USE OF ENVIRONMENTAL INDICATORS IN A MULTI-CRITERIA ANALYSIS OF THE IMPACT OF MAR ON GROUNDWATER DEPENDENT WETLANDS

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ABSTRACT

The following pages present an attempt to design a system of environmental indicators to monitor the evolution of an aquifer by means of recent artificial recharge works. In this way, it is possible to value its effectiveness and to follow the evolution and the interaction between the different technical, economical and environmental aspects. For the study of its evolution and the degree of interaction, a system of ranges-weights and a multi-criteria evaluation polygon have been designed. The application of the proposed methodology allows to know the “state of pressure”, to correct adverse environmental impacts and to systematically improve the efficiency of technical operations.

KEYWORDS

Artificial recharge of aquifers, environmental indicators, evaluation of environmental impact, PSR system, Coca-Olmedo wetlands complex.

INTRODUCTION

This paper is based on the experience acquired during the artificial recharge of the *Cubeta of Santiuste* (Segovia) aquifer, promoted by the General Secretary of Rural Development of the Spanish agriculture ministry (MAPA). It has been applied in two selected wetlands of the Coca-Olmedo Complex *(Rey Benayas, 1991)* susceptible of regeneration by means of artificial recharge: the lagoons of *Las Eras* and *La Iglesia*, in Villagonzalo de Coca (Segovia) *(González, 1989; Fdez. Escalante, 2005).*

The following pages present a method for environmental impact evaluation, management and control of artificial aquifer recharge operations (AR), particularly in cases were wetland restoration is possible. We propose an environmental indicators system (most of own design), and a multi-criteria evaluation polygon to tackle and synthesize the evaluation and monitoring processes. The method allows to reflect quantitative, qualitative, evolutionary, ecological aspects, etc., as well as the qualitative evolution of all kind of waters in the study area.

DESCRIPTION OF THE SYSTEM

The *Santiuste* basin is a small aquifer with 85 km^2 in extension that is limited by the Voltoya and Eresma rivers to the East, and low permeability Tertiary outcrops to the West.

Saline wetlands abound. Despite its reduced size, it is considered an important irrigation area that depends heavily on groundwater (figure 1). Intensive pumping led to a siginificant drop in the water table and in turn to severe wetlands degradation.

In 2002, an artificial recharge project for the aquifer was implemented by government initiative. The scheme is based on a small dam that taps the Voltoya river, carrying the water from a altitude of 817 m above sea level, by gravity down to a transferring station located at 814 m above sea level. A 10 km long pipeline starts from this station, carrying the water down the slope to a 36 m^3 deposit. The main recharge ditch, dug out through the 20 per cent of the old watercourse of the *Ermita* stream, starts from this deposit to the surroundings of the Eresma river, where the irrigation area ends. The trace of the ditch goes down 30 m of height difference and 0.28% slope through a 10.7 km distance. This ditch has 54 stopping devices with the aim of facilitating the infiltration and decant processes. A parallel service road is being built 4 m away from the ditch that gets elevated 50 cm above the terrain height and will serve as a barrier against possible overflows.

The infiltration surface is over 33,300 m^2. The maximum directed flow of water surplus from the Voltoya river is about 0,5 m^3/s between November and April, although it may decrease or even get stopped according to river flow and characteristics of the considered hydrological year. The sheet of water inside the ditch will range between 50 and 100 cm in height but it will tend to be 80 cm. Four infiltration ponds were built in 2004, for a total surface of over 200m^2. Net infiltration is estimated at 1.5 Mm^3 per cycle.

New water resources have both triggered an increase in irrigated area and a new disponibility environmental flows. Without these resources, wetlands would have probably been lost completely. Over the 2005 summer, remedial measures have been applied to recover La Iglesia and Las Eras wetlands by diverting water from the artificial recharge scheme to the western sector of the aquifer.

