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Angel Udias, Roman Efremov, Lorenzo Galbiati, Giuliana Coscera and Gisella Ghiang

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Robust multi criteria wastewater treatment alternative selection - a case study

Angel Udías Moinelo
DEIO, Universidad Rey Juan Carlos, Móstoles (Madrid), Spain, angelluis.udias@urjc.es

Roman Efremov
DEIO, Universidad Rey Juan Carlos, Móstoles (Madrid), Spain, roman.efremov@urjc.es

Lorenzo Galbiati
Agència Catalana de l'Aigua. C. Provença 204, Barcelona, lgalbiati@gencat.cat

Giuliana Coscera
AudingIntraesa S.A., Esplugues de Llobregat, Barcelona, gcoscera@audingintraesa.com

Gisella Ghiang
AudingIntraesa S.A., Esplugues de Llobregat, Barcelona, gchiang@audingintraesa.com

ABSTRACT. This paper presents a methodology to select optimal robust wastewater reclamation and reuse treatment strategies to achieve the European Water Framework Directive (WFD) objectives in the inner Catalonia watersheds. Current state-of-the art of reclamation technologies can produce water of any desired quality (including drinking quality). However, the quantity and quality of water undergo changes over time, and the increasing number of efficient treatment processes made the selection of an optimal treatment a difficult task for planners and decision-makers. In our study, a Robust Multi-Criteria Decision Support Strategy for Watershed Restoration was developed through the integration of a multi objective genetic algorithm, a water quality model (Qual2k), a multicriteria decision aid method and statistical model for simulation of unfavorable scenarios. This Decision Support System was applied to the internal Catalonia watersheds. In this paper we present some results for the Besos watershed. This study shows that our multi objective genetic algorithm can be particularly useful in wastewater reclamation and reuse as it can provide assistance in the evaluation and selection of water treatment alternatives. The multicriteria approach has also the advantage of providing the stakeholders a clear idea of the trade-off between water status and the cost to achieve such situation.

KEYWORDS. European Water Framework Directive; Wastewater reclamation; Uncertain water quantity and quality; Multicriteria genetic algorithm; Robust treatment plant selection.

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

The Water Framework Directive (2000/60/EC, WFD) is the core of the EU water legislation. It provides the foundation for long-term sustainable water management by taking due account of environmental, economic and social considerations. The main objective of the WFD is to achieve "Good Ecological Status" (GES) for all European Water Bodies (WB) by the end of 2015. A Program of Measures (PoM) must be selected for each WB in order to reduce and/or eliminate current threats and, therefore, achieving GES by 2015. However, it is not mentioned how these combinations of measures should be selected in order to achieve cost-effective robust strategies against changes in the environmental conditions. For each WB, there are millions of different combinations of wastewater reclamation and reuse treatments (strategies) and, thus, in each location it is not clear which is the adequate wastewater treatment technology or reutilization level.

An additional difficulty is that the decision maker must simultaneously consider treatment cost and water quality goals. Moreover, the river flow and the quality of water should be considered as random variables that change for each month and year, and Waste Water Treatment Plants (WWTP) must be selected to operate over a long period of time (more than 30 years of operation).

Mathematical programming methods such as linear programming, integer programming, non linear programming or dynamic programming have been used to solve the cost optimization problem for regional wastewater treatment (Asano et al., 1996), (Cai et al., 2001). Some approaches also consider river flow as a random variable constructing a probabilistic water quality management model (Fujiwara et al., 1987). Recently (Cho et al., 2004), Genetic Algorithms (GAs) were applied to solve the optimization wastewater treatment problem. These approaches usually relies on optimizing a single objective function, which may be an aggregation of quantitative and qualitative objectives in a single weighted objective function, or by optimizing one of the objectives and using the remaining ones as constraints. The main drawbacks of this approach are that significant information about trade-off characteristics is lost. In recent years, Multi Objective Evolutionary Algorithms (MOEA) (Deb, 2001) have been applied to obtain the Pareto trade-off optimal set of solutions for watershed management multi-objective problems with very good results in a single execution (Muleta and Nicklow, 2005). In all the above mentioned papers, the water quality parameters considered were limited to the either dissolved oxygen (DO) or the biochemical oxygen demand (BOD). In all these approaches a water quality model (WQM) was used to simulate the spatial and temporal evolutions of contaminants. We used Qual2k (Brown and Barnwell, 1987) in our study.

