-dependent sub-sectors, which have different productivities. Unfortunately, it is difficult to estimate the economic value of water in the industrial sector. Data gathered from the literature is scarce. Figure 5.3 displays the results of the few identified studies that estimate the value of water in different industrial sectors [Wang and Lall, 1999, Renzetti and Dupont, 2003, Kumar, 2006, Strzepek et al., 2006]. Results are very variable. For instance, at the world level the value of water in the paper sector is comparable to the average value of industrial value [Strzepek et al., 2006], but it is three times lower in China [Wang and Lall, 1999] and four times higher in India [Kumar, 2006].

Therefore, we would not use this data, we would need to calibrate the productivity differential between water-dependent and non water-dependent production. Within our modelling framework, water-dependent technologies of production are preferred to non water-dependent technologies because they are more productive. Therefore, the quantity of water available determines the quantity produced in these sectors. Data on water quantities used in the different locations is not available. We would use ODDYCCEIA to provide such information. In order to run ODDYCCEIA, information on the productivity differential is needed in order to value industrial water and determine water allocation between sectors and locations. This productivity differential would be calibrated so that it would be consistent with population repartition, total production at country scale from the NEG model, and water availability in the different locations, using ODDYCCEIA.

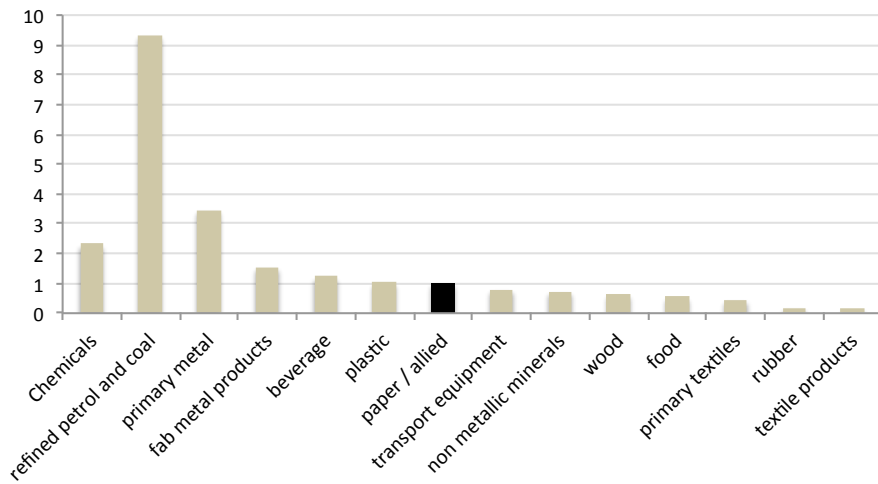
Another difficulty is that inputs for the agricultural sector (machinery, fertilisers, pesticides) should be produced by the industrial urban sector, but we do not have a real sectorial representation of the industrial sector. It would probably be better not to close the model for that element.

### Conclusion

The coupled models would give the final evolution of water constraints, and activities and population locations. A possible use of this framework is to evaluate different water management policies and their outcomes in terms of economic dynamics. In particular, supply-side and demand-side policies could be compared. On the supply-side, it is possible to evaluate the impacts of using non conventional resources, or changes in dams dimensions. On the demand side, it is possible to look at the impacts of incentives to use less water-intensive (but more costly) technologies, incentives or barriers to

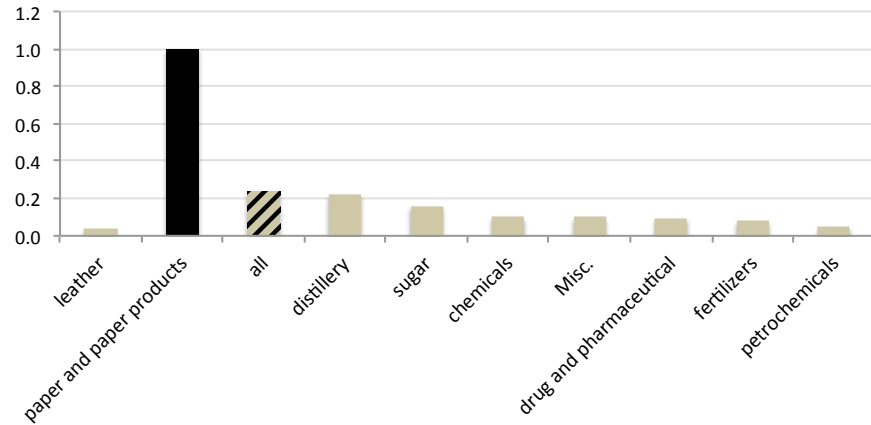


(a) Wang and Lall (1999), China

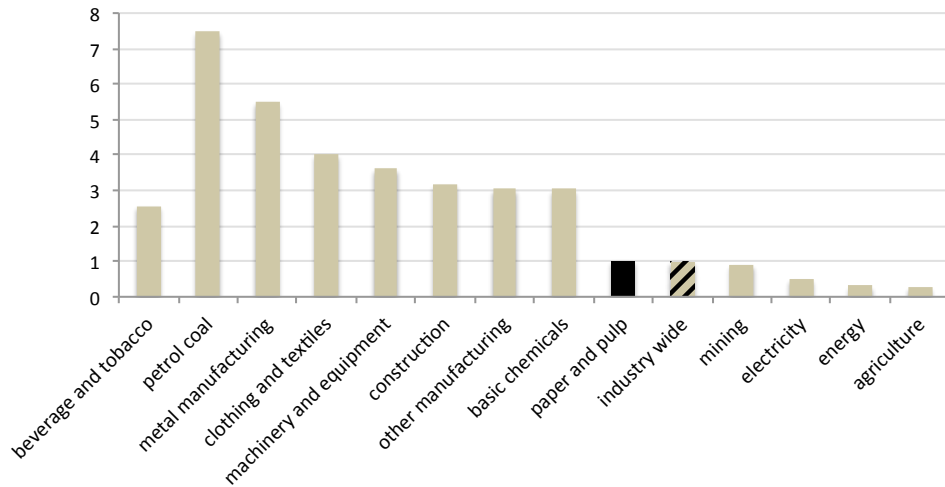


(b) Renzetti and Dupont (2003), Canada

Figure 5.3: Value of water (per volume) in the different industrial sectors, normalized to the paper sector (in black). The striped bar corresponds to the industry wide average value.



(c) Kumar (2006), India



(d) Strzepek et al. (2006), world

Figure 5.3: Value of water (per volume) in the different industrial sectors, normalised to the paper sector (in black). The striped bar corresponds to the industry wide average value. - Continued

mobility, etc.

The proposed approach should be pertinent in a long-term perspective, it enables to contemplate modifications in development paths. Instead of considering water scarcity as an issue to solve locally, it is possible to examine the issue from a broader perspective. In this context, it could be pertinent to incorporate inertia effects and costs obstacles to migration into the formalism, as it has been done for other issues, such as urban dynamics [Gusdorf et al., 2008].

As a further development, the framework could be coupled with integrated assessment models (IAM), for instance Imaclim-R [Sassi et al., 2010], REMIND [Leimbach et al., 2010] or IMAGE [Vuuren et al., 2011].



# CONCLUSION

The question underlying this thesis is how heterogeneously distributed water constraints might foster inter-basin interactions in the Mediterranean region in the next decades, in particular in terms of economic activities and population mobility.

To assess future localised water constraints, it is necessary to project future inflows and demands, represent man-made reservoirs, and project the economic benefits of water uses, in order to represent reservoirs operation and compare supply and demand in each basin.

The developed methodology projects the combined impacts of population growth, economic development and water costs on future domestic water demands, and the impacts of climate change and crops prices on future irrigation water demands, in terms of both quantity and economic benefits. For the domestic sector, the approach is to build three-part inverse demand functions, calibrated at the country scale, taking into account structural change (Chapter 1). For the agricultural sector, the economic benefits of irrigation water are calculated based on a yield comparison approach between rainfed and irrigated crops (Chapter 2). The methodology reconstructs water infrastructure networks and compares potential withdrawals to the associated available water supplies. Operating rules of the reservoirs and water allocation between demands are determined based on the maximisation of water benefits over time and space. A parameterisation-simulation-optimisation approach is used, with hedging parameters and branch allocation parameters optimisation (Chapter 3).