In view of new irrigation developments, MAR has turned into the only viable alternative to reduce environmental impacts and to reach more sustainable agricultural practices. MAR allows to monitor relevant parameters (controllable features) as to how the 'pressure state' evolves with time. This in turn facilitates setting sociacl and environmental target states. However, give the complexity of the system, evaluation must be open to uncontrolled variables.

METHOD

The proposed system is consistent with the rules of the Spanish and European legislation for the elaboration of Environmental Impact Assessments (EsIA), as per the Law RD. 6/2001, and is based on environmental engineering approaches.

The design of environmental indicators is based on the PSR Framework *(Friends & Raport, 1979)*, which distinguishes between Pressure, State and Response indicators.

The multi-criteria evaluation polygon (or variogram) that we present is original and based on the experimental control of a wetlands system along five years of development of the first author's PhD Thesis *(Fdez. Escalante, 2005).* A more detailed explanation may be found in Fdez. Escalante et al 2005.

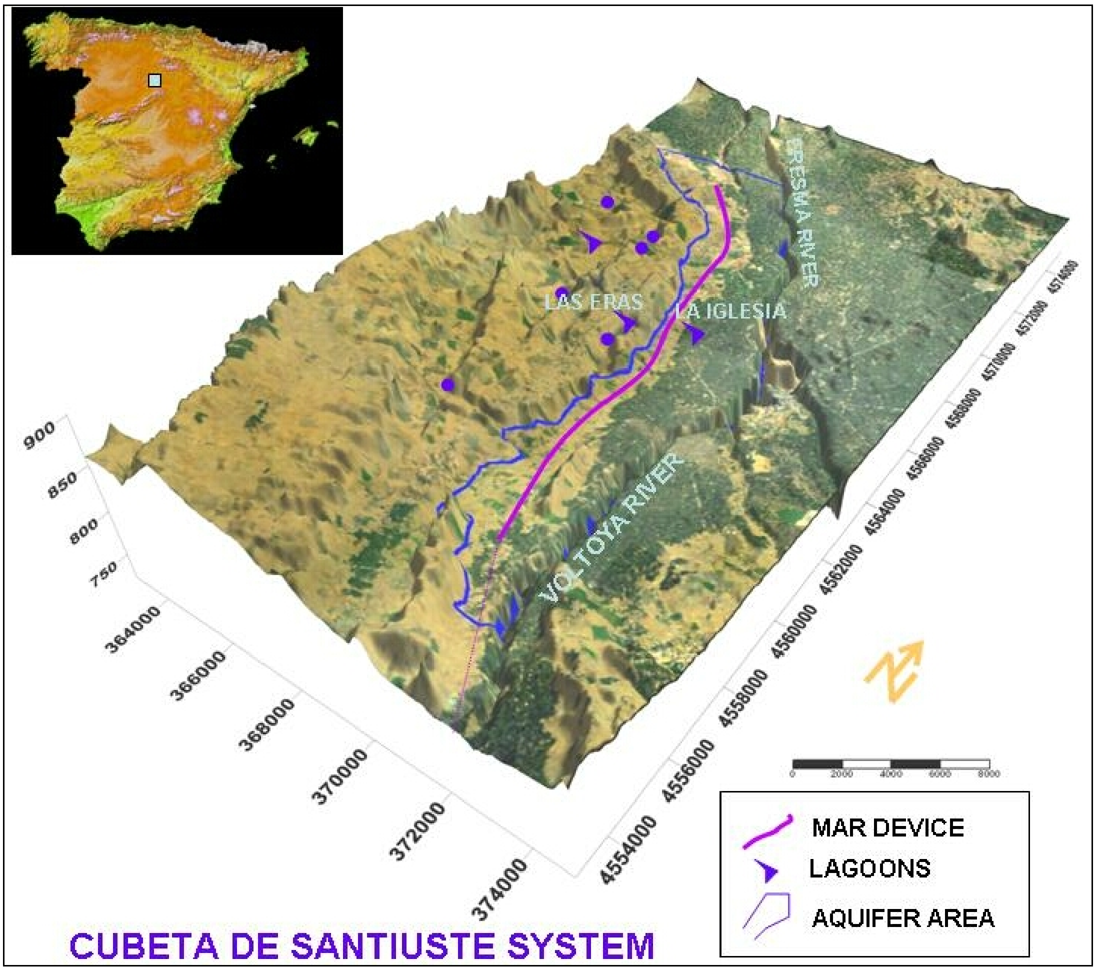

Figure 1. Representation of the Cubeta de Santiuste aquifer showing MAR device and the most significant lagoons.