In (Udías et al., 2009) a Multi Objective System of Efficient Strategy Selection (MOSESS) was developed, which is a tool for generating the set of Pareto-optimal strategies, that is, the best cost-efficient combinations of WWTP and water reuse. MOSESS integrates the Qual2k water quality model with a MOEA considering cost and various water quantity and quality criteria simultaneously, including, total nitrogen (TN), total ammonia (TA), total phosphorus (TP) and total organic carbon (TOC). The inflows were 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, e.g. (Haimes, 1998). This paper shows how MOSESS can be applied to consider several scenarios of lateral inflows and selecting a robust solution in order to achieve the WFD's objectives. The management model has been applied to the internal Catalan basins. In this paper we focus on the case study of the Besos basin.

Table 1. WWTP technologies considered by ACA (Q: capacity of WWTP in m^3/day)

Treatment Type	***Nutrient Effic. Remov. (%)***				***Cost (€/m³)***	
	ISS	***NH_4***	***NO_3***	***P***	***Construct.***	***O&M***
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	$3.172Q^{-0.357}$	$5.342Q^{-0.337}$
Nitrification–denitrification 70%	95	70	70	0	$3.447Q^{-0.357}$	$5.342Q^{-0.337}$
Nitrification–denitrification 70% P removal	95	70	70	100	$3.447Q^{-0.357}$	$5.574Q^{-0.337}$
Nitrification–denitrification 85% P removal	95	85	85	100	$4.137Q^{-0.357}$	$5.574Q^{-0.337}$
Advanced	100	95	95	100	$4.413Q^{-0.357}$	$6.604Q^{-0.337}$

2. PROBLEM STAGE.

The European Directive 91/271/EEC 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 1,300 WWTPs in order to reduce the impact of discharges on all Catalonian superficial WBs. As an example for the Besos basin, the ACA is planning to build 38 WWTPs and to reuse treated water at 8 possible locations. Note that each plant may be selected from 7 different wastewater treatment technologies (Table 1) and it must be decided whether or not it is optimal to implement each reutilization. The total number of strategies for the Besos basin is $7^{38}*2^{8}$.

The solution involves finding the ‘best’ strategy in order to meet the WFD’s objectives within a reasonable cost. This strategy should be robust, i.e. its consequences should not change drastically with respect to reasonable changes in the scenarios, due to uncertainty in factors such as climate or resources exploitation level.

2.1. Study area

Even though the methodology was applied to the internal Catalan watersheds, most of the results presented in this paper correspond only to its application at the Besos basin. Besos basin is located in Catalonia, in the North-East of Spain, it covers a surface of 1020 Km^2 and it has a natural annual average inflow of 3.5 hm^3. Its homonymous river has a main channel of 50,7 km and discharges into the Mediterranean Sea.

Twelve monthly models were run using monthly data from year 2000 to 2008 at eight water quality control points (Aiguafreda, Castellar del Vallès, La Garriga, Llica de Vall, Montcada I Reixac, Montornès, del Valles, Santa Coloma de Gramanet, Santa Perpètua de Mongoda). The seven water quality parameters measured by ACA at these points are: TA, TN, TP, TOC, DO, suspended solids (SS) and BOD.

3. METHODOLOGY REVIEW

3.1 Water Quality Model

Water Quality Models (WQM) seek to describe the spatial and temporal evolution of contaminants and constituents characterizing a river flow. Many highly reliable simulation models are available today for estimating the behavior of physical systems such as water bodies, with reasonable computational requirements. We chose Qual2k (Pelletier and Chapra, 2004) as the WQM for this application.

In order to apply the Qual2k model to a river network, the river system must be divided by river elements, which have roughly uniform hydraulic characteristics. In each river cell, the model computes the major interactions between up to 16 state variables and their value for steady state and dynamic conditions.

