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Cost-Effectiveness Analysis for a Heavily Modified Water Body (HMWB): the Lambro-Seveso-Olona system case study.

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Cost-Effectiveness Analysis for a Heavily Modified Water Body (HMWB): the Lambro-Seveso-Olona system case study.

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Abstract: The Lambro-Seveso-Olona system (L-S-O) is a effluent dominated watershed which derives from a strong urbanization process of natural river basins. The average population density in the L-S-O area is among the highest in Italy and Europe. Industry is also highly developed. Although at present the L-S-O system does not receive untreated wastewaters, depurated effluents constitute about half of its streamflow. This river has a long history of poor quality status, due to the high concentration of pollutant loads and the poor dilution. Recently new chemical quality standards have been set by the Italian legislation as support for the WFD Good Ecological Status. These standards are very restrictive, and make extremely challenging the achievement of the good ecological status. Aim of this study is to analyse the restoration possibilities of the L-S-O system. Elements are provided for a Cost-Effectiveness analysis.

Key words: Cost-Effectiveness analysis; heavily modified water bodies; QUAL2K; river restoration; wastewater management.

Introduction

The EC Water Framework Directive (WFD) introduced several innovations into European water policy, including the integration of economic approaches. Economic considerations play a role to justify exemptions from the overarching aim of the Directive, i.e. to achieve good status of all water bodies by 2015. If reaching this objective in time should be disproportionately costly, either the 2015 deadline may be extended, or the objective may be relaxed. The WFD requires Member States to distinguish between ‘natural’ and ‘heavily modified water bodies’ (HMWBs). The latter are designated as having an acceptably lower ecological status as the result of hydromorphological pressures, which cannot be removed because of the high social or economic cost. Because of this, the quality targets for HMWBs are ‘good chemical status’ (compliant to natural water bodies) and ‘good ecological potential’, pragmatically defined as the ecological quality expected under the conditions of the implementation of all possible measures (see Borja and Elliott, 2007). This may result sometimes in disproportionately costly restoration measures or even ecologically meaningless solutions. The Lambro-Seveso-Olona system (hereinafter L-S-O, Fig.1) is one of the most densely populated in Europe. Industry is also highly developed, chemical, textile, paper, pulp and food industries being the most representative. Although at present the L-S-O does not receive anymore untreated wastewaters, depurated wastewaters constitute about half of the streamflow. Recently new chemical quality standards for macropollutants (i.e. LIMeco index according the legislative decree n.152, 2006) have been set by the Italian legislation as support for the good ecological status according the WFD (see Table 1). The new index makes challenging the achievement of water quality objectives for the Lambro-Seveso-Olona system. Aim of this study is to analyse the L-S-O restoration possibilities through a Cost-Effectiveness approach.

Figure 1 Lambro-Seveso-Olona system (L-S-O). Hydrography and major urban areas are shown.

Methods

Scenario Analysis

QUAL2K (Chapra et al., 2008) was used to develop a quantitative understanding of the inputs and processes affecting the water quality of the Lambro-Seveso-Olona system. Measurements of different water quality parameters, coming from the Lambro-Seveso-Olona watershed, were used to implement the water quality simulations.

Table 1 LIMeco index recently enforced by the Italian legislation. Scores need to be assigned according to the thresholds and the final score is the average of the 4 parameter scores.

	Thresholds				
LIMeco	*high*	*good*	*moderate*	*Poor*	*bad*
100-DOsat[1]	≤ 10	≤ 20	≤ 40	≤ 80	> 80
N-NH4 (mg/l)	< 0.03	≤ 0.06	≤ 0.12	≤ 0.24	> 0.24
N-NO3 (mg/l)	< 0.6	≤ 1.2	≤ 2.4	≤ 4.8	> 4.8
Total-P (ug/l)	< 50	≤ 100	≤ 200	≤ 400	> 400
Score	**1**	**0.5**	**0.25**	**0.125**	**0**

[1] **DOsat** is Dissolved Oxygen at saturation.

