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[Simulation and multicriteria optimization modelling approach for water regional restoration Management](#)

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Abstract: This paper presents a methodology to select the optimal robust wastewater reclamation program of measures (PoM) to achieve the European Water Framework Directive (WFD) objectives in the inner Catalonia watersheds. The integrative methodological tool developed incorporates a water quality model (WQM) to simulate the simultaneous effects of the PoM used to reduce pollution pressures on the hydrologic network. It includes a Multi-Objective Evolutionary Algorithm (MOEA) to identify efficient trade-offs between PoM cost and water quality. Interactive Decisions Map (IDM) - a multi-criteria visualization-based decision and negotiation support tool is used to provide the stakeholders a clear idea of the trade-off between water status and the cost to achieve such situation. Finally a simulation model to make a sensibility analysis under the environmental uncertainties is run. Moreover, the tool is oriented to guide stakeholders and water managers in their decision-making processes. Additionally, this paper analyzes the results of the application of the management tool in the inner Catalan watershed in order to perform the European WFD. This tool has been a key to design part of the PoM which will be implemented to achieve the objectives of the WFD in 2015 in all the Catalan catchments.

Simulation and multicriteria optimization modelling approach for water regional restoration management

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This paper presents a methodology to select the optimal robust wastewater reclamation program of measures (PoM) to achieve the European Water Framework Directive (WFD) objectives in the inner Catalonia watersheds. The integrative methodological tool developed incorporates a water quality model (WQM) to simulate the simultaneous effects of the PoM, used to reduce pollution pressures on the hydrologic network. It includes a Multi-Objective Evolutionary Algorithm (MOEA) to identify efficient trade-offs between PoM cost and water quality. Interactive Decisions Map (IDM) - a multi-criteria visualization - based decision and negotiation support tool is used to provide the stakeholders a clear idea of the trade-off between water status and the cost to achieve such situation. Finally a simulation model to make a sensibility analysis under the environmental uncertainties is run. Moreover, the tool is oriented to guide stakeholders and water managers in their decision-making processes. Additionally, this paper analyzes the results of the application of the management tool in the inner Catalan watershed, in order to perform the European WFD. This tool has been a key to design part of the PoM which will be implemented to achieve the objectives of the WFD in 2015 in all the Catalan catchments.

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1. Introduction

Water availability is often jeopardized by the poor quality of this precious resource. Watersheds are constantly subject to increasing threats such as over-exploitation of both surface and ground water, and rising levels of contamination from point and diffuse sources of pollution. In this context, it has become vitally important to develop and apply

1 new political and management strategies and methodologies aimed at reversing this trend
2 in water quantity and quality degradation.

3 The Water Framework Directive [10] [11] [12] is the core of the EU water
4 legislation. It provides the foundation for long-term sustainable water management by
5 taking due account of environmental, economic and social considerations. The main
6 objective of the WFD is to achieve “Good Ecological Status” (GES) for all European
7 Water Bodies (WB) by the end of 2015. A Program of Measures (PoM) must be selected
8 for each WB in order to reduce and/or eliminate current threats and, therefore, achieving
9 GES by 2015. However, it is not mentioned how these combinations of measures should
10 be selected in order to achieve cost-effective robust strategies against changes in the
11 environmental conditions.

12 Current state-of-the art of reclamation technologies [1] [21] can produce water of
13 any desired quality (including drinking quality). However, the quantity and quality of
14 water undergo changes over time, and the increasing number of efficient treatment
15 processes made the selection of an optimal strategy a difficult task for planners and
16 decision-makers. For each WB, there are millions of different combinations of
17 wastewater reclamation treatments (strategies) and, thus, in each location it is not clear
18 which is the adequate wastewater treatment technology or reutilization level.

19 An additional difficulty is due to the fact that the decision maker must
20 simultaneously consider treatment cost and water quality goals, that makes multiple
21 criteria analysis (MCA) a logical approach [16]. Moreover, the river flow and the quality
22 of water should be considered as random variables for each day, and Waste Water
23 Treatment Plants (WWTP) must be selected to operate over a long period of time (more
24 than 30 years of operation).

25 Water Quality Models (WQM) may quantify and simulate the effectiveness of PoMs
26 in increasing water quality and quantity. Even though WQMs themselves are useful for
27 evaluating single what-if scenarios and testing potential management alternatives, they
28 are unable to automatically solve the multi-criteria (cost, water quality, water availability)
29 optimization problems involving the selection of the best cost-effective PoM trade off.
30 Thus, linear programming [7] [22], non-linear programming [13] and integer
31 programming [2] have been used to solve the cost optimization river water quality
32 management model for regional wastewater treatment. Some approaches also consider
33 river flow as a random variable constructing a probabilistic water quality management
34 model [13]. Recently [8], Genetic Algorithms (GAs) were applied to solve the
35 optimization wastewater treatment problem. These approaches only consider one or two
36 water quality parameters or usually rely on optimizing a single objective function, which
37 may be an aggregation of quantitative and qualitative objectives in a single weighted
38 objective function, or by optimizing one of the objectives and using the remaining ones as
39 constraints. The main drawbacks are that significant information about trade-off
40 characteristics is lost and optimal decisions should be based on the general state of the
41 watershed with regard to contaminations, political strategies and the socio-economic
42 situation.

