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THE ECONOMICS OF WATER EFFICIENCY: A REVIEW OF THEORIES, MEASUREMENT ISSUES AND INTEGRATED MODELS

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SUMMARY - The present paper focuses on the economics of water efficiency, in its theoretical foundations, statistical developments, and interactions with hydrology. After defining the various concepts of water use efficiency and the main techniques for its valuation, the paper presents the main indicators that can be used for measuring economic efficiency in water use and the basic characteristics of an integrated hydrologic-economic water accounting system. Finally, the main issues at stake in integrating different perspectives into a comprehensive model are presented, in order to give suggestions on how to design appropriate policies for water resources planning and management.

Key words: water economics, river basin modelling, water efficiency.

INTRODUCTION (Section 1)

The pressures of societies and the economy, combined with traditional approaches to water supply and management, have led to the unsustainable use of world’s freshwater resources. Indeed, in some areas of the Mediterranean basin, it is essential to implement appropriate water-savings policies, in order to avoid shortages, ecological degradation, and even permanent economic and social consequences. With the growth in population and the demand for economic development, increasing the efficiency of water use is certain to become more and more important.

Improving efficiency and increasing conservation are the cheapest, easiest, and least destructive ways to meet future water needs. They are also the most politically- and environmentally-responsible measures to be implemented in the sector. However, there are dissimilar perceptions on what the determinants of water efficiency are in the end, and what policies should be implemented to pursue the goal of efficient and wise water management.

Two main approaches, the hydrological/engineering approach and the economic/institutional approach, have usually confronted on what methodologies and performance ratings to use to measure water efficiency. The former approach focuses on the abstraction, storage, distribution, treatment and disposal activities related to the hydrological cycle and its variability. These models give rise to the recommendations of implementing supply-side measures, such as infrastructure expansion and investment in reduction of leakages.

On the other hand, the economics of water deals with the ways to improve social gains form the use of a scarce resource. It uses optimization techniques under alternative institutional policies, in order to maximize the benefits of an allocation of an exogenous amounts of water in the economy. This approach follows from the joint analysis of production and environmental costs, and of demand conditions, and is at the basis of the introduction of demand-management policies, such as cost-recovery, environmental taxes, water use permits tradable on special markets.

In the last decade or so, a trend has emerged toward integrating economic and institutional considerations into complex hydrological modeling, and to represent hydrological relationships to determine the available amount of water into economic models. Such analyses are based on the recognition that there complex interactions exist within a territory of reference, between the user’s system, represented by the economy, and the water resource system, represented by the hydrological cycle. The ongoing integration of different perspectives into a comprehensive model is a fundamental task in designing appropriate policies for water resources planning and management.

The present paper focuses on the economics of water use efficiency, in its theoretical foundations, statistical developments, and contacts and interactions with the hydrologic science. Water use efficiency includes any measure that reduces the amount of water used per unit of any given activity, consistent with the maintenance or enhancement of water quality. Anyhow, it is when water prices reflect the full social costs of developing supplies, that the incentives are created to use the resource efficiently and rationally. Hence, when resources are correctly valued, reflecting its contribution to production, the incentive exists, through the forces of supply and demand, to use those resources efficiently though the introduction of technological change. The achievement of economic efficiency in resource use is a major economic policy aim, for it means that the economy is approaching its maximum in the context of available resources. The economics of water resource addresses these issue, both on a sector basis through stand-alone analyses, and in a comprehensive manner, through multi-objective approaches.

The purpose here is illustrative, not comprehensive or definitive. Nonetheless, these aspects are considered of special interest to the WASAMED project, since they give suggestions on how to integrate the different approaches in water resources modelling, planning and management in the Mediterranean. From table 1, it is evident that total renewable waster resources pre capita vary widely between participating countries. Moreover, water use efficiency is especially important in this region, since many of the Mediterranean countries suffer high levels of water stress, as shown by the last two indicators in table 1, displaying the pressure on water resources from agriculture. In some instances, the dependency ratio, is equal to the part of the renewable water resources which originates outside the country, is worryingly high.

The rest of the paper is organized as follows. Section 2 introduces the different meanings of efficiency in water resources use, focusing on economics but stressing the ways the various approaches can complement each other. It also introduces the basic concepts of water economics, especially in the agriculture sector. Section 3 briefly analyses the basic principles of water supply and demand, carrying out examples of stand-alone economic analyses of water resources. Section 4 examines the techniques used to assess the value of water use, focusing especially on the agricultural production functions that are used in complex modeling. Section 5 reviews water accounting principles and the techniques for modeling the interactions between the hydrologic and the economic conditions and the institutional framework. It also examines the main indicators developed to measure water efficiency and productivity in related sectors, and how they can be used for policy-making. Section 5 draws some policy conclusions and proposes directions for future empirical research.

A MULTI-FACED APPROACH TO WATER EFFICIENCY (Section 2)

It is commonly intended that achieving water efficiency consists of optimizing water use. Indeed, different points of view should be considered when investigating water use efficiency. Absolute or physical efficiency means using the least possible amount of water for any activities. Economic efficiency seeks to derive the maximum economic benefit for the society. Institutional efficiency qualifies the functions of an institution regarding its water-related tasks. Social efficiency strives to fulfill the needs of the user community. Environmental efficiency looks at natural resource conservation. Finally, technological efficiency refers to the process of finding ways for extracting more valuable products from the same resources. Depending on the conditions of each users system, these non-exclusive definitions of water use efficiency can be achieved simultaneously. In any case, it is clear that efficient water use should be approached in a multi-objective, cross-sectional and comprehensive manner. In particular, it should include the management of both supply and demand, assigning an economic value to water resources (Garduño and Cortés, 1994).

Table 1. Basic water data WASAMED countries (Source: FAO AQUASTAT, 2003, unless specified)

	Groundwater: produced internally (10^9 m^3/yr)	Surface water: produced internally (10^9 m^3/yr)	Overlap: surface and groundwater (10^9 m^3/yr)	Water resources: total internal renewable (10^9 m^3/yr)	Water resources: total internal per capita (m^3/inhab/yr)	Water resources: total renewable (actual) (10^9 m^3/yr)	Water resources: total renewable per capita (actual) (m^3/inhab/yr)	Dependency ratio (%)	Ag water withdrawal (1998, as % of total renewable water resources)	Total water withdrawal (1998, as % of total renewable water resources)
Algeria	1.70	13.20	1.00	13.90	429.80	14.32	442.8	2.93	27.51	42.39
Cyprus	0.41	0.56	0.19	0.78	965.30	0.78	965.3	0.00	21.79	30.77
Egypt	1.30	0.50	0.00	1.80	24.53	58.30	794.4	96.91	101.20	117.20
Germany	45.70	106.30	45.00	107.00	1,297.00	154.00	1,866.0	30.52	6.05	30.55
Greece	10.30	55.50	7.80	58.00	5,284.00	74.25	6,764.0	21.89	8.42	10.46
Italy	43.00	170.50	31.00	182.50	3,182.00	191.30	3,336.0	4.60	10.46	23.19
Jordan	0.50	0.40	0.22	0.68	121.10	0.88	156.8	22.73	86.36	114.80
Lebanon	3.20	4.10	2.50	4.80	1,294.00	4.40	1,189.0	0.76	20.88	31.31
Malta	0.05	0.00	0.00	0.05	127.50	0.05	127.5	0.00	19.80	100.00
Morocco	10.00	22.00	3.00	29.00	933.60	29.00	933.6	0.00	37.97	43.45
Palestine	-	-	-	-	-	-	-	-	-	-
Portugal	4.00	38.00	4.00	38.00	3,773.00	68.70	6,821.0	44.69	12.82	16.39
Spain	29.90	109.50	28.20	111.20	2,704.00	111.50	2,711.0	0.27	21.74	31.96
Syria	4.20	4.80	2.00	7.00	384.10	26.26	1,441.0	80.26	72.09	75.97
Tunisia	1.49	3.10	0.40	4.19	422.20	4.595.00	462.4	8.70	47.12	57.45
Turkey	69.00	186.00	28.00	227.00	3,139.00	213.60	2,953.0	1.52	13.05	17.57
Mean	14.98	47.63	10.22	52.39	1,605.00	63.46	2,064.0	21.05	33.82	49.56
Std. Dev	21.52	64.45	14.87	72.41	1,614.00	72.38	2,162.0	30.73	29.87	35.78

Such approach is required because both population and water are unevenly distributed, such that different areas experience differing degrees of water stress. Moreover, keeping it constant in terms of quantity, absolute water supply is diminishing in terms of quality. Hence, water allocation is a highly controversial subject, particularly in arid and semiarid zones. Most water planners assign priority to water use in the following hierarchical order: human consumption, food production and industrial production. However, this criterion has often caused conflicts because in many countries the priority of development strategies is not necessarily to improve the quality of life through sanitation and good health, but rather through the development of industry and exports (food and finished products). Above all, people's fundamental right to clean water and sanitation at and affordable price should be recognized. But in the past, the prevailing lack of awareness about the economic value of water has led to its being wasted and to its use with a negative impact on the environment. Moreover, indirect benefits such as environmental and psychological ones have not been included, as they are difficult to quantify. In practice, the value water is considered inferior to its real worth and this gives rise to inefficient use.

For much of the time, water management has focused on manipulating water supplies from natural source to where it was needed. In this supply management, water is thought of as a requirement to be met, not as a commodity the demand for which can be altered. Thus, water use efficiency has often meant satisfying all possible demands for the resource. It is only comparatively recently that the focus has shifted on how demand can be satisfied without massive supply developments. In particular, the concept of allocation of water based on its values in alternative uses has become increasingly important, and, with it, consideration of water use efficiency.

Water use in most socioeconomic activities can vary widely depending upon the interplay of many factors. Many of these factors, such as pricing policies, comprise products of public decision-making. Others, such as the selection of production processes, are private decisions, but again are the product of many forces that change through time. Thus, policies and practices which lead to improved water use efficiency bring about an array of possible choices for adapting to local circumstances. The establishment of a dynamic balance between interventions in water supply and demand, taking into account the variability of supply in time and space, the changes in demand, and the limits and opportunities of technology, is the final goal of the society. This will enable to dispose of water supply in adequate amounts for human groups with positive growth rates (increasing population) and provide responses that are better suited to availability and demands.

Economic and institutional issues in water use efficiency

Any method of increasing water use efficiency should be subjected to a technical evaluation in order to obtain an estimate of the actual reduction in water demand or discharge resulting from using the method. However, economic and environmental factors are of foremost importance. Where water development costs and competition for available capital are rising, the concept of physical or engineering efficiency is limited by its inability to address the value of any specific use of water in relation to alternative uses for the same water.[1] An exclusive emphasis on improving the engineering efficiency of a given water use, therefore, may lead to unproductive expenditures if the value of that use is less than the value of some other use of the same water. Hence, the economic efficiency concept should be taken into account.

While the hydrological cycle is at the basis of physical calculations of water efficiency, the concept of the factors of production is the starting point for analyzing economic efficiency. Three generalized factors underlie all productive activities: natural resources, labour and capital. In particular, natural resources are added to varying amounts of labour and capital, to bring about production of goods and services.

This general paradigm applies not only to the goods and services traded in markets (or sometimes by other means), but also to some which may be quite far removed from market processes, like

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[1] Physical efficiency means using the least possible amount of water for any activities. Such technical evaluations basically measure the ratio between water pumped into a system and water delivered to consumers or end uses. More on physical water efficiency is presented in section 5 on water accounting and related indicators.

recreation. In any event, these three factors of production combine in varied combinations to yield products for consumption.

Economic efficiency in a production setting involves technical and allocative components. Production is technically efficient when the maximum possible output is generated with a given set of inputs, or when a selected output is produced at minimum cost. Allocative efficiency involves the optimal combination of inputs and occurs when the marginal prices of each of the factor inputs are equal. In turn, the way in which the factors combine depends upon their relative prices.[2]

The economic approach to deciding the most desirable allocation of water is to use the principles of economic efficiency in order to ensure that water is supplied to its most valuable uses. In an economic sense, two principles or rules are the criteria which guarantee the greatest efficiency in the allocation of a resource. These are (Agudelo, 2001):

The principle of ‘equimarginal value’, which means that the marginal benefit, or incremental value, per unit of resource used should be equal across all uses. When equality of marginal values is achieved, further redistribution of water can make no sector better off without making another sector worse off. The principle, then, is that the resource should be allocated in such a way that all users or consumers derive equal value in use from the marginal (the last) unit used or consumed. It should be noted that this principle presupposes an homogeneous good, which is not really the case with water; surface water, for instance, cannot be interchanged with ground water.

The principle of ‘marginal cost pricing’, which means that the marginal benefit of use of the resource should be equal to the marginal cost of its supply. Whether an enterprise is private and unregulated, private and regulated, or public, the condition that the price set should be equal to marginal cost is the desired situation from the point of view of economic efficiency considerations (provided the principle of equimarginal value is also met).

Where free competition in the economic sense exists, market processes tend to automatically bring about this optimum. If government policies dominate price-quantity determination because of public ownership or regulation, political processes replace market processes. When water prices are low relative to the costs of other inputs and in relation to the costs of developing supplies, the resource will be overused and efficiency of use will be correspondingly low.[3]

Three general considerations emerge. First, the level of attention paid to water use efficiency is directly proportional to the prices charged for water servicing. Second, rising prices lead to increasing attention to water use characteristics, and, over the long run, to more efficient water use, improved productivity and reallocation among users. Finally, when water prices reflect the full social costs of developing supplies, incentives are created to use the resource efficiently and rationally, reflecting its value in production or in its various other uses. In other words, rising prices generate powerful incentives for increasing water use efficiency.

