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Water Quality as a Limiting Factor: Concepts and Applications to the Mid-Ebro Valley

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Introduction

The scarcity of water, when considered in its generic sense, has become an increasingly important phenomenon in recent years. The dry cycle which ended in Spain in the hydrological year 1994-1995, revealed an important problem whose resolution, to judge by the analyses that were offered at the time, lies in a significant change in the way water resources are managed.

Indeed, leaving to one side the consideration of the rainfall that might momentarily relieve the problems which emerged during such a „drought“, the water data series and the evolution series of water uses reveals that, even when precipitation is maintained within its historical average values, the difference between the streamflow that is „demanded“ and the flows that are available has narrowed to a worrying extent. The traditional „supply policies“ that have up-to-now been the solution adopted in Spain (Pérez-Díaz et al., 1996) have entered a phase in which they are being questioned, given the increasing costs they suppose (Naredo, 1997; Arrojo, 1996). Therefore, and whether or not the effects of desertisation and climatic change on the physical availability of water are demonstrated, demand management policies have come to the fore as a possible solution to the important problem of allocation that now confronts us.

All the above considerations must be qualified in one important aspect that encompasses them all; namely that water quality indicators have worsened significantly throughout Spain during the last twenty years. Far from being a problem that stands independent of the rest, the degradation of water quality constitutes a key factor when explaining the supply problems that are increasingly being suffered in many areas of the country. Indeed, although everyone is conscious of the problem of water degradation, the overall figures for water in Spain have been calculated by concentrating the analysis exclusively on the quantities of water available and those demanded (Ministry of Public Works, Transport and Environment (MOPTMA), 1993). Naredo and Gascó (1994), in their recent publication „Spanish Water Accounts“, have provided a first approach to considering this phenomenon, by developing and applying new concepts to all the Spanish basins, with the aim of integrating the qualitative and quantitative aspects of water.

The aim of our paper is to define and apply a similar methodology, but in this case taking a smaller area as the basis of study, namely that part of the Ebro Basin which corresponds to the Region of Aragón.

The paper is divided into three parts: In the first we present the physical, institutional and socio-economic framework of the area under study. In the second, we define the theoretical concepts required to develop the water accounts in this area. Finally, we construct a simulation model of the hydrological systems and of water uses in order to apply these theoretical concepts.

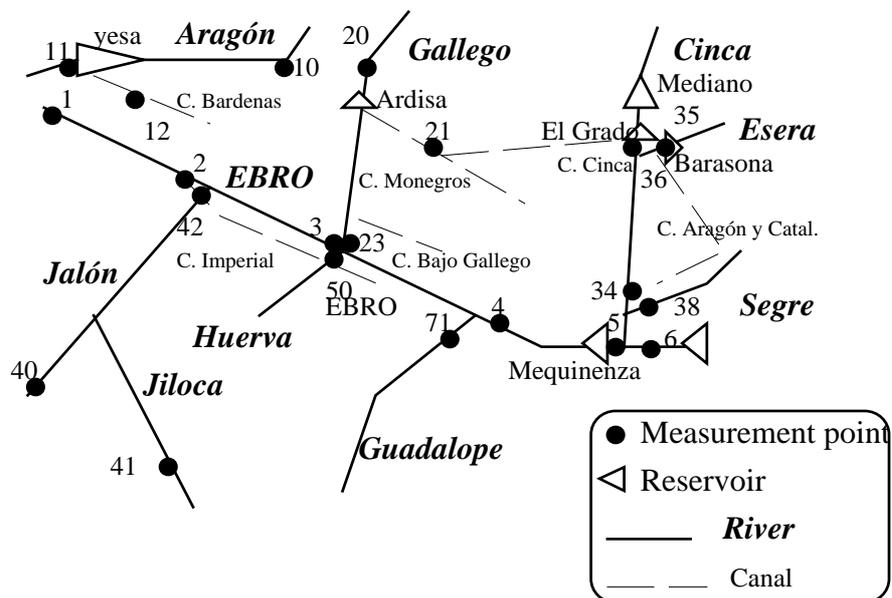
Description of the physical area: The Hydrological System

Following the terminology of Weber (1993), the approximation from the supply side corresponds to the „hydrological system“, whilst that of the demand side is the „use system“ of the water. The hydrological system is made up of natural and artificial channels and reservoirs.

