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MULTICRITERIA GENETIC ALGORITHM FOR WASTEWATER RECLAMATION AND REUSE DECISION

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Summary. *Wastewater reclamation and reuse is being viewed increasingly as a sustainable approach to integrated water resources management, in order to achieve the European Water Framework Directive (WFD) goals. The current state-of-the art of reclamation technologies can produce water of any desired quality (including drinking quality). However, the increasing number of efficient treatment processes has made the selection of an optimum treatment a difficult task for planners and decision-makers. Mathematical programming methods, such as integer programming, non linear programming, dynamic programming have been used to solve the multi criteria problem for regional wastewater reclamation and reuse systems. In this study a Multi-Criteria Decision Support Management in Watershed Restoration (MCDSMWR) was developed through the integration of a multi objective genetic algorithm and a water quality model (QUAL2K). This Decision Support System was developed and applied to the inner Catalonia watersheds and in this paper we present some results for the Llobregat watersheds. This study showed that multi objective genetic algorithm can be particularly useful in wastewater reclamation and reuse problems as it can provide assistance in the evaluation and selection of water treatment alternatives. The multicriteria approach also has the advantage of giving the stakeholders a clear idea of the trade-off between water quality and the cost to achieve this quality.*

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 WBs 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 change in the environmental conditions. For each WB, there are millions of different combinations of wastewater reclamation and reuse treatments (strategies) and, thus, in each treatment plant it is not clear what is the adequate purification or reutilization level. An additional difficulty is that the decision maker must simultaneously consider treatment cost and water quality goals.

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[1,2]. Some approaches also consider river flow as a random variable constructing a probabilistic water quality management model[3]. Recently [4], Genetic Algorithms (GAs) were applied to carry out wastewater treatment optimal selection. These approaches usually relies on optimizing a single objective function, which may be an aggregation of quantitative and qualitative objectives into a single weighted objective function, or by optimizing one of the objectives and imposing the constraints on the remaining ones. The main drawbacks of this approach are that significant information about trade-off characteristics is lost. In recent years, Multi Objective Evolutionary Algorithms (MOEA)[5] 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[6,7]. 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.

In [9] a Multi Objective System of Efficient Strategy Selection (MOSESS) was developed, which is a computer tool for generating the set of Pareto-optimal strategies, that is, the best cost-efficient combinations of Wastewater treatment plants (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). In this work a new computational framework for Multi-Criteria Support Decision Management in Watershed Restoration (MCDSMWR) has been developed to aid in water management during WFD implementation in the internal Catalan catchments. In this paper we focus on the case study of the Llobregat catchment.

	Nutrient Effic. Remov. (%)				***Cost (€/m^3)***	
Treatment Type	***ISS***	***TA***	***TN***	***TP***	***Icost.***	***Ocost***
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	$4.413Q^{-0.357}$	$6.604Q^{-0.337}$

Table 1 : WWTP technologies considered by ACA (Q: capacity of WWTP in m3/day)

2 METHODOLOGY REVIEW

The European Directive 91/271/EEC has the goal of protecting the environment from the adverse effects of waste water discharges. In response to these directives, the Catalan Water Agency (ACA) 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 spills on all Catalonian water catchments. As an example, for the Llobregat watersheds the ACA is planning to build or upgrade 220 WWTPs and possibilities to reuse water at 22 locations. Note that as each WWTP may be selected from 7 different wastewater treatment technologies (Table 1), and for each reutilization we must decide whether or not is implement it, the total number of strategies for the Llobregat basin is $7^{220}*2^{22}$

The solution involves finding which strategy, that is, which combination of WWTPs, is the best in order to meet the WFD’s objectives within a reasonable cost. This goal has to be applicable for each watershed in Catalonia, considering that each of them has a different number of WWTP, as well as different physical-chemical characteristics and objectives to be achieved.

2.1 Llobregat catchment

. The Llobregat basin (Figure 1) is located in Catalonia, NE of Spain and it flows into the Mediterranean Sea. It covers a surface of 4,980 Km^2, with a main channel of 175 linear km, and 26 tributaries. It has a natural average annual inflow of 19 m^3/s.

Twelve monthly models were estimated using monthly data from year 2000 to 2008 at seventy four water quality control points. The ACA measures seven water quality parameters: TA, TN, TP, TOC, DO, suspended solids (SS) and BOD at all the seventy four stations.