This last point leads directly to the issue of water institutions. The legal systems of societies are endlessly complex, and beyond the scope of this paper.[4] Nonetheless, a few characteristics can be pointed out which clearly affect water efficiency decisions. First of all, most nations employ systems of building codes, which specify minimum standards that must be met in new or renovation construction. Until recently, the matter of water efficiency has rarely formed part of these codes. However, until codes and standards are modified, improved water efficiency will be very difficult to achieve. Similarly,

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[2] Firms or consumers normally will tend to use relatively more of the cheaper inputs, and relatively fewer of the more costly ones. If any of the required inputs has a very low, or zero price, to the user, then as much as possible of that input will be used. Here lies one of the fundamental problems of water resources management. As outlined earlier, water supplies have been cheap historically in most areas of the world, even in semi-arid areas. This basic factor plays a major role in explaining why water usage per unit of production is high, why recycling rarely reaches its full potential and why water usage per capita is higher in some countries than in others.

[3] Basic pricing considerations also play a major role in explaining why pollution occurs. Waste removal, in the majority of cases requires the use of environmental resources, such as water. When this input is available free of charge, it is invariably cheaper than any other option for waste disposal. The resulting overuse leads directly to water pollution problems.

[4] For an analysis of the institutional implications of water management, see Billi, Meroz, and Quarto (2004).

the ability to charge self-supplied water users royalties for the use of water constitutes formal legal arrangements, which can be manipulated to induce adequate incentives.

Above all, the fundamental institutional issue underlying water use efficiency is that of the regime of property rights. The rights to natural resources of any kind display varying degrees of ownership on the spectrum from public to private. At the public end of the scale, access is completely open to all citizens. The resource is essentially free for the taking. With open access, no incentive exists to manage the resource in a conserving, efficient manner, except through moral suasion. At the other end of the spectrum, where private ownership pertains, access to the resource belongs exclusively to its owner, is enforceable under law and is both divisible and transferable. Under such conditions, positive incentives do exist for effective management and efficient use.[5]

The point is that water typifies common property resources, with non-exclusivity, non-enforceability and low prices. Under these conditions, little incentive exists for conserving, efficient resource use. Indeed, in many cases, the potential for overuse and abuse is strong, and management becomes a very complex and difficult undertaking. But the theory goes further by suggesting that externalities, under such conditions, will rise to socially unacceptable levels, and that, over time, the development of private or quasi-private arrangements of rights will develop. Currently, in some parts of the world, the development of water markets for re-allocating water supplies, and the fledgling use of effluent discharge fees and tradable permits for pollution control reflect the growing reformation of property rights to water. Under such conditions, the development of increasingly efficient water use practices is an accompanying trend. The principle emerging here is that water use efficiency is partially a response to the property rights prevailing in a society. The greater the degree of private ownership, the greater the use of water efficient practices.

The aforementioned three key concept of water use efficiency (physical, economic and institutional) can be seen as related to each other in a sequential way. Figure 1 exemplifies this relationship and gives evidence of the fact that the story of changing social uses of water forms a spiral movement, oscillating between a perceived scarcity of the natural resource, and the implementation of the means required to overcome such scarcity. While at the beginning, engineering solutions were put in place to overcome water scarcity, and technical productive efficiency was sought to ameliorate the use of water, nowadays we have moved to demand management, in term of allocative and institutional efficiency. This process has been called by Ohlsson and Turton (2000) “the turning of a screw” and is displayed in Figure 1. The movement to economic and institutional considerations has been key to facing properly water problems, since besides physical scarcity, it is necessary to overcome the conflicts generated by competing uses, that is the so-called “social water scarcity”.

Other aspects of water use efficiency

Social and political realities, technological innovations and environmental constraints in different regions or nations of the world also play important roles in the use of water, and therefore, in efficiency considerations. In a sense, the economic factors singled out above form a subset of these realities. Socio-political factors are embedded into the fabric of societies. Many of them are subtle and indirect in their effects on efficient water use, and the best that can be done is to deal with those factors that seem to have particular importance to the issue at hand.

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[5] Demsetz (1967), and later Pearse (1988), have illustrated that the progression from common property to private ownership of resources reflects a response to social cost externalities. When resources are plentiful relative to demands, no incentive exists to develop property rights systems, and common property characteristics apply. However, as population growth and economic growth occur, conflicts over access to the resource rise in number and seriousness. There comes a time when the social costs, or externalities, of such conflicts rise to such a degree that it becomes worthwhile to reform the basic property rights (a costly undertaking in itself) to bring about increasing degrees of private ownership.

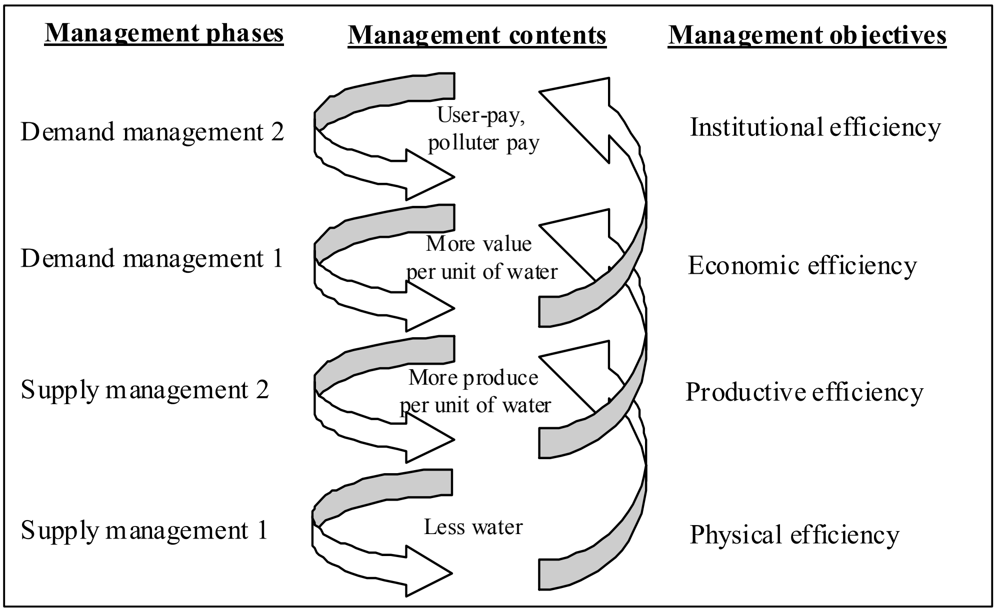

Fig. 1 The different phases of water management strategies

The other caveat is that the social factors are quite complex, and would, if dealt with comprehensively, merit a detailed treatment of their own. It is thought, however, that even a brief treatment will yield a few principles and observations. The discussion that follows deals briefly with: a) effects of social tastes and preferences, b) effects of technological innovation, and c) introduction of environmental considerations.

The issue of social tastes and preferences is deeply embedded in societies, and may be a major influence on the ways in which individuals and groups view the need for water use efficiency. For example, water supply abundance creates general attitudes that water is very plentiful, and thus the need to conserve is not felt. This makes efforts at water efficiency more difficult than in less water-abundant areas. A further example relates to a characteristic commonly termed “green lawn syndrome”. This term refers to the attitudes that residential landscaping should be green, with healthy lawns, trees and shrubbery. These attitudes have led in the past to excessive water demands, particularly in drier areas, with subsequent overcapitalization of water infrastructure. In drier areas, the use of water efficient landscaping is gradually being accepted as an alternative to the green lawn syndrome. The point here is that deeply ingrained attitudes, tastes and preferences are important considerations in moving towards increased water use efficiency.

Technological change also has a great impact on water use efficiency. On the supply side, the progression of technology has vastly increased the resources available, through the discovery of new reserves and stocks. Supplies have been expanded even more by advances enabling the use of less accessible resources, of lower quality, and lesser concentrations. Even land, though limited in the spatial sense, has been augmented enormously in its capacity to produce crops. On the demand side, technology has progressively reduced and eliminated our dependence on particular resources for particular purposes. Technological innovations have more than offset the depletion of resources through consumption: notwithstanding the economic growth of the past century, the demand for almost all natural resources and for food has risen slower than the supply.

For present purposes, it is important to understand the forces driving all the creative technological effort that has overcome the limits of nature’s endowment. Owners of land and natural resources are constantly striving to generate the greatest possible value from them. And those who need these resource commodities are constantly searching for cheaper sources of supply, alternative materials that are less costly, and ways of using them more efficiently. Both suppliers and demanders, driven by the financial incentives created by resource commodity markets, direct their creativity towards overcoming scarcity. The lesson for water use and its efficiency is that, when resources are correctly valued, commensurate with their contribution to productivity, the incentive exists to use those resources efficiently though the introduction of technological change. This principle relates back to earlier points made about the economic forces underlying water use efficiency.

Finally, the environmental approach to water use efficiency takes a broader view of the issue, emphasizing the need for integrated approaches to its management. This is where water quality considerations become important, as opposed to concentrating on the quantitative aspects. An environmental view highlights the often-ignored fact that water quantity and quality are tightly interlinked, such that actions that affect one dimension have inevitable effects on the other.[6]

This principle, as suggested at the outset of the section, means that water use efficiency should only be considered when they maintain or enhance water quality. The extent to which efficient water use can forestall or even prevent development would be considered under environmental appraisal.

Why an economic perspective for analyzing water use efficiency?

While the classical concept of water efficiency are helpful in describing changes in the volume and quality of water available, they are not sufficient for describing all of the economic implications of current or alternative allocation practices. This task requires understanding in economic terms the direct and indirect impacts of water use decisions, including opportunity costs and externalities.

The primary objective of the economic analysis of water resources is, thus, demand management and efficient allocation among its various uses. Under growing scarcity, valuing water appropriately and allocating it to the uses in which it has the most value, promotes rational use of scarce resources and greater overall societal net benefit. Allocation mechanisms should resolve trade-offs and balance competing demands, both within and between sectors, as well as between countries and regions.

A second domain in which water economics plays a fundamental role is the study of the interdependencies of the water sector with the wider economic and social domain. This interdependence generates externalities, which are uncompensated effects of one agent (or group) to another. The fact that someone could be harmed by another, or get a benefit from him, without a counterpart transaction, create inefficiencies. This calls for a careful analysis of externalities.

A third objective of the economic analysis of water is cost recovery. This means pricing water at its full long-run marginal cost, which includes O&M costs, capital costs, opportunity costs, and costs of economic and environmental externalities. Finally, economics is the basis for calculating financing needs. In this sense, economic estimation of financing requirements is a precondition for rehabilitation and improvement of sector performance, and for identifying and mobilizing additional financial resources.

The first and second of the aforementioned objectives assumes particular importance.[7] The economics of water has devoted much time to the study of allocative trade-offs and externalities. While traditional measures of water efficiency can even indicate that after a certain threshold there is little scope for saving water, there may still be significant opportunities to increase the net value generated by limited resources. This is the role of the economic analysis of water allocation, which aims at both improving the distribution of water among its uses, and reducing the negative external effects of one use on the others. This helps identifying opportunities and designing policies to improve water management practices.

In what follows, a straightforward microeconomic framework of irrigation activities, composed of a production possibilities frontier, is presented to demonstrate how externalities and opportunity costs

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[6] The common wisdom is that a reduction in water use without an accompanying decline in waste generation will cause wastes to increase in concentration. The consequences of the latter can vary in their effect on quality. Such increases in waste concentration may overwhelm the ability of existing treatment plants to operate effectively. On the other hand, increased waste stream concentrations might actually enhance the operation of waste treatment systems. The point here is not so much the actual answer to this issue, which, in any event, probably depends on local conditions, but rather the illustration of an additional principle of water use efficiency.

[7] The third objective is the specific focus of section 3.1, while the fourth objective is overlooked in the present work.

can prevent a region or nation from achieving economic efficiency, even when irrigation is described by high measures of technical water efficiency (Wichelns, 2002a).

The key concept of water productivity is to be introduced now. It is the quantity of produce (crops or other goods) that can be obtained per each unit of water used (Molden, 1997). Water productivity can be increased by improvements in agronomic practices, varying crop varieties, and supply and demand management, both regionally and at the farm level. In economic words, increasing water productivity means increasing the technical efficiency of production.

Technical and allocative efficiency can be jointly represented in a graphical setting such as that in Figure 2. The continuous convex curve depicted in Figure 2 is the production possibilities frontier, i.e. the locus of technically-efficient combinations of outputs that can be obtained with a given set of resources. Points above the frontier are not feasible, while points below it could be achieved with fewer inputs and are thus inefficient. For example, point E is technically efficient, while point F is not feasible and point I is inefficient. The frontier also describes the technical trade-off that must be considered when choosing crop combinations. The shape of the curve reflects diminishing incremental returns in the production of each crop, that is the opportunity cost of augmenting the production of one crop at the expense of the other.