Description of the hydrological system

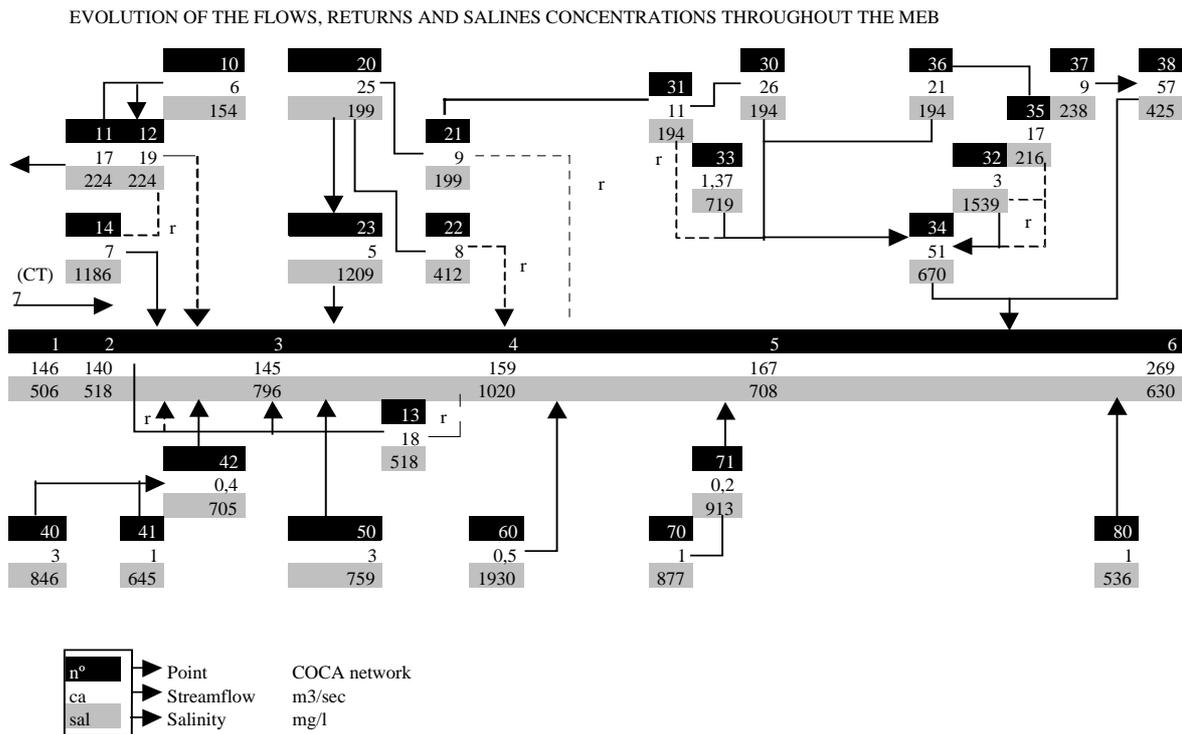
The mid-Ebro Basin (MEB) corresponds approximately to the territory of the Region of Aragón, one of the 17 autonomous regions into which Spain is divided.

Map 1: Schematic Map of MEB



The set of data is somewhat more extensive than is reflected in the above schematic map. Specifically, the set of data selected for the area of study, with the rivers, canals, reservoirs and measurement points for the hydrological year 1994-1995 is represented in Diagram 1.

Diagram 1



The hydrological database that represents the flow system of the MEB is made up of three principal sources:

- The water control network of the Ebro Basin (the COCA network)

- The study of the hydrological resources of the Ebro Basin (the ERHCE study, published by the Ebro Hydrological Confederation (CHE) in 1993)

- The study of the natural contributions in the Ebro Basin (this is an internal CHE document whose main results have been published in the PHCE Yearbook, 1995) These publications provide detailed information on the flows, contributions and qualities of the main rivers at a series of points that constitute our reference network (see Map 1). With respect to the reservoirs and aquifers, none of those that lie in the MEB act as water accumulators/disaccumulators within one determined hydrological year.

The MEB is made-up of two main subsystems, the left bank and the Right Bank, whose waters flow into one common collector, the river Ebro. From the West, the sub-basin receives the waters from the initial stretch of the Ebro itself (point number 1). From the East, it receives important contributions from the river Segre (point number 38). Whose basin belongs almost entirely to Catalunya. All these external contributions, together with those corresponding to the rivers included in the sub-basin, constitute the physical availability of the resource in the reference area.