## **Main results**

The methodology was applied to nineteen countries of the Mediterranean basin for the domestic sector, and to Algeria for both domestic and irrigation sectors and the comparison with the supply side.

In terms of domestic demand, the developed modelling represents how developing countries undergo structural change, shifting from demand being constrained by equipment and revenue to demand being constrained by water costs. In developing countries, demand per capita catches up with



that of developed countries in the next decades. An overshoot effect can occur before demand per capita begins to decrease with the increased water costs. As demand per capita increases and reaches less-essential uses, the marginal value of the last unit demanded decreases. These evolutions are more rapid in certain countries than in others, depending on the pace of economic development and population growth.

Some countries might need to resort to costly water supply sources (e.g. desalination) to replace non-renewable sources, and experience a strong increase in water cost. If this cost increase was supported by domestic users through domestic water price increase, it could strongly decrease demands. For instance, if Libya had to rely at 100% on desalination for domestic water, water demand per capita would be decreased by 44% in 2060 compared with a standard price evolution scenario (Chapter 1).

In Algeria, the results show that the domestic sector becomes a major sector of water consumption in 2050. The quantities demanded catch up with those of the irrigation sector (Chapter 2).

In general, water values are higher for the domestic sector than for irrigation uses. With the results for Algeria, value estimations come close to simple ranking rules between uses, because domestic demand is still constrained by revenue and consists mostly of essential and high value uses. In cross-border basins, for Tunisia and Morocco the projected increase in GDP per capita leads to a demand for domestic water extending to low-value uses. For such uses, trade-offs with irrigation uses are possible. In any case, water valuation could be useful for intertemporal trade-offs.

Overall, the results show that the supply-demand imbalance will increase in most Algerian basins in the future, under the simulated socioeconomic and climate scenario (Chapter 3).

Under future conditions, in some basins demand satisfaction (in terms of value) can be increased by up to 22.5% when using economic criteria to determine reservoirs operation rules. It suggests that global changes may be an incentive to use valuation in operating rules in these basins. In other basins, the benefits of reservoirs management based on economic criteria are less pronounced. In this case, trade-offs could arise between implementing economic based operation policies or not. The costs and difficulties of implementing economic based priorities between uses should be compared to the expected gains in water benefits.

### **Implications of the multi-basin approach**

The main challenge of the approach was to combine a large-scale coverage with a representation of basin-level characteristics.

This large scale is suitable to study the impacts of global socioeconomic and hydroclimatic changes on the water sector on a multi-basins scale. Being able to represent contrasted situations between basins makes it possible to

consider the water scarcity issue from a broader perspective than the usual water basin management level and consider possible interactions between basins. The model could be applied to the study of any issue requiring a wide area, such as virtual water trade or activities and population relocalisation due to water supply reduction or water demand value changes.

In particular, the framework could be used to look at water scarcity induced migration, via impacts on economic activities and their spatial organisation, by coupling ODDYCCEIA to an economic geography model, following the formalism described in Chapter 5. The coupled framework would make it possible to consider the interactions between the economic and environmental spheres, through the water factor. Since the literature on environmental migration shows that environmental factors are mostly indirect drivers of migration, this approach appears to be particularly relevant.

The generic nature of the framework, necessary to maintain a global-local focus, has its limits. Some data are not available at global scale, and specific data collection or assumptions have to be made on a per-country basis (e.g. irrigation costs, domestic water costs). Using a single method for both developed and developing countries may prove difficult, for instance when modelling structural change effects on domestic water demands (Chapter 1). There can also be non-negligible errors in reservoirs-demands network reconstruction when using only globally available data, as revealed by the application to Algeria (Chapter 3).

However, the framework is not designed to provide a detailed representation of catchments for operational purposes, but rather to represent localised impacts of global changes, with an extended geographic coverage. In this context, and given the scarce globally available data, especially for countries from the eastern and southern Mediterranean rims, a generic method seems appropriate.

Despite identified limitations, it has the merit of offering an innovative framework for taking into account the economic value of water at large-scale, which has been lacking in previous large-scale assessments. It makes it possible to evaluate impacts of water scarcity in terms of unrealised economic benefits, and model water allocation between competitive uses.

The modular and generic nature of the framework makes it suitable to apply to other large-scale regions concerned with water supply-demand balance under global changes. In particular, it can be used for developing regions with low data-availability. The framework could also be extended to a global coverage.

## Perspectives

The generic hydroeconomic model could be used to evaluate different scenarios. In particular, different socioeconomic development paths or different scenarios of crops prices increase in the future may impact water values and the trade-offs between water uses. The model could also be used to evaluate different water management policies. It should be possible to assess the benefits of supply-side or demand-side adaptation policies: changes in dams (dimension, operation, construction, etc.), or the mobilisation of alternative water supply sources (e.g. desalination), changes in efficiency ratios (use of less water-intensive technologies, reduction of leaks in distribution networks, etc.), crop adaptation, etc.

When coupled with the economic geography model, the framework could be used to evaluate the outcomes of these management strategies in terms of economic dynamics. The impacts of incentives or barriers to mobility could be investigated.

A first perspective for this work would be to implement the ODDYCCEIA-New Economic Geography model coupling proposed in Chapter 5. For the industrial sector, it was not possible to estimate the economic value of water based on literature: so far, studies are scarce and do not provide robust results. Implementing the coupling with the economic geography model could enable to calibrate the productivity differential due to water in the industrial sector. As a further development, the framework could then be coupled to Integrated Assessment Models [Sassi et al., 2010, Leimbach et al., 2010, Vuuren et al., 2011].

On another scope, it would be interesting to consider other water supply sources and other water-using sectors, for a more comprehensive framework. In particular, it would be relevant to take into account groundwater, since some areas rely on groundwater as a complementary or major water supply source. Other sectors of water use could also be taken into account, such as electricity production (cooling, hydropower), environmental flows, etc.

The generic hydroeconomic model could be coupled to specific demand models, for instance land use models (e.g. MAgPIE [Lotze-Campen et al., 2008], GLOBIOM [Havlík et al., 2011], Nexus Land Use [Souty et al., 2012]) for irrigation demand, or electricity sector models (e.g. TIMES model [Loulou et al., 2005]) for cooling and hydropower water demands. The framework's large scale would be particularly pertinent to consider the electricity sector, since electricity markets are of a large scale. The relevance of using water for producing electricity and the relative benefits of different production technologies could be investigated, depending on the price of electricity. The modelling developed in this thesis could improve the representation of water in water-energy nexus frameworks [Dubreuil et al., 2013], in order to investigate if future energy mixes are plausible with regard to water availability.

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## Appendix A

# The economic value of water

## Tensions sur les ressources en eau : l'enjeu de l'évaluation économique

This appendix presents an overview of water valuation concepts and methods. The main text is in French, preceded by a summary in English.

### Summary

There is growing concern about water allocation issues between uses and sectors, in particular in regions where tensions on the resource are increasing. The economic approach proposes to clarify these allocation trade-offs by quantifying the value of water in its competing uses.

The concept of “value” may be unclear for non economists, it must not be confused with price or cost. In a first part, this document recalls the main economic concepts useful for water valuation: utility, willingness to pay, marginalism, economic surplus, etc.

Since water is a particular good, it is necessary to develop non-market valuation methods. Different methods are developed for the different uses. This document focuses on domestic, industrial and agricultural uses. Two main types of methods are used: the residual method, and econometric methods.

The residual method is used for producers' uses. It isolates the marginal contribution of water to the total value of the produced output from other inputs' contributions. The main difficulty is to correctly specify the production function and identify all inputs and their prices, because any error directly impacts the estimated residual value. The method relies on assumptions about technologies of production. It is grounded in the theoretical framework of production theory.

Econometric methods are used mostly for the domestic sector, and can also be used for the industrial sector. Demand functions are statistically estimated. Attention must be paid to the choice of variables and the choice of functional form. The methodology has certain limitations, such as representativity and data validity. It is based on historical observed behaviours and circumstances, and future conditions could fall outside the estimation's validity domain.

Results displayed in the literature for different sectors and countries show that estimated water values are higher for domestic and industrial uses than for agricultural uses. Studies on industrial water valuation are very scarce.