All the measurements came from the monthly monitoring activity, carried out by ARPA, the Italian regional environmental protection agency, during the period 2009–2010 at 26 sampling stations. Such water quality monitoring refers mainly to low-or mean-flow conditions, less than 25% of the measurements available concerning higher flow conditions. QUAL2K simulations relied also on the direct measurements of the input point sources made available by ARPA. Non point sources contributions, not particularly relevant in this area, were estimated by difference from instream measurements and modeling outputs considering only point sources (see Azzellino et al., 2006 for method description). Five scenarios were considered targeting the improvement of water quality:

1. *Dir.271/91* the upgrade of the existing wastewater treatment plants (hereinafter referred as WWTPs) up to the requirements of the Directive 271/91EC (many of the existing WWTPs are more than 20-30 year old and still fail to comply with the Directive 271/91EC); in this scenario the assumed treatment is a conventional "*pre-denitrification/nitrification + phosphorus removal + filtration*" scheme.
2. *MBR* the full replacement of the actual technology with a secondary membrane treatment stage (MBR) in all the existing WWTPs larger than 50,000 PE.
3. *RO* the upgrade of the actual technology with a tertiary Reverse Osmosis treatment (RO) operating at a 50/50 blend in all the existing WWTPs larger than 50,000 PE.
4. *PostDen* the upgrade of the conventional activated sludge treatment scheme (see Dir.217/91 scenario) with an additional post-denitrification treatment aimed to lower the effluent nitrate concentrations in all the existing WWTPs larger than 50,000 PE.
5. *O3/GAC* the upgrade of the conventional activated sludge treatment scheme (see Dir.217/91 scenario) with a ozonation treatment with a subsequent granular activated carbon (GAC) filtration aimed to lower the organic micropollutant concentrations in the effluent. The treatment scheme is assumed in all the existing WWTPs larger than 50,000 PE. Table 2 show the WWTP effluent concentrations assumed in the model for the considered scenarios.Additionally, hybrid scenarios were obtained assuming to improve the conventional treatment of the Dir.271/91 just for some plants located in critical positions along the river stretches and combining different technologies (i.e. MBR and GAC/O3, see Figure 2). In such hybrid scenarios, the restoration of the instream morphology and of the riparian vegetation was also assumed.

Effectiveness evaluation

Scenario effectiveness was defined by nine indicators (see Table 3), specifically designed to quantify the improvement of water quality and of the river ecological status due to the different alternatives.

Table 2 Effluent concentrations assumed in the wastewater treatment plants as function of the plant size (expressed as People Equivalent, PE) in the considered scenarios.

mg/l	Dir 271/91CE		MBR	RO	PostDen	GAC/O3	
	PE <100,000	PE >100,000	PE >50,000	PE >50,000	PE >50,000	PE <100,000	PE >100,000
BOD	10	10	4	4	10	5	5
COD	60	60	15	30	60	40	40
N-org	0.75	0.5	0	0	0	0.75	0.5
NH3	2.25	1.5	1	1	2	2.25	1.5
NO3	12	8	9	4	4	12	8
Total-P	2	1	0.5	0.5	2*	2	1
Micropollutant removal efficacy		-	0.5	0.3	-	1	