The network of canals that redistribute the water within the basin has the main purpose of supplying specific irrigation systems, such that the quantity which circulates and the moment at which it does so, is determined by the agricultural activity to which the water is supplied. Finally, all the returns and, in general, the non-consumed flows, have their „mouth“ in Ribarroja (point number 6).

Description of the socio-economic structure of the MEB: The Uses System

In Aragón water is regarded as public property, at least in general terms, and its use is subject to a system of concessions granted for a given period of time. The institution that regulates and manages these concessions is the CHE. Public works of a hydraulic nature and the actual operating expenses of the CHE fall under the national budget, with the users having to pay a part of these costs, an amount which is related neither to the quantity used and nor, therefore, to the cost of supplying and storing that quantity.

Thus, the management system of the resource could be equated with that of a public monopoly, where the rate per unit of water meets a revenue collecting objective, although it does not correspond with either the average costs or the marginal costs of this unit. Of course, this is no more than a summarised and highly simplified description of the water management system implemented in the MEB, but we will nevertheless take this elementary framework as given in what follows.

The area of study corresponds to the majority of the Region of Aragón. This area is characterised by a very unequal distribution of population and economic activities, giving rise to a significant concentration of both in a relatively small area along one particular stretch of the River Ebro, with the city of Zaragoza acting as its main centre. We describe this area as the Ebro Corridor and a large part of the GDP and Added Value of the MEB is generated within it. The rest of the area presents a very low population density and its economic activity is concentrated basically in agricultural and livestock farming.

We have taken the hydrologic year 1994-1995 as the reference period, although it must be said that, in the light of the time series data (CHE, 1993), this was not an average or representative year with respect to the climate enjoyed by the MEB; rather, it corresponds to a dry year. Having said that, we decided to use the most recent period possible and for which we had socio-economic data that was geographically detailed. Furthermore, the characteristics of the limiting factor of water quality are logically more obvious in a period of low rainfall than in one of high rainfall.

Physical Consumption and Degenerating Consumption

In Economic Theory, the idea of consumption corresponds to the concept of making it impossible to use a given good for a specific function at a later date. Thus, whilst the physical destruction of a good implies consumption, there can also be consumption when subsequent use is prevented. This is precisely the case with water, where we can note both types of consumption (physical destruction and the deterioration of the physical-chemical conditions) and where they combine to result in a determined quantity of available resource of a given quality.

This supposes that in the case of water, we must extend the definition of consumption to encompass the following two elements:

- Physical consumption: any definitive withdrawal of water from the Hydro System
- Degenerative consumption: the quantity of water of a determined quality that is lost as a result of a physical-chemical degenerative process suffered by the resource.

Units of volume serve to measure physical consumption, but in order to measure degenerative consumption we must also define a level of quality that we consider as „acceptable“. This obliges us to leave to one side a large number of problems that fall within water quality. As Alberto (1985) and Naredo (1994) indicate, the quantity of dissolved salts is a good approximation of the general quality of water in semi-arid territories such as our area of reference.

Calculation of Physical Consumption

We make a double approximation of physical consumption: from the point of view of the supply of water and from the point of view of its demand.

Calculation from the point of view of supply:

We have two alternative forms of measuring the physical supply (OF)

$$OF = PL - ETNA - RET \quad (1)$$

or

$$OF = CF + DEL \quad (2)$$

where:

PL: The annual volume of precipitation in the form of rain or snow

ETNA: Annual volume evapo-transpired by the soil and by non-agricultural plants

RET: Increased (or decreased if it is negative) volume of water retained on the surface or in the sub-soil throughout the year; that is to say, the final volume minus the initial volume

CF: The volume consumed by agriculture, industry, supply and losses in reservoirs and artificial conduits

DEL: Annual volume supplied by the river/s and its/their where it meets the sea or joins another independent sub-basin

Equalities (1) and (2) correspond to two alternative ways of measuring the physical supply: the first, considering how this is generated and the second in function of ex-post physical supply/physical demand equality. On the basis of the available data, we can obtain the physical supply from expression (1) and subsequently determine the physical consumption by the difference between the OF so obtained and the flow observed at the final point of the sub-basin being considered:

$$CF = OF - DEL \quad (3)$$

Calculation from the point of view of demand:

There is another indirect way of approximating the physical consumption from the point of view of the demand for water. In effect, if we are capable of reflecting all the productive activities that consume water and estimating the volumes of resource used as well as the rate of return, then we can approximate the volume of water consumed in a given basin. As we will see, the greatest difficulty presented by this method lies in the availability of good approximations of the rates of agricultural return, given that the other activities represent only a small part of total consumption (not greater than 10%). Thus, this second method can be expressed generically as:

$$CF_i = X_i \cdot U_i \cdot (1-r_i)$$

where X_i represents some indicator of the level of activity of the i^{th} sector and U_i is the volume of water used per unit of activity. The rate of return r_i completes the circle through we obtain the physical consumption CF_i by way of this alternative method.