RESULTS. DESIGN OF ENVIRONMENTAL INDICATORS

Pressure indicators

A set of ten pressure indicators has been designed, for the purpose of controlling the direct and indirect impacts of human activities. These are evaluated consequently by the importance and the intensity of those human activities that can generate environmental stresses or impacts. Their determination is carried out in the field (direct measures).

To reach the "state of pressure" and to get an accurate impact assessment, a system of ranges-weights must be applied so as to homogenize the intensity and scale of the different concurrent environmental impacts. This is carried out by means of correction factors added to those 'less expressive' indicators. Accumulative impacts and synergies are introduced to the system by means of assessment factors. For example the impact of a three-year drought is more significant than twice the stress of a two-years one. This *modus operandi* is similar for the remaining groups of PSR Framework indicators.

The system is to be applies to each wetland or or key element under restoration. An assessment should be carried out at least once a year, following adequate data-collection campaigns. This allows for an evaluation of how the restoration process is affecting wetlands. Dealing with all individual wetlands in a joint manner allows for an assessment of the aquifer situation.

The following list outlines the main pressure indicators. Their detailed definition, ranges-weights values applied and corrective factors for accumulative impacts and synergies (e.g. inter-year climatic variations) should be consulted in the bibliographical references *(Fdez. Escalante, 2005; Fdez. Escalante el al, 2005).* The result is a numerical value whose variability allows to evaluate progress over time. This may provide information on environmental aspects (whether environmental impacts have been reduced between two consecutive measurements) or social and economic conditions (whether agricultural production has increased). The evolution of the total "state of pressure" correponds to aggregating the evolution of the first two indicator types (state and pressure) and the third one (reponse) once anthropic action has begun.

1.- Aquifer overexploitation by irrigation
2.- Total organic carbon (TOC) in the waters of AR
3.- Modernization and improvements of AR and irrigation devices.
4.-Eficciency in water use
5.-Socioeconomic evaluation
6.-Political background of the activity
7.- Proximity to the device of ar (*Tt*)
8.- Area of influence (m)
9.- Presence of groundwater and temperature- dependent ecosystems
10.- Relationship of wetlands with other aquifers, springs, wetlands, etc.

State indicators

These describe the quality of the environment and of the natural resources associated to processes of socioeconomic exploitation. In addition, these also reflect the changes caused in the environment. Their evaluation is based on analytic methods which allow for quantification of "performance response" *(MIMAM, 1997).*

Within the PSR system, these are the most adequate indicators for the application of specific techniques to control parameter variations over time. Results suggest that the most viable option is factorial analysis by means of a correlation matrix such that those correlated are independent and not redundant and that duplicities may be omitted *(Rey Benayas et al, 2003).*

List 2 summarizes the main ten state indicators. Five of those are of general application and five designed *ex profeso*. In accordance with the previous operating system, the scales of ranges–weights and corrective factors would be applied.

1.- Aquifer contaminated by nitrates (A1 MIMAM, 1997)
2.- Rivers and wetlands with good quality according to the biotic index bmwp´ (A3 MIMAM, 1997)
3 General quality index (ICG, A4 MIMAM, 1997)
4.- Characterization of the vulnerability of diffuse contamination (CRIPTAS)
5.- Aquifers affected by continental saline intrusion (A2 MIMAM, 1997 modified)
6.- Groundwater salinization

7.- turbidity and total of dissolved solids (TSD) in the water of AR
8.- Groundwater table in observation wells
9.- Difference of average table between the phreatic level and AR level in each "*hydroenvironment unit*" *(Fdez. Escalante, 2005)*
10.- Soil clay percentage. Sample taken from 15 cm deep (AR channel clogging indicator)

Once completed the "characterization template" which includes most of the precise data to apply the system of indicators, the environmental stress evaluation in the intervention area (space) referred to each cycle of artificial recharge (time) is carried out. As a result, a specific EIA index can be obtained, taking into account that an arithmetic average is applied to all those that span several-years.