43 The non-linearity of the WQM, the integer character of the decision variables
44 (WWTP) and the five criteria simultaneously considered, makes Multi Objective
45 Evolutionary Algorithms (MOEA) methods to be more efficient than traditional
46 optimization methods to identity tradeoff among multiple objectives. In recent years,
47 (MOEA) [9] have been applied to obtain the Pareto trade-off optimal set of solutions for
48 watershed management multi-objective problems with very good results in a single
49 execution [18]. In all the above mentioned papers, the water quality parameters
50 considered were limited to the either dissolved oxygen (DO) or the biochemical oxygen
51 demand (BOD). In all these approaches a water quality model (WQM) was used to
52 simulate the spatial and temporal evolutions of contaminants.

53 Our methodological approach integrates the Qual2k [20] water quality model with a
54 MOEA considering cost and various quality criteria simultaneously, including, total
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nitrogen (TN), total ammonia (TA), total phosphorus (TP) and total organic carbon (TOC).

The inflows were, first, considered to be constant in each monthly model. Specifically, the median values of inflow with respect to several years of observations were taken. However, we need to take into account uncertainty in more detail, in our particular context of environmental change. In fact, the approach is not reliable in environmental design: a very negative impact on the ecosystem can be caused by a very low probability event. Many works have suggested not limiting to expectations as the only criterion for selecting decisions under risk, but considering several criteria that would more fully characterize the distribution of the indicators of interest, see [15]. In order to overcome all this difficulties and assist the management of water quality at catchment scale, an integrative methodological tool is proposed in this paper. The management methodology and tools developed has been applied in the inner Catalan catchment in order to achieve the WFD goals. This paper describes how to identify the global and local problems in each watershed, how the tool helps in the decision and negotiation process and how the PoM has been finally successfully selected.

2. Problem stage.

The European Directive [10] [11] [12] has the goal of protecting the environment from the adverse effects of waste water discharges. In response to this directive, the ACA (Catalan Water Agency) has developed an urban and industrial WWTP program that identified a number of suitable locations to build 670 WWTPs (with an estimated inversion cost of 800 M€) in order to reduce the impact of discharges on all Catalonian superficial WBs.

Nowadays there are a wide variety of WWTP technologies that provide different efficiency levels in the removal of water pollutants [21]. The problem is to decide, according to cost-effective idea, which is the most convenient type of WWTP at each location. For the PoM implementation analysis, ACA considers seven WWTP technologies types, which are described in table 1 in terms of their nutrient removal efficiency and cost. Then, in one river with a number n of WWTP possible locations, there are 7^n different PoM possible combinations (strategies). So for the Catalan basins the number of possible strategies varies between values around 10^{28} to 10^{183} (see table 2). It's not easy to select just a few effective strategies from all these possibilities

Table 1

Cost and nutrient removal efficiency of the WWTP technologies considered by ACA

Treatment Type	Nutrient Effic. Remov.				Cost	
	(%)				(€/m ³)	
	<i>ISS</i>	<i>NH₄</i>	<i>NO₃</i>	<i>P</i>	<i>Investment</i>	<i>Operation</i>
Primary	50	0	0	0	Fix (222)	-0.0001Q ^{0.115}
Secondary	90	30	0	0	2.758Q ^{-0.357}	4.645Q ^{-0.337}
Nitrification (60%)	95	60	0	0	3.172Q ^{-0.357}	5.342Q ^{-0.337}
Nitrif.–denitrif. 70%	95	70	70	0	3.447Q ^{-0.357}	5.342Q ^{-0.337}
Nitrif.–denitrif. 70% P removal	95	70	70	100	3.447Q ^{-0.357}	5.574Q ^{-0.337}
Nitrif.–denitrif. 85% P removal	95	85	85	100	4.137Q ^{-0.357}	5.574Q ^{-0.337}
Advanced	100	95	95	100	4.413Q ^{-0.357}	6.604Q ^{-0.337}

Q: capacity of WWTP in m³/day

Find the effective PoMs (strategies) is not only difficult for the large number of possible PoMs, but also because the comparison between one strategy and other depends on cost (investment and operational) and various water quantity and quality criteria simultaneously, including, total nitrogen (TN), total ammonia (TA), total phosphorus (TP), inorganic suspended solids (ISS) and total organic carbon (TOC). All these values are taken into account in the WFD and the solution involves finding the best tradeoff strategies in order to meet the WFD's objectives within a reasonable cost.

Water resources planning and management is a sub-field of natural resource management in which decisions are particularly amenable to multiple criteria analysis [23]. Decisions in water management are characterized by multiple objectives and multiple stakeholder groups. Decision maker are increasingly looking beyond conventional benefits cost analysis towards techniques of MCA that can handle a multi-objective decision environment [16].

Furthermore, final decision can't be taken only under the perspective of deterministic scenarios. Water quality and quantity status is subject to uncertainty and varies markedly throughout the year. The selected strategies should remain as close as possible to the efficient with respect to reasonable changes in the scenarios, due to uncertainty in factors such as climate or resources exploitation level.

