

Influence of salt concentration and topographical position on water resource quality: The Spanish Case Study

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Abstract

Water resource quality (WRQ) is affected by salt concentration and topographical position. Indeed, an increase in salt concentration, which decreases water availability for animal and plant nutrition, and lower altitude, which diminishes the potential for production of hydropower, negatively affects WRQ. Therefore, it is useful to develop indicators like osmotic power (OP) and hydraulic power (HP) to evaluate, respectively, the influence of salt concentration and topographical position on WRQ. The main objective of this work was to evaluate the WRQ in 11 hydrographical basins in peninsular Spain. In this paper, OP, HP and the total power (TP), obtained by adding OP to HP, were calculated at three different basin levels:

- Height H_{25} (m) corresponding to 25% of total surface area of the basin
- Height H_{50} (m) corresponding to 50%
- Height H_{100} (m) corresponding to 100%.

Results showed that OP, HP and TP values of water basins decreased from the northern to the southern parts of peninsular Spain, according to water scarcity and hydrographical characteristics of water basins. The higher OP, HP and TP values, the higher is WRQ of the basin. Therefore, TP, OP and HP can be used to evaluate WRQ at the administrative water basin level as a basis for water resource management. Indeed, these indicators can assist water managers and planners in deciding between inter-basin water transfers and water desalination, especially in countries where water is a scarce resource.

Keywords: water resource quality (WRQ), hydraulic power (HP), osmotic power (OP), total power (TP).

Introduction

Peninsular Spain has a surface area of 493 771 km² that can be divided into 11 administrative hydrographical basins corresponding mostly to natural hydrographical catchments (Fig. 1). The climate is Mediterranean and seasonal except in the north where it is humid and in the south-east where it is semi-arid. Climate, topography and rock weathering determine salt-water concentration associated with osmotic energy. The relief, with a mean altitude of 568 m, determines a topographical position associated with potential hydraulic energy.

The Spanish Water Act (SWA) considers water to be a matter of general interest (BOE, 2001a) as water is a scarce resource in Spain. Indeed, making water availability an issue for public planning should ensure its rational use in harmony with the environment. The Spanish National Hydrological Plan (SNHP) is a useful instrument to:

- Identify different supplies
- Rationalise water availability
- Guarantee an ecologically sound water supply
- Achieve sustainable water usage

Public investments in hydraulic infrastructure and the water desalination industry have been laid out by the Spanish National Hydrological Plan (SNHP) for the period 2001 to 2008 (BOE, 2001b). The investment projected is approximately €2 000m/a⁻¹. SNHP gives priority to investments in exploitation systems that do not require external transfer to cover demands. In Spain,

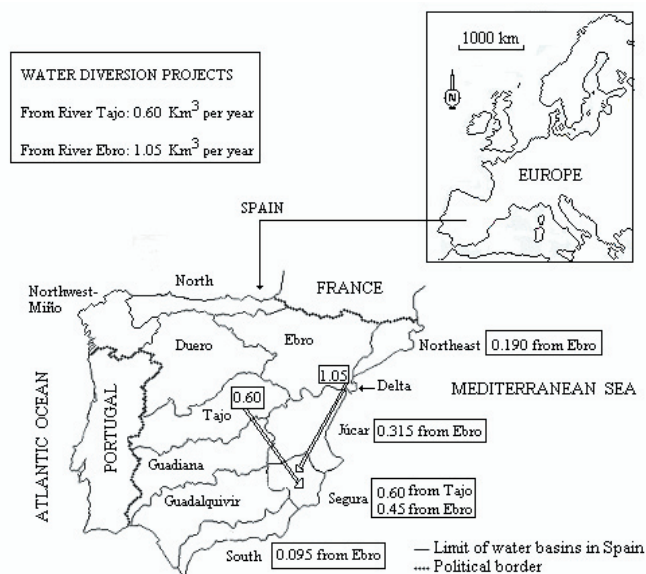


Figure 1
Hydrographical basins of Spain and the main water transfer projects

water resource management has traditionally been based on temporal regulation of surface waters by dams and bars, due to seasonality of water precipitation and evapotranspiration (cold and rainy weather in winter, warm and dry in summer, and intermediate in autumn and spring). Water transfers have been considered and implemented only in situations of structural scarcity demonstrated over years, and then in areas where the highest potential productivity of irrigated land over dry land

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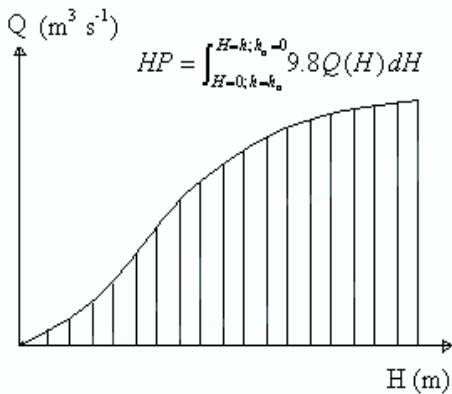


Figure 2
Flow-height graph and hydraulic power (HP) of the main course of a hydrographical basin

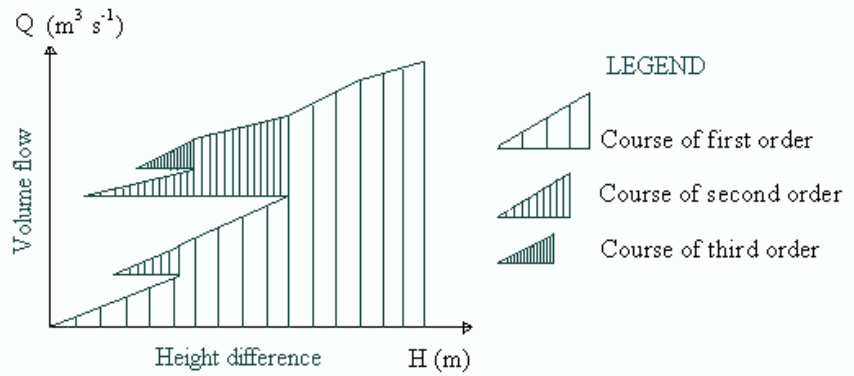


Figure 3
Flow-height graph of an elemental hydrographical basin with courses of different orders

exists. Nevertheless, water transfers projected by the SNHP have met with strong public opposition in the donor territories and created great controversy due to water being considered a symbol of life and prosperity. One result has been that the SNHP has encouraged alternative ways to obtain high-quality water resources by desalinating sea-water and brackish water and by recycling and purifying wastewater (Gascó, 2004). Indeed, plans are afoot to amend the water policy, increasing the investment in desalination plants and decreasing the investment in water transfers. Therefore, in Spain, and in other countries, useful water resource management demand indicators or tools to measure water resource quality (WRQ) can assist governments and catchment management agencies to implement water policy.