Plusieurs régions du monde connaissent des situations de rareté de l'eau, et l'accentuation de la pression sur les ressources par un certain nombre de facteurs, comme le changement climatique, la croissance de population, la pollution des eaux, ou encore les changements d'usage des sols, accroissent le problème dans le temps et dans l'espace, à des niveaux locaux et globaux. Ces tensions peuvent conduire à l'émergence ou à l'aggravation de conflits entre usages, ou entre pays. Ainsi, les préoccupations d'allocation de la ressource entre usages et utilisateurs sont croissantes.

La question de l'arbitrage entre plusieurs utilisations de l'eau qui peuvent être très différentes se pose. Comment comparer des choses qui ne semblent pas comparables et résoudre ces conflits d'usage ? Ce document présente la façon dont l'approche économique propose de répondre à ces questions.

## 1.1 Quel rôle pour l'évaluation économique dans la gestion de l'eau ?

### 1.1.1 Gérer l'eau comme un bien économique

La Conférence internationale sur l'eau et l'environnement, ayant eu lieu à Dublin en Irlande en janvier 1992, signe la prise de conscience mondiale de l'importance de la ressource "eau" : il est reconnu que la situation des ressources mondiales en eau est désormais critique, que l'eau douce est rare et que son utilisation doit se faire avec considération. L'un des quatre principes de la déclaration de Dublin, adoptée à la clôture de la conférence, est que "l'eau a une valeur économique dans toutes ses utilisations concurrentes et doit être reconnue comme un bien économique" [ICWE, 1992].

Il est donc recommandé que les politiques de l'eau soient analysées avec des techniques d'évaluation économique. La gestion de bassins hydrologiques nécessite de pouvoir mesurer les bénéfices liés aux changements de disponibilité de la ressource : faut-il investir dans la capture, le stockage, l'approvisionnement et le traitement de nouvelles ressources en eau ? Une réallocation de l'eau entre des secteurs concurrents est-elle pertinente ?

Utiliser des outils économiques ne veut pas dire prôner la mise en place de marchés de l'eau en tant que mécanisme d'allocation de la ressource, par plus que cela ne sous-entend une privatisation de la ressource [Chong and Sunding, 2006]. L'objet de l'approche économique est de fournir une aide à la décision, pour des questions d'investissements, d'allocation etc. en prenant

en compte la “valeur” de l’eau ; l’enjeu est de concevoir une infrastructure de gestion de l’eau qui servira au mieux la société [Harou et al., 2009]. Il n’y a pas incompatibilité entre la reconnaissance des qualités vitales de l’eau pour les humains et une approche économique de la gestion de l’eau [Young, 2005].

### 1.1.2 Un cadre pour l'évaluation des arbitrages entre des usages concurrentiels

Dans des conditions de rareté ou pénurie d’eau, un point de vue économique aide à identifier des allocations efficaces, et à réduire les pratiques de gaspillage. En effet, l’eau est en général allouée selon des traditions et conventions historiques, institutionnelles, politiques et sociales. Ce mode de partage des ressources en eau peut mener à des surdimensionnements des infrastructures, à des gaspillages, et est lent à s’adapter à de nouvelles conditions environnementales, ou à des changements dans les demandes. Des techniques économiques peuvent aider à allouer des ressources rares, en identifiant les compromis appropriés entre les différents usages de l’eau, qui reflètent les valeurs et les choix de la société [Harou et al., 2009]. Représenter l’intérêt des usages de l’eau en une mesure étalon commune (monnaie) permet en effet de poser un cadre pour une comparaison objective, sur une même base, d’usages qui peuvent être très différents (Cf. section 1.3).

### 1.1.3 Un outil pour la résolution de conflits et la promotion de la collaboration

Par ailleurs, au delà des questions d’efficacité des infrastructures de gestion de l’eau, [Fisher, 2005] soulignent que l’évaluation de la valeur de ressources contestées peut aider à dissiper les potentiels conflits régionaux ou globaux, et aboutir à une situation de collaboration. La monétarisation clarifierait le conflit, en convertissant un problème de gestion complexe et multi-objectif en un problème plus simple, avec un objectif unique. De plus, l’analyse menée par les auteurs révèle que les sommes mises en jeu sont souvent relativement modestes. Par exemple, la valeur de l’eau en controverse entre les Palestiniens et les Israéliens s’élèverait à beaucoup moins de 100 millions de dollars par an. Son calcul se base sur l’idée que l’eau ne peut pas coûter plus cher que quand elle provient de la désalinisation, qui peut fournir de l’eau en quantités “illimitées”. En effet, si une ressource est plus coûteuse que la désalinisation, mieux vaut alors renoncer à cette ressource, et avoir recours à la désalinisation. Ainsi, la valeur d’un mètre cube d’eau est bornée par la valeur d’un mètre cube d’eau produit par désalinisation. En multipliant cette valeur par la quantité d’eau en jeu, on peut avoir une estimation de la valeur totale maximale des ressources convoitées. En évaluant la valeur de l’eau au centre de conflits, ces derniers peuvent cesser de paraître insolubles

(comme dans l'exemple, développé par l'auteur, du plateau du Golan, entre la Syrie et Israël), ce qui ouvre la voie à la négociation et la coopération. Toutefois, certains problèmes stratégiques ne sont pas pris en compte par cette méthode, comme le fait que si l'un des pays en conflit bloque l'accès à l'eau de l'autre pays cela génère un problème de court terme d'accès à la ressource (un temps d'adaptation est nécessaire pour développer l'accès à de nouvelles ressources).

## 1.2 L'approche de l'économiste : comment mesurer la valeur d'un bien ?

### 1.2.1 Concept d'utilité

Quand l'eau est une ressource rare, elle devrait être gérée et allouée de façon efficace, c'est à dire de façon à maximiser les bénéfices qu'elle procure à la société [Harou et al., 2009]. L'approche économique fournit des méthodes permettant d'évaluer les compromis entre des objectifs différents et concurrentiels, en exprimant leurs résultats via un dénominateur commun : l'utilité.

La consommation de l'eau fournit un certain nombre de biens ou services (possibilité de boire, de se laver, de se baigner ou d'avoir d'autres activités récréatives etc.), dont le consommateur tire une utilité. L'eau permet également de produire des biens qui seront ensuite consommés directement ou indirectement (possibilité d'irriguer ses cultures, production d'électricité etc.). L'utilité est une mesure du bien-être et de la satisfaction obtenue par la consommation directe de l'eau ou des biens finaux qu'elle permet de produire.

L'analyse suppose que les agents économiques maximisent leur bien-être tel qu'ils le conçoivent. L'économiste va s'intéresser à ces préférences des individus, pour en tirer des implications à l'échelle d'un groupe ou à une plus grande échelle (Becker, 1993, cité par [Young, 2005]). En théorie, l'utilité n'est pas comparable entre agents (l'utilité est subjective et ordinale). Pour pouvoir construire une fonction d'utilité sociale, des hypothèses additionnelles sont utilisées permettant d'agréger les fonctions d'utilité individuelles en les pondérant. Il s'agit d'une approche normative qui repose sur deux choix : d'une part au niveau de chaque agent on suppose un comportement utilitariste, ensuite au niveau de la société on ajoute des hypothèses de comparabilité et d'agrégation des utilités. Une situation est considérée comme étant optimale quand l'utilité sociale est maximisée.

L'approche économique va tenter de passer de la notion d'utilité des biens et services, qui représente bien le bien-être des agents, à une valeur plus facilement mesurable et utilisable. En effet, l'utilité est intéressante en théorie car elle rend bien compte de l'hétérogénéité de agents, de l'hétérogénéité des biens et services qu'ils peuvent consommer, des relations complexes qui

peuvent exister entre eux, et permet de révéler les conflits entre agents. Cependant, elle n'est pas observable, et le fait qu'elle agrège des biens et services incommensurables la rend difficile d'utilisation. L'analyse économique décrite dans les sections suivantes va permettre de passer de l'utilité au surplus qui rend commensurable les consommations des différents biens, puis du surplus à des valeurs monétaires observables, qui pourront servir de point de départ pour les politiques d'amélioration de la gestion de l'eau.