2.1. Study area

The study area was all the internal Catalan watersheds (NE of Spain) whose main characteristics are described in Table 2. All there flows into the Mediterranean Sea.

For each inner Catalan catchment 12 monthly models was build and calibrated separately according to the real catchment (physical) characteristics and data set observed from year 2001 to 2008 at water quality control stations (see table 2). In each station measures of eight water quality parameters are available: dissolved oxygen (DO), suspended solids (SS), biochemical oxygen demand (BOD), chemical oxygen demand (OD), ammonium (TA), nitrogen(TN), total phosphorus(TP), total organic carbon TOC.

Table 2

Main characteristics of the inner Catalan river basin ordered from north (left) to south (right)

	Muga	Fluvia	Ter	Tordera	Besos	Llobregat	Foix	Gaia	Franco
A (km ²)	863	1008	2989	879	1029	5045	319	429	828
L(km)	67	104	212	59	52	163	45	67	60
P(mm ^{yr} ⁻¹)	807	859	828	770	643	675	573	563	575
Q(m ³ s ⁻¹)	3.3	9.4	17.1	7.2	6.8	19.3	0.3	0.3	1.1
QCS	13	9	25	14	18	49	5	3	9
WWTP	43	64	131	50	38	217	35	34	56
Strategies	10 ³⁶	10 ⁵⁴	10 ¹¹⁰	10 ⁴²	10 ³²	10 ¹⁸³	10 ²⁹	10 ²⁸	10 ⁴⁷
NQE	54	75	370	90	120	540	55	55	95

A: surface, L: Length, P: precipitation; Q: natural average annual inflow, QCS: number of quality control stations, WWTP: number of WWTP locations, NQE: number of elements in the Qualk model

3. Methodology

The approach proposed in this paper and applies to select the adequate PoM in order to meet the WFD in the inner Catalan catchments, combines a WQM, a mathematical

1 optimization model, Interactive Decision Maps (IDM), see [17], and a statistical
 2 simulation analysis. Since decisions concerning state and cost are made at a catchment
 3 level, a model for each basin was developed. The use of WQM makes it possible to
 4 estimate, among other factors, TN, TA, TP and TOC values in each river stretch. For each
 5 catchment scenarios these estimates provides information about each PoM performance.
 6 The WQM use in this study is QUAL2k. The mathematical optimization model
 7 developed is a Multi-Objective Evolutionary Algorithm (MOEA). The key idea is to
 8 minimize the investment and operation cost and maximizes the quality of the water
 9 resources. In a reasonably small number of WQM executions, the genetic algorithm
 10 provides hundreds of cost-efficiency PoM, which delimitate the non-dominated Pareto
 11 frontier of each basin. On this stage we apply IDM – a multiobjective tool that helps the
 12 decision maker to visually screen almost all alternatives retaining a few ones for a
 13 detailed study. Finally, for some of the strategies, chosen with IDM, we use a simulation
 14 model to analyze the sensitivity of each strategy to changes in the input variables of the
 15 WQM.
 16

17 3.1. Water Quality Model

18 Water Quality Models (WQM) seek to describe the spatial and temporal evolution of
 19 contaminants and constituents characterizing a river flow. Many highly reliable
 20 simulation models are available today for estimating the behavior of physical systems
 21 such as water bodies, with reasonable computational requirements [24] [26]. According to
 22 these references, one of the most popular river and stream water quality models are
 23 Qual2e [4]. We chose Qual2kw [20] as the WQM for this application because is a
 24 modernized version of the Qual2e model and it is easily embedded in the optimization
 25 algorithm.
 26

27 In order to apply the Qual2k model to a river network, the river system must be
 28 divided by river elements, which have roughly uniform hydraulic characteristics. In each
 29 river cell, the model computes the major interactions between up to 16 state variables and
 30 their value for steady state and dynamic conditions. The entire internal Catalan river
 31 channel was modeled and specifications about it can be seen in table 2.
 32

33 A range of inputs are used in the water quality models, including topography,
 34 climate and anthropic pressures predicted for the year 2015, the year in which the Water
 35 Framework Directive's objectives take effect. All the monthly models were created with
 36 the monthly median values forecasted for the year 2015.
 37

38 3.2. Optimization Model

39 If a scenario involves an arbitrary optimization problem with M objectives, all of
 40 which to be maximized and equally important, a general multi-objective problem can be
 41 formulated as follows:
 42

$$\begin{aligned}
 & \text{maximize } f_m(x), \quad m=1,2,\dots,M \\
 & \text{subject to: } g_j(x) \geq 0, \quad j=1,2,\dots,J \\
 & \quad \quad \quad h_k(x) = 0, \quad k=1,2,\dots,K \\
 & \quad \quad \quad x_i^{(L)} \leq x_i \leq x_i^{(U)} \quad i=1,2,\dots,n
 \end{aligned} \tag{1}$$

43 where x is a vector of n decision variables: $x = (x_1, x_2, \dots, x_n)^T$. In this case, a Pareto
 44 optimal objective vector $f^* = (f_1^*, f_2^*, \dots, f_M^*)$ is such that it does not exist any feasible
 45 solution x' , and corresponding objective vector
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$f' = (f_1', f_2', \dots, f_M') = (f_1(x'), f_2(x'), \dots, f_M(x'))$ such that $f_m^* \leq f_m'$ for each $m = 1, 2, \dots, M$ and $f_j^* < f_j'$ for at least one $1 \leq j \leq M$.