An indicator is useful if it is of fundamental interest in decision-making, simplifies or summarises important properties, visualises phenomena of interest and quantifies and communicates relevant information (Gallopín, 1997). Indeed, indicators are the ideal means by which progress towards sustainable development of basins can be measured (Walmsley et al., 2001). For example, indicators can be used to evaluate the sustainability of the urban water systems (Morrison et al., 2001) or to estimate water quality in agro-rural watersheds (Mtetwa and Schutte, 2002).

The promotion of sustainable water use is the main purpose of the European Union water framework directive (CEC, 2000). This directive established planning processes at the hydrographical basin level as the basis for water resource management (Kallis and Butler, 2001). The analysis of water resources has been incorporated in the Spanish system of natural resource accounts by the Minister for the Environment. This has occurred at the administrative hydrographical basin level and includes both quantity and quality aspects. The inland water resource accounts were tabulated in terms of quantity in Spain for a mean hydrological year (1980 to 1989) (Naredo and Gascó, 1994) following the pilot methodology adopted by the Organisation for Economic Cooperation and Development (OECD, 1993). However, calculating inland water resource accounts in terms of quality is problematic due to the concept of water resource quality and its measurement (Margat, 1986). Water resource quality has been studied several times, analysing chemical properties like dissolved oxygen (Campolo et al., 2001), conductivity or alkalinity (Interlandi and Crockett, 2003) or nutrients and metals in the surface water (Simeonov et al., 2003). However, since water quality and water quantity are often closely linked, modelling methods (Malan et al., 2003) or other tools should be used to

integrate water quality and water quantity in river basins.

There are not many studies that relate water resource quality to power qualities which can be evaluated by hydraulic power (HP) (W) and osmotic power (OP) (W). Total power (TP), obtained by adding OP to HP, can give an idea of the total power of a basin. Currently, this fact is very important as an increase in the price of energy (energy = power · time) can affect the short-term implementation of water policy (water transfer or water desalination) in the countries where water is a scarce resource.

The objective of this study was to calculate OP, HP and TP for the assessment of the WRQ at the hydrographical basin level as the basis for water resource planning and management, and as a first step in the design of water resource accounts based on quality.

Methods

Hydraulic power (HP)

The water resources of a hydrographical basin can be exploited as an energy resource for hydroelectric production and HP (MW) can be evaluated by integration of a mass flow-length graph (Fig. 2).

According to mass-energy relationship, the HP (MW) of a river basin in the earth gravitational field ($g \approx 9.8 \text{ m}\cdot\text{s}^{-2}$) and for a water density $\rho_w (\approx 1000 \text{ kg}\cdot\text{m}^{-3})$ can be evaluated by integration of a volume flow-height graph according to Eq. (1):

$$HP = \int_{H=0; h=h_0}^{H=h; h_0=0} 10^{-3} \cdot 9.8 \cdot Q(H) \cdot dH \quad [1]$$

where:

- H (m) is the height difference between a river course position at height h (m) and the reference level placed at height h_0 (m) over sea level
- Q(H) is the water flow ($\text{m}^3\cdot\text{s}^{-1}$) measured in a river course at the position H (m).

Therefore, HP is the minimum power value necessary to transport natural water flow Q from sea level to position H (m) in a river course.

Tributaries of all orders can be integrated by using their flow-height graphs (Fig. 3). In general, height and water-volume flow can be approximately considered as objects with additive properties; so, HP analysis may be valid for the purpose of the present study.

Therefore, an HP value can be useful when classifying hydrographical basins according to their hydroelectric power production capacity.

Osmotic power (OP)

Water salt concentration defines a water property linked to water desalination. The system most used to desalinate water is reverse osmosis (RO). Briefly, this process requires energy consumption for the filtration of sea-water through a semi-permeable membrane similar to a plant cell-wall. The power needed for this process is called osmotic power (OP) (Fig. 4).

According to the first principle of thermodynamics, work and energy are equivalent concepts, and thus OP could be obtained as seen in Fig 4. OP (MW) can be evaluated by the integration of an osmotic pressure-volume flow where Q ($\text{m}^3 \cdot \text{s}^{-1}$) is the water flow which depends on the osmotic pressure π (kPa) of the water solution. OP can be calculated for both pure and sea-water as follows:

- For pure water

$$OP = 10^{-3} \cdot \int_{\pi=0}^{\pi} Q(\pi) \cdot d\pi \quad [2]$$

- For sea-water

$$OP = 10^{-3} \cdot \int_{\pi=\pi_s}^{\pi=\pi_s} Q(\pi) \cdot d\pi \quad [3]$$

where:

- π is osmotic pressure of water solution
- π_s is osmotic pressure of sea-water solution.

Osmotic pressure π (kPa) can be estimated with electrical conductivity EC ($\text{dS} \cdot \text{m}^{-1}$ at 25°C) whose value depends on the ionic properties of water solutions. The relationship for natural water solutions (Richards, 1954) is:

$$\pi \approx 36.48 \text{ EC} \quad [4]$$

Applying Eq. [4] results in:

- For rain-water with volume-weighted mean value of EC $\approx 0.046 \text{ dS} \cdot \text{m}^{-1}$ 25°C (Hontoria et al., 2003), $\pi \approx 1.7 \text{ kPa}$
- For sea-water with EC $\approx 54 \text{ dS} \cdot \text{m}^{-1}$ 25°C , $\pi \approx 1970 \text{ kPa}$.

Therefore, rain-water π can be considered negligible with respect to sea-water π .

The OP needed to desalinate a water volume flow Q ($\text{m}^3 \cdot \text{s}^{-1}$), with the sea-water salt concentration ($54 \text{ dS} \cdot \text{m}^{-1}$) equal to the natural water salt concentration at a given point in the river course, can be calculated by the following equation:

$$OP \text{ (MW)} = 10^{-3} \cdot Q \cdot (1970 - 36.48 \cdot \text{EC}) \quad [5]$$

where:

- EC ($\text{dS} \cdot \text{m}^{-1}$ 25°C) is the weighted (by water flow) mean EC of water samples in the river stream.