Allocative efficiency describes the maximization of the net benefit, for example the revenue from crop production, by the allocation of a resource. This is achieved in the single point where the ratio of output prices is equal to the rate at which the output of one product (for example, cotton) must be reduced in order to increase the output of another product (for example, rice). In Figure 2, this occurs when the line PP, describing the ratio of output prices of cotton (PC) and rice (PR) is tangent to the production possibilities frontier.8 Farmers interested in maximizing revenues will choose to produce C1 units of cotton and R1 units of rice, and they will respond to any changes in output prices by adjusting crop choices and moving along the frontier.[9]

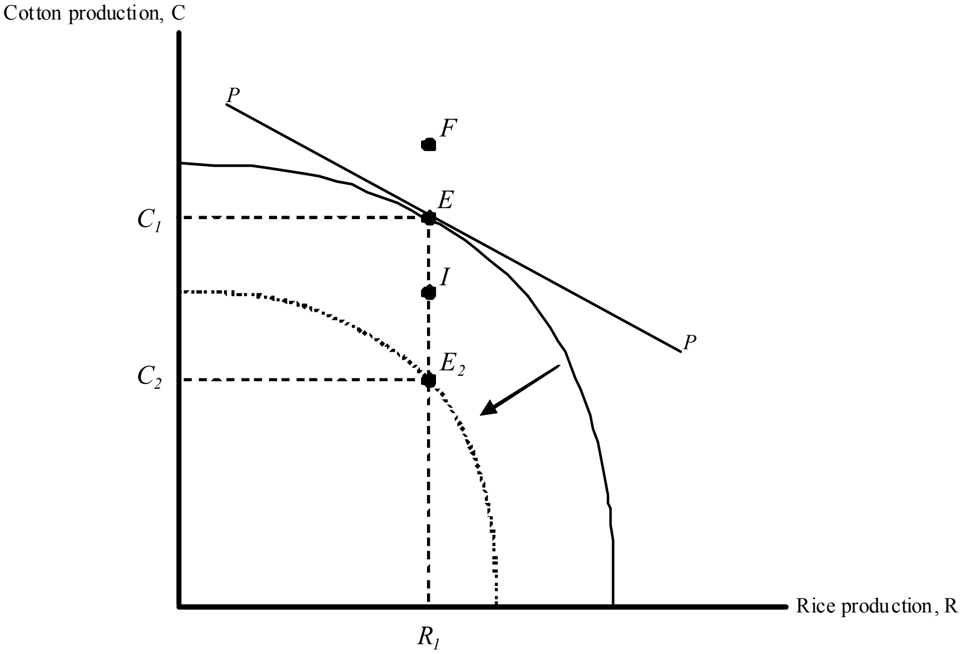

Fig. 2. Technical and allocative efficiency in a production possibilities frontier

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[8] The slope of PP is – P_R / P_C.

[9] Similarly, a production possibilities frontier can also be used to describe production opportunities throughout a region or nation with multiple uses of water resources.

The economic value of production at point E is both technically and allocatively efficient. Conversely, an inefficient point such as I might be the result of water rationing, degraded water quality, inability to obtain water when needed, unreliable supply, overexploitation by head-end users.

The production possibilities frontier is also useful in analyzing the effects of externalities caused by upstream users to a downstream activity. When a negative externality occurs along the water flow, it affects both crops and the result is the dotted production possibilities frontier depicted in figure 1. This new frontier exemplifies a situation where waterlogging and salinization, caused by upstream irrigation activities, reduce the feasible set of downstream production alternatives. This is reduced by the area between the original and the shifted frontiers. The maximum value of crop that can be produced with a given set of resources is less. For example, it is no more possible to produce the pair (C1, R1); if the quantity of rice is to be the same, water should be diverted and cotton production must be reduced to C2.

When it is the cultivation of one crop that generates a negative externality on another, the production possibilities frontier assumes the shape represented in Figure 3. The rotation of the frontier indicates that the maximum achievable production of cotton is reduced at all levels of rice production. The revised feasible set includes the inner curve and the line segment BA. The maximum possible output of cotton, point A, can be achieved only if rice is not produced.

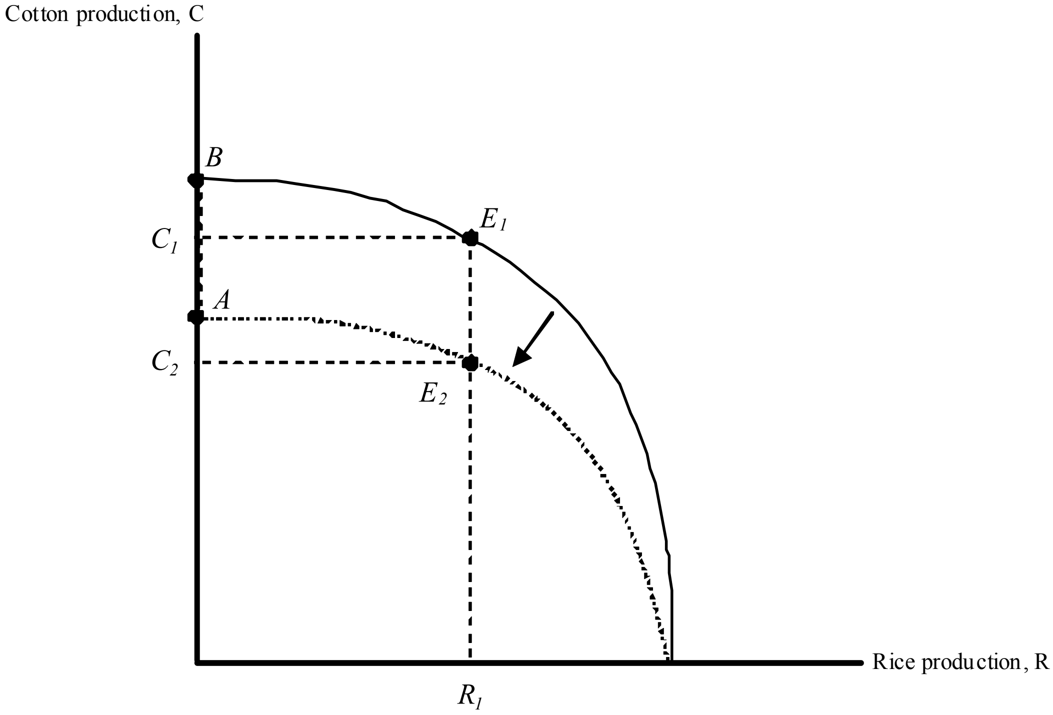

Fig. 3. Efficiency constraints in a production possibilities frontier

The analysis of negative externalities is a particularly important, yet very difficult, aspect of the economic analysis of water. As noted by Perry et al. (1997), while surface runoff and subsurface drain water can be used beneficially by downstream farmers, agricultural return flows usually are lower in quality than the water diverted originally, due to higher concentration of salt, pesticides or nutrients. In addition, return flows may not be available to downstream farmers at the time when the water can be used most productively. The intensity of external effects in water use is perhaps greater than in any other sector of the economy. This is why a careful assessment of water values requires accounting for externalities, as explored in more detail in section 4.

MAJOR COMPONENTS OF THE ECONOMIC ANALYSIS OF WATER RESOURCES (Section 3)

The supply and demand for water can be traced back to the so-called 'hydro-social water cycle' (Merrett, 1997). This relates the natural hydrological cycle to the production and consumption activities related to water. The cycle starts from the natural flow in a catchment, which is variable both during the course of a year, and from a year to another.[10] Then, there are the seven main phases of supply: abstraction, storage, treatment, distribution, wastewater collection, treatment, and disposal. These seven phases are the sources of supply costs and require major construction works. Return flows are then released into the freshwater network, such as surface sources, ground reservoirs, and the sea. Between freshwater distribution and wastewater treatment, consumption takes place in several sectors of the economy.

Other sources of supply costs, that require engineering interventions, are internal and external re-use, and recycling. Internal re-use refers to the process of treating internally the water used in the production process, in order to employ it in the same or related processes. External re-use means making wastewater suitable for being utilized in other uses. Recycling includes the activities related to releasing wastewater to the freshwater network, supplementing the natural downstream flows.

After this brief overview of the hydro-social water cycle, the remaining of the section is intended to give some other elements of the economics of water resources. The starting points are the basic economic concepts of supply and demand. Supply is mainly analyzed in this section, while section 4 gives special focus to valuation techniques of demand components.

The economic perspective of water supply

The supply of water, from an economic perspective, is driven by the costs of constructing and operating the infrastructure, the opportunity cost of these resources in alternative uses, and the correction for external side effects on economic agents beyond the transaction in analysis. Figure 4 is the well-known representation of Rogers et al. (2002) of the total cost to societies of supplying water. Environmental externalities are given evidence as fundamental non-economic supply costs, then they are not given special treatment in this paper.

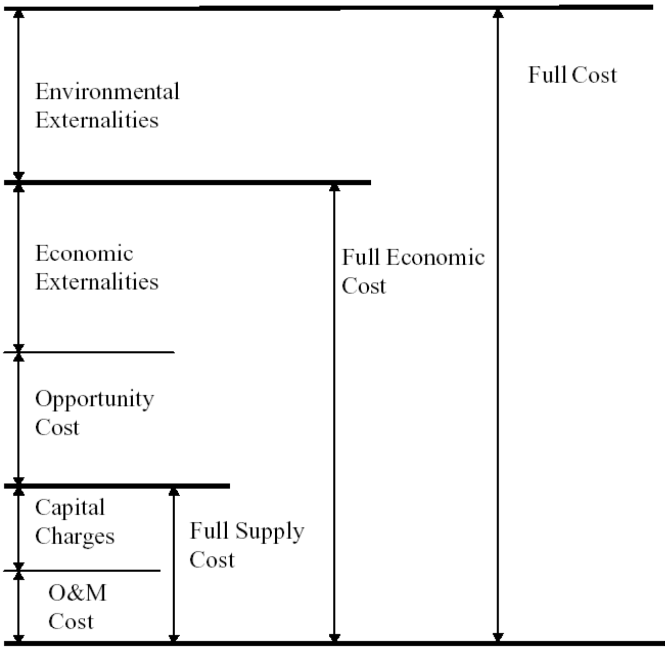

Fig. 4. Components of water supply cost

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[10] The variability of the natural flow calls for the economic analysis of supply reliability, alternative sources and storage facilities. On these issues the paper will return later.

Supply costs are one of the focuses of the economic analysis of water; on these costs will be based the discussion in this sub-section. In the literature they are usually referred to as ‘use costs’ and are distinguished in headworks costs, incurred in abstraction, storage and treatment, and network costs, for distribution, wastewater collection and disposal. Water supply costs can be fixed or variable (Merrett, 1997). When costs are converted into a monetary measure, one can single out those capital expenditures that are incurred for the purchase of resources whose expected life is greater than 12 months. They are called fixed costs and include the main construction works. Conversely, current expenditures, paid for the purchase of resources used up routinely in the production process. These variable costs include those for freshwater itself, materials, chemicals, labor, and so on, required to operate and maintain the system.

The total cost function is the sum of the two and is expressed as quantitative relationship describing the cost of supplying output in any time-period at each scale of output, from zero to the system’s theoretical capacity. It is function of the quantity of water supplied to the economic system. In the analysis of the water industry, supply can refer, as appropriate, to any single stage of the hydro-social cycle, or to the system as a whole. Unless otherwise specified, in the following the total cost of water supply will be referred to. Total water costs functions are technical relationships that for economic analyses can be approximated by a quadratic function, usually expressed in the following form:

$$TC(Q) = aQ^2 + bQ + c \tag{1}$$

where TC are total costs, Q is the quantity of water, and a, b and c are the parameters of the relationship, estimated through regression analysis. Average costs are equal to total costs divided by the unit of water produced, that is AC = TC / Q. However, costs that are looked upon by economists are usually expressed in marginal terms, i.e. the resources that have to be employed if capacity needs to be expanded to produce another unit of water. The focus on marginal costs is explained by the fact that it is the appreciation of incremental costs of getting one more unit of water, instead of the absolute cost paid for each unit, that contributes to determining the right incentives to proper use. Marginal costs are expressed as $MC(Q) \equiv \partial TC / \partial Q$ and, in the short-term, are strictly positive, due to scarcity or capacity constraints. Hence, marginal costs tend to be increasing in the short term, at least after a threshold.

Combining the three cost concepts gives a measure of economies of scale in water supply. This is given by the output elasticity of total costs, which is defined as the percentage change in total costs per unit percent change in quantity. In symbols:

$$\varepsilon_{TC,Q} = \frac{\partial TC / TC}{\partial Q / Q} = \frac{\partial TC / \partial Q}{TC / Q} = \frac{MC}{ATC} \tag{2}$$

The elasticity $\varepsilon_{TC,Q}$ can be lower or higher than unity, depending on whether there are economies or diseconomies of scale respectively; or it may be equal to unity, if costs are constant all along the relevant values. When average costs are falling, as happens in those phases of the value chain where there are economies of scale (treatment and network operation), marginal costs are less than average costs. For raw water abstraction, the opposite is true, since usually the closest, cheapest sources are those which are used first. The slope of the costs curve of abstraction is, therefore, strictly positive, since marginal costs are greater than average costs. The total cost of supplying water can exhibit several slopes, each depending on the relative strength of the two opposite effects. Determining whether the first case or instead the second prevails is an empirical mater and is essential in characterizing each alternative sources of supply, whenever different degrees of scale economies are displayed.

Another key aspect is the distinction between short- and long-run costs. In the former, increased daily output is possible through operational changes or by organizational innovations demanding new procedures. In the long term, additional capital equipment is required, either in new projects or for the expansion of existing infrastructure and plants. Whenever economic analysis is used for determining the societal cost of providing water to the whole system, the long-run perspective is required and, therefore, the long-run marginal cost should be calculated and compared to water demand. This is because, in order to produce even modest levels of output, major works are necessary, as long as the infrastructure is operating close to its maximum capacity. This is called the ‘indivisibility’ character of water provision, and allow for higher elasticity of supply in the long run. This perspective is accordingly used throughout the rest of the paper.

Increasing long-run marginal costs give rise to an upward-sloping supply schedule, since higher costs are incurred by producers to expand the quantity of water.

Opportunity costs of water supply alternatives

The opportunity cost is defined as the value of a resource in its highest-value alternative use (Briscoe, 1996). In this sense, a water supply project imposes two opportunity costs: that of water resources, which could be used in alternative supply projects, and that of other resources used up in the proposed project, that can be used elsewhere. While the latter is beyond the scope of this paper and of many water projects, few remarks can be accounted for in this discussion about the opportunity cost of water itself.

First, the opportunity cost of water depends on the specific attributes of the supply, in terms of location and hydraulic connections. If water can be used only by the proposed project, it has a very low opportunity cost, since other uses elsewhere are prevented in any case by the physical characteristics of the source. Conversely, the opportunity cost is maximum when transfers of water from one use to another are relatively easy to implement, and grow up as a source becomes more densely used.