Calculation method on the basis of the uses system

We have sufficient information to calculate the CF by way of this second method. Let us briefly consider the data and its possibilities.

- The cultivated surface area, by district, and livestock census, by district. The Aragonese Regional Government (DGA, 1995).
- A study of water use standards according to economic activities. (CHE, 1990)
- The Municipal Population Census. The Aragonese Institute of Statistics (IAE, 1997a)
- The District Income Statistics, (IAE, 1997b)

- A study on the water needs of the crops. Faci et al. (1993) and Tabuenca (1995).

On the basis of these data, the process applied to the sectors has been as follows:

Agriculture and livestock

Combining the above data bases as they refer to the uses system, we can obtain a good approximation of the volume of water that would be used if irrigation was employed with total efficiency of 100%. On the other hand, once obtained the physical consumption in each area we can estimate the rate of return, that is to say, that part of the total water supply for irrigated areas which returns to the riverbeds from which it was extracted. Drawing on O'Heady and Nicol (1975), there is a direct relationship between the rate of return and the total level of efficiency at which irrigation is employed: $r = t [1 - e_t (1 - lix)]$, where t , lix are the natural return and the lixiviation rate respectively.

From this relationship, we introduce irrigation efficiency into our hydrological model as a endogenous variable with the aim of obtaining that value of the efficiency that corresponds with the volumes of returns observed. In other words, knowing the physical consumption, we can obtain the efficiency with which the water has been used.

Industry, services and urban uses

The process followed to obtain the water uses for the non-agricultural productive sectors, has been as follows:

1) Estimate the quantity of water used in industry and services for each of the 21 districts into which the Region of Aragón is divided.

1 a) Reconstruct the total effective district production for each sector on the basis of the Gross Added Value per district. IAE, 1997 b.

1 b) Apply the water standards used per worker for the production and employment data corresponding to the 1992 input-output tables. CHE, 1990.

1 c) Obtain some ratios of water use per unit produced (m^3 /pesetas) for each sector.

1 d) Apply the above ratios to the 1992 data on district production.

1 e) Make a specific study of the Hotel and Health-care (hospitals) sectors. In this case, we start from some standards per hotel room or per bed installed, which are then applied to a district distribution of the same. The result of this calculation was aggregated to the uses of these sectors, which had been calculated earlier exclusively in function of the number of employees.

2) Calculate the district population from the 1995 Census data. (IAE, 1997a).

2 a) Apply a standard per inhabitant according to the PHCE Annual Report. CHE, 1993.

Calculation of Degenerating Consumption

We can measure the degenerating consumption of a user or group of users on the basis of the quantities of salts they contribute or through the equivalent volume of water, that is to say, the volume of water of a given concentration that contains the same mass of contributed salts. However, given that water flows become saline for natural reasons and by the intervention of man, increased salinity (in total mass or in concentration) simultaneously reflects both types of phenomena.

In general, if c_i is the concentration of salts at the i^{th} point and F_i is the flow at the same point, then:

$$S_i = F_i c_i, \quad (4)$$

is the mass of salts contained in F_i or, if we consider that the concentration of salts c_e or the standard concentration is an amount that is admissible per unit of water, then we can express the observed flows in terms of this concentration and equate the loss of quality with the reduction of water of concentration c_e throughout the basin. Thus, F_e or the flow of standard water which contains the quantity of salts moved by uses or by natural phenomena, is equal to:

$(F_i c_i)^f - (F_i c_i)^i$; where $(F_i c_i)^f$ means final mass of salt and $(F_i c_i)^i$ means the mass of salt before the particular use, then:

$$F_e = ((F_i c_i)^f - (F_i c_i)^i) / c_e \quad (5)$$

If we wish to express the loss of available water as a result of salinity, we can calculate the volume of standard water (of concentration c_e) which would be totally degenerated by the mass of mobilised salts. This volume would be:

$$F_d = ((F_i c_i)^f - (F_i c_i)^i) / (c_d - c_e); \quad (6)$$

where c_d is that concentration of salts for which the totality degenerated.