Therefore, OP is the minimum power necessary to desalinate Q from a sea-water salt concentration to a natural water salt concentration at a given point in the river course. A given Q flows spontaneously from the highest OP value towards the lowest OP

$$\text{Osmotic power} = OP \quad OP = \frac{\tau}{t} \quad \tau = \text{work} \quad t = \text{time}$$

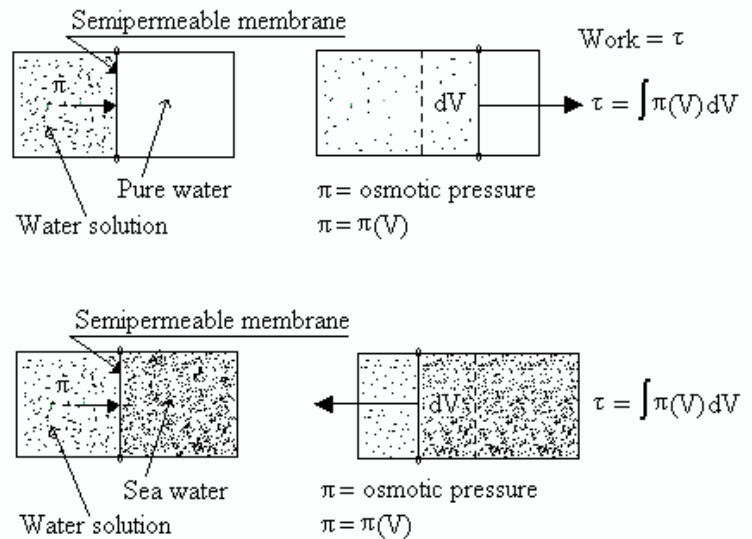


Figure 4
Work and Osmotic Power (OP) produced by passage of pure water through a semi-permeable membrane

value, because water flows spontaneously from dilute to concentrate solutions, as it does from high to low altitude.

According to Eq. [5], the higher the OP value of a given basin, the higher the WRQ of the given basin, because the (fresh-water semi-permeable membrane sea-water) system has more potential for production of osmotic energy. Conversely, more energy is needed to desalinate sea-water to the salt concentration level of freshwater in the basin. This fact is very important as the cost of water desalination by RO depends on the energy price. Therefore, the calculation of OP can be a useful tool for planning sea-water desalination projects. Indeed, desalination of sea-water and brackish water could be a reliable source of freshwater and could be an alternative to inter-basin water transfers, mainly because the cost of desalinated water is decreasing (Wangnick, 2001) while the cost of water obtained by conventional methods is increasing.

Total power TP

Total power TP (MW) can be obtained by the next expression:

$$TP = HP + OP \quad [6]$$

According to this expression, TP can be defined as the minimum power needed to transport a desalted sea-water flow Q from sea level to position H (m) in a river course. This minimal TP value does not consider thermodynamic and mechanical efficiency or the loss of potential hydraulic charge in the transport channel. Nevertheless, TP can give an idea of the total power of a basin.

Materials

Monitoring networks

Two networks of monitoring stations have been employed to study the meteorological and hydrological characteristics of Spanish hydrographical basins:

TABLE 1
Controlled river length L_c (%) and controlled runoff surface S_c (%) with respect to total stream-flow length L_t (km) and total surface S_t (km²) in the Spanish hydrographical basins

Basin	N_{ms}	H_{ms}	N_{hs}	H_{hs}	L_t	L_c (%)	S_t	S_c (%)	H_o
Northwest-Miño	8	594	7	340	1662	26	12910	100	0
North	42	181	23	63	5223	26	40894	40	0
Northeast	36	326	41	194	3487	30	16493	92	0
Duero	62	879	38	795	9168	31	78954	84	240
Tajo	62	742	49	560	7944	27	55645	100	170
Guadiana	22	419	57	369	5804	55	59677	95	0
Guadalquivir	41	370	35	176	6555	42	63972	91	0
South	17	715	16	243	2439	43	17969	24	0
Segura	29	382	14	276	1396	52	18870	79	0
Júcar	42	589	22	340	4649	38	42988	35	0
Ebro	55	645	60	354	11760	38	85399	100	0
Total	416		362		60087		493771		
Mean						37		76	
Weighted mean		568		409		36		81	58

N_{ms} : number of meteorological stations; H_{ms} : mean height of meteorological stations average; N_{hs} : number of hydrological stations; H_{hs} : mean height of hydrological stations; H_o : height of output flow (sea level except for the rivers Duero and Tajo). Weighted mean was obtained by considering total surface area of each hydrographical basin.

TABLE 2
Climatic and hydrological data in the hydrographical basins of peninsular Spain

Basin	N_{mo}	AP	t_m	AP-PE	AP-RE	Q_{ap}	Q_o	R
Northwest-Miño	125	18.98	12.5	9.58	11.31	602	383	0,64
North	594	53.77	10.7	25.14	26.61	1705	912	0,54
Northeast	347	12.29	14.2	0.17	1.74	390	74	0,19
Duero	378	50.92	11.0	-5.93	13.30	1614	385	0,24
Tajo	262	35.61	12.5	-8.91	11.22	1128	348	0,31
Guadiana	504	33.72	14.5	-17.01	5.42	1069	145	0,14
Guadalquivir	820	37.10	16.7	-20.47	5.46	1176	161	0,14
South	277	9.88	14.0	-6.29	1.26	313	53	0,17
Segura	169	7.17	13.5	-8.87	0.51	227	7	0,03
Júcar	358	23.43	13.5	-10.10	0.64	743	72	0,10
Ebro	617	51.66	10.5	-12.39	15.28	1638	387	0,24
Total	4451	334.53	13.1	-55.08	92.75	10606	2925	0,28

N_{mo} : number of meteorological observatories; AP (km³ year⁻¹): mean annual atmospheric precipitation; t_m (°C): mean annual temperature; AP-PE (km³ year⁻¹): mean annual absolute abundance; AP-RE (km³ year⁻¹): mean annual relative abundance; Q_{ap} (m³ s⁻¹): mean inflow from atmospheric precipitations; Q_o (m³ s⁻¹): mean river outflow to sea except for the rivers Duero and Tajo; R = Q_o/Q_{ap} : total run-off coefficient.

- A network of 4 451 meteorological stations
- Another network of 362 streamflow measurement stations.