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

3.2 Optimization Model

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

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

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

$$F = [f_1, f_2, f_3\ f_4, f_5] \tag{2}$$

$$Min\ f_1 = \sum_{Nmont=1}^{12} \left[\sum_{Nwwtp=1}^{NumWWTP} \left(ICost_{Nwwtp} + OCost_{Nwwtp} \right) \right] \tag{3}$$

$$Max\ f_k = WaterQuality_{constituen\,k} \tag{4}$$

where:

- $ICost_{Nwwtp} = f(Q_D, X_T)$: 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.
- $OCost_{Nwwtp} = f(Q_P, X_T)$: 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.
- $WaterQuality_{NH_4}$, $WaterQuality_{NO_3}$, $WaterQuality_{PO_4}$ and $WaterQuality_{TOC}$ 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.

$$f_k = \begin{cases} \dfrac{\sum_{i=1}^{nm}\sum_{j=1}^{nr}(LDM_{ij}^k - VI_{ij}^k)/LDM_{ij}^k}{nm \bullet nr} & if\ the\ WFD\ levels\ are\ met\ for\ every\ reach\ and\ month \\ -\dfrac{\sum_{i=1}^{nmi}\sum_{j=1}^{nri}(LDM_{ij}^k - VI_{ij}^k)/LDM_{ij}^k}{nm \bullet nr}, & otherwise \end{cases} \tag{5}$$

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"*. Other metrics are possible and have been analyzed (Boon *et al.*, 1997), but we just consider it more appropriate reference for the quality limits proposed by the WFD.

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

$$\boldsymbol{X_T} > \boldsymbol{X}_{\min} \quad \forall \boldsymbol{T} \qquad \boldsymbol{X_T} \in \{1, \cdots, 7\} \tag{6}$$

We developed a Multi Objective System for Efficient Strategy Selection (MOSESS) which provides the Pareto efficient Program of Measures strategies set. It is based on the Multi Objective Evolutionary Algorithm (MOEA) which applies binary Gray encoding (Goldberg, 1989) for each chromosome (optimization string) corresponding to a specific set of WWTP and reutilization. The length of each optimization string corresponds to a total number of genes, one for each facility. Each gene uses 3 bits to encode the 7 sewage treatment levels of WWTP decision variables and 1 bit to encode the reutilization decision variables. For example, in the Besos watershed, with 38 possible WWTP and 8 reutilization locations, the number of genes is 38+8 and the chromosome length is 38x3+8 = 122 bits. Each chromosome represents one of the $7^{38}*2^{8} \approx 3.3 \times 10^{34}$ different strategies, as noted above. The MOSESS algorithm (see Figure 1) applies the usual GA procedures of selection, crossover and mutation to generate the new population. Also introduces elitism by maintaining an external population that preserve the best solutions found so far and incorporate part of the information in the main population by means of the crossover. In each generation, the new solutions, belonging to the internal population, are copied to the external when they are not Pareto dominated by any solution of this external population. If solutions of the external population are dominated by some of the new solutions, these solutions are deleted from the external population. The external elitist population is simultaneously maintained in order to preserve the best solutions found so far and to incorporate part of the information in the main population by means of the crossover In this recombination process selecting each of the parents through a fight (tournament), between two randomly-selected chromosomes from the external Pareto set (according to a density criterion) or from the population set (according to ranking determined through a dominance criterion) (Udías, 2009).