Second, the relative importance of opportunity costs is determined by the regime of property rights enforced in each context. Where transfers of water are prohibited by law or customs, then the opportunity costs are close to zero. On the contrary, where private markets are free to operate, opportunity costs assume relevance since welfare maximization requires that the best supply project alternative is chosen.

Third, opportunity costs are different in each single water use: high-valued uses impose a lower cost on low-valued ones, than what is the case in the opposite situation.

Where opportunity costs are high, conflicts among users may arise, hence proper inter-sector and intra-sector allocation choices have to be made, and even rationing may be an option. This is essential to assure that water flows could be exploited to the benefits of the best alternative use. The estimation of opportunity costs entails calculating water benefits in other alternative uses, hence it will be explored in section 4.

The demand for water

The consumption side of the economics of water resources is represented by three major types of economic agents: households, farmers and other firms. The residential sector is composed of households that use water in final consumption, whereas in the agriculture and industrial sectors, water is a raw input required for the production process. In this lays the key difference between the residential demand, which is direct, and agricultural and industrial demand, which is indirect and derived as requirement for the production of other final or intermediate goods. Relevant demand-side economic sectors other then agriculture are hydropower, navigation and waste dilution.

In the present context, the focus is on water demand in the agriculture sector, which is the focus of the WASAMED project, and is the major consumer in Mediterranean countries, as evident from the table 2, which shows the latest available data on sectoral water withdrawals.

Table 2. Water withdrawals, total pre-capita and by sectors (Source: FAO AQUASTAT)

1998-2002	Households (%)	Agriculture (%)	Industry (%)	Total water withdrawal per capita (m^3/inhab/yr)
Algeria	21.91	64.91	13.18	194.1
Cyprus	29.17	70.83	0.00	301.5
Egypt	7.76	86.38	5.86	968.7
Germany	12.35	19.79	67.86	570.9
Greece	16.34	80.44	3.22	708.3
Italy	18.19	45.10	36.71	771.9
Jordan	20.79	75.25	3.96	189.5
Lebanon	32.61	66.67	0.72	383.8
Malta	79.21	19.80	0.99	128.5
Morocco	9.76	87.38	2.86	419.0
Palestine				
Portugal	9.59	78.24	12.17	1,121.0
Spain	13.44	68.03	18.52	869.5
Syria	3.31	94.89	1.81	1,148.0
Tunisia	13.83	82.01	4.17	271.4
Turkey	14.81	74.23	10.95	533.7
Mean	20.20	67.60	12.20	571.9
Std. Dev	18.08	22.63	18.12	342.9

Each demand type has particular estimation techniques, which will be analyzed in section 4. Here it suffices to specify that the demand for water is based on the monetary evaluation of the benefits that an additional unit of water provided to each agent. The inverse demand curves, in which the quantity is a function of the price, are downwards sloping, since the benefits of an additional unit of water are decreasing. Each sector is characterized by a specific relation between water quantity and the benefits derived, hence the demand curves have different slopes. The total demand schedule is the horizontal sum of the marginal benefit of water use in all the relevant sectors.

Taking agriculture as the focus sector, a generic equation for the inverse water demand schedule of all farmers is be the following (Tsur and Dinar, 1995):

$$D(p) = \sum_{i=1}^{n} L_i q_i(p) \tag{3}$$

where the aggregate water demand D is the sum of each farmer's optimal demand of water per unit of land, qi (p), derived form water being an input in the production process, multiplied by the land endowment, Li.

Welfare analysis of alternative sources of supply

In institutional settings characterized by non-competitive markets, the demand and supply schedules can be partially independent of costs and value considerations, since other political and social factors may play a major role in determining the price at which water is sold. Conversely, in competitive markets, strict economic efficiency is guaranteed by the price mechanism. This can be demonstrated by using partial equilibrium analysis of market clearing, carried out by relating water quantity to its price in an agriculture market. The difference between increased costs and benefits gives the net benefits to society. Efficiency equilibrium is attained at a price where supply and demand meets. If the price is lower then the costs required of meeting the current demand, then there is a deadweight loss, that is a decline in net benefits for the society.[11]

The purpose here is to use partial equilibrium analysis to explain briefly the advantage of estimating the supply of water form alternative sources, following Zekri and Dinar (2003). In figure 5, the demand for water in agriculture, D, and different curves of water supply are shown, which reflect both use and opportunity costs of supplying water. Public supply, Sp, at service level Qp is provided at price Pp. There, the quantity of water demanded is Qp', but this quantity cannot be provided by public supply, which is therefore exogenously fixed. The part of consumers that are not satisfied would be willing to pay up to P1 to improve the service. Hence, there are incentives to introduce alternative supply projects, represented by the supply schedules SA1 and SA2. Given the current demand, the two alternative projects can provide the same quantity Q2 of water at the same price P2, but are characterized by different elasticity of supply to price:

$$\varepsilon_S = (\partial Q / Q)/(\partial P / P) = (\partial Q / \partial P)(P / Q) \quad (4)$$

The same formulae applies to the elasticity of demand, ε_D. Under public supply, social surplus is given by the area abcQp. Social surplus with SA1 is equal to the area hbf. Hence an alternative supply is socially justifies whenever hbf – abcQp > 0, or alternatively cdf > ahdQp. Social surplus with SA2 is equal to the area cfd'. With two alternatives, the best project is given by the comparison of the net benefits with SA1, | cdf – ahdQp | with those with SA2, | cfd' – a'd'Qp |.

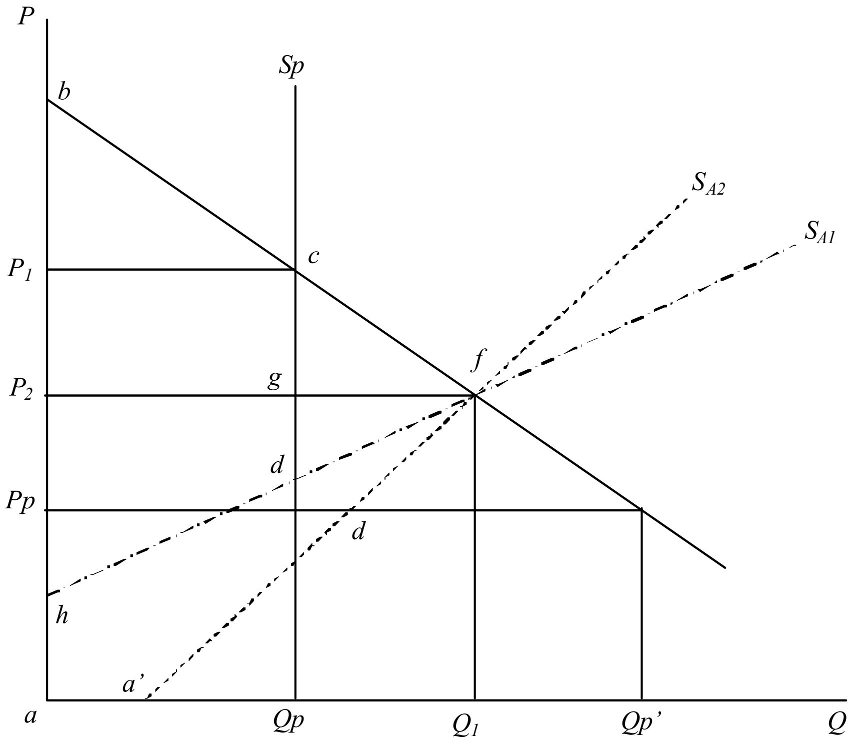

Fig. 5. Partial equilibrium analysis of alternative sources of water supply (Source: Zekri and Dinar (2003)

Estimation of supply and demand elasticities makes it possible to empirically calculate the areas under supply and demand functions. When quantities are known, assuming an invariable demand function, one can derive the incremental benefits. The observed quantities of public and alternative

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[11] We point to the works of Young (1996) and Briscoe (1996) for the analytics of these results.

supply give the incremental quantities, $\partial Q = Q_1 - Qp$. Similarly, $\partial P = P_2 - Pp$. Therefore, the estimated elasticity can be used to specify supply and demand functions and perform welfare comparison. In particular, the area V under the demand curve between two points of consumption, say Qp and Q1, can be calculated in discrete terms as follows:

$$V = \left[P_1 \times Q_p^{(1/\varepsilon_D)} \Big/ 1 - 1/\varepsilon_D \right] \times \left[Q_p \Big/ Q_p^{(1/\varepsilon_D)} - Q_1 \Big/ Q_1^{(1/\varepsilon_D)} \right] \qquad (5)$$

Box 1. Case study of alternative supply sources in rural Tunisia

The estimation of elasticity of supply and demand for water has been carried out by Zekri and Dinar (2003) for rural Tunisia, where the public supplier, SONEDE has expanded production in rural areas, traditionally supplied by associations of joint use called ACI. Their main results are summarized in table 3. According to authors' estimations, the water sector in Tunisia presents conflicting results. In 1996, ACIs were more efficient than SONEDE form a cost perspective. The price-to-cost ratio, which indicates the cost recovery rate of the supply agency or instead the level of subsidization, clearly shows that ACIs recovered a larger proportion of their O&M costs. Moreover, while ACI members paid 21% of the total costs, SONEDE customers paid only 18%.

However, both systems were highly subsidized, in that ACIs receive substantial public subsidies and SONEDE used cross-subsidies among regions. Furthermore, both systems operated at a sub-optimal scale (declining marginal costs), what is evident from the negative values of the producer surpluses. The high consumer surpluses indicate instead that consumers would be willing to pay more for improvements. Hence, there is scope for additional steps, such as price increases, in order to expand supply to a more efficient scale.

Table 3 Welfare analysis of supply alternatives in rural Tunisia, 1996 (Source: Zekri and Dinar,2003)

	SONEDE	ACI
Total cost per unit of water (TD/m3)	0.422	0.929
Average O & M cost of water (TD/m^3)	0.241	0.148
Average charge per consumer (TD/m^3)	0.190	0.195
Total bill per consumer (TD)	44.6	13.0
Price-to-cost ratio (%)	45	132
Cost elasticity of supply	-1.42	-0.78 / -0.42
Price elasticity of demand	-0.24	- 1.30
Total consumer surplus	2.45	5.04
Total producer surplus	-1.91	-10.64
Total social welfare	0.54	-5.60

METHODS FOR DETERMINING THE VALUE OF WATER (Section 4)

In adopting new strategies for water management, a central issue concerns effective evaluative procedures. In the definition of water conservation, two criteria have suggested that the methods adopted must reduce water use or consumption and must also be socially beneficial. This section examines the demand side of the economics of water, exploring the evaluation criteria that can be used in assessing various water demand management measures.

Economic or allocative efficiency addresses the value of scarce resources available to society. Thus, concern with the economic efficiency of water use creates a concern about net values of water in alternative uses and whether existing institutions are flexible enough to permit the allocation of existing supplies in such a way that society as a whole derives maximum value from those supplies.

In an economically efficient resource allocation, the marginal benefit of the employment of the resource is equal across uses, and thus social welfare is maximized. Hence, there is a case to understand the underlying economics of water demand and value in various economic sectors. The starting point is figure 6, which shows the various components of water value identified by the well-known study of Rogers, Bhatia and Huber (1998). As evident, in order to arrive at determining the full value of water to societies, several components have to be included in the calculation.[12]

A common aspect to valuation techniques is therefore the need to consider many possible benefits that water produces. The economic value of water, in each location, each use and each time, is given by the sum of:

- *value to users*, calculated on the basis of marginal value product, which is an estimate of per unit output for a unit of water used;
- *net benefits form return flows*, derived from aquifer recharge during irrigation, or downstream benefits of water diversion during hydropower generation;
- *net benefits form indirect uses*, derived when the water diverted for one purpose is used for another purpose;
- *adjustment for societal objectives*, in order to take into consideration the wider considerations, such as poverty alleviation, gender empowerment and food security.

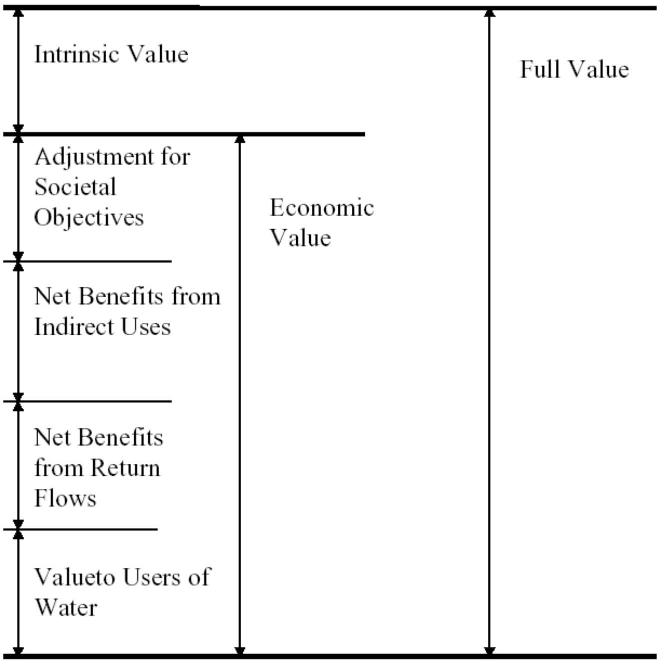

Fig. 6. Components of water demand value (Source: Rogers, Bhatia, Huber, 1998)

The authors also refer to the intrinsic value, reflecting environmental, social and cultural benefits, in order to arrive to the full value of water. Nonetheless, the present paper focuses on the economic value and presents an overview of the main techniques employed for estimating the marginal benefits to users. In fact, when competition among uses arises, a careful examination of marginal benefits in each use could help identifying large disparities and aid pressure for legal change in allocation rules. In addition, marginal benefits of water use should be compared to marginal costs of water supply proposals, in the interest of promoting economic efficiency and fiscal responsibility (Gibbons, 1986). In general, the economic equilibrium can be achieved through the operation of price signals in a competitive market place. Nevertheless, in the absence of market-clearing prices, there are a number of alternative means of estimating the value of a resource.

