Searching for a compromise between ecological quality targets, and social and ecosystem costs for heavily modified water bodies (HMWBs): the Lambro-Seveso-Olona system case study

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ABSTRACT

The Lambro-Seveso-Olona (L-S-O) system derives from the human regulation of the natural hydrology of the territory around Milan city area. The average population density in the L-S-O area is among the highest in Italy and Europe. Industry is also highly developed in this basin: chemical, textile, paper, pulp and food industries being the most important ones. Although, at present, the L-S-O system no longer receives the untreated wastewaters of the Milan urban area, treated wastewaters constitute about half of the streamflow. Biotic communities in this river have a long history of poor quality status, having suffered great damage due to domestic and industrial discharges. Recently, new chemical quality standards for macropollutants have been set by the Italian legislation as support for the good ecological status according to the Water Framework Directive (WFD). This new index is very restrictive, and it makes it extremely challenging to achieve the water quality objectives for the L-S-O system. The aim of this study is to analyse through a modelling exercise the restoration possibilities of the L-S-O system, investigating both the source apportionment of the macropollutants, the discharge limits that should be set to achieve the good quality status and their corresponding cost.

Key words | heavily modified water bodies, QUAL2K, restoration

INTRODUCTION

The European Union 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. Due to this, the quality targets for HMWBs are ‘good chemical status’ (compliant to natural water bodies) and ‘good ecological potential’ (GEP), pragmatically defined as the ecological quality expected under the conditions of the implementation of all possible measures (see Borja & Elliott 2007). This may result sometimes in disproportionately costly restoration measures or it may even result in ecologically meaningless solutions. The Lambro-Seveso-Olona (L-S-O) system is not a natural watershed since it derives from the human regulation of the natural hydrology of the territory around Milan city area. The Olona and Seveso rivers were not originally natural tributaries of the Lambro river but now they are. The Olona river in fact merges into the so-called southern Lambro river, which merges in its turn into the Lambro river about 20 km upstream of the Lambro confluence into the Po river. The Seveso river, sadly known for the ICMESA ecological disaster that occurred in 1976, is now connected to the Lambro-Olona system since its waters flow through the channel system beneath the Milan urban area, and as the Redefossi channel flows into the
northern Lambro river (Figure 1). The L-S-O watershed is densely populated. The average population density in this area is higher than 1,000 inhabitants/km² (peak values are more than 7,000 inhabitants/km² in the Milan urban area and around 1,500–2,000 inhabitants/km², respectively, in the areas of the provinces of Varese and Como which are mostly drained by the Lambro). These population densities are among the highest in Italy and Europe. Industry is also highly developed in this basin: chemical, textile, paper, pulp and food industries being the most important ones. Although, at present, the L-S-O system no longer receives the untreated wastewaters of the Milan urban area, depurated wastewaters constitute about half of the streamflow (PTUA 2004). Biotic communities in this river have a long history of poor quality status, having suffered great damage due to domestic and industrial discharge (Battegazzore & Renoldi 1995; Camusso et al. 1995). The L-S-O system constitutes also the most polluted tributary of the Po river, the largest Italian river. Although representing only 6% of the Po river drainage area (L-S-O watershed has a drainage area of about 2,700 km²), the significant contribution of this river system to the Po river pollutant load has been largely documented (Pettine et al. 1996; Palmeri et al. 2005; Salvetti et al. 2006).

Recently, new chemical quality standards for macropollutants (i.e., LIMeco index according to legislative decree no. 152, 2006) have been set by the Italian legislation as support for the good ecological status according to the WFD. This new index considers dissolved oxygen (i.e., deficit for dissolved oxygen saturation, 100-DO_sat), ammonia and nitrate concentration, and total phosphorus concentrations and is extremely restrictive, particularly concerning nitrate and phosphorus (see Table 1). The new index makes it challenging to achieve water quality objectives for many Italian rivers and, consequently, it makes it extremely hard to reach good quality for the L-S-O system. The aim of this study is to analyse the restoration possibilities of the L-S-O, focussing both on the source apportionment of the macropollutants and on the effluent limits that should be set by law, to achieve good quality status according to the LIMeco index. Based on the modelled scenarios, the technical and economic feasibility of the requested discharge limits are evaluated.