These two networks control 81% of the total runoff surface (S_c) and 36% of the total streamflow length (L_c) of the hydrographical basins. Table 1 shows L_c (%) and S_c (%) values. L_c (%) defines the relationship between river length controlled by monitoring stations and total streamflow length (L_t) of a hydrographical basin. S_c (%) defines the relationship between surface runoff controlled by monitoring stations and the total surface area (S_t) of a hydrographical basin.

Data

Mean meteorological data were obtained for a period of 30 years (1971 to 2000), and mean hydrological and chemical data were obtained for a period of 20 years (1981 to 2000). Table 2 sum-

marises the climatic and hydrological data of these meteorological stations. Real evapotranspiration RE (km³·a⁻¹) was obtained by the difference between inflows measured by meteorological stations Q_{ap} (km³·a⁻¹) and outflows measured by streamflows stations Q_o (km³·a⁻¹). Total runoff coefficient R was measured by ratio Q_o/Q_{ap} .

Table 3 shows the regression equation between meteorological and hydrographical data and the height H (m) of monitoring stations in the studied basins.

Linear regression analysis between the surface area S (km²) of every basin and the height of meteorological stations H (m), at a confidence level = 99%, gives the following relationship:

$$S = a - b \cdot \ln H \text{ with a mean } R^2 = 85.89 \quad [7]$$

where:

$$\text{Maximum } R^2 = 98.88$$

$$\text{Minimum } R^2 = 73.34.$$

Basin	N _o	Regression equation	r	R ²	SEE	CL
Northwest-Miño	7	S = 43713-6821*lnH	-0.99	98.88	544	99%
	8	tm = 16.59 - H*0.69/100	- 0.97	94.41	0.55	99%
	8	AP = 800.0 + 1.13*H	0.81	65.75	267.7	95%
	8	PE = 849,4 - 0,24*H	- 0.87	75.09	44.5	99%
North	23	S = 28336-5272*lnH	- 0,92	84.39	2090	99%
	42	tm = 11.38 - H*0.36/100	- 0.75	56.04	0.70	99%
	42	AP = 1264.5 + 0.28*H	0.16	2.59	376.6	Not at 90%
	42	PE = 719.6 - 0.11*H	- 0.67	45.31	25.6	99%
Northeast	41	S = 26584-4019*lnH	- 0.97	93.77	1156	99%
	36	tm = 15,78 - H*0.48/100	- 0.90	81.78	0.86	99%
	36	AP = 660.2 + 0.26*H	0.56	31.47	144.9	99%
	36	PE = 800.1 - 0.15*H	- 0.89	79.15	29.8	99%
Duero	38	S = 753488-109171*lnH	- 0.91	82.27	8313	99%
	62	tm = 16.16 - H*0.59/100	- 0.77	59.46	0.83	99%
	62	AP = - 95.7 + 0.84*H	0.55	29.86	220.1	99%
	62	PE = 888.2 - 0.19*H	- 0.54	29.31	50.6	99%
Tajo	56	S = 208881-30112*lnH	- 0.97	94.68	3561	99%
	62	tm = 16.63 - H*0.56/100	- 0.90	80.64	0.84	99%
	62	AP = 378.3 + 0.35*H	0.44	19.58	221.4	99%
	62	PE = 957,4 - 0.21*H	- 0.89	79.28	33.6	99%
Gadriana	56	S = 115151-15352*lnH	- 0.87	75.69	8537	99%
	22	tm = 15.99 - H*0.35/100	- 0.81	66.16	0.67	99%
	22	AP = 547.8 + 0.04*H	0.06	0.34	187.8	Not at 90%
	22	PE = 906.1 - 0.13*H	- 0.63	40.02	43.7	99%
Guadalquivir	35	S = 85951-12248*lnH	- 0.96	91.60	5134	99%
	41	tm = 18.21 - H*0.40/100	- 0.87	75.79	0.87	99%
	41	AP = 602.4 - 0.06*H	- 0.14	2.08	161.0	Not at 90%
	41	PE = 957.3 - 0.15*H	- 0.71	51.06	58.2	99%
South	16	S = 8208-1103*lnH	- 0.89	78.91	514	99%
	17	tm = 16.71 - H*0.38/100	- 0.89	78.78	1.11	99%
	17	AP = 496.3 - 0.07*H	0.30	9.12	133.3	Not at 90%
	17	PE = 1017.2 - 0.16*H	0.87	75.06	53.3	99%
Segura	14	S = 20096-2621*lnH	- 0.93	85.83	1949	99%
	29	tm = 14.71 - H*0.31/100	- 0.73	52.79	1,00	99%
	29	AP = 295.8 + 0.22*H	0.61	37.75	96.7	99%
	29	PE = 907.4 - 0.15*H	-0.67	45.16	56.5	99%
Júcar	22	S = 53978-6863*lnH	- 0.91	82.18	4789	99%
	42	tm = 16.31 - H*0.48/100	- 0.80	64.66	1.40	99%
	42	AP = 533.3 + 0.02*H	0.05	0.21	170.9	Not at 90%
	42	PE = 885.8 - 0.18*H	- 0.79	63.14	54.5	99%
Ebro	70	S = 192058-27041*lnH	- 0.86	73.34	15102	99%
	55	tm = 12.67 - H*0.34/100	- 0.83	69.25	1.06	99%
	55	AP = 325.0 + 0.43*H	0.75	55.90	182.5	99%
	55	PE = 852.6 - 0.16*H	- 0.63	40.24	92.23	99%

r: Correlation coefficient; R²: R-squared percent; SEE: standard error of estimation; CL: confidence level for a significant relation between meteorological and hydrographical data and height H (m) of monitoring stations; S (km²): controlled runoff surface extension; tm (°C): mean annual temperature; AP (km³ year⁻¹): atmospheric precipitation; PE (km³ year⁻¹): potential evapotranspiration.

On the other hand, linear regression analysis between potential evapotranspiration PE (km³·a⁻¹) and the height of monitoring stations H (m), at a confidence level = 99%, gives the following relationship:

$$PE = a - b \cdot H \text{ with a mean } R^2 = 56.62$$

where:

Maximum $R^2 = 79.28$
 Minimum $R^2 = 29.31$.