### 1.2.2 Concept de valeur économique et de consentement à payer

Un atelier de travail sur le thème de la "valeur de l'eau", rassemblant des chercheurs, gestionnaires de l'eau, représentants des gouvernements et ONG, a noté que le concept de "valeur" de l'eau n'était pas forcément clair pour les non-économistes, et ne devait pas être confondu avec les concepts de prix, ou de coût [Matthews et al., 2010].

En effet, la valeur économique est différente du prix, et des biens n'ayant pas de prix de marché peuvent tout de même avoir une valeur économique [Hanemann, 2006]. La distinction entre le prix de marché et la valeur économique est notamment déjà notée par Adam Smith dans un passage de son traité sur la richesse des Nations. Il y différencie deux sens du concept de valeur : i) la valeur d'usage, qui exprime l'utilité d'un bien particulier, et ii) la valeur d'échange, qui correspond au pouvoir d'achat d'autres biens que confère la possession du bien donné.

Dans son historique de l'évolution du sens de "valeur économique", [Hanemann, 2006] note que l'acception moderne du concept a été formulée par Dupuit (1844), qui définit le « sacrifice maximum, en termes monétaires, auquel le consommateur est prêt » comme la mesure de la valeur d'usage du bien, et par Marshall (1879, 1880), qui définit la mesure économique de la satisfaction comme "ce que l'individu serait prêt à payer pour connaître cette satisfaction plutôt que de la manquer". Ces définitions illustrent bien que la mesure de la valeur du bien correspond à ce qu'il vaut aux yeux des individus, et non à ce qu'il coûte. Un bien peut être bon marché à produire (coût faible), bon marché à l'achat (prix faible), mais être précieux pour son acquéreur.

Ainsi, dans son ouvrage sur la détermination de la valeur économique de l'eau, [Young, 2005] définit l'évaluation économique comme la tentative d'attribuer une mesure monétaire aux préférences des individus pour certains événements ou alternatives. L'un des concepts fondamentaux est bien le concept de consentement à payer (terme utilisé aujourd'hui, noté CAP), c'est à dire la somme maximale qu'un individu est prêt à dépenser pour obtenir une unité d'un bien ou d'un service.

Finalement, on pourra dire qu'une politique de gestion de la ressource en eau a des bénéfices quand il y a des effets positifs pour lesquels les partis



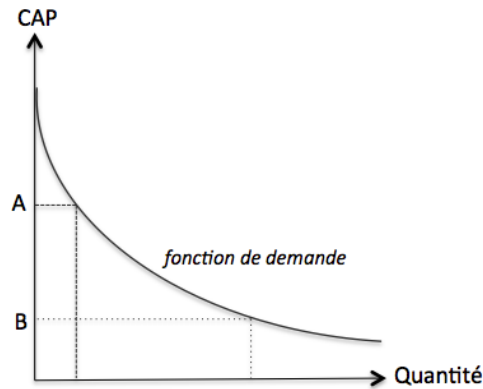


Figure A.1: Fonction de demande : consentement à payer (CAP)

concernés sont prêts à payer, les coûts correspondant quant à eux à la valeur des opportunités perdues lors de l'allocation de la ressource à un projet donné, ou bien au CAP pour éviter des effets négatifs.

### 1.2.3 Concept de Marginalisme

Le concept de marginalisme est central en économie, pour exprimer le bénéfice (ou le coût) d'une unité additionnelle de ressource "à la marge". Il est nécessaire de distinguer les valeurs et coûts marginaux, des valeurs et coûts moyens ou totaux.

L'idée clé est qu'en général les bénéfices et les coûts de l'utilisation de l'eau vont varier avec les quantités utilisées, et non être fixes [Harou et al., 2009] : en effet, l'eau est plus précieuse en période de sécheresse qu'en période humide, et de même les coûts d'approvisionnement en eau ne sont pas proportionnels à la quantité demandée, car si les ressources majeures en eau ont déjà été mises à contribution il faut ensuite avoir recours à des ressources plus difficiles et donc plus coûteuses à exploiter.

Ainsi, une courbe de demande représentant le consentement à payer du consommateur pour différentes quantités d'eau est décroissante : pour une faible quantité d'eau, le consentement à payer marginal est élevé ( $A$ ), par contre, lorsque le consommateur dispose déjà d'une certaine quantité d'eau, son consentement à payer pour une unité supplémentaire sera plus faible ( $B$ ), car il en a "moins besoin" (notion d'utilité marginale décroissante). Cf. Figure A.1, l'axe des abscisses représentant la quantité d'eau disponible, l'axe des ordonnées représentant le prix unitaire, ou consentement marginal à payer.

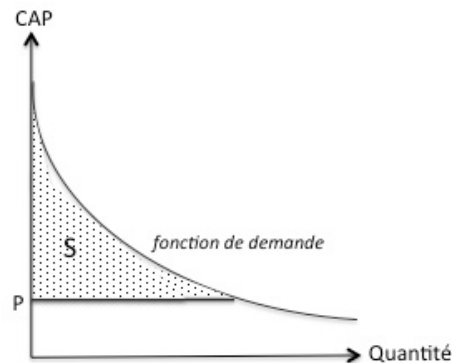


Figure A.2: Fonction de demande : surplus

### 1.2.4 Concept de surplus économique

Le surplus du consommateur consiste en la différence entre ce qu'il serait prêt à payer pour les quantités consommées, et la valeur qu'il paye effectivement à prix unitaire constant. Le paiement total ne reflète pas la valeur totale de l'ensemble des unités de bien consommées. Cf. Figure A.2, où  $P$  est le prix unitaire constant du marché, et l'aire sous la courbe notée  $S$  le surplus du consommateur (i.e. l'intégrale de la différence entre le prix qu'il était prêt à payer, illustré par la courbe de demande, et le prix effectivement payé  $P$ ).

## 1.3 L'eau, un bien complexe

### 1.3.1 Des caractéristiques particulières

L'eau étant omniprésente, on a tendance à considérer que sa définition et ses caractéristiques sont bien connues, mais il peut être nécessaire de revenir sur certaines de ses particularités pour comprendre ce que cela implique en termes de gestion de la ressource.

#### Des usages multiples

Les utilisations de l'eau sont diverses : au delà de son rôle pour la consommation humaine, elle intervient dans de multiples processus de production (industrielle, électrique), mais aussi dans la dilution et le transport des déchets, comme espace récréatif ou habitat écologique etc. [Young, 2005].

Le tableau A.1, adapté de [Moran and Dann, 2008], présente une vue d'ensemble des divers usages de l'eau :

Ainsi, selon ses usages, l'eau peut être considérée comme un bien public ou comme un bien privé [Young, 2005]. Un bien est dit "bien public" lorsque sa consommation par un individu ne diminue pas sa disponibilité pour les

Table A.1: Vue d'ensemble des divers usages de l'eau

Catégories d'usages			
Prélèvement de l'eau			Pas de prélèvement
Consommation de l'eau		Pas ou peu de consommation	
Pour la consommation directe	Pour la production d'autres biens		
Usages domestiques et municipaux	Irrigation, Élevage, Processus industriels	Hydroélectricité (avec conduite forcée), Refroidissement (centrales électriques, industrie etc.), Aquaculture	Navigation (sur lacs, rivières et canaux associés), Fonctions écologiques, Usages récréatifs, Fonctions esthétiques, Hydroélectricité (au fil de l'eau), Évacuation des effluents agricoles, industriels etc.

autres individus (il est “non rival”), et qu’il n’est pas possible d’exclure un individu de la consommation de ce bien (il est dit “non excluable”). C’est le cas par exemple des cours d’eau ou lacs à vocation récréative ou esthétique. Par opposition, un bien est un “bien privé” quand les usagers peuvent être exclus de sa consommation s’ils ne payent pas pour le service (bien excluable), et que la consommation par un individu diminue la quantité de bien disponible pour les autres individus (bien rival). C’est le cas de l’eau utilisée pour la consommation domestique par exemple.