MATERIAL AND METHODS

QUAL2K (Chapra et al. 2008) was used to develop a quantitative understanding of the inputs and processes affecting the water quality of the L-S-O system. Measurements of different water quality parameters, coming from the L-S-O watershed, were used to implement the water quality simulations. All the measurements came from monthly monitoring activity, carried out by ARPA, the Italian
Table 1 | LIMeco index recently enforced by Italian legislation. Scores need to be assigned according to the thresholds, and the final score is the average of the four parameter scores.

<table>
<thead>
<tr>
<th>LIMeco</th>
<th>High</th>
<th>Good</th>
<th>Moderate</th>
<th>Poor</th>
<th>Bad</th>
<th>LIMeco</th>
</tr>
</thead>
<tbody>
<tr>
<td>100-DO&lt;sub&gt;sat&lt;/sub&gt;</td>
<td>&lt;10</td>
<td>&lt;20</td>
<td>&lt;40</td>
<td>&lt;80</td>
<td>&gt;80</td>
<td>High</td>
</tr>
<tr>
<td>N-NH&lt;sub&gt;4&lt;/sub&gt; (mg/L)</td>
<td>&lt;0.03</td>
<td>&lt;0.06</td>
<td>&lt;0.12</td>
<td>&lt;0.24</td>
<td>&gt;0.24</td>
<td>Good</td>
</tr>
<tr>
<td>N-NO&lt;sub&gt;3&lt;/sub&gt; (mg/L)</td>
<td>&lt;0.6</td>
<td>&lt;1.2</td>
<td>&lt;2.4</td>
<td>&lt;4.8</td>
<td>&gt;4.8</td>
<td>Moderate</td>
</tr>
<tr>
<td>Total-P (µg/L)</td>
<td>&lt;50</td>
<td>&lt;100</td>
<td>&lt;200</td>
<td>&lt;400</td>
<td>&gt;400</td>
<td>Poor</td>
</tr>
<tr>
<td>Score</td>
<td>1</td>
<td>0.5</td>
<td>0.25</td>
<td>0.125</td>
<td>0</td>
<td>0.17</td>
</tr>
</tbody>
</table>

The STAR_ICMi index (Erba et al. 2009) available in all the L-S-O monitoring stations was also used to correlate the river chemical status to the reference biological metric. Quantile regression was used to correlate the STAR_ICMi 95th percentile values to the corresponding chemical ranges through the GRETL software (GNU Regression, Econometrics and Time-series Library, Cottrell & Lucchetti (2011)). Economic considerations were drawn following the approach proposed by Sipala and colleagues for the E.Wa.T.R.O. (evaluation of wastewater treatment and reuse options) project (see Sipala et al. 2003) and from Cotè et al. (2004) and De Carolis et al. (2004) for membrane biological reactor (MBR) treatments. Investment costs were evaluated as 30% of the total costs (i.e., investment + operation and maintenance). Moreover, when considering the upgrading of existing plants, 50% of the E.Wa.T.R.O. costs was estimated.

**RESULTS AND DISCUSSION**

QUAL2K models 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. QUAL2K enabled assessment of the apportionment of the main pollutant sources in the system. Wastewater treatment plants (WWTPs) constitute more than 90% of the waste flow discharged to the river system, 91% of the discharged organic load and 99.4% of the total nitrogen load. At the watershed closure (i.e., at the Po river confluence) the cumulated flow of discharges accounts for about 40% of the river streamflow. It is also relevant to note that WWTPs in the L-S-O range from very small (i.e., less than 2,000 PE, about 20% of the total number), to medium size (i.e., 2,000–10,000 PE, 25% of the total number) to bigger sizes. More than 40% of the WWTPs are larger than 10,000 PE and a little less than 10% are larger than 600,000 PE and account for the majority of the discharged pollutant load. However, the latter being situated almost all around the Milan urban area where the river has already acquired a low quality status, they do not constitute the most significant pressure.
for river water quality. 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 river length is classified in between poor and bad quality status (see Figure 2). Less than 10% of the river length is classified as good or high quality.