[8]

TABLE 4
Streamflow Q (m³·s⁻¹), height H (m), and hydraulic power HP (MW) corresponding to 25%, 50% and 100% of the total surface area of each hydrographical basin

Basin	n	Q ₂₅	Q ₅₀	Q ₁₀₀	H ₂₅	H ₅₀	H ₁₀₀	HP ₂₅	HP ₅₀	HP ₁₀₀
Northwest-Miño	7	84	145	266	377	236	0	312	335	0
North	23	157	289	554	85	44	0	131	126	0
Northeast	41	32	44	70	275	114	0	86	49	0
Duero	38	116	186	327	841	742	577	956	1354	1848
Tajo	49	53	87	154	635	406	166	330	345	251
Guadiana	57	24	53	110	558	273	0	134	142	0
Guadalquivir	35	48	104	216	304	103	0	145	105	0
South	16	4	13	31	496	230	0	21	30	0
Segura	14	13	12	10	423	125	0	53	15	0
Júcar	22	23	29	40	574	206	0	129	57	0
Ebro	60	203	332	589	452	249	0	899	810	0
Total	362	758	1294	2367				3195	3368	2099

n: number of streamflow stations.

TABLE 5
Streamflow Q (m³·s⁻¹), electrical conductivity EC (dS·m⁻¹ at 25 °C) and osmotic power OP (MW) corresponding to 25%, 50% and 100% of the total surface area of each hydrographical basin

Basin	N	Q ₂₅	Q ₅₀	Q ₁₀₀	EC ₂₅	EC ₅₀	EC ₁₀₀	OP ₂₅	OP ₅₀	OP ₁₀₀
Northwest-Miño	189	84	145	266	0,09	0,08	0,06	166	285	524
North	630	157	289	554	0,09	0,11	0,16	309	569	1089
Northeast	3110	32	44	70	0,68	0,93	1,44	62	86	134
Duero	1428	116	186	327	0,16	0,22	0,35	228	366	640
Tajo	11204	53	87	154	0,60	0,68	0,84	103	169	299
Guadiana	4435	24	53	110	1,19	1,34	1,66	47	102	210
Guadalquivir	3101	48	104	216	0,76	0,95	1,32	94	202	415
South	1055	4	13	31	1,28	1,68	2,49	8	25	58
Segura	383	13	12	10	0,53	0,81	1,38	25	23	19
Júcar	773	23	29	40	0,84	1,12	1,68	44	55	76
Ebro	1312	203	332	589	0,37	0,49	0,74	397	648	1144
Total	27620	758	1294	2367				1484	2529	4608

N: number of water samples.

TABLE 6
Total power TP (MW) corresponding to 25%, 50% and 100% of the total surface area of each hydrographical basin

Basin	TP ₂₅	TP ₅₀	TP ₁₀₀
Northwest-Miño	478	621	524
North	440	695	1089
Northeast	147	135	133
Duero	1184	1719	2487
Tajo	433	514	550
Guadiana	181	244	210
Guadalquivir	239	307	415
South	30	55	58
Segura	77	38	18
Júcar	173	112	76
Ebro	1296	1458	1145
Total	4679	5898	6706

Absolute water scarcity or abundance at regional level

Economic aspects depend on absolute and relative water scarcity or abundance. Absolute scarcity (AP to PE) is defined by the difference between atmospheric precipitation (AP) and potential evapotranspiration (PE) which determines water use by soil-vegetation cover (Gascó and Gascó, 1999). Relative abundance (AP to RE) is defined by the difference between AP and real evapotranspiration (RE), which depends on soil-water management. At the regional level, absolute and relative scarcity or abundance (Table 2) can be obtained from hydrographical and meteorological data. Absolute scarcity is usual in Mediterranean and arid or semi-arid countries. Only northern basins (Table 2, Fig. 1) with udic climate types have absolute abundance.

There are some regions in Spain with absolute scarcity (negative sign) and relative abundance (positive sign). The actual difference between absolute scarcity and relative abundance depends on differences in economic development of individual regions in Spain. This fact has caused a "water war" between central and peripheral regions. This "water war" has actually intensified due to the plan to transfer 1 km³·a⁻¹ of water from the Ebro Basin to the Segura and other basins. This conflict has flared due to huge differences in water prices, which vary

from €0.3·m⁻³ for irrigation use to €1 000·m⁻³ of bottled drinking water. This range of water prices makes water desalination to supply water demand a viable alternative. Moreover, desalination of inland brackish water by the RO procedure could be economically more efficient than desalination of sea-water in terms of Eq. [5].

Hypotheses

Three surface water hypotheses were considered to calculate HP (MW) (Table 4), OP (MW) (Table 5) and TP (MW) (Table 6) of Spanish hydrographical basins:

- Height H₂₅ (m) corresponding to 25% of total surface area of the basin
- Height H₅₀ (m) corresponding to 50%
- Height H₁₀₀ (m) corresponding to 100%.

Results and discussion

Spain has an orography marked by a wide altitude range, from sea level to high mountains (for example, Mulhacen Mountain, which reaches 3 483 m). The HP estimated (Table 4) with the available data can contribute to classifying the different basins according to their potential power. Exploitation of this innate water power has been realised through temporal regulation of water flow by placing hydroelectric power plants in dams located in the most favourable areas.

In Spain, operational hydroelectric power plants with a capacity of 14 200 MW produce approximately 32 000 GWh per year (an average use of 2 253h·a⁻¹) according to the SNHP (DGOH, 1989). This value is close to the total HP₅₀ value (3 368 MW) that equals to 29 504 GWh. Therefore, technical advances should encourage the construction of additional hydroelectric power plants to produce more power. The SNHP plans to increase capacity by 7 000 MW to produce an additional value of 14 000 GWh (average use of 2 000 h·a⁻¹).

Table 4 shows how natural HP varies greatly from one basin to another according to the height H and water flow Q of every basin. Northwest, North, Duero, Tajo and Ebro Basins showed higher HP values due to their altitude and volume flow. Finally, it must be pointed out that the height of the output flow measurement stations H₀ was zero (at sea-level altitude) in all basins except for those in the Duero and Tajo Basins, due to streamflow measurement stations being located near the Portuguese border. Thus, HP is a useful index which could assist decision-makers of various countries in selecting the best basins and places where hydroelectric power plants should be located.