### Une interdépendance des usages

Par ailleurs, toutes les utilisations de l’eau ne sont pas consomptives. Le glossaire de l’Agence Européenne pour l’Environnement [European Environment Agency, 2012] définit un usage consomptif comme “l’eau prélevée qui n’est plus disponible car elle a été évaporée, transpirée, incorporée dans des produits industriels ou agricoles, ou consommée par les humains ou animaux”. Une utilisation consomptive implique donc une perte de l’eau, alors qu’une utilisation non-consumptive restitue au système les volumes utilisés. Par exemple, l’irrigation est un usage largement consomptif, car l’eau est évapotranspirée, percolée etc., tandis que l’utilisation de l’eau pour la génération d’énergie hydroélectrique est non-consumptive, l’eau étant restituée en aval et disponible pour de nouveaux usages, l’utilisation domestique de l’eau a également une composante non-consumptive, les eaux usées collectées et traitées pouvant être réutilisées. Ainsi, l’interdépendance entre les usages est omniprésente : l’eau est rarement entièrement perdue par évaporation

au cours de la consommation ou des activités de production, qui génèrent en général des flux de retour vers les cours d'eau ou les aquifères, et peut être réutilisée [Young, 2005].

### **Un bien mobile, variable, coûteux à stocker et à transporter**

L'eau est une ressource renouvelable, qui circule sur Terre lors de son cycle, les précipitations et eaux de surfaces sont mobiles, il s'agit de flux et non de stocks. Par ailleurs, les précipitations et flux de surface peuvent varier de façon importante d'une année à l'autre, d'une saison à l'autre etc. en fonction des conditions climatiques. Ainsi, le moment, la localisation et l'altitude auxquels l'eau est disponible sont des paramètres importants ; l'eau ne peut pas être stockée à bas prix ni transportée sur de trop longues distances ou en altitude [Chong and Sunding, 2006]. Il existe par ailleurs des ressources non conventionnelles, comme l'eau issue des nappes souterraines fossiles (épuisables), ou l'eau issue de processus de désalinisation (ressource « infinie », mais avec un coût élevé).

#### **1.3.2 Absence de marché**

L'allocation optimale d'un bien privé peut se faire au travers d'un marché compétitif, dans un certain cadre d'hypothèses concernant le bien et le marché. Il est ainsi notamment nécessaire que les droits de propriété soient bien définis et applicables, et que les coûts de transactions soient bas (Cf. théorème de Coase). Sous ces conditions, le marché permet que le bien soit alloué à son utilisation la meilleure du point de vue économique. Mais quand on en vient à l'allocation de l'eau, ces hypothèses ne sont pas vérifiées en plusieurs points [Aylward et al., 2010].

En effet, les caractéristiques uniques de l'eau en font un exemple classique de l'incapacité du marché à atteindre une allocation économiquement efficace. L'existence d'externalités, les coûts de transaction élevés, le fait que l'eau soit pour partie un bien public, font partie des raisons pour lesquelles des marchés libres ne serviront pas toujours le mieux la société en ce qui concerne l'allocation des ressources en eau [Young, 2005] :

- Tout d'abord, l'eau est mobile, les coûts d'exclusion de la ressource sont donc très élevés : des droits de propriété exclusive, qui sont la base d'une économie de marché, sont difficiles à établir et coûteux à faire appliquer ;
- De plus, l'eau est une ressource complexe, multifonctionnelle, ce qui fait que les coûts de transaction et de gestion sont élevés ;
- Les usages de l'eau génèrent de nombreuses externalités. Par exemple, l'extraction d'eau pour l'irrigation peut épuiser les flux aval, et mener à la perte d'habitats écologiques ;

- Par ailleurs, plus que pour la plupart des biens, les valeurs sociales et culturelles liées à l'eau sont souvent en conflit avec les valeurs économiques, l'eau a statut de bien "collectif" : comme l'eau est essentielle à la vie, "il est essentiel de reconnaître le droit fondamental de tout être humain à l'accès à l'eau potable et aux services d'assainissement à un prix abordable" [ICWE, 1992].

Ainsi, il n'y a pas de véritable marché de l'eau, et les prix pratiqués ne reflètent pas la véritable valeur de l'eau. Dès lors, comment fournir aux politiques de l'eau un signal de rareté de la ressource, si celui-ci n'est pas disponible via les marchés ?

## 1.4 Quelles méthodes d'évaluation pour l'eau ?

Face à la nécessité de trouver d'autres moyens d'estimer la valeur de la ressource, les économistes ont développée des techniques d'évaluation "non marchande" : l'évaluation économique s'intéresse à la valorisation en termes monétaires de biens auxquels les individus accordent de l'importance, l'évaluation non marchande va appliquer la même notion aux biens qui ne sont pas vendus sur un marché [Hanemann, 2006]. Cette section s'attache à décrire les diverses méthodes d'évaluation non marchande qui ont pu être développées et mises en œuvre pour les différentes activités de consommation ou de production.

### 1.4.1 Classifications des méthodes

La palette de méthodes existantes peut être classifiée de différentes manières. On peut tout d'abord différencier les méthodes selon les types d'usages de l'eau. Globalement, les méthodes développées pour évaluer les biens publics sont différentes de celles développées pour les biens privés. Par ailleurs, les usages de type "bien privé" peuvent être subdivisés en usages "producteurs", où l'eau est un bien intermédiaire dans la production d'un autre bien (ex : agriculture ou industrie), et usages "consommateurs", où l'eau est un bien directement utilisé par les consommateurs (ex : usages domestiques pour la boisson, la cuisson et l'hygiène). [Young, 2005] ; et pour ces deux catégories d'usage, on aura à nouveau des méthodes assez différentes. En effet, l'évaluation est faite différemment selon si l'eau est considérée comme un bien final, ou un bien intermédiaire [Harou et al., 2009], et différentes théories économiques (théorie de la consommation ou théorie de la production) sont mises en jeu.

On peut également différencier les méthodes selon le type de technique de quantification : les techniques inductives ou déductives, qui diffèrent par les procédures mathématiques et les données employées. Les techniques dites inductives (ou statistiques) utilisent un raisonnement inductif, en général des

procédures statistiques ou économétriques, pour déduire des généralisations à partir d'observations individuelles. Les techniques dites déductives (ou mécanistes) ont recours à la construction de modèles basés sur un certain nombre de postulats comportementaux (comme par exemple la maximisation des profits ou de l'utilité des agents), et des hypothèses empiriques adaptées au cas étudié [Young, 2005].

Par la suite, on choisit de s'intéresser en détails aux méthodes développées pour les usages de type bien privé, qui posent le problème de la rivalité entre usagers, que ce soit pour la consommation directe ou pour la production d'autres biens. Les autres biens et services de l'eau, notamment environnementaux, peuvent être évalués par un éventail de méthodes, telles l'évaluation contingente, la méthode des coûts de transport, la méthode des prix hédoniques etc. qui ne seront pas développées ici. Les deux grandes techniques les plus largement utilisées pour les usages de type bien privé sont présentées ci-dessous en détails.

### 1.4.2 Méthode résiduelle et méthodes apparentées

La méthode résiduelle, et les autres approches qui lui sont liées, sont des méthodes de type déductif, applicables pour les usages "producteurs" de l'eau. Quand l'eau est un input dans un processus de production, la demande en eau va être influencée par la technologie de production du bien final, et par la demande du bien final. Dans ce cas, estimer la valeur économique de l'eau revient à isoler la contribution marginale de l'eau dans la valeur totale de l'output produit : la valeur résiduelle [Harou et al., 2009].

#### Bases théoriques

Ces approches sont basées sur la théorie de la production ; la fonction de production de l'industrie correspond à la description technique de l'entreprise, le comportement de l'entreprise est centré sur la maximisation des profits et la minimisation des coûts [Young, 2005].

Comme le décrivent [Hellegers and Davidson, 2010] et [George et al., 2011], ces approches reposent sur le fait que pour un producteur, dans un certain cadre, la valeur issue de la production d'un bien est exactement égale à la somme des valeurs des inputs nécessaires pour le produire :

$$Y * P_y = \sum (P_i * X_i)$$

où  $Y$  est la quantité de bien produite,  $P_y$  son prix, tandis que les  $X_i$  sont les quantités des inputs  $i$ , et  $P_i$  leurs prix. Par exemple, pour une fonction de production à deux inputs,  $e$  étant l'eau et  $j$  un autre input, on aura :  $Y * P_y = P_j * X_j + P_e * X_e$ , avec  $X_j$  et  $X_e$  les quantités nécessaires d'input  $j$  et d'eau pour produire la quantité  $Y$  de bien final, et  $P_j$  le prix connu de

l'input  $j$ .  $P_e$  est la valeur inconnue du bénéfice unitaire de l'input « eau », en réarrangeant l'équation, on peut en déduire :

$$P_e = (P_y * Y - P_j * X_j) / X_e$$

Estimer les bénéfices économiques relatifs à un input sans prix tel que l'eau revient donc à isoler la portion de bénéfice dû à l'eau des contributions de tous les autres inputs impliqués dans le processus de production : en retranchant de la valeur du produit final les valeurs connues de tous les autres inputs on détermine la valeur résiduelle de l'eau.