*PE<100,000 2 mg/l, for others 1 mg/l

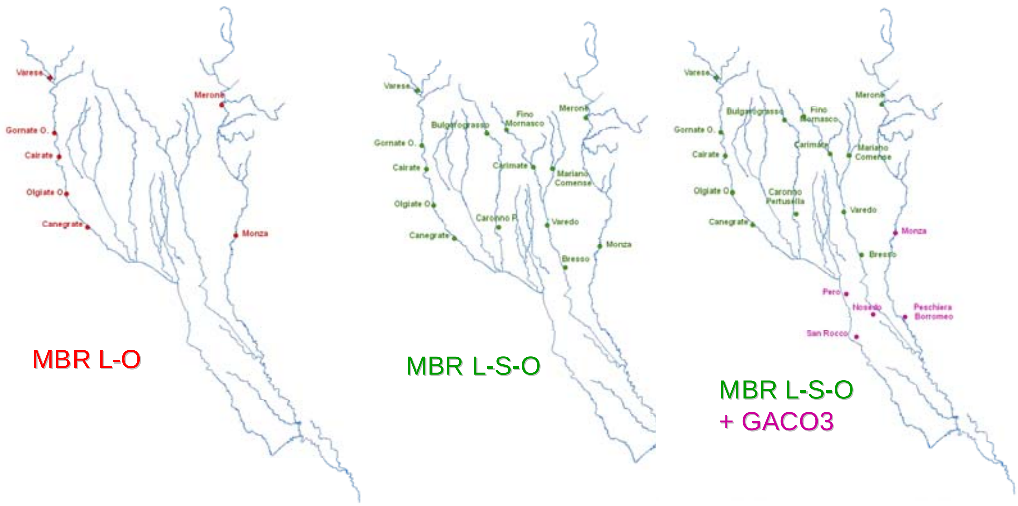

Figure 2 Hybrid scenarios for Lambro-Seveso-Olona system (L-S-O). *MBR L-O*: MBR treatment is assumed only for the shown WWTPs located in Olona and Northern Lambro river stretches; *MBR L-S-O*: MBR treatment is assumed only for the shown WWTPs located in Olona, Seveso and Northern Lambro river stretches; *MBR L-S-O*+GAC: MBR treatment is assumed only for the shown WWTPs located in Olona, Seveso and Northern Lambro river stretches and a GAC/O3 treatment is assumed for all the WWTPs larger than 700,000 PE.

Three were the indicators concerning the polluting loads (i.e. COD, Total-N and Total-P loads). Other two indicators concerned water quality taking into account the *Distance from the LIMeco target* (e.g. the Italian legislation set LIMeco index ≥ 0.5 as target threshold for the good quality status, therefore the distance considered is 0.5 – observed LIMeco) and a new index (GEP3) considering alternative thresholds for the water quality of this system. GEP3 was defined as follows:

$$GEP3\ (km) = L_i \times \Sigma\ [(COD)_{Ti}; (N\text{-}NH4)_{Ti}; (Total\text{-}P)_{Ti}] / 3$$

where

L_i is the reach unit length;

Table 3 Effectiveness indexes used in the Cost-Effectiveness Analysis

Effectiveness Indexes	Description
1. COD river load	COD cumulated river load in the river unit
2. Total-N river load	Total-N cumulated river load in the river unit
3. Total-P river load	Total-P cumulated river load in the river unit
4. DistanceLIMeco	Distance from the LIMeco target for the good quality status
5. GEP3	Good Ecological Potential according COD, N-NH4 and Total-P
6. STAR ICMi	STAR_ICMi index (Erba et al., 2009)
7. Morphological Index	Morphological index after Siligardi et al., 2007
8. Vegetation Index	Vegetation Index after Siligardi et al., 2007
9. Micropollutant Index	Micropollutants removal efficacy (see Table 2)

$(COD)_{Ti}$, is a dummy variable equal to 1 or 0 whether the river reach is matching or not the threshold for COD (i.e. 30 mg/l if 100-DOsat ≤ 20% or 15 mg/l otherwise);

$(N\text{-}NH4)_{Ti}$, is a dummy variable equal to 1 or 0 whether the river reach is matching or not the threshold for N-NH4 (i.e. 1 mg/l).

$(Total\text{-}P)_{Ti}$, is a dummy variable equal to 1 or 0 whether the river reach is matching or not the threshold for Total-P (i.e. 0.5 mg/l).
GEP3 chemical thresholds were identified by means of a quantile regression approach as described in Azzellino et al. 2012.

As measure of biological integrity the STAR_ICMi index (Erba et al., 2009) was used since it was available for all the L-S-O monitoring stations. Two indicators were extracted from the IFF index, the italian index concerning the evaluation of the river morphological and vegetation aspects (Siligardi et al., 2007). Specific threshold values were identified by means of a quantile regression approach and were assumed for the good quality status of morphology and vegetation (see Azzellino et al. 2012 for details about the analysis). Finally the effectiveness for removing organic micropollutants was evaluated and attributed to every reach unit depending on the WWTP treatment scheme (see Table 2).