The QUAL2K modelling was also used to evaluate the effluent limits required to achieve good LIMeco quality status. Besides ammonium, whose concentration is extremely high all through the river and denotes the presence of untreated wastewaters and of scarcely efficient removal treatments, the most challenging parameters to control in order to achieve a good LIMeco status appear to be nitrate and total phosphorus, which should be removed at a level of 1–2 and 0.2–0.4 mg/L, respectively. These limits are hardly achievable by conventional activated sludge treatments. Only a tertiary reverse osmosis (RO) filtering stage would guarantee adhering to these limits and that would increase the treatment costs by 2.5–2.7-fold with respect to the conventional ‘nitration/denitration + phosphorus removal + filtration’ treatment scheme. Moreover, it should be observed that throughout the L-S-O system more than 160,000,000 m³/y of wastewaters need to be treated, and this would imply investments of the order of hundreds of millions of euros. On the other hand, even in the hypothesis of the full RO scenario (i.e., all the WWTPs operating a RO treatment), there would be concerns for the river ecosystem due to the fact that RO is not a selective treatment and its full-scale application could significantly alter the ion balance of the system, posing a risk to the osmolarity of riverine organisms.

Article 4 of the WFD specifies the environmental objectives of the WFD, i.e., the ‘good status’ for ground- and surface waters and the ‘GEP’ for HMWBs. It also specifies several conditions under which exemptions from these objectives can be applied for, including economic conditions (i.e., disproportionate costs). More specifically, two types of exemptions are foreseen under Article 4: Article 4.4 specifies the conditions under which the 2015 deadline for achieving the good status may be extended (to 2021 or to 2027); Article 4.5 specifies the conditions under which the environmental objectives may be permanently lowered to less stringent levels. It is generally understood that the lowering of objectives requires a more thorough justification than the extension of the deadline, as the former has a permanent effect. Given that the achievement of the ‘good quality status’ according to the LIMeco index, although theoretically feasible through the wide application of RO technology, would lead to the paradox of damaging the river ecology because of the lack of selectivity of the treatment, a ‘GEP’ should be pragmatically defined for the L-S-O system, under the conditions of the implementation of all possible measures not leading to disproportionate costs. It is true that the practical interpretation of the terms ‘disproportionately costly’ remains largely disputed. However, although the ultimate judgement on the disproportionality of costs is a political decision, some objective criteria have been proposed to ensure a transparent decision-making process (see Görlach & Pielen 2007).

One interesting example can be drawn from the Seine-Normandy pilot study. In this study a pragmatic approach was put forward by Laurans (2006). Laurans suggested a two-stage approach: in a first step, proportionality of costs should be assessed in proportion to the current level of expenditure. If the annual costs of all measures needed to achieve good status do not exceed the current expenditure...
for water management by more than 20%, they would not be considered as disproportionate. If they do exceed 20%, a more detailed analysis is needed. While Laurans admits that the 20% threshold is selected somewhat arbitrarily, it appears practical, also when considering the uncertainties associated with cost estimates. Thereby, the first step serves as a simple pre-test to screen out cases where no further analysis is needed. If the additional costs of WFD implementation exceed 20% of current water management expenditure, this would not lead to an automatic exemption: exemptions should only be applied for where the additional costs are not balanced by corresponding additional benefits.

In the second step, the proportionality of costs should therefore be assessed by comparing costs and benefits of the planned measures. In this perspective, market benefits (such as tourism and drinking water supply) should be considered as well as non-market benefits (such as non-use values of improved water quality). In Laurans’ opinion the results of such cost–benefit analysis should serve as a basis for discussion with stakeholders. Thus, following Laurans’ methodology, we considered three scenarios:

1. **Dir. 271/91**: the upgrading of the existing WWTPs up to the requirements of Directive 271/91EC (many of the existing WWTPs are more than 20–30 years old and still fail to comply with Directive 271/91EC).
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 RO treatment operating at a 50/50 blend in all the existing WWTPs larger than 50,000 PE.

We also tried to evaluate the costs of these scenarios within the perspective of the Seine-Normandy study. Figure 3 shows the QUAL2K simulations of the three scenarios with respect to the present status (i.e., according to the classification based on 2009 measurements). Model simulations allow us to conclude that none of the considered alternatives would change the present Limeco quality status, which would remain about the same.