### Difficultés

En pratique, les inputs sont beaucoup plus nombreux que dans l'exemple ci-dessus, et de natures diverses : matériel et équipement, travail, ressources naturelles, capital etc., ce qui rend l'analyse plus compliquée. [Young, 2005] propose une revue détaillée des difficultés posées par l'application de la méthode résiduelle.

Il est indispensable de bien spécifier la fonction de production, le principal problème est de correctement lister et quantifier tous les inputs pertinents. Il est essentiel de ne pas omettre de variables, et de ne pas faire d'erreurs sur leurs prix, car toute erreur se répercute sur l'estimation du résidu. Cela peut être particulièrement difficile par exemple dans le cas des inputs propres, c'est à dire détenus par l'entreprise elle même (terrains et autres ressources naturelles appartenant à l'entreprise, créativité entrepreneuriale, travail non salarié des propriétaires de l'entreprise etc.) : il est difficile d'évaluer la valeur de tels inputs pour les retrancher aux revenus de la production, car ils ne sont pas monétisés.

### Extensions de la méthode résiduelle

La méthode résiduelle s'attache à évaluer le consentement à payer (CAP) d'un producteur pour l'utilisation en quantité optimale de l'input "eau" dans la production d'un unique produit. Cependant, dans les cas plus réalistes il peut être nécessaire d'étudier des cas où la quantité d'eau disponible varie, ou bien les cas d'entreprises produisant plusieurs biens différents. Pour cela, il faut faire appel à d'autres méthodes, dérivées de la méthode résiduelle. Ainsi, la méthode des changements de rente permet d'estimer la valeur de l'eau pour une entreprise produisant plusieurs biens, et les modèles de programmation mathématique, quant à eux, permettent d'évaluer les effets de potentiels changements dans le mix d'inputs, ou dans la technologie d'utilisation de l'eau (changements de la fonction de production).

### Conclusions sur l'ensemble de méthodes apparentées à la méthode résiduelle

Ces méthodes sont intéressantes car elles proposent une estimation d'un substitut de prix par unité d'eau, qui peut être comparé aux coûts des politiques proposées, le résultat étant facilement compréhensible pour les non-spécialistes. Par ailleurs, ces techniques sont relativement faciles d'application, et permettent une estimation des bénéfices non seulement pour des situations observées, mais également pour des scénarios hypothétiques. Et dans le domaine agricole, où la méthode résiduelle trouve ses principales applications, les données nécessaires sont souvent disponibles. Les limitations de ces méthodes résident dans le cadre d'hypothèses de la théorie de la production (rendements d'échelle constants et équilibre statique, ce qui peut être problématique), et dans le fait que si l'analyste ne parvient pas à correctement rendre compte de tous les coûts de production, il risque de surestimer la valeur résiduelle liée à l'eau [Young, 2005]. Ainsi, ces méthodes doivent être appliquées avec une soigneuse connaissance du cadre théorique, et avec des données adéquates et exactes. Elles sont plus adaptées aux cas pour lesquels le processus de production est simple, stable dans le temps, et où l'eau est un contributeur significatif dans la valeur de la production. Ainsi, elles sont plus utilisées pour évaluer les usages de production agricole que pour les usages de production industrielle.

#### 1.4.3 Méthodes économétriques - Demandes dérivées

Il s'agit de méthodes de type inductif, basées sur la théorie de la consommation. Ce sont les méthodes les plus largement utilisées pour le secteur domestique, et elles peuvent aussi être appliquées au secteur industriel.

##### Principe

Pour déterminer la valeur de l'eau utilisée, on peut calculer le surplus des consommateurs. En effet, en mesurant la différence entre ce que le consommateur est prêt à payer pour un bien (programme de demande) et ce qu'ils paye effectivement pour l'ensemble du bien consommée, le surplus est une mesure de la façon dont la société valorise le bien en question [George et al., 2011].

Davidson et al. (2009, cité par [George et al., 2011]) suggèrent que la valeur de l'eau pour les consommateurs domestiques et industriels peut être calculée dès lors que l'on connaît le prix ( $P$ ) et la quantité consommée ( $Q$ ) pour une année donnée, ainsi qu'une estimation de l'élasticité-prix ( $\varepsilon$ ). L'élasticité-prix représente la sensibilité de la demande au prix, elle est égale au pourcentage de variation de la demande résultant d'un pourcent de variation de prix. En effet, la pente de la fonction de demande ( $\beta$ ) peut être calculée en utilisant la formule :  $\beta = \varepsilon * P/Q$  Connaissant la pente de la



courbe de demande, il est alors possible de calculer le surplus du consommateur pour une consommation et un prix donné :  $c'$  est l'équivalent de l'aire sous la courbe de demande, au dessus du prix payé pour l'eau (Cf. Figure A.2).

Les quantités consommées et les prix sont des données observables, mais l'élasticité-prix de la demande ( $\varepsilon$ ) doit être estimée afin de pouvoir calculer le surplus. Cette estimation repose sur des techniques économétriques, qui étudient la réponse de la demande au prix à partir de données de consommation et de prix observées [Harou et al., 2009], ainsi que des variables pouvant jouer sur les préférences des consommateurs (variables climatiques revenu etc.). Les paramètres de l'équation de demande sont estimés via des techniques de régression multiple, l'objectif final étant de déterminer l'élasticité-prix.

### Difficultés

La principale difficulté est de bien spécifier la fonction de demande :

- bien choisir les variables à inclure dans l'analyse statistique en dehors des variables de quantité d'eau et de prix (variables climatiques, revenu des ménages etc.), qui peuvent avoir un impact important sur la consommation,
- bien choisir la forme fonctionnelle pour l'estimation statistique (la façon dont la demande évolue avec le prix est-elle considérée linéaire, non linéaire ?),
- bien choisir la spécification du prix : prix marginal (si on considère que les consommateurs sont informés sur les prix) ou prix moyen (que l'on peut penser plus facilement perçu par les consommateurs).

Par ailleurs, une difficulté particulière surgit quand la tarification de l'eau se fait par blocs croissants, c'est à dire quand le prix de l'eau varie selon des paliers de consommation : les  $x$  premiers mètres cubes consommés par le ménage sont à un certain prix, les  $y$  suivants à un autre prix etc. Un problème d'endogénéité se présente alors : on cherche à déterminer comment la quantité varie en fonction du prix, or le prix est lui même fonction de la quantité consommée par les ménages. Des techniques sont développées pour contourner ce problème (par exemple, spécification du prix de la forme Taylor-Nordin).

Enfin l'obtention de données peut être limitante, car il faut suffisamment d'observation sur les prix et les demandes pour pouvoir déterminer une estimation fiable des fonctions de demande, ce qui est difficile à obtenir (nombre limité de cas où l'eau est facturée volumétriquement).

Table A.2: Vue d'ensemble des méthodes d'évaluation non marchande les plus utilisées

Méthode	Principe	Applicable aux usages	
		producteurs	consommateurs
Méthodes Déductives			
Méthode résiduelle (et extensions)	Connaissant la valeur du bien produit, on lui soustrait les valeurs connues de tous les inputs autres que l'eau, et on en déduit la valeur résiduelle de l'eau.	✓	
Transfert de bénéfices	Les résultats d'évaluations des bénéfices pour des sites et des projets donnés sont utilisés pour déterminer les bénéfices pour d'autres sites ou d'autres projets.	✓	✓
Coût alternatif	Si un projet donné est moins coûteux qu'un autre projet permettant d'arriver au même résultat, alors le bénéfice de la meilleure alternative est égal au coût du deuxième meilleur projet.	✓	✓
Méthodes Inductives			
Méthodes économétriques - Demandes dérivées	Des techniques statistiques permettent de modéliser les fonctions de demande, en particulier la réaction de la demande au prix, à partir de données observées. Le surplus des consommateurs en est déduit.	✓	✓
Méthode des prix hédoniques	Méthode de révélation des préférences des consommateurs, basée sur l'évaluation de la contribution des différentes caractéristiques d'un bien à sa valeur totale.		✓
Évaluation contingente	Technique économétrique basée sur des sondages, destinée à révéler la valeur attribuée à certains biens ou ressources.		✓

#### 1.4.4 Vue d'ensemble des méthodes utilisées

Pour donner un aperçu de la diversité de méthodes existantes, le tableau A.2 (basé sur [Young, 2005, Harou et al., 2009, Aylward et al., 2010]) présente une vue d'ensemble des méthodes les plus souvent présentes dans la littérature.