Estimation of Physical Consumption and Degenerating Consumption on the basis of geo-referenced data

The correspondence between the sub-basins of the hydrological system and the districts of the uses system is as follows:

Model	<u>System according to the hydric data network</u>	<u>Districts according to demand side approximation</u>
Model 1	All the MEB	All districts
Model 2	System 1. Aragón System (up to the Yesa reservoir) System 2. Sistema Gallego System 3. Sistema Cinca-Esera System 4. Sistema Jalón-Jiloca-Queiles System 5. Sistema Ebro corridor system System 6. Sistema Guadalupe-Martín-Matarraña	Jacetania, Cinco Villas Jacetania(p), Hoya de Huesca Sobrarbe, Ribagorza, Somontano, La Litera, Bajo Cinca, Monegros Daroca, Cuenca Jiloca, La Almunia, Calatayud, Borja Zaragoza Cuencas mineras, Bajo Aragón, Caspe

Schematic representation of the model:

The joint model is made up of four blocks, as follows:

1. Network of points on the hydrological system with data on accumulated contributions, flows and salinity
2. Table of district water demand expressed in terms of the rate of return and, therefore, of the efficiency with which the water is used. At a practical level, this means that the demand on each district will depend on the total efficiency of the irrigation. For the other sectors, the rates of return used are those indicated by the MOPTMA (1993) and by the PHCE Annual Report, which calculate the return of industrial uses and of urban supply at 80% ($r = 0.8$).
3. Flow network and salinity of interconnecting canals. The salinity in the canals is considered as constant and equal to that observed at the specific diversion point.
4. Estimated data on evaporation in reservoirs, as well as entries to and exits from the MEB not specified in the earlier block, etc.

Table 1

CALCULATION MODEL 1

<u>HIDRILOGICAL SYSTEM</u> <u>(Hm³/year)</u>	Total
AGGREGATE MEB CONSUMPTION	2748.07

Average efficiency in irrigation: $e_t = 0.47$
 Average rate of return $r = 0.31$

	<u>USE SYSTEM</u> <u>(Hm³/year)</u>				
	Agriculture	Livestock	Industry	Urban	Total
USE	3750.76	31.56	326.14	141.51	4249.97
	88%	1%	8%	3%	100%
CONSUMPTION	2604.20	6.31	109.26	28.30	2748.07
	95%	0.2%	4%	1%	100%
RETURN	1146.56	25.25	216.88	113.21	1501.90
	76.34%	1.68%	14.44%	7.54%	100.00%

These four blocks interact amongst themselves in such a way that, given certain hydrological data in blocks 1, 3 and 4, we can recalculate the demand estimations of block 2 on the basis of a new value for irrigation efficiency. The joint model allows us to obtain a solution for the total efficiency of irrigation and for its rate of return that gives coherence to both the hydraulic system and the uses system.

The values of irrigation efficiency per sub-system correspond to the result of the entries to and exits from each district and to the result of using one unit of water n times. As we can see from Tables 1 and 2, the overall efficiency obtained in Model 1 (0.47) is in agreement with the average efficiency of the sub-systems of Model 2 (0.47).

Table 2 (1)

	<u>CALCULATION</u>		MODEL 2	(1)
	r	e_t	difference	
	ret. Rate	effic	resp. Average	
SYSTEM 1	0.34	0.40	-0.07	
SYSTEM 2	0.28	0.52	0.05	
SYSTEM 3	0.28	0.52	0.06	
SYSTEM 4	0.32	0.44	-0.03	
SYSTEM 5	0.30	0.47	0.00	
SYSTEM 6	0.32	0.44	-0.03	
Average	0.30	0.47		

Table 2 (2)

CONSUMPTION	Agriculture irrigation	Livestock	Industry	Urban	TOTAL
SYSTEM 1	471.16	0.65	1.80	1.40	475.01
SYSTEM 2	281.22	0.48	1.03	1.61	284.34
SYSTEM 3	885.41	2.25	2.89	2.87	893.43
SYSTEM 4	405.90	0.94	2.39	3.47	412.71
SYSTEM 5	392.77	1.07	13.09	16.80	423.72
SYSTEM 6	145.73	0.92	88.06	2.14	236.85
TOTAL	2582.19	6.31	109.26	28.30	2726.06