In our case, the vector x contains the waste water treatment alternatives, which correspond to each WWTP (strategies), which are planned to be constructed in the region. We use five objectives to reflect the trade-off between minimizing the total annual cost of the implemented WWTP and maximizing water quality.

$$F = [f_1, f_2, f_3, f_4, f_5] \quad (2)$$

$$\text{Min } f_1 = \sum_{N_{\text{mont}}=1}^{12} \left[\sum_{N_{\text{wwtp}}=1}^{N_{\text{umWWTP}}} (ICost_{N_{\text{wwtp}}} + OCos_{N_{\text{wwtp}}}) \right] \quad (3)$$

$$\text{Max } f_k = \text{WaterQuality}_{\text{constituent } k} \quad (4)$$

where:

- $ICost_{N_{\text{wwtp}}} = f(Q_D, X_T)$: is the investment needed to build a WWTP (monthly cost with a 15-year payback period). This cost is a function of the design flow (Q_D) and the type of treatment technology applied (X_T), see Table 1.
- $OCos_{N_{\text{wwtp}}} = f(Q_P, X_T)$: is the monthly operating cost. This cost is a function of the amount of water treated in one month (Q_P) and the type of treatment technology applied (X_T), see Table 1.
- $\text{WaterQuality}_{NH_4}$, $\text{WaterQuality}_{NO_3}$, $\text{WaterQuality}_{PO_4}$ and $\text{WaterQuality}_{TOC}$ are the respective concentrations [mg/l] of TA, TN, TP, and TOC in the river water.

To assess the quality of water in a basin over a year it is necessary to define a quality function (metric), e.g. as shown in equation (5). This quality function has two different approaches, depending on whether it is measuring the achievement of the good ecological status or its failure. Positive values of the metric mean that the WFD objectives are reached every month and for every basin stretch. A negative value means that the WFD objectives are exceeded for at least one reach and one month.

$$f_k = \begin{cases} \frac{\sum_{i=1}^{nm} \sum_{j=1}^{nr} (LDM_{ij}^k - VI_{ij}^k) / LDM_{ij}^k}{nm \bullet nr} & \text{if the WFD levels are met} \\ \frac{\sum_{i=1}^{nmi} \sum_{j=1}^{nri} (LDM_{ij}^k - VI_{ij}^k) / LDM_{ij}^k}{nm \bullet nr}, & \text{otherwise} \end{cases} \quad (5)$$

where:

$k, 2 \leq k \leq 5$: contaminant index,

nm : number of months,

nr : number of reaches,

nmi : number of months that exceed the WFD limits,

nri : number of reaches that exceed the WFD limits,

LDM_{ij}^k : concentration limit of the contaminant "k" in stretch "j" and month "i", allowed by the WFD's goal,

VI_{ij}^k : concentration of the contaminant "k" in stretch "j" and month "i"

1 Other metrics are possible and have been analyzed [3], but just consider it more
2 appropriate to describe as the reference for quality are the limits proposed by the WFD.

3 The decision variables in this problem are the “ X_T ”, the treatment technology to be
4 applied at each WWTP. A discrete value with possibilities can be assigned to each
5 variable. In some cases, according to the physical-chemical characteristics of the
6 stretches, a constraint for the minimum wastewater treatment technology could be added.
7 The mathematical formulation of that constraint is the following:

$$8 \quad X_T > X_{\min} \quad \forall T \quad X_T \in \{1, \dots, 7\} \quad (6)$$

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11 We apply a MOEA optimizer, capable to mitigate the limitations of standard Multi
12 Criteria Decision Making methods [25] which provides the Pareto cost-efficient PoMs
13 (efficient strategies) set. In many multi-objective optimization problems, knowledge
14 about this set helps the decision maker to choose the best alternative. The multi-objective
15 simultaneous analysis of the global influence of all the WWTP is one of the main
16 advantages of the proposal methodology over other approaches that make individual cost-
17 effectiveness analyses of each WWTP.

18
19 In the MOEA, each state of the system (strategy) of concern of each possible
20 solution of a mathematical problem is represented by a string of genetic factors called
21 chromosomes [14]. A set of chromosomes makes up a generation. The generation evolves
22 through the genetic operations called selection, crossover and mutation. Also introduces
23 elitism by maintaining an external population (set of chromosomes) that preserve the best
24 solutions found so far and incorporate part of the information in the main population by
25 means of the crossover. In each generation, the new solutions, belonging to the internal
26 population, are copied to the external when they are not Pareto dominated by any solution
27 of this external population. If solutions of the external population are dominated by some
28 of the new solutions, these solutions are deleted from the external population. The
29 external elitist population is simultaneously maintained in order to preserve the best
30 solutions found so far and to incorporate part of the information in the main population by
31 means of the crossover. In this recombination process selecting each of the parents
32 through a fight (tournament), between two randomly-selected chromosomes from the
33 external Pareto set (according to a density criterion) or from the population set (according
34 to ranking determined through a dominance criterion) [27].