A particularly significant example is the indicator adopted for clog control (channel clogging is considered one of the biggest impacts for the implementation of AR).

The study of the cake with binocular glass after the first year of artificial recharge shows that the initial sandy texture is strongly altered. Fines are located around the surface of the grains. Seeds and grains of pollen, indicial tests of the influence of the organic activity in the aquifer, are also observed. The presence of particles blackened by oxide suggest possible influences of the dissolved oxygen concentrations in the system. Some clogging indicators have been applied previously, like the Index of Failure in Membrane (MFI), whose initial valuation for the study area in its first cycle of artificial recharge was from 25 to 30 s/l^2 (MFI units).

As a consequence of the huge technical difficulty to control the stress effect of several impacts (physical, biological and indirectly chemical clogging for surface systems of artificial recharge influenced by total organic carbon (TOC); the percentage of initial clay; infiltration surface; time of artificial recharge; infiltrated volume, and so on) we have proposed a specific indicator for the study area and similar scenarios that corresponds to variations in the percentage of fines in the soil and its evolution along each artificial recharge year/cycle. This evaluation is carried out by means of a granulometric analysis, using a 200 ASTM sieve. Monthly samples are taken at the surface level and at a depth of 20 cm in the different stations of control of the AR channel.

The percentage of fines (by weight) with regard to the initial value indicates the stress change. The difference of weights is subjected to a corrective factor to enlarge the value due to its great importance. In principle, we propose to divide the laboratory value by the number of days of artificial recharge from the beginning of the cycle until the date of sampling. This value is multiplied by 100, to get an assessment level in the order of the remaining indicators. The average value is used as a global indicator at the end of the cycle of artificial recharge. For the test site this has varied from 7 to 17 units in the first cycle.

Figure 2 shows the application of this system to La Iglesia lagoon. In August 2003, the 'pressure state' was estimated at 2035. By August 2005, MAR had resulted in a significant decrease of pressure (1835) despite severe drought conditions.

Response indicators

These indicate the level of social and political involvement in environmental matters and resources, corresponding to the policies and actions that the economic and environmental agents carry out to protect the environment.

Proposed indicators have provisional character, and are subject to checking the response of the performances in the long term.

Table 3 presents a group of fifteen response indicators and their calculation method, according to PSR framework (Friends & Raport, 1979), ranges and weights.

1.- Evolution of the dimensions of the AR device
2.- Sand deposit of channels, dams, natural or artificial riverbeds, etc.
3.- Increase of the erosion in the banks, slopes and influence areas
4.- Bench marks and slopes differences
5.- Changes in hydrogeological parameters
6.- Devices clogging and changes in channels bed permeability
7.- Dissolved oxygen concentration in observation wells
8.- Evolution of groundwater quality due to manures and nitrogen fertilizers uses
9.- Total carbonate concentration in AR water
10.- Crops affection inside the influence area
11.- Native vegetation affection inside the influence area
12.- Changes of ecological conditions in wetlands
13.- Variations in the water level in wetlands and specially those below the ground surface
14.- Reduction of undue consumption of water
15.- Nutrients balance in irrigation areas related to AR activities

DESIGN OF A POLYGON OF MULTI-CRITERIA SPECIFIC EVALUATION

A multi-criteria polygon is a graphic and parametric variogram that reflects in an intuitive, visual, quick and pedagogic way the evolution of the quantitative, qualitative and environmental aspects during and after each artificial recharge cycle, as well as their incidence in directly related factors *(Bascones, 2000; Custodio, 2000; Barbier et al, 1997; Fdez. Escalante and Cordero, 2002).*

Assigning a weight to each parameter with incidence in the state of the evaluated elements allows for the use of a variogram like matrix when relating factors with processes. This is in contrast with the record of initial characterization, which only identifies impacts.

