CASE STUDY

Designing CSO storage tanks in Italy: A comparison between normative criteria and dynamic modelling methods

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Using a case study on the Lambro River and the Stream Bevera, this paper compares the use of dynamic modelling with the “normative criteria” to evaluate the effects of Combined Sewer Overflows (CSOs). The normative criteria is the method currently used in Italy to design first flush water tanks to reduce the pollutant discharges. The dynamic modelling technique compares the natural river conditions and the conditions in the river when a CSO occurs. This study finds that the current law, which is based on an effluent standard approach, can significantly underestimate the size of the CSO storage tanks needed to prevent pollution. An alternative is to change the law to use a stream standard approach and to require the CSO tanks to be sized based on the volume and concentration of the pollutants at the CSO. By using a dynamic model of the river, it was found possible to provide a more accurate estimate of the size of the CSO storage tanks required to prevent pollution. Furthermore the paper finds that without a model, it is almost impossible to evaluate the effect of CSOs and changes to the size of the CSO storage tanks.

Keywords: combined systems overflow; modelling; normative; river quality; pollution

Introduction

Water pollution spoils the water we use in our homes, the rivers and streams we use for recreation, the water needed for business, and harms other forms of life, including the fish we eat. Plans for the reduction of pollution and the restoration of natural sustainable conditions are vital. Water pollution is a worldwide problem, which may be more easily resolved by working together to establish international standards, tools and techniques. By using a case study on the Lambro River and the Stream Bevera located in the southern part of the Como Lake District (North of Italy), this paper considers the advantages of sizing Combined Sewer Overflows (CSO) storage tanks using dynamic modelling, compared to sizing the CSO storage tanks using the “normative criteria”. This paper give a comparison of the effects of CSOs in the highly polluted Lambro River and Stream Bevera. During low river flows, the impact of the first flush (the area’s first highly polluted water runoff) from the CSO water is more significant as the river has a very limited ability for self-purification.

The Italian Normative Criteria

The law (see the law D.L.vo 152/2006) identifies, classifies, sets criteria, and regulates the urban discharges from significant water bodies. It requires that regions regulate the first flush waters from CSOs. Each region has a slightly different approach to regulation. The Lombardia Region requires that every overflow must be provided with first flush water tanks by the end of 2016. Both Combined Sewer Systems and Separated Sewer Systems are regulated. The regulation quantifies the volume to be detained as 50 m³ for every hectare of impervious surface, i.e. the first 5 mm of the rainfall events. The limitation of this method is that it does not consider the concentration of the pollutants. The concentration of pollution is dependent upon many factors: the type of activities, highways or parking versus playgrounds, the shape of the catchments and the speed at which the water runs off into the sewers and is transported. These all affect the concentration of pollutants at the overflow. Clearly, the application of the same criteria to the operation of overflows on...
separated sewers and combined sewers is unwise. More information on the factors that should be considered in the operation of overflows is available in Mustard et al. (1987), Gromarie-Mertz et al. (1997), Maglionico and Pollicino (2004).

**Dynamic modeling**

The area was monitored to record all of the climatic, hydro geological and urban information necessary to describe its particular characteristics. The next step was to build a worst case hydraulic and quality model and determine the simulation parameters. Using the model and specific hydrological data, the accumulation and the washing away of pollutants, the quantity of TSS discharged, and dispersion of the pollutants in the river during storm events were simulated. The software used for simulations was Wallingford Software’s InfoWorks RS model 2007. (Infoworks is a well-know integrated software for simulating flows in rivers, in channels and on floodplains. It has been developed by Wallingford Software Ltd. www.wallingfordsoftware.com.) This paper demonstrates the value of using dynamic water quality modelling of the behaviour of the whole CSO event to size the CSO storage tanks, instead of sizing the CSO storage tanks using the normative criteria. It demonstrates the benefits of a new regulation that would require hydraulic control of the overflows and the installation of first flush water tanks based on the natural conditions in the river, to minimize the effects of discharges.