35
36 Our MOEA model, applies binary Gray encoding for each chromosome
37 (optimization string), that is decoded into the treatment level at the WWTP it represents,
38 and then with the treatment level, the water quality is forecasted by the Qual2k model.
39 We evaluate the fitness value of the chromosome from the results of the forecasts of
40 water quality and treatment cost. The fitness value of the quality objectives is evaluated
41 by ec. 5.

42 3.3. Screening stage

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44 As we usually consider more than two criteria, a special technique is used to study
45 the trade-off between them, consisted of hundreds of alternatives that compose the
46 approximation of Pareto frontier. We use IDM that permits to visualize simultaneously
47 trade-offs for up to 7 criteria, see [17]. IDM has been extensively used in water
48 management issues [5] [6].

49
50 The information on the Pareto frontier displayed by the IDM technique simplifies the
51 decision maker’s job. Each stakeholder easily identifies on a decision map his region of
52 interest (according to his preferences), by simple click of the computer mouse. This pre-
53 selects some alternatives which are subject to more accurate analysis involving robustness
54 analysis. That is, from this pre-selection made on deterministic basis, we realize the
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1 simulation in order to check if the corresponding strategies (sets of WWTP) are robust
2 decisions, that is, remain efficient under changeable environmental conditions.
3

4 **3.4. Simulation Model**

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6 Water quality models are generally deployed in such cases to provide insight on
7 source assessments and their impacts on water quality targets as well as the consequences
8 of varied management scenarios (e.g. [19]).
9

10 However, the different parameters, such as quantity and quality of waste treatment
11 discharges, irrigation return flows and urban runoff, that characterize regional water
12 quality, are probabilistic in nature. Thus the attainment of managerial goals will
13 inherently exhibit the characteristic of uncertainty.
14

15 Stochastic models attempt to mitigate these issues to some degree by representing
16 modeled phenomena as a distribution of possible outcomes. A common implementation is
17 to perturb input parameter, for example, through the use of Monte Carlo simulations, and
18 assess likely outcomes from the results.
19

20 With the information available on each basin, the correlation between different
21 climatic variables, such as precipitation in the nearby measurement stations, variable
22 flows and water quality data was analyzed in order to define adequately the dependencies
23 between these variables. An independent random variable for each month was then
24 generated, such that all input variables concerning the flows in watersheds, as well as
25 several such as extraction for irrigation, are dependent from this random variable. The
26 other random variables for the simulation are the concentrations of contaminants in
27 industrial and municipal discharges.
28

29 We construct a simulation model in order to govern each of the monthly Qual2k
30 watershed models and in which is fixed the type of WWTP, and execute several
31 thousands times in order to analyze statistically the results for each of the criteria.
32

33 **4. Results**

34

35 After each basin was calibrated and validated, it was integrated into the MOEA,
36 which had previously been developed and tested. In a reasonably small number of WQM
37 executions, ranging from 6,000 to the 10,000 depending on the watershed characteristics
38 and the number of WWTP [27], MOEA provides an approximation of the Pareto frontier
39 of each basin. When 5 criteria (cost, TA, TN, TP and TOC) are simultaneously under
40 consideration, the number of efficient strategies provided by MOEA is quite high (several
41 hundred).
42

43 This is the fundamental information upon which the stakeholder will base the
44 decision process, but to have to examine such large quantities of raw data would turn the
45 decision process into a certain failure. Figure 1 shows an IDM example that visualises the
46 Edgewort-Pareto Hull, $H(Y)$, for three criteria, i.e. the tradeoff between the cost, TA, TP,
47 contaminants for the Llobregat watershed. The contaminant criteria are assigned to the
48 axes of the map, whereas the cost criterion is assigned to the grey scale. The total scale of
49 the cost criterion is divided into several half-open intervals of equal length. The slices of
50 $H(Y)$ in the plane of the axis criteria for the values of the third criterion corresponding to
51 the endpoints of the intervals are superimposed on a single screen; each slice is a specific
52 color; the legend on the right of Figure 1 matches the color of each slide to the end point
53 for the interval this slice was computed for. Note that a slice corresponding to a worse
54 value for this criterion encloses the slice corresponding to a better value. This guarantees
55 that non-dominated frontiers for these slices never intersect, even though they might
56 touch. The values for the rest of quality criteria: TN and TOC, are set to their lower
57 positions.
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In some cases, it may be useful to omit some data that is irrelevant to the decision-making information, namely, the precise shape of the tradeoff curves between the two quality criteria: TA and TP, considering a decision map with “smoothed” tradeoff curves, see Figure 2. Technically, this is achieved by approximating the convex hull of $H(Y)$, see [17]. The removal of “noisy” information on the tradeoff curves helps the decision maker to concentrate on the essential interdependences between the different criteria.