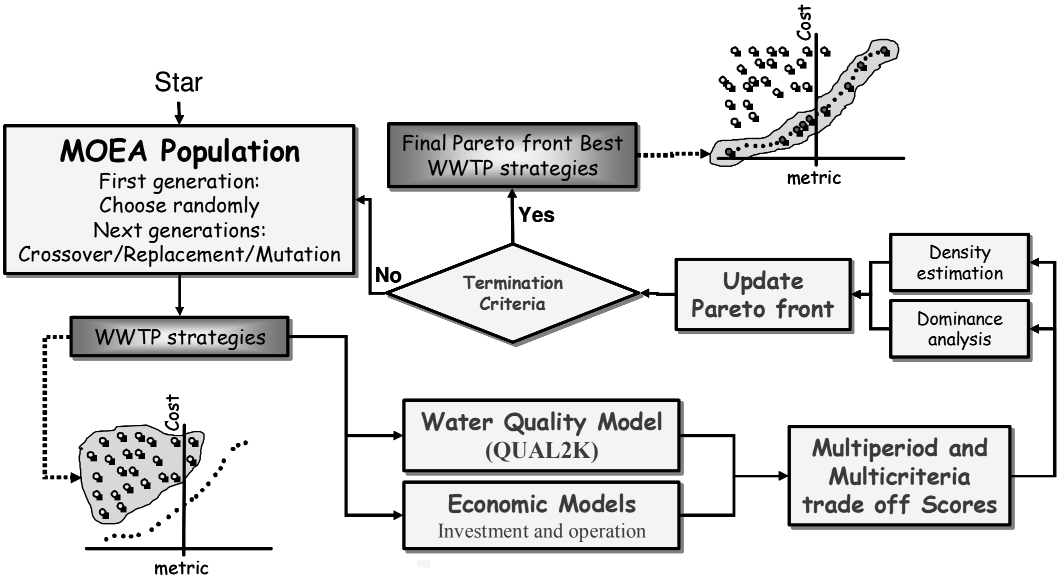

Figure 1: MOSESS algorithm scheme

The MOSESS algorithm shows good convergence to the Pareto front with only 6,000 evaluations of the WQM. The best convergence is achieved with 10 points crossover operator, low size population (10 chromosomes each generation), mutation rate of 0.5%. Without elitism the algorithm does not reach the same convergence as with elitism, even with more than 1,000 evaluations of the WQM. The number of criteria also reduces the convergence process. With five criteria it takes approximately twice number of evaluations than considering only two criteria in the optimization process.

3.3 Screening stage

As we usually consider more than two criteria, a special technique is used to study the trade-off between them, consisted of hundreds of alternatives that compose the approximation of Pareto frontier. We use IDM that permits to visualize simultaneously trade-offs for up to 7 criteria, see (Lotov et al., 2004). IDM has been extensively used in water management issues (Bourmistrova et al., 2002, 2005).

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

3.4 Simulation Model

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

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

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

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

4. RESULTS AND DISCUSSION

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

This is the fundamental information upon which the stakeholder will base the decision process, but to have to examine such a large quantity of raw data would result practically imposible without a special tool. Figure 2 shows an IDM example that visualises the Edgewort-Pareto Hull, H(Y), for three criteria, i.e. the tradeoff between the cost, TA, TP, contaminants for the Llobregat watershed. The contaminant criteria are assigned to the axes of the map, whereas the cost criterion is assigned to the grey scale. The total scale of the cost criterion is divided into several half-open intervals of equal length. The slices of H(Y) in the plane of the axis criteria for the values of the third criterion corresponding to the endpoints of the intervals are superimposed on a single screen; each slice is a specific color; the legend on the right of Figure 2 matches the color of each slide to the end point for the interval this slice was computed for. Note that a slice corresponding to a worse value for this criterion encloses the slice corresponding to a better value. This guarantees that non-dominated frontiers for these slices never intersect, even though they might touch. The decision map is visualized for the case when now limits are imposed on the rest of quality criteria: TN and TOC.

In some cases, omitting some data that may be irrelevant for the decision-making is as useful approach. Namely we disregard 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 (Lotov et al., 2004). The removal of “noisy” information on the tradeoff curves helps the decision maker to concentrate on the essential interdependences between the different criteria.

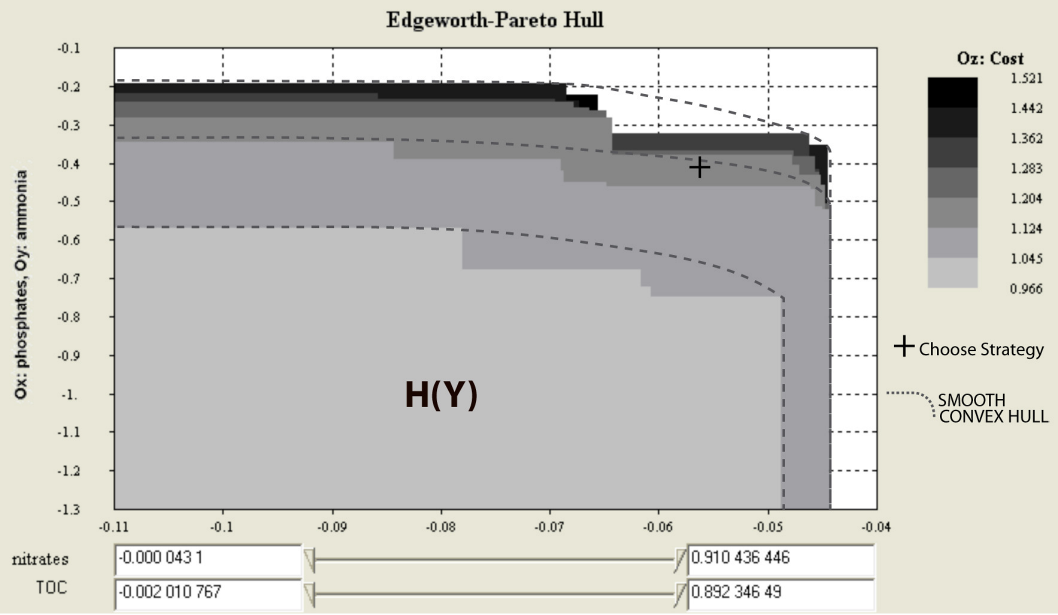

Figure 2: Example of simple EPH decision map with the corresponding smoothed convex hull.