**Modelling**

Hydrological and hydraulic modelling was used to develop flow and pollutographs to model the effect of the pollution in the river. The area modelled covers a reach of approximately 5 km of the Lambro River and a reach of 3 km of the stream Bevera, their junction, and three overflows. Runoff and water quality models were used to develop flow hydrographs and pollutographs of the CSOs into the river. The next step was to use a river model to simulate the effect of these CSOs in the river. In Figure 1 a plan view of the river model, developed in InfoWorks RS,
is shown. The model specifies the physical parameters of the catchment, the stream and river. To describe the catchment, the model requires: the area, the shape including length and width dimensions, the slope and the type of surface (i.e. grass or parking), and the pollutants on the catchment. The river is described using cross section data. To simulate the flow in the river and the CSO operation, storm event data are required.

**Event data**

To evaluate the operation of the CSO, a range of storms with return periods less than one year to five years were required. As historical rainfall event data was not available, hyetographs were created using the usual DDF equation:

\[ h(\vartheta, T) = a(T) \cdot \vartheta^{n(T)} \]  

(1)

where \( h \) [mm] is the expected rainfall depth of a given duration \( \vartheta \) [h] and return period \( T \) [years]; \( a \) and \( n \) are the DDF curve parameters, dependent on the return period \( T \) and which values are reported in Table 1. As the DDF curve parameters are available only for higher return periods, which are the less relevant for the CSOs, for the more frequent low flow storm events \( (T < 1 \text{ year}; T = 2 \text{ years}; T = 5 \text{ years}) \) the parameters were computed using the Gumbel frequency distribution with the calculated parameters based on the longer return period storms. As the probability distribution of the DDF curves is logarithmic, the parameters for storms with return period less than one year can be obtained by dividing those of \( T = 2 \text{ years} \) by two. The event parameters are shown in Table 1.

Table 1. DDF curves parameters – provided by the Authority, and estimated values.

<table>
<thead>
<tr>
<th>( T )</th>
<th>( a )</th>
<th>( n )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(&lt; 1 \text{ year})</td>
<td>15.05</td>
<td>0.305</td>
</tr>
<tr>
<td>( 2 \text{ years})</td>
<td>30.09</td>
<td>0.305</td>
</tr>
<tr>
<td>( 5 \text{ years})</td>
<td>44.41</td>
<td>0.305</td>
</tr>
<tr>
<td>( 20 \text{ years})</td>
<td>62.84</td>
<td>0.306</td>
</tr>
<tr>
<td>( 100 \text{ years})</td>
<td>84.54</td>
<td>0.308</td>
</tr>
<tr>
<td>( 200 \text{ years})</td>
<td>92.76</td>
<td>0.308</td>
</tr>
<tr>
<td>( 500 \text{ years})</td>
<td>103.61</td>
<td>0.308</td>
</tr>
</tbody>
</table>

With the given rainfall parameters, the maximum discharge flowing into the river network was calculated using the time–area method and the rational formula:

\[ Q = 2.778 \cdot C \cdot i_{t} \cdot A \]  

(SI units)  

(2)

with \( Q \) [l/s] discharge; \( C \) [-] afflux coefficient set equal to 0.3; \( i_{t} \) [mm/h] rainfall intensity; \( A \) [ha] area of the catchment.

The rainfall intensity was computed for a duration \( \vartheta \) equal to the concentration time \( T_{c} \) using the Giandotti’s Formula (widely used for the Italian catchments) for each of the three catchments:

\[ \vartheta = T_{c} = \frac{4 \cdot \sqrt{A} + 1.5 \cdot L}{0.8 \cdot \sqrt{H}} \]  

(3)

Where \( A \) is again the area of the catchment, but in \([\text{km}^{2}]\) in this formula, \( L \) the length of the main reach \([\text{km}]\), \( H \) is the mean altitude of the catchment \([\text{m}]\), referred to the altitude of the catchment outlet. Concentration times for the three catchments are given in Table 2 together with the catchment characteristics. Results were checked for consistency with data provided by the Po Agency, which is the Agency in charge of the whole Po catchment, and so of all its tributaries, among them the Lambro and Bevera.