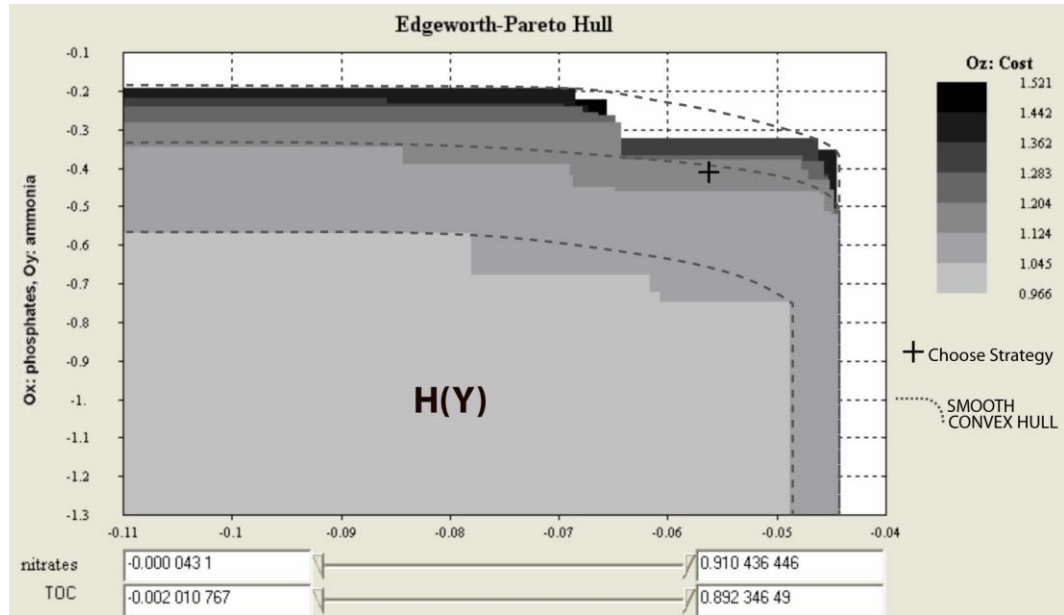


Fig 1: Example of simple EPH decision map with the corresponding smoothed convex hull.

† Choose strategy.

Therefore, exploration of the Pareto frontier by means of the IDM map (fig 1) helps to understand the criterion tradeoffs and to identify a preferred criterion point directly at the Pareto frontier. Also by means of the Pareto front visualisation, e.g. (fig 1) observe that even for the most intensive sewage PoM, it is impossible to satisfactorily achieve the WFD’s objective for all the criteria.

Furthermore, the slope of these criteria quality curves (or the Pareto front curves) for each cost level indicates the water quality sensitivity to the water treatment actions. It shows the cost increase required to achieve a unitary water quality improvement for each strategy.

Qualitatively, three regions of interest can be identified in the Pareto front. In this paper, these regions are named: economic, balanced and environmental. The first is the region where the PoM are inexpensive and implements purification treatments that are less intense on average. The "environmental," implements fairly intensive purification treatment and is quite expensive, and the “balanced region” which would be fall in the range between the two.

For example, in the Besos basin, where the MOEA provides a Pareto front of approximately 500 strategies, Table 3 shows the representative values of these three areas, and another two located in the most economical and most expensive regions (all the WWTP are of the “advanced” type).

Table 3

Example of the five decision regions, characteristics strategies points, order from most economical to most costly for the Besos basin

Regions of compromise	Cost (M€/month)	TA	TN	TP	TOC
Cheapest	0,397	-0,9976	-0,0007	-0,0031	0,8064
Economic	0,528	-0,6018	-0,0007	0,9338	0,8040
Balanced	0,630	-0,3225	0,7956	0,9356	0,8057
Environmental	0,699	-0,2655	0,7938	0,9355	0,8076
Expensive	0,871	-0,2318	0,7983	0,9391	0,8852

Table 3 shows the cost and quality results of five strategies of the Pareto set obtained, considering 5 objectives for the Besos basin. For each one of the five PoM (strategies) selected, the WQM execution provides different outputs for each parameter and river stretch. The quality values showed in table 2 are the result of these outputs evaluated by means of the metric proposed in ec.(5). Each one of these strategies represent one of the five regions of interest.

While TOC is not affected by investment variations in wastewater treatments, the other quality indicator improves in a different way with the water treatment levels of investments. The average quality of phosphate becomes very good from small investments and, with regard to nitrates, the small breaches in the WFD disappear with intermediate investment. For the TA the investment produces significant improvements, but fails to achieve compliance with the WFD goals, even with the most expensive treatment. The “expensive” alternative region is 24% more expensive than the “environmental” one and 38% more than the “balanced” strategies region, with improvement in TN, TP and TOC negligible and in TA between 13% and 29 %, but it never reaches the WFD goal. The “balanced” strategies regions are, on average, 19% more costly than the “economic” ones, but manages to clearly eliminate the problems of TN in the basin and reduce the average ammonia concentration in a 47%.

So far, however, the decision process has been conducted under a deterministic point of view. The next methodological step is to carry out an uncertainty analysis for each of these five previously selected regions of interest. By running the simulation model tool, it is possible to determine the statistical distribution of each PoM strategy under probabilistic daily environmental and social conditions.