The evaluation of environmental impacts and their control is presented in two simultaneous ways: numerical and graphical.

- Numerical: This is the result of applying system ranges-weights and corrective factors. It allows for assigning a global value to all the concurrent impacts in each cycle or period of measurement. It can be used as a global or integrated stress evaluation. The differences between numerical calculations can be also used as an achievement of the target indicator.

- Graphical: This consists on a variogram where a given set of fields, (whose stress evaluation values has been determined based on empiric experiences or technical approaches), is encircled by an ‘envelope’ line. The chosen graphical representation for the polygon of evaluation multi-criteria has been a histogram of horizontal bars. Each bar includes from 4 to 6 fields corresponding to the final assessment level of each impact. The enveloping line works as an affection degree indicator for each time.

The proposed methodology stages are:
1) Pick the best indicators for each specific situation.
2) Hierarchization of the indicators according to their magnitude.
3) Range intervals are established in an arbitrary way, based on technical concepts and an empirical base. Therefore, these can be modified in other scenarios different to the Coca-Olmedo wetlands Complex.
4) Attribution of the weight to each indicator range. In different scenarios, this attribution is carried out by the people in charge of evaluation.
5) Attribution of an evaluation or correction factor to each indicator in function of their index of incidence, i.e. the relative importance of each indicator for the proposed objective. In the practice, the corrective factor is a multiplier for the ranges-weights result (see *Fdez Escalante et al* (2005) in www.uax.es/publicaciones/tecnologia.htm).
6) Multiplication of the ranges of each indicator by their weight, application of a function factor (especially for accumulative impacts and synergies) and calculation of all the variables.
7) Attribution of a category or level of final evaluation to each numerical result of the proposed qualitative calculation of ranges-weights. Six affection degrees are considered: worthless (1), fair (2), moderate (3), intermediate (4), severe (5) and high (6).

With these results, graphical representation can be carried out in three successive stages:

1) Shade the categories until the maximum evaluation level. The scales can be redefined for each category in other scenarios or corrected for the case of defining the “state of pressure” for each specific setting.
2) Layout of the enveloping line encircling the shady fields (or affection degrees) of the multi-criteria evaluation polygon for each scenario.
3) Study of the variation of this final product along the time during the control program. Relative variations allow to appreciate if the stress is increasing (migration of any field of any impact to the right or elevation of the final numerical value) or the corrective measures work appropriately (the enveloping line has been displaced to the left in any field or there is a decrease of the global value of the multi-criteria evaluation).

An example of the final design of the multi-criteria evaluation polygon is presented in the figures 2 a) and b). Although this initially takes pressure and state indicators into account, it leaves space to for aggregation of the response indicators.

The final result is a numerical value that corresponds to the evolutionary state of the activity, wetland or key element, and an enveloping line or “polyline” encircling fields shadowed in the diagram (fields included in each affection degree). This "polyline" facilitates its use as indicator by comparison between different years/cycles. The final numeric value is lower and, consequently, MAR is achieving its objectives in wetlands recovering. Environmental impacts have been reduced particularly for the first and second state indicators and the ninth and tenth response indicators.