Pour conclure sur les avantages et limitations respectifs des deux grands types de méthodes : Les méthodes inductives sont intéressantes car, quand elles sont basées sur de véritables observations de comportements réels ou bien sur des réponses à des enquêtes, elles présentent l'avantage de refléter le comportement économique réel des agents. Toutefois, la fiabilité des résultats obtenus par ces techniques inductives est sensible à plusieurs facteurs, parmi lesquels la représentativité et la validité des données utilisées, ainsi que le

choix de la forme fonctionnelle utilisée pour ajuster les données. Par ailleurs, une autre limitation est que le comportement observé est historique, et pour pouvoir travailler sur des comportements futurs il peut être nécessaire de supposer des paramètres hors du domaine de validité de l'estimation statistique. Quant aux méthodes déductives, leur grand intérêt est leur flexibilité, puisqu'elles peuvent être construites de manière à représenter n'importe quel futur économique, ou n'importe quelles conditions technologiques souhaités. Toutefois, elles connaissent aussi certaines limitations, étant donné qu'elles reposent sur des hypothèses comportementales, et également sur des hypothèses de technologies de production ou de consommation. Ainsi, la fiabilité des résultats de ces méthodes sera sensible à ces hypothèses, ainsi qu'aux choix de spécification du modèle [Young, 2005].

Ainsi, il existe un certain nombre de méthodes permettant d'estimer la valeur de l'eau dans ses différents usages, malgré la difficulté de l'absence de valeur de marché. Toutefois, ces méthodes présentent un certain nombre de limitations, et [Euzen and Morehouse, 2011] notent qu'il est encore nécessaire de continuer à améliorer ces techniques d'évaluation non marchande de la ressource en eau.

## 1.5 Le bénéfice social de l'eau et ses difficultés d'évaluation

### 1.5.1 Évaluation des bénéfices privés ou des bénéfices pour l'ensemble de la société

Lors de l'analyse de bénéfices, on distingue deux positions de comptabilité : privée et sociale. Le point de vue "privé" mesure les impacts en termes de prix auxquels sont confrontés les agents économiques étudiés. Le point de vue "social" prendra en compte les prix ajustés en fonction des taxes, subventions et autres interventions publiques [Young, 2005]. Le choix de point de vue peut se faire selon l'échelle de l'étude (locale, régionale, nationale etc.), les valeurs et bénéfices de l'eau évalués peuvent être soit les bénéfices privés (pour un projet local) soit les bénéfices pour l'ensemble de la société.

Ainsi par exemple, dans l'application de la méthode résiduelle, des ajustements sont nécessaires pour que l'évaluation soit faite du point de vue social : en effet, si l'intervention du gouvernement ou l'inefficience des marchés mènent à des prix d'inputs ou d'outputs qui ne sont pas ce que les prix d'un équilibre compétitif seraient, alors la valeur imputée au résidu, reflétant seulement le point de vue privé, ne sera pas le reflet de l'intérêt de la société [Young, 2005]. De même, lors du calcul des surplus des consommateurs, pour une évaluation du point de vue de la valeur pour la société dans son ensemble, il faut veiller à ce que le prix pris en compte ne soit pas le prix payé pour l'eau, qui peut être grandement influencé par les taxes ou subventions publiques, mais le coût nécessaire pour fournir la dernière unité

d'eau consommée [George et al., 2011].

### 1.5.2 Difficulté de prise en compte tous les bénéfices sociaux

Toutefois, même lorsque l'évaluation des bénéfices est réalisée du point de vue de la société dans son ensemble, la valeur que la société attache à la réalisation d'objectifs socio-politiques, comme la distribution des revenus, le développement rural, ou l'accès à la nourriture à faible coût, n'est quasiment jamais reflétée dans la valeur de l'eau estimée dans les différentes études [Hellegers and Davidson, 2010].

Certaines études se sont intéressées à cette question, comme par exemple dans le cas de l'estimation de la valeur de l'eau pour l'agriculture irriguée dans la zone aride de Haryana en Inde [Rogers et al., 1998]. La valeur de l'eau qui y est calculée pour l'usage agricole correspond à différence entre la valeur nette du produit cultivé avec irrigation et la valeur nette sans irrigation, rapportée au volume d'eau utilisé pour l'irrigation. Mais l'auteur souligne que le bénéfice social que constitue la disponibilité en biens alimentaires, ainsi que le prix modéré de ces denrées (résultant de la plus grande quantité de production permise par l'agriculture irriguée), accessibles aux populations les plus modestes, doit être pris en compte dans l'estimation du bénéfice total de l'usage agricole de l'eau. Ce bénéfice social étant difficile à quantifier, l'auteur a recours à un moyen détourné pour le prendre en compte : le prix du produit agricole est augmenté de 50%. Une des quatre principales conclusions du rapport de [Rogers et al., 1998] est que, de même qu'il est indispensable de prendre en compte l'ensemble des coûts liés à l'utilisation de l'eau, il est crucial de refléter les objectifs sociétaux de réduction de la pauvreté et de sécurité alimentaire dans l'évaluation de la valeur de l'eau (ainsi que les autres bénéfices indirects associés à l'irrigation).

Ce type d'étude montre une prise de conscience de l'importance de comparer les usages en termes de bénéfice social global de l'eau, c'est à dire ne pas se limiter aux bénéfices économiques directs mais prendre en compte également les bénéfices indirects pour l'ensemble de la société. Cependant, pour l'instant la littérature propose peu de méthodes permettant une évaluation plus précise de ce bénéfice social global de l'eau.

## 1.6 Quelques résultats pour différents usages et pays

### 1.6.1 Une valeur de l'eau plus élevée pour les usages domestiques et industriels que pour les usages agricoles

[Aylward et al., 2010] ont fait un travail de compilation des résultats de plusieurs études d'évaluation de la valeur de l'eau pour différents usages, dans différents pays. Les résultats ont été homogénéisés, de façon à présenter des valeurs moyennes de l'eau, en US\$2008/m<sup>3</sup>. Le tableau A.3 présente

Table A.3: Synthèse des valeurs de l'eau compilées pour différents usages et continents

Type d'usage	Continent					Moyenne	Nombre d'observations
	Afrique	Amérique du Nord	Amérique du Sud	Asie	Europe		
Domestique	0,65	0,91	0,68	0,30	0,71	0,59	48
Industrie		0,06		1,31	0,86	39	
Agricole	0,28	0,21	0,57	0,28	0,14	0,28	92
Moyenne	0,37	0,34	0,64	0,64	0,42	0,48	
Nombre d'observations	63	32	6	72	6		

une synthèse globale des résultats compilés, par grand type d'usage et par continent.

Ces moyennes cachent parfois une très grande variabilité entre les résultats des différentes études. Ainsi, pour le secteur domestique, les valeurs variaient de 0,01 à 2,88\$/m<sup>3</sup> en Afrique, et de 0,04 à 1,22\$/m<sup>3</sup> en Asie. Pour le secteur industriel en Asie les résultats recensés allaient de 0,01 à 6,94\$/m<sup>3</sup>, et pour le secteur agricole en Afrique, de 0,01 à 1,97\$/m<sup>3</sup>.

Pour les valeurs agricoles, une certaine variabilité peut s'expliquer. En effet, l'analyse des valeurs estimées par type de culture montre que l'eau a une plus grande valeur dans la production de produits agricoles à haute valeur ajoutée : l'eau utilisée pour irriguer des cultures à faible valeur (comme le maïs, le sorgho, les bananes, le blé etc.) a une valeur moyenne de 0,04\$/m<sup>3</sup>, alors que pour la production de cultures à plus forte valeur (tomates, concombres etc.) cette valeur atteint en moyenne 0,80\$/m<sup>3</sup>, soit une multiplication par vingt. Mais étant donné les grands écarts de contexte à l'intérieur même des continents, et le relativement petit nombre d'études pour certaines localisations géographiques, il est difficile de tirer des conclusions des chiffres par continents.