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[12] The issue of water valuation has been also discussed during the Expert Group Meeting on Strategic Approaches to Freshwater Management, held in Harare in 1998. The Meeting recommended considering the value of water within the broader context of Integrated Water Resources Management (IWRM). Hence, in what follows, a basin-wide approach to economic valuation will be used, although priority is given to valuing water for agriculture.

Classification of major water use values

A long-standing debate on how to value water has led to recognizing the need to have a clear analysis of what this means. In fact, it is widely recognized that water has traditionally been regarded as a free resource of unlimited supply with zero cost at supply point and, at best, water users have been charged only a proportion of the cost of extraction, transfer, treatment, and disposal. All associated externality costs of water have been ignored and users have been offered very little incentive to use water efficiently and not waste it (WWAP, 2003, pp. 327-8).

However, water has a value to society in all its uses. To be exact, it has several values, each specific to each location, each use and each time. Hence, valuing water is an exercise that should be undertaken systematically and consistently in water resource planning and management. The key issue is the cost imposed on others by a particular use of the resource, which is called opportunity cost.

The economic valuation of water resource starts form the premise that water can be considered a natural asset, the value of which resides in its ability to create flows of goods and services over time (Agudelo, 2001). Values derived from water can be mainly divided into use values, also know as extrinsic or direct values, and nonuse values, called intrinsic or passive or existence values.[13]

In the present paper, the interest is centered around use values, that is the economic benefits derived from direct use of water by consuming it or its services. Comparing marginal values between sectors, in fact, allows assessing the economic efficiency of allocations among them. For a fair comparison, adjustments are required to express values in commensurate terms of place, time, source and quality. This can be done by further specifying the different categories under which water use values can be classified, as in Figure 7.

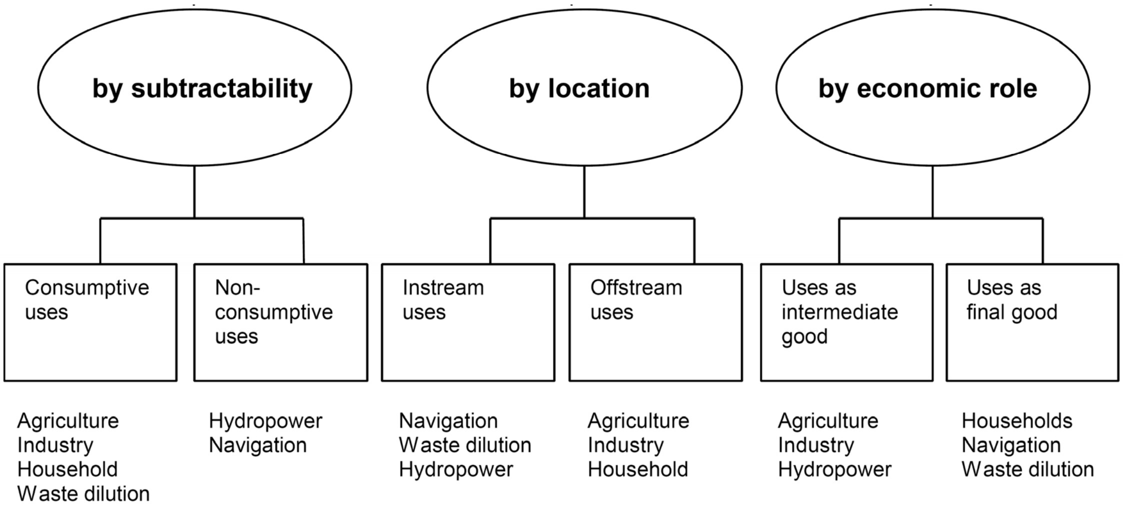

Fig. 7. Specifications of water use by three criteria (Source: Agudelo, 2001)

According to their subtractability, water use values can be divided into consumptive and non-consumptive values. If the former case, as in the main sectors of the economy, water is no longer available for further uses.[14] Considerations about competition are paramount, since consumption by one economic agent generate a negative externality on others, in terms of opportunity costs in alternative projects. Complementarities also assume relevance, as water can be used repeatedly or even simultaneously for different uses. Finally, changes in water quality are important too, since they may differently affects beneficial uses elsewhere.[15] Conversely, non-consumptive use values include

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[13] Option values, that is the desire of individuals who do not actually use water to preserve nonetheless its integrity for future eventual uses, is also a nonuse value.

[14] In this sense, it is essential to keep in mind the distinction between withdrawal and consumption, due to the possibility of reuse and recycling of water withdrawn.

[15] Accordingly, the waste dilution properties of water can properly be classified as consumptive uses.

the benefits received in the activities that leave water and its properties essentially intact. Hydropower and navigational uses are the main examples.

Another breakdown of water uses is by location. Those uses occurring in a watercourse and dependent on its flow characteristics are called instream uses. Those uses for which water has to be removed from the watercourse are called offstream uses. The distinction assumes relevance since water is a bulk commodity, that is its transportation is extremely costly per unit of water. Hence, the location becomes a crucial element in assigning values to water, because adjustments have to be made to reflect the site-specific nature of offstream uses. Important offstream uses are those related to the three main economic sectors, while the main instream uses are navigation, hydropower and waste dilution.

Finally, by their economic role, water values can be distinguished according to the level of the value chain in which they appear, so as to distinguish between intermediate or final water uses. Water is a final good for households and uses in navigation and waste dilution, while it is an intermediate good in all other economic sectors, which use water as an input in the production process. This is reflected in the different methods that can be used to estimate water use values in the different sectors.

The focus of the paper is on agricultural uses. These can be classified, according to the aforementioned scheme, as offstream consumptive uses of an intermediate good. Coherently, the estimation technique used mainly in agricultural research are explored in the next sub-sections. Beforehand, in Box 2 an overview of the trends in water uses in the two other main sectors of the economy is provided for OECD countries.

Table 4 instead presents some indicators related to a broad estimation of potentials for expanding water uses in agriculture in WASAMED countries. It can be firstly noted that the weight of the agriculture sector, in terms of area cultivated and population employed, is clearly dependent on total land and morphological characteristics. More importantly, irrigation potentials are substantially different, implying different scopes for irrigation extensions and diverse opportunity costs of doing so. On the other hand, those countries whose cultivated areas are close to be fully covered by irrigations services, would face higher incremental costs of expanding irrigation. Finally, the percentage of irrigated area on total cultivated land highlight the infrastructure-poor countries and show where potential improvements are likely to cost less at the margin. Hence, a close economic investigation of water resources availability, supply costs and willingness to pay, that take all those elements into account, would be especially helpful to guiding water policies.

Box 2. Global trends in water use by sector

Registered trends in water use vary among countries and, within countries, among sectors.

Globally, agriculture is responsible for about 69% of total freshwater abstraction. The corresponding figure for OECD countries is 45%. Agricultural demand for water is projected to increase substantially over the next few decades, as much of the additional food that will be needed to feed the world's growing population is expected to come from irrigated land.

Over the past 20 years, there has been a continuous upward trend in water use for irrigation in many OECD countries, associated with an increase in irrigated land area that has been mainly encouraged by government investment in irrigation infrastructure and by irrigation water subsidies. For most countries, irrigation water represents over 80% of total agricultural water use, with much of the remainder being accounted for by livestock farming.

While agriculture is likely to remain the primary abstractor of freshwater in the near future, industry will be the fastest growing water user overall, largely due to rapid industrialization in many non-OECD countries. Industry is the fastest growing user of freshwater resources worldwide, and demand from this sector is expected to more than double over the next two decades.

Industry accounts for 23% of global water abstraction, weighted towards the OECD countries but with industrial use in developing countries growing. The most water-intensive industries include pulp and paper, chemicals, and food and beverages. Another important emerging trend in many OECD countries is the growing use of freshwater for cooling in electricity production.

The remaining 8% of global water abstraction is used by households.

Source: OECD (2003)

Table4. Main agriculture water indicators in WASAMED countries in 1998 (Source: FAO AQUASTAT)

	Cultivated area (arable land and permanent crops) (1000 ha)	Total economically active population in agriculture (1000 inhab)	Drained area as a percentage of cultivated land (%)	Irrigation potential (1000 ha)	Area equipped for irrigation: full control - total (1000 ha)	Part of area equipped for irrigation actually irrigated (%)	Area equipped for irrigation as perc of irrigation potential (%)	Area equipped for irrigation as percentage of cultivated land (%)
Algeria	8,265	2,660	0.74	510	513	79.61	111.60	6.89
Cyprus	113	31		37				
Egypt	3,400	8,475		4,420	3,422	100.00	77.42	100.00
Germany	11,997	923			485			4.043
Greece	3,846	753			1,422			36.97
Italy	11,064	1,220			2,698			24.39
Jordan	400	192		85	77			
Lebanon	313	43		1775				
Malta	10	2		2				
Morocco	9,283	4,274	6.97	1,664	1,417	97.50	86.70	15.54
Palestine	19				12	0		
Portugal	2,358	609			632			26.80
Spain	18,715	1,220			3,640			19.45
Syria	5,421	1,563		1,250	1,267			
Tunisia	4,908	958	4.01	560	367	99.75	70.36	8.03
Turkey	28,523	14,697		8,500				
Mean	6,790	2,508	3.91	1,721	1,329	75.37	86.52	26.97
Std. Dev	7,885	4,027	3.12	2,731	1,269	42.98	18.00	29.60

Values inferred from the markets: are they reliable?

In section 3.4, a technique has been presented that has been used to select the best source of water supply when one or more alternatives are possible. The analysis therein calculated the water demand making use of regression techniques that use data from actual transactions in irrigation water markets.

The market approach accomplishes the estimation of the value of water by means of the observation and analysis of market transactions (rentals and sales) of either or both water rights and land properties with irrigation facilities. In the latter case, the value is implicitly packaged in the value of the property and is given by the difference between the price of irrigated land and the price of comparable non-irrigated land.

It turns out that, for estimations to be reliable, well-functioning water markets and irrigation land property markets should be in place. This possibility is ruled out if water markets are poorly functioning or are absent at all, as seems to be the case in many countries (Briscoe, 1996; OECD, 2003). The study of the performance of water markets is outside the scope of this paper, being already analyzed in a previous paper of the WASAMED project (Billi, Meroz, and Quarto, 2004). However, it is worth mentioning the limitations, some technical and one theoretical, of the technique used to estimate water values from market observations, when these market are in place.

From a technical point of view, it should be firstly noted that observed rental prices are usually referred to the short term, whereas observed prices for perpetual water rights give a more correct picture of long-term incremental marginal value of water. However, for the purposes of planning horizon, the price for perpetual water rights has to be converted in annual values, using capitalization formulas. This in turn requires the selection of appropriate planning period and interest rates, which is a non-trivial task. Moreover, the assumption implicit in capitalization formulas that the annual value is constant over time is also unrealistic from a long-term perspective, since inflation and variation of real values of water can influence expectations and profitable opportunities.

From a theoretical point of view, water values estimated from market transactions may be unreliable since they tell little about the actual shape and elasticity of demand to an expansion of the sources of supply. In figure 8, P0 is the price observed from market transactions. However, the historical estimated demand is known only up to this market price. Before undertaking a project, the willingness to pay for more quantities of water is unknown. Hence, form that point onwards, the water demand D may take either of the different shapes D1, D2 or D3 in figure 8, so the actual prices would vary greatly. This effect is not taken into consideration in market estimates, which usually assume an invariant demand.

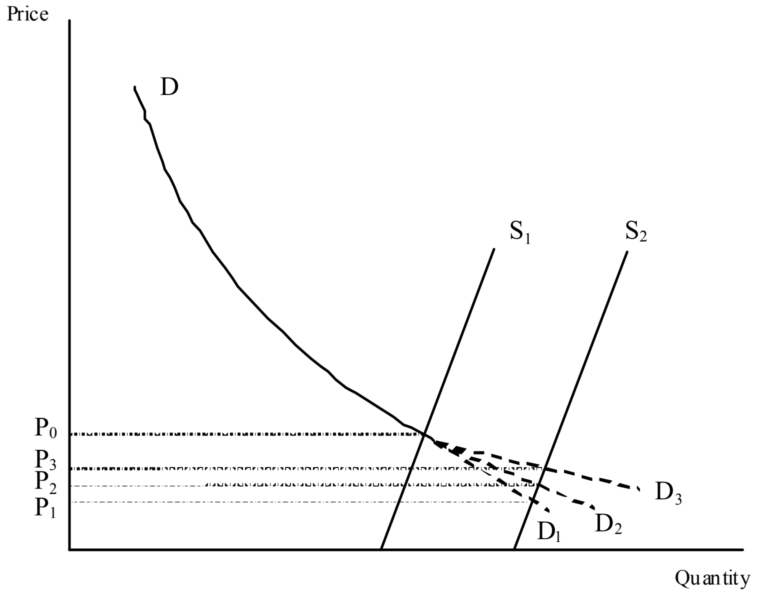

Fig. 8. Limitation of current market prices as a measure of water value Source: Agudelo (2000)

What precedes imply that even when prices are easily discoverable, they are an imperfect and frequently bad-performing estimations of the values of water. This suggests that market estimations should be complemented by valuation techniques that rely on other kind of data.[16]

Non-market estimation of the value of water as an intermediate good

The framework for valuing water should link changes in the physical characteristics (quantity and quality) of the resources to changes in the level of services or uses of water, and to how each society value these changes. The methods usually assess on-site water values with point estimates. That is, water valuation is a highly-focused activity that should be carried out at least at the level of the single service or basin. Moreover, for off-stream values to be compared to in-stream values, the former values have to be reduced by the cost of transporting or pumping and distributing water to end users.[17]

Valuation techniques are based on the concept of shadow pricing. Shadow prices are dollar values a resource display in a given situation, when all internal and external economic (and frequently social and environmental) factors are taken into account. Non market valuation techniques are evolving, in response to social and environmental pressures and the desire of policy-makers to adopt more informed decisions. Shadow pricing of water is base on four alternative approaches: the residual imputation; the change in net income; the value added; and the alternative cost. The second approach is a variant of residual imputation. Both are base on the estimation of the farmers' production function and use the same analytical apparatus developed in the present paper. They are referred to as the 'farm budget approach'. In what follows, this approach is emphasized.[18]

The basic procedure estimates the farmers' production functions and then infers the demand function from the analysis of optimal water use patterns, utilizing mathematical programming methods. The technique starts form the theory of cost-minimizing producers that use an input up to the point in which its dollar-value marginal contribution to the production (value of marginal product – VMP) equals its price or marginal cost of supply. This is the basic point of benefit-cost analyses of development projects.