Values of OP (Table 5) show the loss of WRQ in the streamflows from the head basin (OP₂₅) to the lowest basin (OP₁₀₀) in terms of high OP values. An OP₁₀₀ value was higher than OP₅₀ in all basins except for the Northwest-Miño Basin because the main rivers of this basin receive flows of better quality in the lower basin. According to the OP₁₀₀ value, the highest water quality corresponds to the North and Ebro Basins and the lowest quality corresponds to the South, Segura and Jucar Basins. This fact shows that these basins, where atmospheric precipitation is low and the climate is

TABLE 7	
Application of hydraulic power (HP), osmotic power (OP) and total power (TP) indicators to the analysis of Tajo-Segura water transfer (0.6 km³·a⁻¹) for high productive irrigated agriculture in hot climate in the south-eastern of Spain	
(1) Natural water resources before an artificial water transfer of 19 m³·s⁻¹	
Upper Tajo Basin	Middle Segura Basin
Q ₂₅ = 53 m ³ ·s ⁻¹	Q ₅₀ = 12 m ³ ·s ⁻¹
H ₂₅ = 635 m	H ₅₀ = 125 m
EC ₂₅ = 0.60 dS·m ⁻¹ at 25 °C	EC ₅₀ = 0.81 dS·m ⁻¹ at 25 °C
HP ₂₅ = 329.8 MW	HP ₅₀ = 14.7 MW
OP ₂₅ = 103.2 MW	OP ₅₀ = 23.3 MW
TP ₂₅ = 433.0 MW	TP ₅₀ = 38.0 MW
(2) Natural-artificial conditions after the artificial water transfer	
Upper Tajo Basin	Middle Segura Basin
Q ₂₅ = 34 m ³ ·s ⁻¹	Q ₅₀ = 31 m ³ ·s ⁻¹
H ₂₅ = 635 m	H ₅₀ = 125 m
EC ₂₅ = 0.60 dS·m ⁻¹ at 25 °C	(*) EC ₅₀ = 0.68 dS·m ⁻¹ at 25 °C
HP ₂₅ = 211.6 MW	HP ₅₀ = 38.0 MW
OP ₂₅ = 66.2 MW	OP ₅₀ = 60.3 MW
TP ₂₅ = 277.8 MW	TP ₅₀ = 98.3 MW
(*) EC ₅₀ = (19·0.60 + 12·0.81) / (19 + 12) = 0.68 dS·m ⁻¹ at 25 °C	
(3) Final minus initial status of HP, OP and TP	
Upper Tajo Basin	Middle Segura Basin
HP ₂₅ = -118.2 MW	HP ₅₀ = 23.3 MW
OP ₂₅ = -37.0 MW	OP ₅₀ = 37.0 MW
TP ₂₅ = -155.2 MW	TP ₅₀ = 60.3 MW
(4) Comparative analysis of both the Tajo-Segura transfer and the sea-water desalination alternative for a water supply of 19 m³·s⁻¹ of EC 0.60 (dS·m⁻¹ at 25 °C) in the middle Segura Basin (125 m)	
Tajo-Segura transfer alternative	Sea-water desalination alternative
HP = -118.2 + 23.3 = -94.9 MW	HP = -23.3 MW
OP = -37.0 + 37.0 = 0.0 MW	OP = -37.0 MW
TP = -155.2 + 60.3 = -94.9 MW	TP = -60.3 MW
(5) Conclusions	
<ul style="list-style-type: none"> • The Tajo-Segura water transfer is unfavourable for the Tajo Basin due to the decrease of water resources in quantity (-19 m³·s⁻¹) and quality: HP (-118.2), OP (-37.0), and TP (-155.2 MW) • It is favourable for the Segura Basin in both quantity (19 m³·s⁻¹) and quality: HP (23.3), OP (37.0) and TP (60.3 MW) • From the Spanish point of view, the transfer was feasible in the decade of 1970s in term of water resource development, but currently is not favoured because the seawater desalination alternative is preferable in terms of TP (60.3 < 94.9 MW). This means that the increase in total power in the Segura basin (60.3 MW) does not compensate for the loss of hydropower in the Tajo Basin (-118.2 MW). 	

arid, could be the best places to locate desalination plants. Indeed, the greatest numbers of desalination plants in peninsular Spain are located in these basins (Gascó, 2004). Therefore, OP is a reliable indicator or index which could assist all players responsible for water management to take objective decisions about the location of desalination plants.

It must be stressed that the main loss of WRQ in term of salt concentration takes place when freshwater is mixed with sea-water. Therefore, attempts made to invert the hydrological cycle and supply demand with desalinated water should always employ, for economic reasons, saline and brackish waters, and should employ sea-water only under extreme

1) Water resources before an artificial out-of-basin river diversion of 33.3 m³·s⁻¹					
Parameters	Ebro	Northeast	Júcar	Segura	South
Q ₁₀₀ (m ³ ·s ⁻¹)	589	70	40	10	31
EC ₁₀₀ (dS·m ⁻¹ at 25 °C)	0.74	1.44	1.68	1.38	2.49
OP ₁₀₀ (MW)	1144.4	134.2	76.3	19.2	58.3
TP ₁₀₀ (MW)	1144.4	134.2	76.3	19.2	58.3
(2) Natural-artificial conditions after the artificial Ebro River diversion					
Parameters	Ebro	Northeast	Júcar	Segura	South
Water transfers (km ³ ·a ⁻¹)	-1.050	0.190	0.315	0.450	0.095
Q (m ³ ·s ⁻¹)	-33.3	6.0	10.0	14.3	3.0
Q ₁₀₀ (m ³ ·s ⁻¹)	555.7	76.0	50.0	24.3	34.0
EC ₁₀₀ (dS·m ⁻¹ at 25 °C)	0.74	(*)1.38	(*)1.49	(*)1.00	(*)2.33
OP ₁₀₀ (MW)	1079.7	145.9	95.8	47.0	64.1
(*) EC = (EC ₁ ·Q ₁ + EC ₂ ·Q ₂) / (Q ₁ + Q ₂)					
(3) Final minus initial status of TP					
Parameters	Ebro	Northeast	Júcar	Segura	South
TP ₁₀₀ (MW)	-64.7	11.7	19.5	27.8	5.8
(4) Comparative analysis of both the out-of-basin Ebro River water flow diversion and the sea-water desalination alternative for water supply of Northeast (6.0), Júcar (10.0), Segura (14.3) and South (3.0 m³·s⁻¹·m) Basins in terms of total power (TP)					
Projects	Total power TP (MW) needed for the same water resource supply in quantity and quality				Total (MW)
	Ebro	Northeast	Júcar	Segura	
Ebro River diversion	-64.7	11.7	19.5	27.8	5.8
Sea-water desalination	0.0	-11.5	-19.2	-27.6	-5.7
(5) Conclusions					
<ul style="list-style-type: none"> The out-of-basin Ebro River diversion is not favourable for the Ebro Basin due to the decrease in water resources in quantity (-33.3 m³·s⁻¹) and quality: OP = TP (-64.7 MW) It is favourable in terms of the increasing water resource quantity and quality for the Northeast (Q = 6 m³·s⁻¹; TP = 11.7 MW), Júcar (10.0; 19.5), Segura (14.3; 27.8) and South (3.0; 5.8) Basins From the Spanish point of view: the conclusion is favourable with respect to the sea-water desalination alternative. This signifies a different TP up to 64 MW to sea-water desalination. 					