La littérature est très pauvre en ce qui concerne l'évaluation de la valeur de l'eau dans l'industrie. Seules trois études ont été recensées par les auteurs, fournissant 39 estimations spécifiques. Ces estimations présentent une plus grande variabilité que pour l'agriculture et l'utilisation domestique (en particulier en Asie).

Ainsi, les chiffres de ce tableau bilan (Table A.3) sont à utiliser précautionneusement, parce qu'ils sont issus de méthodologies différentes, et que l'ensemble des données n'est pas toujours assez fourni pour pouvoir donner une valeur moyenne fiable (certaines valeurs reflètent un très petit nombre d'observations). Cependant, on peut tout de même conclure que les valeurs estimées sont plus élevées pour les usages domestiques et industriels que pour les usages agricoles.

### 1.6.2 Précautions dans l'interprétation des résultats en termes de gestion de l'eau

[Hellegers and Davidson, 2010], ayant travaillé sur le bassin de Musi en Inde, notent que les résultats d'estimation de la valeur de l'eau doivent être interprétés avec attention, notamment dans le cas de l'irrigation. La culture avec la plus basse valorisation de l'eau n'est pas forcément celle qu'il faut sacrifier lorsque l'accès à l'eau est limité. En effet, les agriculteurs choisissent leurs types de cultures pour plusieurs raisons : certaines cultures peuvent être des cultures de subsistance pour leur propre consommation, il faut prendre en compte l'importance des rotations culturales, et les agriculteurs préfèrent répartir les risques de maladies, ainsi que les risques liés à la volatilité des prix des produits agricoles, en diversifiant les cultures, quitte à perdre en efficacité économique d'utilisation de l'eau.

L'évaluation économique ne fournit pas "la" réponse, mais fournit une information pour la prise de décision politique

[Kadigi et al., 2008] ont étudié l'allocation de l'eau dans le Great Ruaha River Catchment en Tanzanie, où la ressource est rare et doit être partagée entre une utilisation hydroélectrique en aval, et des utilisations agricoles en amont. La production hydroélectrique génère un plus grand bénéfice économique par mètre cube (59 à 226 Tsh/m<sup>3</sup>, contre 15,3 Tsh/m<sup>3</sup>), mais ces deux usages sont importants pour la région : les rizières sont le moyen de subsistance de 30000 familles d'agriculteurs du bassin, et contribuent à environ 14 à 24% de la production nationale de riz, tandis que la centrale hydroélectrique génère 59 à 65% de la production nationale d'électricité. Les décideurs publics doivent déterminer l'allocation optimale d'une ressource rare entre ces deux secteurs, dont l'un génère les plus grands bénéfices sociaux (anti-pauvreté) tandis que l'autre génère les plus grands bénéfices économiques. L'information quant à la valeur de l'eau dans ses usages concurrentiels est alors la clé pour promouvoir un débat informé sur la gestion et l'allocation de l'eau, en identifiant le point de départ pour négocier des compromis acceptables.

Au final, l'évaluation économique ne doit pas déterminer l'allocation optimale de la ressource de façon arbitraire, mais est une aide à la prise de décision politique, en fournissant une meilleure connaissance des enjeux de l'allocation.

En conclusion, les préoccupations sont croissantes autour des questions de répartition des ressources en eau entre des secteurs concurrents, particulièrement là où les tensions sur les ressources s'accroissent. L'approche économique propose d'explicitier ces compromis d'allocation, en quantifiant la valeur de l'eau dans chacun des usages en compétition. Comme l'eau n'est pas un bien marchand comme un autre, il est nécessaire de développer des méthodes particulières, d'évaluation non-marchande, permettant d'estimer

la valeur de l'eau dans ses différents usages. Ces méthodes sont très utiles dans de nombreux contextes, même si un certain nombre de voix s'élèvent pour encourager l'intégration d'un plus large spectre de valeurs écologiques et sociales de l'eau. Finalement, l'évaluation économique apporte une compréhension de la valeur de l'eau dans ses différents usages, et des implications de réallocations de la ressource d'un secteur à un autre. Ainsi, elle est un outil utile pour la prise de décision politique, en fournissant des informations sur lesquelles baser les négociations, dans le but d'atteindre une gestion efficace et soutenable des ressources en eau, et d'éviter les conflits.

**Titre :** Rareté de l'eau et relations interbassins en Méditerranée sous changement global. Développement et application d'un modèle hydroéconomique à large échelle

**Mots clés :** Ressources en eau, Changements globaux, Modélisation hydroéconomique, Large échelle, Méditerranée

**Résumé :** Les changements globaux, socio-économiques et climatiques, vont très probablement accroître les tensions sur les ressources en eau dans la région méditerranéenne dans les prochaines décennies. Dans un contexte de contraintes en eau inégalement distribuées géographiquement, des interactions entre bassins pourraient se développer. Par exemple, les activités dépendantes de l'eau pourraient quitter les zones où l'eau est rare pour rejoindre des endroits où elle est plus abondante. Pour étudier cette question, il est intéressant d'évaluer les contraintes en eau localisées, en termes de quantité d'eau et de valeur économique, en combinant une modélisation à l'échelle du bassin à une couverture géographique étendue. Cette thèse mobilise comme cadre méthodologique celui de la modélisation hydroéconomique générique.

La première partie de la thèse est consacrée à la projection et à la valorisation des demandes en eau. Pour le secteur domestique, des fonctions de demande inverse en trois parties sont construites, en tenant compte des changements structurels, et sont calibrées à l'échelle des pays. Pour le secteur

agricole, le calcul de la valeur économique de l'eau d'irrigation repose sur une méthode de comparaison de rendements entre les cultures pluviales et irriguées.

La deuxième partie se concentre sur l'aspect approvisionnement en eau du modèle hydroéconomique. Pour modéliser la gestion des réservoirs, une approche économique est utilisée, fondée sur la maximisation inter-usages et inter-temporelle des bénéfices liés à l'eau. Afin de déterminer les règles d'allocation, une approche "paramétrage-simulation-optimisation" est utilisée, avec des paramètres prudentiels et des paramètres de répartition entre les branches. Le modèle est appliqué à l'Algérie, à l'horizon 2050.

La dernière partie de la thèse suggère de s'intéresser aux impacts du manque d'eau sur la localisation des activités économiques et les migrations de population qui s'ensuivent, en se plaçant dans le cadre théorique de l'économie géographique et en utilisant le modèle hydroéconomique développé dans la thèse.

**Title :** Water scarcity and inter-basin interactions under global changes. A large-scale hydroeconomic model applied to the Mediterranean region.

**Keywords :** Water resources, Global changes, Hydroeconomic modelling, Large scale, Mediterranean

**Abstract :** Global socioeconomic and climatic changes will increase the pressure on water resources in the Mediterranean region in the next decades. This thesis contemplates the question of how heterogeneously distributed water constraints might foster inter-basin interactions. To do so, it is necessary to assess localised water scarcity in terms of both water quantities and economic values, in a framework combining a river basin level modelling with an extended geographic coverage. The methodological approach used is generic hydroeconomic modelling.

The first part of the thesis is dedicated to the projection and valuation of water demands. For the domestic sector, the approach is to build three-part inverse demand functions, calibrated at the country scale, taking into account structural change. For the agricultural sector, the economic benefits of irrigation water are calculated based on a yield comparison approach between rainfed and irrigated

crops.

The second part concentrates on the supply-side of the hydroeconomic model. Operating rules of the reservoirs and water allocation between demands are determined based on the maximisation of water benefits over time and space. A parameterisation-simulation-optimisation approach is used, with hedging parameters and branch allocation parameters optimisation. The model is applied to Algeria, at the 2050 horizon.

The last part explores how this hydroeconomic model could be used to investigate inter-basin issues. In a context of heterogeneous water availability between basins, water dependent activities could relocate from water scarce areas to less constrained locations. The last chapter of the thesis suggests looking at the impacts of water scarcity on economic activities location and population migration in an economic geography framework.