STATE/PRESSURE INDICATORS	<	ASSESMENT LEVEL				>
1). Rivers and wetlands with good quality according with the biotic index (BMWP).					100	
2). Quality General Index (ICG).					100	
3). Aquifers contaminated by nitrates.		112				
4). Charazterization of the vulnerability to diffuse contamination (CRIPTAS).			151			
5). Salinization of aquifers by continental saline intrusion.			458			
6). Groundwater salinization.			458			
7). Assesment of turbidence and TDS in AR waters.	< 25					
8). Level of water in observation wells.	3,2					
9). Difference of levels between water table and the level of water for artificial recharge.			2,8			
10). Soil fines percentage. Initial index of clogging.	14%					
1). Aquifer overexploitation by irrigation.		50****				
2). Nutrient balance in AR waters.		50****				
3). Modernization and improvements of the devices.		50****				
4). Efficciency in water use.		50****				
5). Socioeconomic evaluation.		50****				
6). Political backdrop of the activity.		50****				
7). Proximity to the AR facilities.		50****				
8). Area of influence.		50****				
9). Presency of hydrodependences or termodependences ecosystems.				100		TOTAL
10). Relationship of the wetlands with other wetlands, springs, lagoons, etc.				100		2035

STATE/PRESSURE INDICATORS	<	ASSESMENT LEVEL				>
1). Rivers and wetlands with good quality according with the biotic index (BMWP).		50****				
2). Quality General Index (ICG).		50****				
3). Aquifers contaminated by nitrates.		112				
4). Charazterization of the vulnerability to diffuse contamination (CRIPTAS).			151			
5). Salinization of aquifers by continental saline intrusion.			458			
6). Groundwater salinization.			458			
7). Assesment of turbidence and TDS in AR waters.	< 25					
8). Level of water in observation wells.	3,2					
9). Difference of levels between water table and the level of water for artificial recharge.			2,8			
10). Soil fines percentage. Initial index of clogging.	14%					
1). Aquifer overexploitation by irrigation.		50****				
2). Nutrient balance in AR waters.		50****				
3). Modernization and improvements of the devices.		50****				
4). Efficciency in water use.		50****				
5). Socioeconomic evaluation.		50****				
6). Political backdrop of the activity.		50****				
7). Proximity to to the AR facilities.		50****				
8). Area of influence.		50****				
9). Presency of hydrodependences or termodependences ecosystems.		50				TOTAL
10). Relationship of the wetlands with other wetlands, springs, lagoons, etc.		50				1835

Figures 2 a) and b). Variograms of *La Iglesia* wetland. Villagonzalo de Coca, Segovia, Spain. First: 2003, August; Second: 2005, August. Encircling line in purple color. The comparison between both polylines determines the stress difference. The final numeric value is lower (2035>>1835) and, consequently, MAR is achieving its objectives in wetlands recovering.

CONCLUSIONS

The application of the proposed methodology can be used to monitor the evolution of the different parameters, allowing to correct some environmental adverse impacts and to systematically improve the efficiency of technical operations.

The evolution of the proposed systems, specially the variogram, shows that it is necessary to change the location of certain AR devices, in order to improve the maintenance program and to apply specific SAT technologies.

The system of indicators constitutes an important novelty for the control of the restoration activities, whose application may allow operators to know whether their performance is appropriate.

The system of environmental indicators seeks to grant to each impact its fair evaluation. This is achieved by applying a system of ranges-weights elaborated on empirical experiences during a five years period. Accumulative impacts and synergies are subject to correction factors. Up to six fields or affection degrees (each assigned a specific colour) are described in this regard.

These environmental indicators may enhance aquifer monitoring, control of the magnitude and scale of the environmental impacts that operate on artificial recharge systems and their quantitative influence on associated ecosystems.

The system of ranges-weights has a matrix character and requires a continuous update as new information becomes available and futher field campaigns yield new data.

The variogram works in turn as an indicator of achievement of the objective (where the objective is to get an operative system of artificial recharge under conditions of minimum environmental impact).

The variogram can be obtained by applying a macro-based computer program that allows for a regular update and to evaluate the type of appropriate performance for the correct administration of the system. The macro is available in Internet for its general access and employment on the part of the interested technicians. The one designed by the authors can be obtained from www.uax.es/publicaciones/tecnologia.htm.

Figure 3). La Iglesia wetland, actually in restoration process thanks to MAR. Villagonzalo de Coca, Segovia, Spain.

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