circumstances. The economic cost of desalting brackish water by RO could be less than the cost of freshwater obtained by other conventional alternatives such as inter-basin water transfers by long-distance channel or pipeline (Uche et al., 2001). Along the eastern and southern coasts of Spain, the problem of sea-water intrusion into coastal aquifers threatens water supplies dependent on desalinated water. When serious, the problem may justify the installation of desalination plants to desalinate sea-water in order to reduce pressure over the coastal aquifers.

Currently, the installed water desalination capacity in Spain surpasses 300 000 m³·d⁻¹. Specifically, 70% is produced by RO because of improvements in membrane technologies, 23% by multi-stage flash and multi-effect distillation, MSF to MED, 5% by vapour compression, VC, and 2% by electrodialysis, ED (Gascó, 2004). Indeed, RO is the most important system installed in south-eastern peninsular Spain and the Balearic and Canary Islands, where the government has tried to lower water prices to promote tourism (MICT, 1992). In terms of water source, 47.1% of desalinated water comes from the sea and 52.9% from brackish water (Medina, 2001). Nevertheless, desalted water accounts for only 0.71% of the water supply in Spain, while inter-basin water transfers total 4.72% and water storage 94.57%. Therefore, construction of new water storages and additions to infra-

structure will continue to play an important role in developing countries (Pigram, 2001), as is the case with many countries with a Mediterranean climate. Water transfers should be done for strong economic reasons. From an economic point of view, it is senseless to transfer large volumes of good freshwater freely or cheaply for inefficient uses, such as for maize production on irrigated lands (0.5 to 1.0m³·kg⁻¹ of produced grain), especially when household users must buy a bottle of water at astronomical prices (€ 0.1 to 1.0·l⁻¹). The water quality factor can be more limiting than the water quantity factor. Water resource management must place the same importance on the quality imbalance as the quantity imbalance. Its aim should be not only to supply household users, but also to supply irrigated land that requires additional water to wash salts away in order to establish an acceptable soil salt balance (Gascó and Gascó, 2003).

Maximum available TP (MW) (Table 6) is the maximum available energy that can be liberated by water per unit of time (s) with respect to sea height level and sea-water salt content. TP in head basins (TP₂₀) rose to 4 679 MW that equalled an annual value of 40 988 GWh in peninsular Spain. TP increased to 51 658 GWh in the mean basin (TP₅₀) and to 58 745 GWh in the low basin (TP₁₀₀). TP can be used to identify, in a quantitative manner, the importance of two power sources: the hydraulic and

the osmotic. According to the TP value, the best quality water is found in the North, Duero and Ebro Basins while the South, Segura and Júcar Basins have the water with the worst quality. Indeed, TP could be a water quality index because it represents the most synthesised quantitative measurement of the natural quality of inland water resources that can be obtained at this time.

Therefore, OP and HP can be considered as qualities of water resources that define the basic environmental state of a particular hydrographical basin. Total power TP, obtained by adding OP to HP, can give an idea of the total power of a basin. This indicator can serve to assess the water quantity and the water quality of a basin because this index integrates water flow ($\text{m}^3\cdot\text{s}^{-1}$) with the energy properties associated with position over sea level and the water salt concentration with respect the sea-water salt concentration. Finally, it should be pointed out that OP, HP and TP values could be used as environmental pressure indicators to:

- Decide between the different systems of water supply (desalination or water transfer)
- Evaluate the environmental cost of desalination, storage and water transfer
- Be applied to each element of the hydrological cycle, for example, groundwater.

In Spain two large water supply projects can be analysed using the HP, OP and TP indicators:

- The Tajo-Segura transfer of $0.6 \text{ km}^3\cdot\text{a}^{-1}$ (Table 7)
- The River Ebro out-of-basin diversion of $1.05 \text{ km}^3\cdot\text{a}^{-1}$ (Table 8).

The general conclusion is that different points of view associated with the spatial scale considered for water resources and supplies produce different recommendations:

- The Tajo-Segura water transfer is favourable for the Segura Basin, but the increase in total power does not compensate for the loss of hydropower in the Tajo Basin. The sea-water desalination supply is a feasible alternative to supply water to the highly productive agriculture in the hot climate of the south-eastern Spain.
- Instead, the Ebro River out-of-basin water flow diversion is a better solution than sea-water desalination in terms of OP and TP due to the increase of osmotic and total power in the Northeast (11.7 MW), the Júcar (19.5), the Segura (27.8) and the South (5.8) Basins compensating for the decrease in total power in Ebro Basin (-64.7).
- The Tajo-Segura project is operative, but the Ebro River diversion project was already under construction when it was cancelled. According to the new SNHP (BOE 2004), the supply will be produced by desalting both brackish water and sea-water. That means that freshwater ($1.05 \text{ km}^3\cdot\text{a}^{-1}$; $0.74 \text{ dS}\cdot\text{m}^{-1}$ at 25°C) will pour into the sea, and then the same quantity will be withdrawn and desalinated. The reasons given for cancelling the Ebro River diversion from the low basin near the sea were the serious social and environmental questions generally raised by major water resource development projects (Pigram, 2001). It is conceivable that the Ebro River diversion would have reduced the available water resources in the Ebro Basin (as part of the water would have been kept in the high and medium basins for the supply of other basins) and in this way have exacerbated some of the

ecological problems that already exist in the Ebro River, its delta, and other coastal wetlands (Horne and others 2003).