Therefore, exploration of the Pareto frontier by means of the IDM map helps to understand the criteria tradeoffs and to identify a preferred criteria point directly at the Pareto frontier. As it can seen on Figure 2, it is impossible to satisfactorily achieve the WFD’s objective for all the criteria, even for the most intensive sewage PoM. Furthermore, the slope of the tradeoff curves for each cost level indicates the water quality tradeoff sensitivity to the water treatment actions.

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 is 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 2 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 2 shows the cost and quality results of five strategies from 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 (5). Each one of these strategies represents one of the five regions of interest.

Table 2. Example of the five decision regions, characteristics strategies points, order from most economical to most expensive 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

While TOC is not affected by investment variations in wastewater treatments, the other quality indicators improve 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. The investment produces significant improvements in TA, 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 %. The "balanced" strategies regions are, on average, 19% more costly than the "economic" ones, but manage to clearly eliminate the problems of TN in the basin and reduce the average ammonia concentration 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 determinate the statistical distribution of each PoM strategy under probabilistic daily environmental and social conditions.

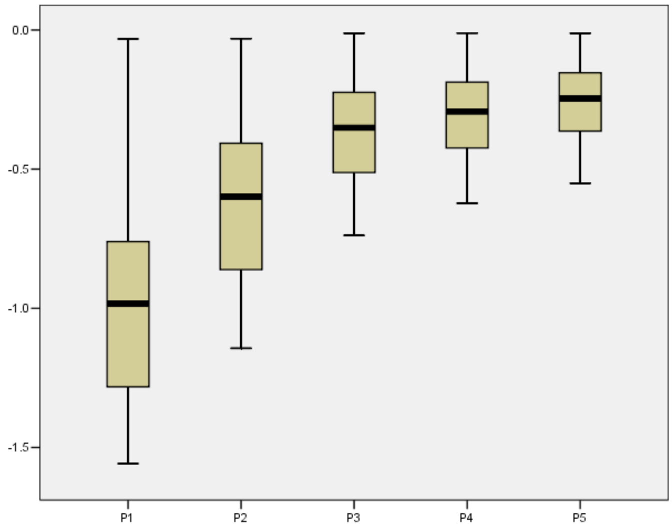

Figure 3. Example of the TA quality metric (ec.5) statistical distribution for the five previously selected WWTP strategies.

Figure 3 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. It is also remarkable how the probability distribution becomes less disperse 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. Figure 4 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, non compliance of 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 5. As one can see form Figures 4 and 5 the WFD limit for ammonia of 0,5 mg/l can be reached only in the best possible environmental and social situation.