Although ineffective in the perspective of the achievement of the good quality status according to the Limeco index, it is worthwhile noting that all the scenarios imply a significant increase of the current expenditure. Table 3 shows the estimated investments for the three scenarios and their comparison with the planned investments for water management (COVIRI 2007). Notwithstanding, the analysis being conducted at a very coarse level, it clearly reveals how significantly the scenarios would affect the current planned expenditure, far exceeding the 20% threshold. Even more relevant would be their economic impact considering that only 57% of the total amount is planned for new infrastructures (i.e., 51 and 78% for the upgrade and the MBR scenarios, respectively). It is not enough to consider these scenarios disproportionately costly, but this analysis urges that further investigations are needed to compare the costs with their expected benefits. Moreover, our study demonstrates that the expected benefits cannot be evaluated based on the Limeco index, which is not sensitive enough to detect improvements in these effluent-dominated streams. Other indexes should be used to assess the GEP of the L-S-O system. From the perspective of proposing new criteria for the evaluation of the GEP we analysed the STAR ICMI...
index (Erba et al. 2009), which is a biological index broadly used in Europe to enforce the WFD, in all the available L-S-O monitoring stations. Quantile regression was used to correlate the STAR_ICMi 95th percentile values to the corresponding chemical ranges (see Figure 4). Based on the quantile regression analysis the following chemical thresholds were identified: BOD: 4 mg/L; COD: 15 mg/L; N-NH₄: 1 mg/L; N-NO₃: 3 mg/L; Total-P: 0.5 mg/L. These thresholds were used to classify every modelled reach as 1 (i.e., water quality over the threshold) or 0 (i.e., water quality below the threshold), and the following index was proposed as GEP:

\[
GEP(km) = L_i \times \frac{\sum [(BOD)_{Ti}; (COD)_{Ti}; (N-NH_4)_{Ti}; (N-NO_3)_{Ti}; (Total-P)_{Ti}]}{5}
\]

where \(L_i\) is the reach length; \((BOD)_{Ti}\) is a dummy variable equal to 1 or 0 whether the river reach is matching or not the threshold for BOD (i.e., 4 mg/L); \((COD)_{Ti}\) is a dummy variable equal to 1 or 0 whether the river reach is matching or not the threshold for COD (i.e., 15 mg/L); \((N-NH_4)_{Ti}\) 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); \((N-NO_3)_{Ti}\) is a dummy variable equal to 1 or 0 whether the river reach is matching or not the threshold for N-NO₃ (i.e., 3 mg/L); \((Total-P)_{Ti}\) 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).

GEP index allows us to discriminate the effectiveness of the different scenarios ranking from the 85 km of the Dir. 271/91 scenario up to the 107 km (i.e., 25% increase of Dir. 271/91 GEP) of the MBR scenario and 106 km of the RO scenario. In the light of these results, and based on the knowledge acquired from the QUAL2K model of the system, a further scenario was analysed: MBR treatments applied to the most critical WWTP effluents (i.e., the effluents that influence the water quality for at least 80 km of the water course). The number of WWTPs that corresponded to this criterion was eight, and they ranged from 30,000 to 70,000 PE. Figure 5 shows the complete results of the scenario analysis with the corresponding estimated expenditures (see Table 3).

### CONCLUSIONS

This study shows clearly the peculiarity of the L-S-O system and demonstrates that a compromise is needed between restrictive quality targets, costs and the real possibility of recovery of such a human effluent-dominated system. Moreover, our study shows that from the perspective of the cost-benefit analysis, the expected benefits should be evaluated with appropriate indexes, adequately sensitive to detect improvements in these effluent-dominated streams. The knowledge acquired through modelling may suggest intermediate scenarios that maximise efficiency, significantly reducing the costs.
Figure 4 | Quantile regressions correlating the STAR ICMI biological index with the main river macropollutants. The ordinary least square regression (OLS) is also shown. The bottom chart shows also the Total-P threshold, identified through the quantile regression, corresponding to the STAR ICMI 95th percentile value.

Figure 5 | Cost-effectiveness analysis of the studied scenarios. Sc MBR8 refers to the MBR treatment applied only to the most critical WWTP effluents.
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