Conclusions

Topographical position and salt concentration affects inland water resource quality. As altitude decreases, the availability of hydraulic energy production diminishes. When salt concentration increases, water availability for plant and animal nutrition decreases. HP and OP can serve to measure, respectively, the influence of the topographical position and the influence of the salt concentration on the water resource quality. Moreover, TP, the sum of OP and HP, can give an idea of the total power of a basin. This is very important due to the fact than an increase in the price of energy can affect the implementation of water policy. Results showed that the higher the OP, HP and TP values, the higher the water resource quality of a basin. Moreover, these indicators can be useful tools for water management because the OP, HP and TP parameters integrate factors of water resource quality and water quantity. Indeed, OP, HP and TP can serve any government in implementing water policy and these parameters can assist in deciding between inter-basin water transfers and water desalination, especially in countries where water is a scarce resource. Indeed, results showed that desalination plants should be located on the basins with the lowest OP values.

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References

- BOE (2001a) Act 1/2001 on Water of the 20th of July. *BOE* **176** 26791-26817.
- BOE (2001b) The National Hydrological Plan, Act 10/2001 of the 5th of July. *BOE* **161** 24237-24250.
- BOE (2004) Act 2/2004, of the 18th of June, on Modification of the Act 10/2001 (The National Hydrological Plan). *BOE* **148** 22453-22567.
- CAMPOLO M, ANDREUSSI P and SOLDATI A (2002) Water quality control in the river Arno. *Water Res.* **36** 2673-2680.
- CEC (2000) Directive of the European Parliament and the Council Establishing a Framework for Community Action in the Field of Water Policy: Joint Text Approved by the Conciliating Committee: 1997/0067(COD) C5-0347/00.
- DGOH (1989) *Plan hidrológico. Documentación básica*. Dirección General de Obras Hidráulicas DGOH del Ministerio de Obras Públicas y Urbanismo MOPU, Madrid, Spain. 550 pp.
- GALLOPIN GC (1997) Indicators and their use: Information for decision-making. In: Moldan B, Billharz S and Matravers R (eds.). *Sustainable Indicators. A Report on the Project on Indicators of Sustainable Development*. John Riley & Sons, Chinchester, England.
- GASCÓ G (2004) Influence of State Support on water desalination in Spain. *Desalination* **165** 111-122.
- GASCÓ G and GASCÓ A (2003) Balance de sales en los regadíos de las principales cuencas hidrográficas de España. *Ingeniería Civil* **131** 189-194.
- GASCÓ JM and GASCÓ A (1999) Adaptación de los cultivos y las labores al régimen de humedad de los suelos en la agricultura tradicional. In: Garrabou R and Naredo JM (eds). *El agua en los sistemas agrarios. Una perspectiva histórica*. Fundación Argentaria, Visor Dis., Madrid, Spain. 85-94.
- HONTORIA C, SAA A, ALMOROX J, CUADRA L, SÁNCHEZ A and GASCÓ JM (2003) The chemical composition of precipitation in Madrid. *Water Air Soil Pollut.* **146** 35-54.

- HORNE AJ, DRACUP J, HANEMANN M, RODRIGUEZ-ITURBE I, MEANS E and ROTH JC (2003) A technical review of the Spanish National Hydrological Plan (Ebro River out-of-basin diversion). Technical report for Fundación de la Universidad Politécnica de Cartagena, Spain. 65 p.
- INTERLANDI SJ and CROCKETT CS (2003) Recent water quality trends in the Schuylkill River, Pennsylvania, USA: a preliminary assessment of the relative influences of climate, river discharge and suburban development. *Water Res.* **37** 1737-1748.
- KALLIS G and BUTLER D (2001) The EU water framework directive: measures and implications. *Water Policy* **3** 125-142.
- MALAN H, BATH A, DAY J and JOUBERT A (2003) A simple flow-concentration modelling method for integrating water quality and water quantity in rivers. *Water SA* **29** (3) 305-311.
- MARGAT J (1986) Methodes de la comptabilisation de l'eau en qualite(s). In : CICPN-INSEE. *Les comptes du patrimoine naturel*. CICPN-INSEE, Paris, France. 354-414.
- MEDINA JA (2001) La Desalación en España. Situación actual y previsiones. *Proc. of International Conference: Spanish Hydrologic Plan and Sustainable Water Management*. Zaragoza, Spain. 7 pp.
- MICT (1992) Orden de 21 de julio de 1992 por la que se aprueban las bases reguladoras sobre subvención a las plantas de potabilizadoras de Canarias para 1992. Ministerio de Industria, Comercio y Turismo. *BOE* **186** 27269-27271.
- MORRISON G, FATOKI OS, ZINN E and JACOBSSON D (2001) Sustainable development indicators for urban water systems: A case study evaluation of King William's Town, South Africa, and the applied indicators. *Water SA* **27** (2) 220-232.
- MTETWA S and SCHUTTE CF (2002) An interactive and participative approach to water quality management in agro-rural watersheds. *Water SA* **28** 337-344.
- NAREDO JM and GASCÓ JM (1994) Spanish water accounts. In: OECD/ENV/EPOC/SE/A (94)2. *Environmental accounting for decision-making*. OECD-ENV-EPOC-SE, Paris, France. 118 pp.
- OECD (1993) *Natural Resource Accounts*. Group on the State of the Environment, ENV/EPOC/SE(93)3, Paris. 28 pp.
- PIGRAM JJ (2001) The global outlook for water resources. *Proc. of International Conference: Spanish Hydrologic Plan and Sustainable Water Management*. Zaragoza, Spain. 7 pp.
- SIMEONOV V, STRATIS JA, SAMARA C, ZACHARIADIS G, VOUTSA D, ANTHEMIDIS A, SOFONIOU M. and KOUIMTZIS TH (2003) Assessment of the surface water quality in Northern Greece. *Water Res.* **37** 4119-4124.
- UCHE J, SERRA L and VALERO A (2001) Hybrid desalting systems for avoiding water shortage in Spain. *Desalination* **138** 329-334.
- RICHARDS LA (1954) *Diagnosis and Improvement of Saline and Alkali Soils*. U.S. Department of Agriculture USDA Handbook no. 60, Washington. 160 pp.
- WALMSLEY J, CARDEN M, REVENGA C, SAGONA F and MALCOLM S. 2001. Indicators of sustainability development for catchment management in South Africa - Review of indicators from around the world. *Water SA* **27** 539-550.
- WANGNICK K (2001) A global overview of water desalination technology and the perspectives. *Proc. of International Conference: Spanish Hydrologic Plan and Sustainable Water Management*. Zaragoza, Spain. 19 pp.