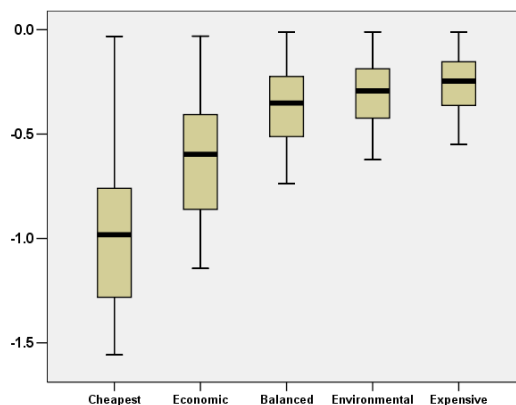


Fig 2: Example of the TA quality metric (ec.5) statistical distribution for the five previously selected WWTP strategies.

Figure 2 compares the TA output probability distribution box plot for the 5 strategies that had been previously selected. It is noted that as the strategies become more intense, improvement is made in the average TA water quality. You can also see how the probability distribution becomes denser with the intensification of the water treatment, so that there is less difference in the quality of the water between the worst and the best scenario.

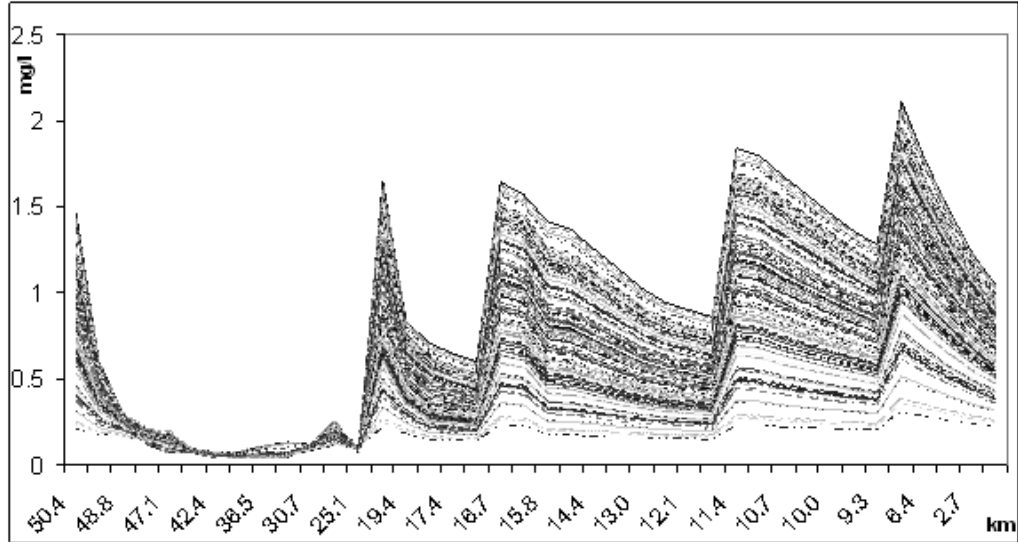


Fig 3: 2D TN concentration statistical distribution along Besos main channel for the balanced strategy. The WFD limit in TA in this stretches is 0,5

Figure 3 shows the Besos main channel spatial distribution of the TA quality probability distribution for the “balanced” strategy. There are no significant pollution problems in the first 25 km of river segment. However, for the last 25 km, it shows that non compliance to the TA WFD limits is very probable in at least 4 stretches. The stakeholder examines the five TA spatial statistical distributions (for the rest of the criteria as well), and also compares the extreme values (that is, the values that would not occur in 95% of cases, etc), see figure 4.