RETURN	Agriculture irrigation	Livestock	Industry	Urban	TOTAL
SYSTEM 1	244.63	2.62	7.19	5.61	260.06
SYSTEM 2	107.30	1.93	4.10	6.46	119.79
SYSTEM 3	337.19	9.01	11.58	11.48	369.26
SYSTEM 4	191.57	3.75	9.57	13.90	218.79
SYSTEM 5	170.76	4.26	52.36	67.20	294.58
SYSTEM 6	68.22	3.67	176.12	8.56	256.57
TOTAL	1119.67	25.25	260.91	113.21	1519.03

USE	Agriculture irrigation	Livestock	Industry	Urban	TOTAL
SYSTEM 1	715.78	3.27	8.99	7.02	735.07
SYSTEM 2	388.52	2.41	5.13	8.07	404.13
SYSTEM 3	1222.60	11.27	14.47	14.35	1262.69
SYSTEM 4	597.47	4.69	11.96	17.37	631.49
SYSTEM 5	563.53	5.33	65.45	84.00	718.30
SYSTEM 6	213.95	4.59	264.18	10.70	493.42
TOTAL	3701.86	31.56	370.17	141.51	4245.09

With respect to degenerating consumption, the results are set out in Table 3, expressed in terms of the mass of contributed salts and in terms of equivalent water of 480 mg/l (water capable of conversion into drinking water according to the US Salinity Laboratory). As we mentioned earlier, this can also be expressed in terms of the volume of water that this mass of salts is capable of polluting to such an extent that it is impossible to reuse it (a reference value for non-reusable water could be 2000 mg/l, Rhoades (1989)).

Table 3

	DEGENERATING CONSUMPTION EXPRESSED IN:		
	Thousand Tm/year	Hm3/year equivalent water	Hm3/year degenerated water
MODEL 1	2692.57	5609.5	1771.42
MODEL 2			
SYST 1	15.61	32.523	10.26
SYST 2	-	-	-
SYST 3	1274.06	2654.3	838.19
SYST 4	-	-	-
SYST 5	431.41	898.77	283.82
SYST 6	56.93	118.61	37.45
direct Ebro	1154.07	2404.3	759.25
TOTAL	2692.57	5609.5	1771.42

Conclusions

When we speak of the water that is available in a given geographical environment, we are referring to a conglomerate of flows with very different qualities in terms of both space and time. In this paper, we have developed a hydrological model of water management in a hydrographical basin, the main objective of which is to integrate a qualitative aspect that is especially important in semi-arid climates, namely salinity and the factors that determine it (particularly the efficiency of irrigation). The data and proposed measurements point to the significant influence of the quality characteristics on the global figures of the water in a basin.

The water in the channels exceeds the salinity limits permitted for supply to the population at numerous points. This is the case in the MEB, even for the average values (see Diagram 1), and is even more noticeable in the summer months. Furthermore, the dilution of the returns in higher quality flows is progressively worsening their quality and carries with it negative external effects on downstream activities.

Specifically, levels of salinity in excess of 2000 mg/l produce severe reductions in crop returns (Doorenbos et al., 1986), giving rise to significant losses in the agriculture sector, quite apart from the costs that such levels generate in industrial uses. This is once again the case for the irrigation effluents in the summer months in the MEB (CHE, 1996). Mention is often made of the low efficiency of irrigation as one of the causes for the presence of salts in the riverbeds (Playán, 1994). The hydrological model developed here shows this low efficiency for all the areas into which the area under study has been divided even, as is the case here, when we obtain the efficiency of the system (for various uses within one irrigation system).

If we bear in mind that the hydrological year chosen was an exceptionally dry period, this low efficiency, together with the extremely low quality of the returns, made their re-use extremely difficult and reduced both the quality and the quantity of water in the riverbeds. The numerous „deficits“ of drinking water and irrigation water that arose during this period were caused, in part, by the presence of this huge amount of salt in the natural flows.

In this sense, the measurements of physical and degenerating consumption we have obtained give us a clear idea of water availability in a comparatively large area. The 2,692,570,000 Tm of salts that were added to the streamflows of the basin are capable of rendering a large volume of water (1,771.42 Hm³) entirely unserviceable, where this resource would, in other circumstances, have been available for alternative types of use or for the maintenance of the hydric eco-system within its equilibrium conditions.

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