In a model agricultural production function, a vector of m crops, Yj, is produced out of employing irrigation water, whose quantity is QW, and n other factors of production, whose quantities are expressed by the vector Xi. Given that, in a competitive equilibrium, the price of each input is equated to its returns at the margin, then the price of the single non-traded input may be derived by making it the residual claimant of the total value product.19 Therefore, solving for the price of water, its shadow price, P_W^*, is equal to its value of marginal product, VMPW, which is given by:

$$VMP_W = P_W^* = \left[\sum_{j=1}^{m} \left(Y_j \times P_j \right) - \sum_{i=1}^{n} Q_i \times P_i \right] \Big/ Q_W \qquad (6)$$

The shadow price given by equation (5) is interpreted as the on-site maximum average willingness to pay for water for that combination of crops. To derive the equivalent marginal value, a refinement has been introduced by the 'change in net income' approach. The value of water is the change in the

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[16] Other aspects that prevent observation from market transactions to be a good indicator of water values are the following: externalities are not accounted for in the individuals' transactions; prices do not reflect in-stream values or other environmental considerations; there may be imperfect competition between suppliers; imperfect and asymmetric information may prevent efficient decision-making; and concerns about equity and conflict resolution are left out of the analysis.

[17] From a higher perspective, the value-flow concept integrates these point estimates in space and time, yielding values of water in the different stages throughout its flow. See Seyam, Hoekstra and Savenije (2003).

[18] The discussion draws heavily from Young (1996).

[19] In this case, the Euler's theorem, that allows the total value of product to be divided into shares, is assumed to hold.

net benefits attributable to the project, which in turn is given by the difference between the with- and without-project net incomes derived from producing that combination of crops. In symbols, calling $Z = \left(\sum Y_j P_j - \sum X_i P_i \right)$ the net income, with inputs is also including water, then the change in net income is equal to $\Delta Z = Z_1 - Z_0$, where the subscripts 1 and 0 refer respectively to the with- and the without-project water situations.

The main problem of using the aforementioned approaches involves specifying the production functions, especially in the long term. This leaves room for both omitting relevant variables, and forecasting inaccurately the levels of output associated with a given increase of an input. However, this technique remains a useful instrument for public planning, which is usually oriented towards the short and, at best, the medium terms. This is especially true today since computer technologies have made available sufficient power to run mathematical programming models that make use of several production functions. These models are important instruments where a large set of activities compete for scarce resources. The models find the profit-maximizing set of activities given the resources constraints. They can trace out a set of net total benefit points, from which a set of marginal values can be derived.[20]

For the sake of completeness, it is worth describing briefly the basic characteristics of the two other approaches mentioned at the outset of this sub-section. The value added approach starts from the net payments to primary economic resources,[21] in order to build up an input-output matrix, organized on a sector-basis, providing a static picture of production processes in the economy. The estimated value of water is referred to a broad sector, such as agriculture, and is equal to the residual value added per unit of the resource, imputed after subtracting for the value added of all other economic resources. The approach gives broad estimations of average values, hence it is less useful in broad basin-wide efficiency analysis, than what it is in planning allocations within a sector.

Finally, the ‘alternative cost approach’ is a variant of cash-flow analysis, aimed at determining the cost of producing an output in the next-best project, and then attributing that cost as the water of water for the proposed project. This technique is better suited for determining the least-cost option of a supply project, than for carrying out complex analyses of efficient allocation in a river-basin context.

Economic analysis of water allocation policies

Having defined the main tools for estimating the incremental benefits of water projects, one can turn out to analyzing a proposal to implement a particular agriculture policy, such as the expansion of an irrigated area. The aim is to single out the true cost of the proposed project by including the opportunity cost of water that can be used alternatively by other agents in the same sector. Many other techniques can be applied, as highlighted before. Here, the aim is informative, hence a simple case is analyzed, and then the results of an empirical test conducted in Egypt is acknowledged in Box 3.

The starting point is 9, which represents the optimal allocation choice between to competing projects. The evaluation of water in each single project gives the estimations of the value of marginal product of water inputs, which are decreasing in the quantity. The optimal choice is taken when Q1 and Q2 water is allocated to project 1 and 2 respectively. With such allocation, the marginal benefits of water are equated across the economy and take the value of λW. Societal benefits are therefore maximized form an economic efficiency perspective with such an optimal allocation.

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[20] This aspect, integrated with geographic information technologies, may provide visual comparisons of the net benefits of alternative policy alternatives. This aspect is further explored in the conclusions.

[21] That are wages, capital, depreciation, rents to primary natural resources, and payments for government services.

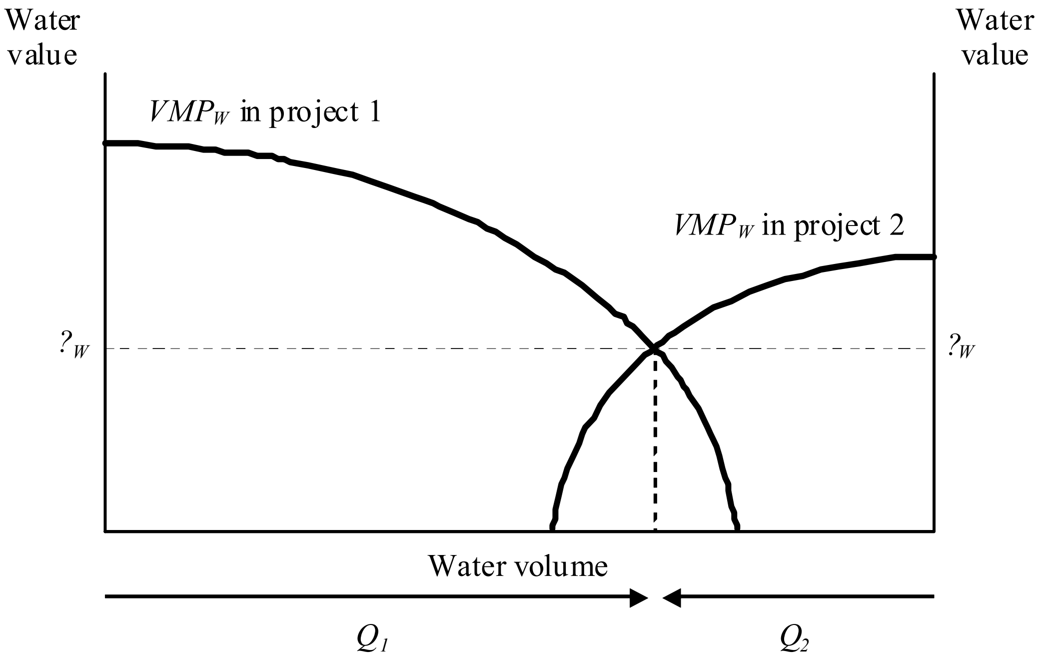

Fig. 9. Optimal allocation of a limited supply of water

Box 3. Allocation scenarios in Egypt with a farm budget approach

Wichelns (2002b) estimated the true costs of a water project in Egypt that proposes to divert water away from the delta region. Through a small-scale simulation model of production regions, the author calculates empirically the optimal allocation of irrigation water under different policy objectives between three irrigation expansion projects, using a farm budget approach to maximize total net revenues from agriculture. The main results are summarized in table 5.

The net revenue impacts of alternative water allocation policies vary with the total volume of water available for irrigation in the three regions. That volume is expected to decline in the future, as municipal and industrial demands increase. Two sets of scenarios are examined, pertaining to two policy objectives: a) the supply is allocated so as to maximize the sum of net revenues generated in the three regions; b) as supply is reduced, the volume of water is held constant in Toshka and Sinai and reduce in the Delta. The optimal irrigation depths in table 5 are used to show the kind of economic analysis that can be done with farm budget estimations.

Under the first policy objective, when water supply is reduced, net revenue is maximized by reducing irrigation depths in all three regions and reducing irrigated area in Sinai, where the marginal productivity of water is the smallest. When water supply is reduced by 10%, it is no longer optimal to irrigate land in Sinai (the case is not reported in the table). The second policy scenario, where all reductions in irrigated area and irrigation depths occur in the Delta, is far less attractive. In this case, the sum of net revenues for each reduction is smaller than under the first policy scenario. The impact of the second policy objective is reflected in the marginal value of water, which increases in the Delta, where the net revenue from crop production declines more sharply. Reallocating water to the Delta is, therefore, welfare improving, since it is the most productive region.

For a similar estimation of water values in Namibia, see MacGregor et al. (2000).

Table 5 Optimal allocation of water in three district in Egypt (Source: Wichelns 2002b)

Policy objectives	a) Maximizing the sum of net revenues			b) Maintain full production in Toshka and Sinai regions		
	Area in prod. (ha)	*Applied water (cm)*	*Net unit revenue (US$/ha)*	*Area in prod. (ha)*	*Applied water (cm)*	*Net unit revenue (US$/ha)*
Regions	*Water supply not limiting*					
Delta	8.3	94.9	711			
Toshka	1.2	9435	435			
Sinai	0.5	93.9	160			
	Water supply reduced by 5%					
Delta	8.3	90.7	707	8.3	89.2	704
Toshka	1.2	89.6	431	1.2	94.5	435
Sinai	0.4	88.2	155	0.5	93.9	160
	Water supply reduced by 20%					
Delta				7.7	77.4	642
Toshka				1.2	94.5	435
Sinai				0.5	93.9	160

ACCOUNTING FOR AND MODELING EFFICIENT WATER USE (Section 5)

The starting point of basin-wide water accounting and modeling is that the water sector interacts with all other sectors of the economy, and could potentially become a binding constraint on economic expansion and growth. This is especially true because while the amount of renewable water resource is practically fixed, water demands will continue to grow and diversify. Thus, the economic challenge is to maximize social and economic benefits under varying circumstances, by efficiently using the available resources.

Water accounting is based on the water balance approach and focused on the hydro-social cycle described at the outset of section 3, that is on the interactions between two systems within a territory of reference: the user's system represented by the economy and the water resource system. The territory of reference can be a country, a region or a river basin. Figure 10 describes these interaction, both between the water system and the economy for a given territory, and their interaction with the economies and the environment of other territories.

Water accounting is not intended to give an explicit valuation of water. Instead, it registers the flows of water over time in and out of the physical system and the economy. Of special interest here is the fact that water is considered a physical asset as all other economic assets, whose stock should be calculated at the beginning and at the end of each given period. The objective is to provide a large amount of data by disaggregating water inflows and outflows per supply source and demand sector, so that specific water accounting indicators can be calculated, as well as more sophisticated estimations of water use efficiency and productivity can be performed.

Modeling differs form accounting in that it explicitly deals with the issue of estimating water values in use and productivity in alternative uses, for the purpose of optimizing its allocation at the basin level. Models developed to this aim use mathematical programming for solving complex equation systems, that usually involve both a simulation model for the hydrologic components, and an optimization model for the economic components.

The main advantages and disadvantages of each of the two techniques are presented in turn in what follows. The underlying thesis is that both tools are necessary for appropriate water planning and management. Economic indicators that can be derived from those methods are acknowledged as well.

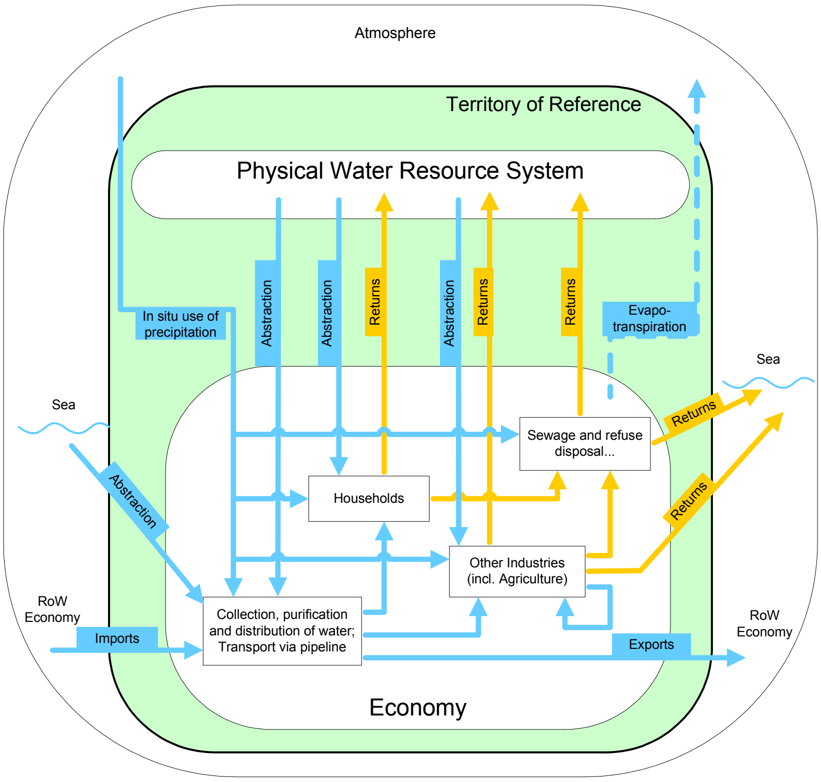

Fig. 10. Main flows of water within the economy (Source: UNDESA/UNSD)

Basic features of water accounting techniques

As evident from figure 11, the first element to consider carefully in water accounting is the water available for abstraction. This is not the net inflow of water, which is the gross inflow (effective rainfall plus[22] surface and sub-surface flows) plus change in storage. In order to obtain the quantity of water available for supply in a given year, the net inflow must be reduced by the amount of water flowed out of the system because already committed to other uses, such as downstream rights or minimum stream flows for the environment. An interesting extension, following Merrett (1997), is to allow for the possibility of water recycling. The supply of water augmented with recycled water would then be:

$$S_C = E + \sum_{p=1}^{n} \delta_P I_P \tag{7}$$

where SC is the total supply corrected for recycling, E is the net inflow, n is the number of discharge points P, IP is a specific flow of recycled water at a defined discharge point, δP is a parameter that reflect the distance of that particular discharge location from the sea, divided by the distance from the sea of the point where that flow was abstracted. This formulae allows taking into consideration the location of the recycling point, such that those plants that collect wastewater downstream and discharge it treated upstream, can be attributed a higher role in total supply. This is an important aspect when considering the valuation of the net economic benefits of a project intended to provide treatment facilities.