Cost evaluation

Economic considerations were drawn following the approach proposed by Sipala and colleagues for the E.Wa.T.R.O. project (see Sipala et al., 2003) and from Cotè et al. 2004 and De Carolis at al., 2004 for MBR treatments. O3/GAC cost were evaluated according Abegglen and Siegrist (2012). Investment costs were evaluated as 30% of the total costs (i.e. Investment + Operation and Maintenance, hereinafter referred as O&M). When considering upgrades of existing plants, 50% of the total cost for a new plant was considered. Both investment and O&M costs were spread linearly over a period of 20 years. Concerning the restoration of instream morphology and of riparian vegetation, based on Italian case studies, a cost of 95,000 euro km-1 and of 85,000 euro km-1 was respectively assumed. For riparian vegetation an additional O&M cost of 5,000 euro/km was also assumed.

Cost-Effectiveness Analysis

The Cost-Effectiveness analysis (CEA) was carried out by means of a multi-criteria approach where effectiveness criteria and cost criteria are analyzed together in order to evaluate the best restoration alternatives. CEA was run through the following steps:

1. An evaluation matrix was created, normalizing each indicator according to a certain value function; initially the value functions were both linear, based on the maximum and minimum values of the alternative measures, and non-linear, based on critical threshold values.

2. Indicators are weighted in order to reflect their relative importance in the computation of the cumulative performance;
3. The cumulative performance, aggregating every single performance on each specific indicator, is computed by means of a selected decision algorithm.

The analysis was performed through the mDSS software (Mulino Decision Support System, Giupponi, 2007), that is endowed with multiple possibilities for choosing value function, weights and decision algorithms. Different value functions were explored to normalize the indicators. Since the inclusion of more complex functions apparently did not affect the results, the typical Min-Max normalization was chosen. The Simple Additive Weighting (SAW) algorithm was chosen because of its simplicity and transparency. The cumulative performance Φ_{SAW} for each alternative scenario/measure (a_i) was given according eq. (1):

$$\Phi_{SAW}(a_i) = \sum_{j=1}^{n} w_j \times u_{ij} \qquad (1)$$

that is the sum of products of the normalized performance uij in each j-criterion of each i- alternative scenario/measure, multiplied by the weight given to each j-criterion. Several configurations of weights were considered throughout the study in order to explore different attitudes of decision makers towards cost-efficiency but we present the results of the one that prevailed. The selected configuration of weights was based on the equivalence of the unit of effectiveness with the unit of costs, so that both are given 50% of the total weight. The two typologies of costs (i.e. investment and O&M) were considered equivalent so a 25% weight was attributed to each. The weights for the effectiveness criteria were the following: 20% to water chemistry (i.e. pollutant loads and concentrations), 8% to the STAR_ICMi index, 12% to morphology and vegetation and 10% to micropollutants. In reason of its constituents the weight for chemistry was subdivided into a 8% contribution due to the pollutant loads (which accounted for a 2% contribution due to phosphorus loads, another 2% contribution due to COD loads, and a 4% contribution due to nitrogen loads), and a 12% contribution due to the water quality indexes (which accounted for a 8% contribution of GEP3, and a 4% contribution for DistanceLIMeco). Morphology and vegetation accounted for a 6% contribution each.

Results and Discussion

The QUAL2K model showed overall a discrete model accuracy (i.e. errors of about ± 20-30%) for the median annual scenario. The median was assumed as reference for the scenarios and it was preferred to the average to avoid any skewness effect present in the water quality measurements. At present, and according to the new LIMeco index, most (i.e. over 200 km out of a total of 253 km) of the L-S-O system is classified in between a poor and a bad quality status. Less than 10% of the river length is classified as good or high quality. Figure 3 shows the effectiveness indexes of the considered scenarios and their respective costs. It can be observed that the scenarios differ largely either for effectiveness or cost (e.g. O3/GAC was the most expensive although comparable in its effectiveness with MBR or RO).