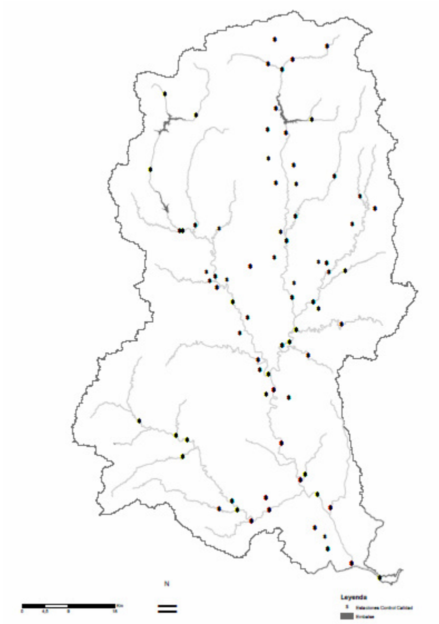

Figure 1: The Llobregat River basin layout, and water quality control stations.

2.2 Mathematical problem formulation

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

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

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 there does not exist any other 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.

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

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

$$Max\ f_k = WaterQuality_i \qquad i = NH_4, NO_3, PO_4, TOC \tag{4}$$

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 rate (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.
- $WaterQuality_{TA}$, $WaterQuality_{TN}$, $WaterQuality_{TP}$ 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), as shown in equation (5). This quality function has two different paths, depending on whether it measures the achievement of the GES 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

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

where:

k, $2 \le k \le 5$: *constituents 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 constituent *"k"* in stretch *"j"* and month *"i"*, allowed by the WFD's goal

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

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 treatment could be added. The mathematical formulation of that constraint would be the following:

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

2.3 MOSESS

MOSESS was developed through the integration of the Qual2k[8] water quality model to calculate each strategy outcome and the MOEA[9] to select the more efficient strategies. This multicriteria optimization algorithm applies binary Gray encoding for each chromosome (optimization string) corresponding to a specific set of WWTP and reutilization. For the application in the Llobregat cachmet, the Qual2k model divides it into 53 reaches and 540 elements of approximately 2 km length. 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 Llobregat watershed, with 220 possible WWTP and 22 reutilization locations, the number of genes is 220+22 and the chromosome length is 220x3+22 = 682 bits. Each chromosome represents one of the $7^{220}*2^{22}\approx 3.5 \times 10^{192}$ different possible strategies.

3 MCDSMWR RESULTS

In the MCDSMWR[9] computer tool it is summarized all the water quality criteria with respect to the cost in the same 2D graph, see Figure 2. In a 2D diagram, the ordinates represent the cost of strategies and the abscissas represent water quality evaluation according to equation (5). Points on the same horizontal line correspond to values of the different water quality criteria evaluated for one strategy, whose cost is the corresponding value in the ordinate axis. Points lying on the left side of the graphs correspond to strategies that do not meet the WFD goals. If all the points corresponding to a strategy are on the right side of the graphs then the strategy meets the WFD goals. Figure 2 shows an example of the trade-off between costs and the GES level reached by 5 different strategies (A, B, C, D and E). Each curve represents a different water quality criterion (TA, TN, TP, TOC). While strategies A and E correspond to the currently existing and maximal (all WWTP advanced type) water treatment, strategies B, C and D were previously selected from the whole set of Pareto efficient alternatives using a special multicriteria visualization techniques, see[10]. Figure 2 enables decision makers to easily compare the effect of different strategies in order to choose one. They also become aware of the cost of improving each water quality criterion, estimate the effects of applying wastewater and reutilization treatments in each basin and find out the minimum cost to achieve GES. Furthermore, this 2D representation shows whether it is possible to achieve the GES or not and it allows us to compare the quality levels for different constituents..

The Pareto set obtained for the Llobregat catchment, considering only three objectives (cost and TA and TOC), is shown in 2D in figure 3. Although the great number of possible different strategies, the MOEA converges efficiently after 10,000 evaluations of the WQM. Figure 3 shows that being TA the constituent more affected by the investment in WWTP, it is impossible to get the WFD limits in TA with even the more expensive proposal measures. However, at the same time, for TOC all the purification strategies involving investments greater than 1200000€ reach the acceptable values defined in the WFD.