Of the available water resources, part flows out of the system in both usable and non-usable form, while part is depleted, either beneficially in a productive activity or non-beneficially, through evaporation, deep percolation into saline aquifers, or waterlogging. In turn, beneficial depletion is composed of both the amount depleted in the process of producing goods and services of value, or

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[22] Effective rainfall is equal to total rainfall in an area minus transpiration and evaporation.

the amount that is naturally depleted through evaporation and other causes (Molden and Sakthivadivel, 1999).

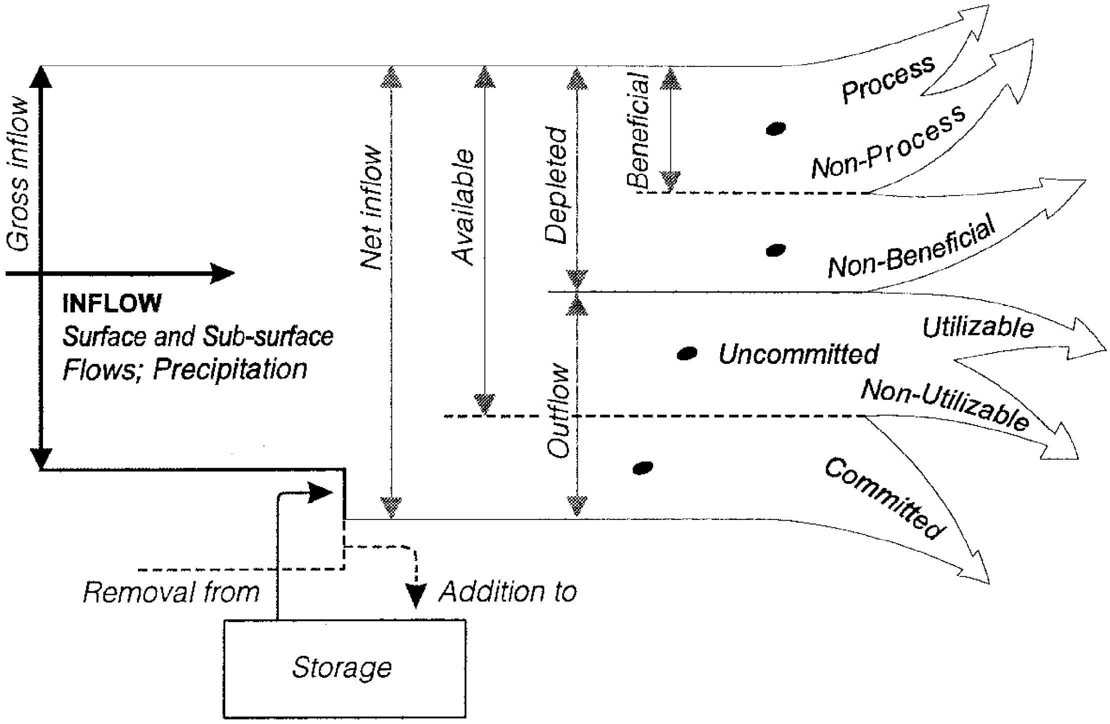

Fig. 11. Main water accounting relationships Source: Molden and Sakthivadivel (1999)

Water accounts can be compiled at the basin, service or use levels. Maintaining a consistency between these various levels is an ambitious, but unavoidable task of future applied research. It is a promising approach in that it gives evidence of the main water uses in the economy, By disaggregating water inflows and outflows per supply source and demand sector. However, the technique is limited in that, in order to provide meaningful economic information, it needs estimating water values through other techniques. It can therefore be considered as a complement, not a substitute, for more sophisticated analysis of integrated models, as those that follow.

Integrated water basin modeling: rationale and classifications

Water resources management modeling represents the most advanced tool for optimal water efficiency, reliability and cost-effective use. Such characteristics as the inherent intricacy of aquifers flows, the host of hydrologic uncertainties, the stochastic nature of water flows, the possibility of using various supply sources simultaneously, the conflicts and complementarities that arise in water use, all make complex mathematical modeling the necessary means to effective planning and efficient management. Results from these models can be interpreted to reveal opportunities for improvement over the status quo.[23]

The hydrologic approach to water resource modeling is mainly concerned with simulating the functioning of a hydrological system and/or optimizing water flows under a technically-inferred objective function. On the other hand, the aim of integrated modeling is to characterize, not only the natural and physical processes, but also the proposed projects and institutional strategies, and to optimize for the maximum net benefit to society under a politically-inferred multiple-objective function, whose weights reflect the underlying social values (McKinney et al., 1999).

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[23] Lee and Dinar (1995) discuss at long the limitations and weaknesses of this sort of models. The results depend on the model assumptions embedded in the objective function. Hence, the degree of accuracy and specification is usually limited. Data limitations, qualitative factors and subjective inference also play a role. Some of these critiques are further explored in the conclusions.

The task of these models is to allow generating both physical savings of water and economic gains, by increasing the output per unit of water used. This involves both using water where it has the most value (an allocation decision), and reducing water losses due to evapotranspiration, salinization, pollution and percolation (an evaluation of a proposed project's benefits).

Water resources management models can be referred to the short or the long term. Short-term models estimate the optimal combination of water quantity and quality for one year or single irrigation season. Long-term models also account for the effects of salt accumulation in the soil profile and, in the extended versions, in the groundwater.

Simulation model is the preferred technique to assess water resources systems' response to extreme, non-equilibrium conditions. Optimization models are based on an objective function and a set of constraints that can include social values and institutional settings. However, integrated hydrologic-economic optimization models always need a simulation component, in order to characterize the hydrologic regime, although usually at a considerably simplified level.

Integrated models can also follow a compartment approach or a holistic approach. Under the former, the main relationships that characterize the hydrologic and the economic systems are represented as stand-alone systems of computable equations, whose output data are transferred between the two components. In the holistic approach, there is one single unit that contains both components, which are tightly connected to a consistent analytical framework.

Finally, it is at the basin level that hydrologic, agronomic, and economic relationships can be best integrated into a comprehensive modeling framework. At this level, in fact, allocation decisions have the widest economic implications. As a result, it is recommended that the design of policy instruments, to make more economically-rational water use, is carried out at this level. The basin as appropriate unit of analysis has long been acknowledged in international fora.

The analytical framework of hydrological-economic optimization

A river basin system is made up of three types of components: (1) sources, such as rivers, canals, reservoirs and aquifers; (2) off-stream and in-stream demands; and (3) intermediate facilities such as treatment and recycling plants. The conceptual framework is developed as a node-link network, with nodes representing physical entities and links the connection between these entities (Rosegrant et al., 2000). The nodes are the sites of the three aforementioned components. At each agricultural demand site, water is allocated to a series of crops, according to their water requirements and economic profitability. Figure 12 shows as example the node-link representation of the Maipo river basin in Chile. The graphical representation also makes it easier to detect the spatial relationships among the various elements.

Water demand is determined endogenously based on empirical agronomic production functions. Water supply is determined through the hydrologic water balance in the river basin with corrections for distribution to the irrigated crop fields at each irrigation demand site. Water demand and supply are then balanced based on social objective functions, such as maximizing net benefits to water use. The calculation of the salt concentration allows the endogenous consideration of this important externality with respect to upstream and downstream irrigation districts.

The major component of integrated hydrologic-economic models is the representation of the production functions for agriculture that include water as an input, and demand functions for domestic and industrial uses, in order to estimate the uses and values of water by sector. Other types of water demand, such as hydropower, recreational and environmental demands, can also be included, though at the cost of complicating the analysis. The specification of the theoretic agronomic production relationships can be done in several ways, some of which have been described in section 4. Here the concept is operationalized in terms of specific econometric estimation models drawn from the literature.

The basic framework is a farm model of constraint optimization, where constraints are given by physical characteristics of water and soil (given by the hydrologic model), institutional policies (prices, property regime), and financial/investment restrictions. The objective function is maximizing the present value of farmers' profits, PA, at each demand site, over a chosen time horizon (Varela-Ortega et al., 1998). The farmers' net profits are given by crop-water functions, which relate crops yields to water applications. One of the most used crop-water function is that of Dinar and Letey (1996), which for each demand site defines:

$$PA = \sum_{t=1}^{T} \frac{\sum_{j=1}^{m} A_j Y_j P_j - \sum_{j=1}^{m} A_j \left(Fc_j + Tc_j \right) - Q_{Wt} P_{Wt}}{\left(1 + r\right)^t} \qquad (8)$$

where Yj, Pj, QW and PW indicate as before the jth crop quantity and price and applied water quantity and price, whereas Fcj and Tcj are respectively the fixed and technological water application costs of crop jth,[24] and the subscript t = (1, .., T) refers to the each time period. Fixed and technological costs can be specified in technical terms and be referred to biophysical determinants, other inputs' costs, and externalities such as salinity in return flows.

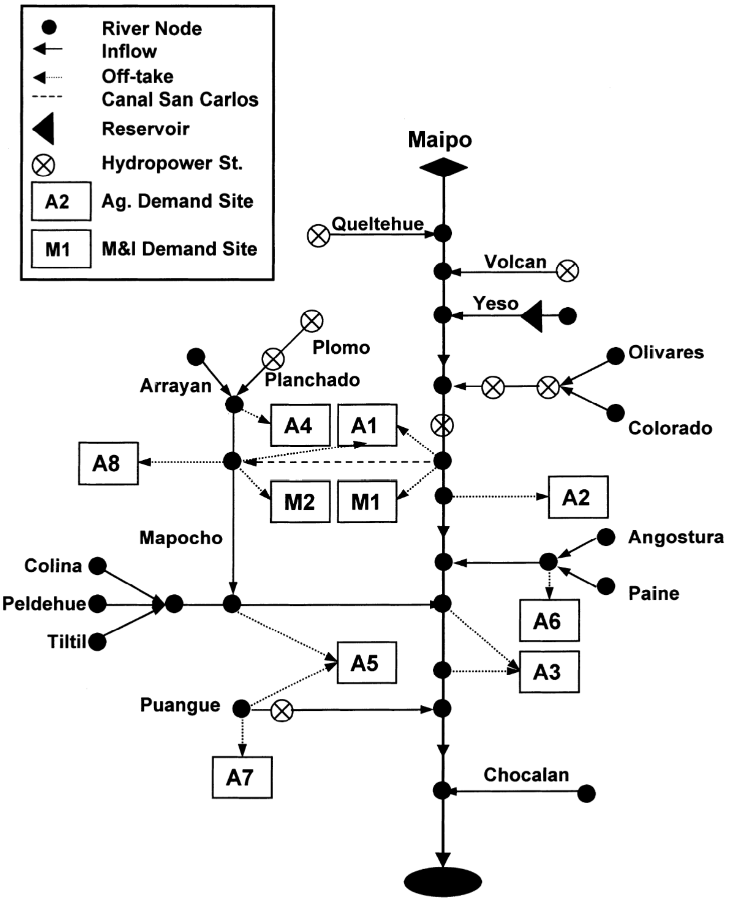

Fig. 12. Schematic representation of a river basin (Maipo, Chile) (Source: Rosegrant et al., 2000

It is important to stress that PA is to be referred to each single demand site, in order to reflect differences in hydrologic conditions. Ideally, it should also account for several cropping patterns. This can be done by further specifying the underlying economic functions, by at the expenses of greater model complexity, more rigidity of the hydrologic model, or its complete absence, such as the analysis that has been applied to the case of a water-scarce basin in southern Spain, as described in Box 4.

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[24] One technological cost parameter is the Christiensen Uniformity Coefficient (CUC), that is used as a proxi for both irrigation technology and management activities. The choice of water application technology can be determined endogenously. See Rosegrant *et al.* (2000).

In a complex system that accounts for all water uses, the objective function solves simultaneously for all the sectoral benefit function.[25] Moreover, the objective function may account for climate uncertainty and varying water storage capacity, using stochastic techniques,[26] or employing more sophisticated tools for incorporating spatial and temporal distribution of the aquifer response to external stresses.[27]

The institutional rules are the very key policy variables. They can dictate, on a command-and-control basis, specific allocations of water resources among irrigation districts, among sectors, and among in-stream and off-stream uses. Institutional can be set so as to resemble more or less the market mechanisms, in order to introduce efficiency elements into the system. An even the introduction of private property rights, as well as markets for permanent allocations and/or rental markets, can be tested out of these models.