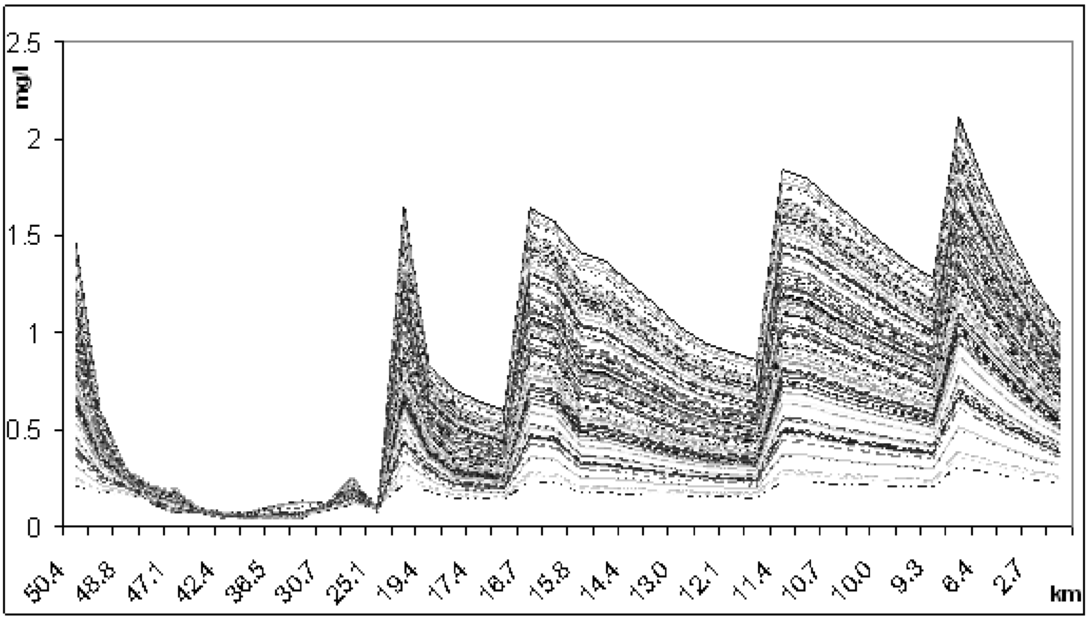

Figure 4. 2D TN concentration statistical distribution along Besos main channel for the balanced strategy. The WFD limit in TA in this stretches is 0,5

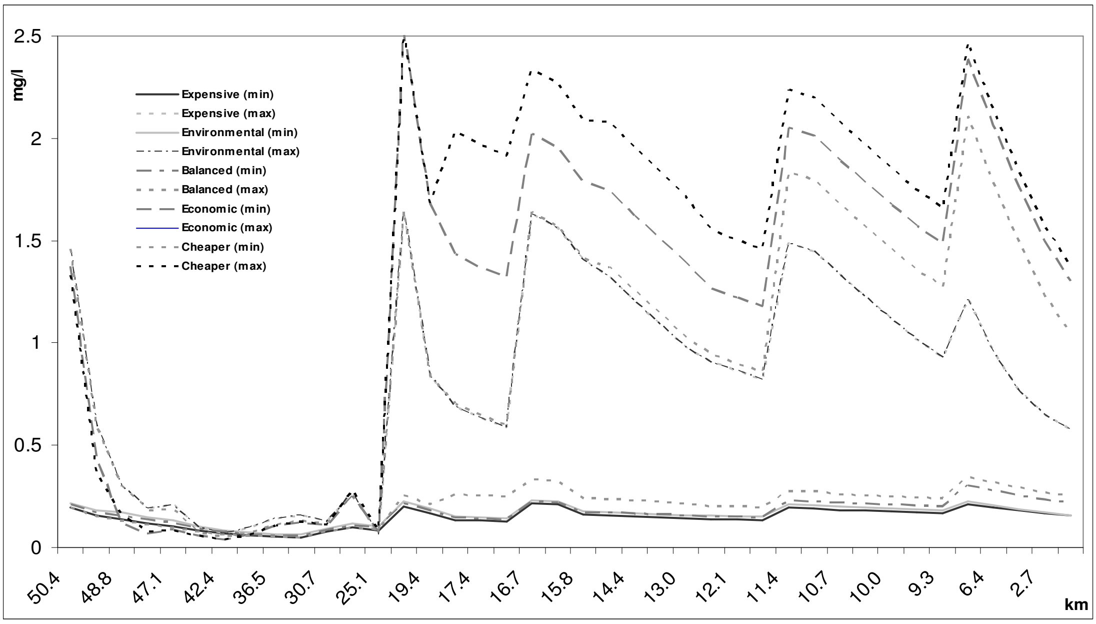

Figure 5. 2D TN concentration statistical extreme probability distribution values along Besos main channel

With the help of this analysis, 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 2, 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 on Figure 2 are listed in Table 3. On this stage, IDM helps to discard most of the alternatives and to select several ones that do not differ greatly on criteria values with respect to the goal (but may differ significantly from the point of view of the implementation). These alternatives may be subject to more careful analysis in order to select the unique alternative. For example, the robustness analysis described above can be repeated for these alternatives. Also these alternatives can be viewed once again on the water quality model Qual2k, but now more attention can be paid to its output since the number of the strategies to study is now reduced to 5.

Table 3. Characteristics of the neighborhoods strategies of the chosen strategy obtained using IDM tool for the Llobregat basin (Figure 2)

	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

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