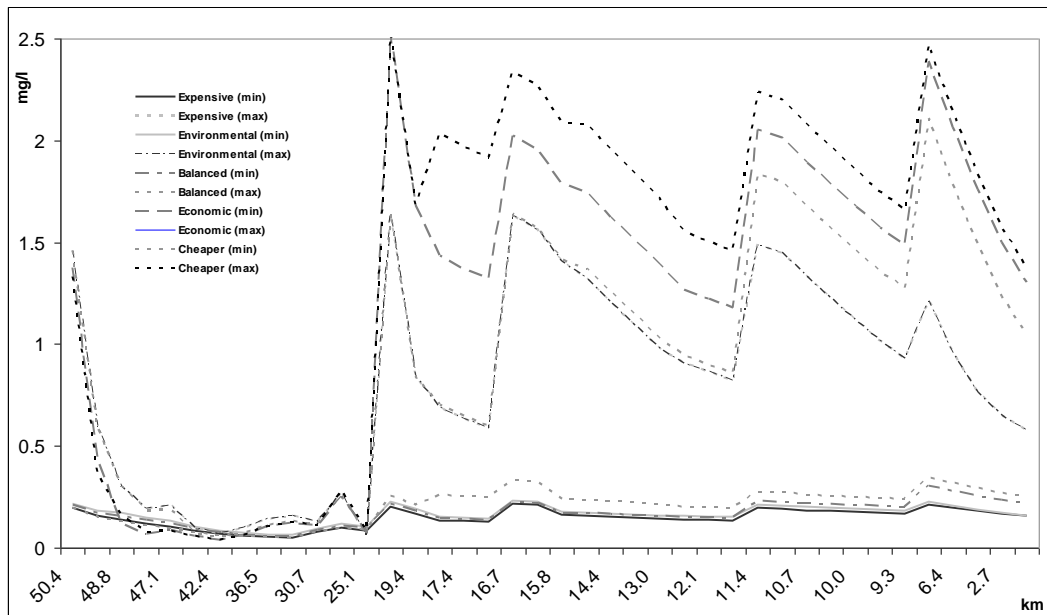


Fig 4: 2D TN concentration statistical extreme probability distribution values along Besos main channel

Given that for all sections shown in Figures 3 and 4 the WFD limits for ammonia is 0,5 in the best possible environmental and social situation, the objectives were achieved in all sections. However the total compliance is relatively unlikely; it will depend on the level of investment in purification and the probability that the limits allowed by the WFD will be violated, which vary significantly. With the help of all these analyses, the stakeholders go through to the next decision phase in which they usually reach an agreement on a single region of interest in which the PoM that will finally be implemented in the watershed is located.

We also apply the IDM to obtain neighboring strategies to the final region selected for the second step. In Figure 1, the goal point designated by the black cross seems to be reasonable enough from the point of view of the tradeoff between the pivotal criteria: phosphates and ammonium. The alternatives located near the goal (fig 1) are listed on Table 4. These alternatives are either subject to more careful analysis, or can be filtered by another technique, possibly through “eye filtering.” Whatever the case, IDM helps to discard most of alternatives and to select several that do not differ greatly on criteria values with respect to the goal.

Table 4

Characteristics of the neighborhoods strategies of the chosen strategy obtained using IDM tool for the Llobregat basin (figure 1)

	Cost	Ammonia	Nitrates	Phosphates	TOC
Your Aspiration	1,2	-0,305	0,9	-0,06	0,88
Nearest Points					
P1	1,1628	-0,5271	0,8999	-0,0582	0,8768
P2	1,1967	-0,2816	0,9066	-0,0642	0,8857
P3	1,2001	-0,4028	0,9032	-0,0469	0,8766
P4	1,2213	-0,5049	0,8937	-0,0581	0,8781
P5	1,3303	-0,3666	0,9021	-0,0472	0,8789
P6	1,3766	-0,3510	0,9057	-0,0443	0,8790

5. Conclusions

This paper presents a new multi-criteria, decision support system for water resources to find the tradeoff solution from conflicting objectives in the context of the way in which the WFD is being implemented in Catalonia

Particularly, an integrative optimization and simulation methodology has been proposed to select the most efficient and robust PoMs to reduce the pressures and associated impacts in order to achieve the WFD’s objectives.

The methodology tool presented in this paper is an effective combination of a WQM, a MOEA, simulation models and a screening Pareto frontiers tool. Qual2k is the WQM that estimates monthly runoff and pollutant loads in the catchments. The MOEA is a multi-criteria genetic algorithm, specially designed and configured to find the efficient tradeoff between restoration cost and water quality criteria. The screening tool helps the decision makers to assess local problems in each basin, and to negotiate and perform more suitable selections. The simulation model performs a probabilistic study of the sensibility of each select efficient strategy to the real, daily conditions of uncertainty (environmental, social). The case study (inner Catalan basins) has been carried out taking into account the wastewater systems. This then translates into seven different cleaning technology alternatives, which also were modeled in terms of both cost and treatment for

1 each pollutant. Thus, in addition to the cost criteria (operating and investment cost), four
2 quality criteria were considered simultaneously: TA, TN, TP and TOC. The non linearity
3 of the WQM, the integer character of the decision variables (WWTP) and the five criteria
4 simultaneously considered, makes MOEA methods more efficient than traditional
5 optimization methods to identify tradeoffs among multiple objectives. A major difficulty
6 in applying the MOEA methods lies in identifying the appropriate parameter settings to
7 ensure that the decision space for the problem is effectively explored and the entire
8 tradeoff curve is identified.

9 This methodology has been shown to be an important resource in evaluating the
10 effectiveness of the actions which are being taken to improve water quality. It provides
11 decision-makers with the opportunity to explore the multi-objective nature of problems,
12 and to discover tradeoffs amongst objectives, which enables them to make decisions
13 given alternative solutions and to achieve PoM management outcomes for the future.

14 The methodology and tools developed have successfully identified the problems in
15 each watershed, both globally and locally, for each one of the criteria considered by the
16 WFD. They also consider the uncertainties of climate and social variables. This tool has
17 been a key to designing part of the PoM which will be implemented to achieve the WFD
18 objectives by 2015. The PoM has been recently approved by the board of directors for the
19 Catalan water authority. It will be endorsed by the Catalan government together with the
20 River Basin Management Plan of Catalonia in the near future. After this phase, the PoM
21 will be implemented in the territory using (among others), the indications and conclusions
22 obtained by the tool that has been analysed in this paper.

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