Box 4. Accounting for different cropping patterns in water-scarce regions

Reca *et al.* (2001a) consider three resolution levels in an optimization model or an irrigation system, where water scarcity is taken as an exogenous external constraint. The objective function is to maximize the benefits of consuming a volume of water today, or instead store it and consume more water the uncertain future. The model is limited to a detailed economic component, hence the hydrologic component is taken as given in the process of economic optimization.

The first sub-problem studies the optimum irrigation timing that maximizes a single crop yields. The second component derives optimal aggregated economic functions associated to each irrigation area, by analyzing optimal land and water allocation for all cropping patterns. Finally, the third level addresses optimal water allocation for a complex distribution system, such as the irrigation system of an entire basin, by taking into account the economic functions for each irrigation area.

The authors in a companion paper (2001b) apply the model to the Bémbezar system in the Guadalquivir river basin in southern Spain, using data produced *ah hoc* from field irrigation evaluations. A deterministic analysis has been carried out in order to compare optimum water and cropping patterns management with actual ones, in a stochastic environment that determines water availability.

The authors conclude, among others, for the superiority of water markets in reducing consumption levels.

INDICATORS OF WATER USE EFFICIENCY AND WATER PRODUCTIVITY

The overview of water economics principles and techniques developed in the previous sections would not be given full significance unless remarks would be made about the appropriate combination of water data and modeling outputs. The purpose of the present section is providing the reader with insights about the most useful indicators of water efficiency used in irrigation analysis and policy making. Indicators are usually expressed as fractions, that is to say ratios between physical measures of water inflows and outflows. Several comments and remarks arisen in the literature are provided.

Technical indicators of efficient water use

The first class of ratios considered herein as a benchmark for reference are the technical irrigation efficiency, which is adimentional (Palacio-Vélez, 1994). Efficient water use, Ef, is defined as the ratio between the actual volume of water used for a specific purpose, Vu, and the volume extracted or diverted from a supply source for that same purpose, Ve. Functionally expressed:

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[25] See for example the water policy analysis of the Mekong river basin in Ringler *et al.* (2004).

[26] See the work of Mejías *et al.* (2004) applied to an irrigation district in southern Spain.

[27] See for example Faisal *et al.* (1997).

$$Ef = {}^{Vu}\!/_{Ve} \quad (9)$$

Efficiency in the use of water in irrigation may be separated into three components: storage, conveyance, and irrigation efficiency. Storage efficiency, Es, is the ratio between the volume of water diverted for irrigation, Vd, and the volume entering a storage reservoir for that same purpose, Ve. In symbols:

$$Es = {}^{Vd}\!/_{Ve} \quad (10)$$

Conveyance efficiency, Ec, is the ratio between the volume of water diverted to irrigation plots, Vp, and the volume diverted from the supply source, Vd, that is:

$$Ec = {}^{Vp}\!/_{Vd} \quad (11)$$

The classical irrigation efficiency, Eu, is defined as the volume of water beneficially used net of evapotranspiration, Vu, divided by the volume of water diverted, Vd, or analogously:

$$Eu = {}^{Vu}\!/_{Vd} \quad (12)$$

When large volumes of surface runoff or deep percolation are generated during irrigation events, the value of irrigation efficiency Eu tends to be low, even if a proportion of the drainage water is used by other farmers. This generates potentials for misinterpreting those low values.[28] Keller et al., 1996 introduced the concept of 'effective efficiency', EE, as:

$$E_E = {}^{Et}\!/_{Vp} \quad (13)$$

where Et is the net crop evapotranspiration and Vp is the net volume of water diverted to a field that reaches the irrigation plots.

Water that becomes usable surface runoff and deep percolation is subtracted from the total volume delivered. Effective efficiency can be also adjusted to reflect water quality. An aggregate version of the effective efficiency is the concept of 'basin' or 'global efficiency', whose value increases when farmers reuse drainage water (Seckler, 1996).

The total efficiency of water use for irrigation, Ei, is given by the product of (10), (11) and (13), that is:

$$E_i = E_S E_c E_E \quad (14)$$

A common deficiency of physical indicators of water efficiency is that they may generate misperceptions among policy analysts, who may interpret higher values as preferable to lower values, without examining the economic implications of alternative allocation scenarios. Yet, without considerations of economic variables it is not possible to determine if higher irrigation efficiency generates greater net economic value to society.

Economic indicators of water efficiency and productivity

The economic indicators of water use efficiency and water productivity take their rationale from the discussion of the previous sections. They are usually expressed as ratios of physical and economic variables referred to a specific time period, though many economic indicators are based on more complex statistical elaborations and actualization of multi-period relationships.

Several indicators have already been given in the previous sections, in particular the measure of economies of scale in water supply (equation (2)) and the elasticity of supply and demand (equation

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[28] When a unit of water in a water basin is diverted from a source to a particular use, three basic things happen to it. First, a part is lost to the atmosphere because of evaporation or evapotranspiration. Second, part of the diverted water may drain to the sea, a deep canyon, or a similar sink where it cannot be captured and reused, in which case it is truly lost to the system. Otherwise, the drainage water flows back into a stream or to other surface and subsurface areas where it can be captured and reused as an additional source of supply. This water is not lost or wasted in physical terms (Seckler, 1996).

(4)), which have an explanatory meaning in themselves, apart from being used in more sophisticated analyses.

The first other key indicator that can be taken as an element in the objective function is water productivity. In principle, water productivity can be calculated for any sector or sub-sector of the economy and is equal to a sector's dollar-value net benefits per unit of time, divided by water used measured in cubic meters per unit period of time. Water productivity can also be calculated at the basin or service level, in order to measure the overall impact of waster policies. Maximizing water productivity across sectors and services within a basin is a major policy objective. Thus, recalling that Zj represents the net benefits for user/sector j and that QWj is the quantity of water used up in the jth production process, water productivity PRW can be written as:

$$PR_W = \sum_{j=1}^{m} \frac{Zj}{Q_{Wj}} \qquad (15)$$

Other economic ratios come from water accounting techniques, which relate annual output to land and water, and provide the basis for comparison of irrigated agriculture, are: output per cropped area, Yca, output per unit irrigation supply, Yds, and output per unit water consumed, Ywc. Respectively, the following ratios express these relationships (Sakthivadivel et al., 1999):

$$Yca = {}^{Y}\!\big/_{A} \qquad (16)$$

$$Yds = {}^{Y}\!\big/_{Vd} \qquad (17)$$

$$Ywc = {}^{Y}\!\big/_{Et} \qquad (18)$$

where Y is the output of the irrigated area in terms of gross dollar value of production at local prices, A is the sum of the irrigated areas (in ha) under crops during the time period of analysis, Vd and Et have the usual meaning of net volume of water diverted to a field, and evapotranspiration. For international comparison, it is useful to convert all values of production in a standardized term, in order to reflect differences in local prices and of tastes throughout the world. To obtain this value, equivalent yield is calculated based on local prices of the crops grown, compared with the local price of the predominant, locally grown, internationally traded base crop, such as wheat. The Standardized Gross Value of Production, SGVP, is equal to:

$$SGVP = \left(\sum_{crop} A_i P_i \frac{P_i}{P_b} \right) P_{world} \qquad (19)$$

where Yi is the yield of crop ith, Pi is its local price, Ai is the area cropped with crop ith, Pb is the local price of the base crop, and Pworld is the value of the base crop traded at average world market price.

More detailed analyses can be performed when a comprehensive modeling framework is put in place. In this case, on the basis of the irrigation water demand functions developed in the previous sections, the profit per unit of water consumed at each demand site, PUWdm, and the same at the basin level, PUWb, can be calculated as follows (Rosegrant et al., 2000):

$$PUW_{dm} = \frac{PA_{dm}}{\sum_{time} WD_{dm,t} - RF_{dm,t}} \qquad (20)$$

$$PUW_b = \frac{\sum_{dm} PA_{dm}}{WDP} \qquad (21)$$

where PAdm is the net profit from irrigation given by equation (8) of section 5.3, whereas WDdm and RFdm are respectively water withdrawal and return flows from demand sites, and WDP is total irrigation water depleted, all taken from a water accounting matrix.

Finally, some indicators can be useful in assessing the degree of cost recovery and financial sustainability of basin water systems, such as irrigation services. Two main indicators assume relevance: the Cost Recovery from Water Billing, RCR, and the Cost Recovery Rate, CRR (RUB, 2002). The first indicator relates the total revenues from billing, TR, to the estimated theoretical cost of reaching sustainability of technical systems, Csts. The second indicator relate the total revenues, TR, minus the subsidy provided, S, to the total actual cost of providing the service, TC. In symbols:

$$RCR = \left({}^{TR}\!/\!{}_{C_{sts}} \right) \times 100 \tag{22}$$

$$CRR = \left(TR - {}^{S}\!/\!{}_{TC} \right) \times 100 \tag{23}$$

Policy-related water indicators and indices

Indicators and indices for water policy-making are instruments of simplification in that they summarize large amounts of measurements to a simple and understandable form, in order to highlight the main characteristics of a system. Information is reduced to its elements, maintaining the crucial meaning fro the questions under consideration. Though the aggregation causes a loss of information, if the indicator is planned properly, the loss will not gravely deform the results. A fundamental different exists between indicators and indices (WWAP, 2003).

An indicator, comprising a single data (a variable) or an output value from a set of data (aggregation of variables), describes a system or process such that it has significance beyond the face value of its components. It aims to communicate information on the system or process. The dominant criterion behind an indicator's specification is scientific knowledge and judgment.

An index is a mathematical aggregation of variables or indicators, often across different measurement units so that the result is dimensionless. An index aims to provide compact and targeted information for management and policy development. The problem of combining the individual components is overcome by scaling and weighting processes, which will reflect societal preferences.

A plenty of indicators exist for evaluating the effectiveness and impact of water policies.[29] The focus here is put on a tool that uses the water accounting technique and poverty analysis to examine water use in relation to specific social goals. The Water-Poverty Accounting Framework (WPAF) is one such tools that gathers the different aspects of water management and use, in specific relation to poverty. The WPAF expands on the water accounting technique outlined in section 5.1, in order to account for how water is used to meet social and economic goals, in particular poverty alleviation. The approach has a bias towards water used for agriculture, sanitation and nutrition, since these are the most significant source of employment for the poor (Biltonen and Dalton, 2003).

Using the WPAF, water allocations required to meet different poverty dimensions can be analyzed for each specific use. The desired and actual situations are then compared to determine options for reallocating water to meet social goals. A set of indicators, based on current and target allocations, has been developed to show the efficiency of water use to meet different demands.

There are two classes of indicators:

- *adequacy ratios*, which indicate how well either current or future needs are being met; and
- *bias indicators*, which show the bias of water allocations either toward or away from meeting certain social goals.

The indicators show where surplus water is available for reallocation and where additional water is required to meet other goals. It is possible to compile a set of indicators for any area, country or region.[30]

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[29] For a comprehensive review, see WWAP (2003) and WaterStrategyMan Project (2004).

[30] For the details about the indicators, we point to the original work of Biltonen and Dalton (2003).

CONCLUSIONS AND PROPOSALS

This concise review has tried to show how fundamental the economic analysis of water is, and could further be, in order to improve water use efficiency and water productivity. The discussion started from the fundamental reasons at the basis of water economics, going ahead through the major techniques developed to assess water supply costs and water demand values, with a focus to the agriculture sector, which is the main topic of the WASAMED project. The paper concludes for the superiority of the choice to push the accounting and modeling analyses of water resources, since they can generate a large amount of useful information and can be integrated into user-friendly policy tools.

There are barriers to the effective use of integrated river basin management modeling, including informational, physical, and application barriers (Lee and Dinar, 1995). Insufficient data, limitations, and poor information about the cultural, social and political norms often limit the development of an effective planning model. Moreover, because basins are irregular and receive flows from multiple sources, difficulties arise when attempting to dived a basin into discrete, manageable subunits. Temporal and special variability also complicate matters. Application barriers are due to the fact that such models are usually formulated and applied to a particular area, they are finely calibrated to address specific problems, and any modifications can be undertaken with additional costs.

However, models are by definition intended to abstract from reality, so the best model is the most adapted to available data and the most transparent in terms of social values embedded in the objective function. Trade-offs exist in model specification. But while an overly simple specification may yield insufficient information to address the problem or unreliable results, a more complex model, that would require extensive data collection, is not always a more preferred option then a simple, cost-effective modelling approach.

However, given the demonstrated usefulness of integrated models, two complementary strategies might be suggested. On the one hand, regular data collection should be improved, to allow for the progressive introduction of more complex models. Agricultural extension services can be a useful tool for finding information on farm possibilities and constraints, in so helping specifying production functions to be used in estimations of water use values. Setting up a comprehensive Water Information System in each country, that uses environmental-economic accounting practices, is a key tool. This in developing countries may require foreign aid, in the form of training, technical assistance and financing of collection stations.

On the other hand, it is necessary to refine and adapt existing tools, and create new models tailored on specific circumstances. Future directions in integrated modelling include the combination of Decision Support Systems (DSS) and Geographic Information Systems (GIS) into comprehensive Spatial Decision Support Systems (SDSS). DSS are interactive programs with a graphical interface, which embed simulation and optimization models to support users in problem solving. GIS offer a spatial representation of water resources systems using existing datasets. SDSS integrate spatial representations and modelling capacity into a single operational framework. Even the Water-Poverty Accounting Framework, referred to in section , 6.3, can be integrated into a geographical information system, with indicators separated into a range of categories and assigned graduated color codes. In this manner, maps can be constructed that demonstrate the current conditions as related to any of the preferred indicators.

Reinforcing these trends would be a decisive step towards helping decision makers with problems that have a spatial dimension, such as water allocation. The combination of reliable datasets, robust models, maps, and statistical analysis components, in fact provides water planners with effective and comprehensive support for taking informed decisions.

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