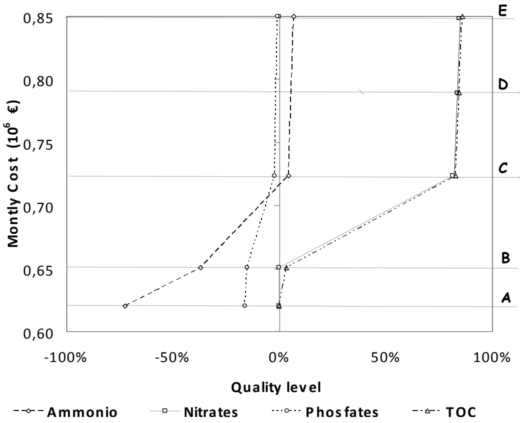

Figure 2: Example of 2D selected strategies multi-criteria visualization

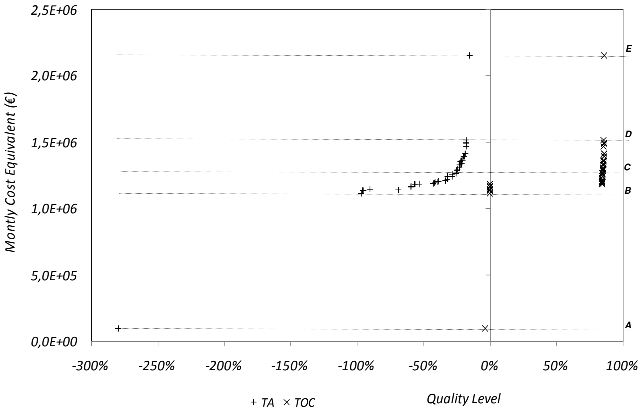

Figure 3: 2D Pareto front representation for the cost, TA and TOC criteria for the Llobregat basin.

In figure 3, the A strategy is not a logical choice because the quality of water in the basin is far from meet the limits of the WFD; the E strategy is a no logical choice too because has a cost rather bigger than the D strategy with a very small water quality improvement. On the other hand, strategies B or D could be reasonable; the first from an economical and the second from a quality point of view. The Pareto front solutions near C strategy looks to be a good balanced between cost and quality criteria, because with large cost increases there are only just small improvements in quality.

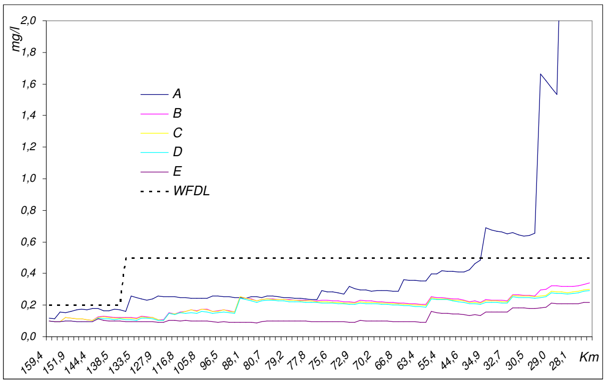

Figure 4: TA concentration along Llobregat main channel for five treatment strategies and WFD Limit

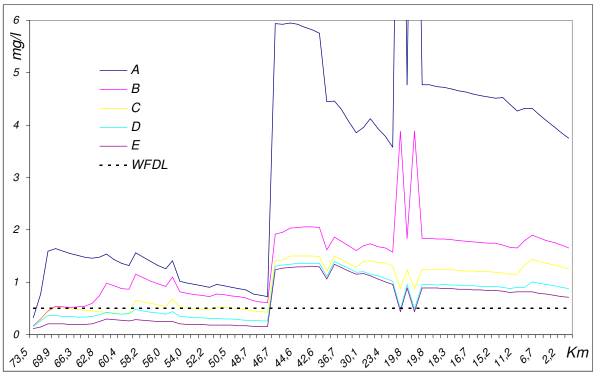

Figure 5: TA concentration along Anoia tributary channel for five treatment strategies and WFD Limit

Figures 4 and 5 show the evolution of TA along the Main Channel of the Llobregat and one of its tributaries, the Anoia, for the 5 treatment strategies (A, B, C, D and E) considered in Figure 3. They also include the maximum TA allowed by the WFD in each river stretch.

In figure 4, it can be observed that in the Llobregat main channel, with the current WWTP strategy (A) there are significant pollution problems in the last 30 km, and that from the B strategy a acceptable quality is achieved. At the same time, it is noticed how the strategies C, D and E do not produce significant improvements to justify a larger economical investment.

However, for the Anoia tributary it is shown that there are important non compliments of the WFD limits for the final 45 km, and that in the first few kilometres only strategies D and E allow to meet the limits.

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