Based on these results, a final set of eight new scenarios was proposed (shown in Table 4) in the attempt to optimize the advantages of each technology, by means of a sort of optimal siting, and, concurrently to minize the costs.

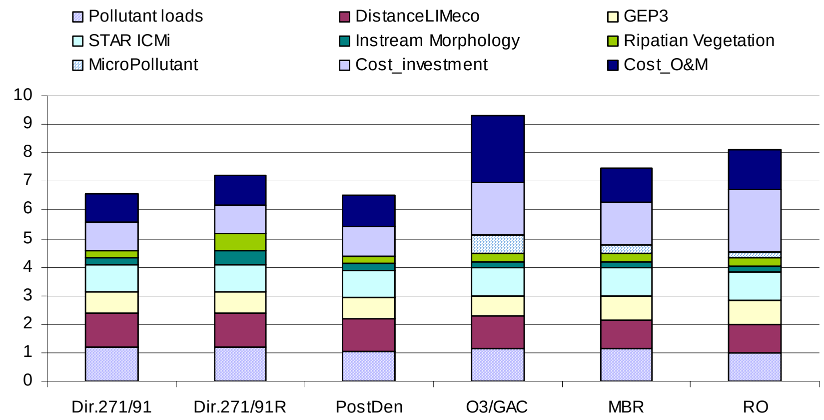

Figure 3. Cost-Effectiveness Analysis of the studied scenarios.

The restoration of the instream morphology and the riparian vegetation was assumed in all the reach units with GEP3 > 0.7. The scenarios were finally analyzed through the CEA mDSS.

Table 4 Final set of scenarios considered for the CEA

Scenarios	Description
Dir.271/91R	upgrade up to the requirements of the Directive 271/91EC + instream morphology and riparian vegetation restoration
MBR L-O	secondary MBR in the WWTPs which influence for more tham half of total river length in the Olona and Lambro rivers
MBR L-S-O	secondary MBR in the WWTPs which influence for more tham half of total river length in the Olona, Seveso and Lambro rivers
MBR**R** L-O	secondary MBR in the WWTPs which influence for more tham half of total river length in the Olona and Lambro rivers + instream morphology and riparian vegetation restoration
MBR**R** L-S-O	secondary MBR in the WWTPs which influence for more tham half of total river length in the Olona, Seveso and Lambro rivers + instream morphology and riparian vegetation restoration
O3/GAC	ozonation treatment combined with GAC filtration In all the WWTPs larger than 50,000 PE
O3/GAC-MBR	secondary MBR in the WWTPs which influence for more than half of L-S-O total length and O3/GAC in WWTPs larger than 700,000 PE
O3/GAC-MBR**R**	secondary MBR in the WWTPs which influence for more than half of L-S-O total length and O3/GAC in WWTPs larger than 700,000 PE + instream morphology and riparian vegetation restoration

Conclusions

This study demonstrates that a compromise is needed between restrictive quality targets, costs and the real possibility of recovery of human effluent-dominated systems. CEA outlined the scenarios maximizing the effectiveness, and significantly reducing the costs.

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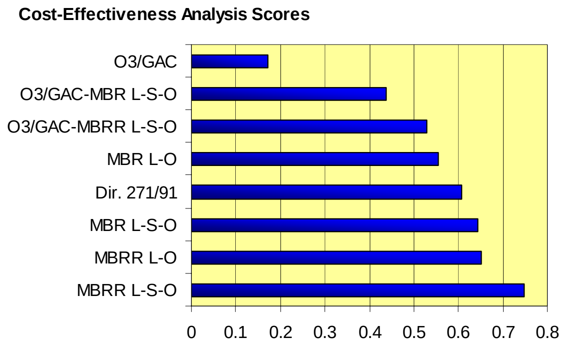

Figure 4. Relative ranking of the eight scenarios according to the Cost-Effectiveness analysis.

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