**Catchment model**

In addition to the catchment runoff, to model the effect of pollutants from the catchment, a water quality model was used. The first step is to model the accumulation of pollutants on the catchment. For this, the Huber and Dickinson model (1988) was used:

\[ Ma(t) = \frac{Acc}{Disp} \cdot (1 - e^{-Disp \cdot t}) \]  

(4)

where \( Ma(t) \) is the partial mass accumulated on the catchment at time \( t \) [kg/ha]; \( Acc \) is the accumulation coefficient [kg/(ha · day)] related to the type of pollutant; \( Disp \) is the disappearance coefficient [day\(^{-1}\)] related to the wind and traffic effects; \( t \) is the previous dry time [days] which represents the time necessary to have a deposit of pollutants on the

Table 2. catchments characteristics.

<table>
<thead>
<tr>
<th>Catchment</th>
<th>( A ) [\text{km}^2]</th>
<th>( L ) [\text{km}]</th>
<th>( h_{\text{average}} ) [\text{m asl}]</th>
<th>( h_{\text{outlet}} ) [\text{m asl}]</th>
<th>( H ) [\text{m}]</th>
<th>( T_{c} ) [\text{h}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lambro upstream junction</td>
<td>12</td>
<td>3.0</td>
<td>300</td>
<td>246</td>
<td>54</td>
<td>3.12</td>
</tr>
<tr>
<td>Bevera upstream junction</td>
<td>20</td>
<td>5.5</td>
<td>280</td>
<td>246</td>
<td>34</td>
<td>5.60</td>
</tr>
<tr>
<td>Lambro to the plant</td>
<td>8</td>
<td>1.5</td>
<td>270</td>
<td>243</td>
<td>27</td>
<td>2.60</td>
</tr>
<tr>
<td>Lambro to the plant (global)</td>
<td>40</td>
<td>7.0</td>
<td>284</td>
<td>243</td>
<td>41</td>
<td>6.99</td>
</tr>
</tbody>
</table>
catchment. The values assumed by the $Acc$ parameter are defined by comparing the catchments urban characteristics with the literature data (Alley 1981, Alley and Smith 1981, Bujon and Herremans 1990) (see Table 3).

Characteristics of the urban catchments discharging at the overflows are reported in Table 4, where $Imp$ is the imperviousness ratio.

The $Disp$ parameter presents a wider variability: American literature (Novotny et al. 1978, 1985) suggests values between 0.2 day$^{-1}$ and 0.4 day$^{-1}$, while French literature (Bujon 1988) estimates 0.08 day$^{-1}$.

Assuming a high density residential area ($Acc = 10$), the shape of the curve describing the storing up process has been analysed with respect to the $Disp$ variability. Results are shown in Figure 2.

Figure 2 shows after a long dry time, of 15/20 days, there will be more than 80% of the total pollutants deposited on the catchment. Such events with dry periods of 1–2 weeks are quite frequent. Therefore, in the paper for each overflow and storm event, the total mass of pollutants deposited on the catchment was computed.

The next step in the modeling process is to determine how much of the pollutant is washed away during a storm event. To model the pollutant wash off, the SWMM model was used (Huber 1986):

$$\frac{dMd(t)}{dt} = - \frac{dMa(t)}{dt} = Ma(t) \cdot Arra \cdot i(t)^{wash}$$

where $Md(t)$ is the mass of pollutant washed away at time $t$ [kg/ha]; $Ma(t)$ is the total mass present over the catchment at time $t$ [kg/ha]; $Arra$ is the washing coefficient whose dimensions are [length$^{-wash}$, time$^{wash-1}$]; $wash$ is a dimensionless numerical parameter; $\Delta t$ is the time step [h]; $i(t)$ is the mean intensity of precipitation in the fixed time step [length$^1$ time$^{-1}$].

The values assumed by the parameters $Arra$ and $Wash$ depend on various factors such as the kind of substance washed away, the intensity of the precipitation and the shape of the catchment. Their variability is discussed in the literature (Ammon 1979, Sueishi et al. 1984, Nakamura 1984).

Using the storing up and washing away processes, pollutographs were developed. Figure 3 shows flows and a pollutograph from the catchment just upstream of the CSO. Figure 4 shows the flow over the CSO into the river, and the concentration of pollutants that go over the overflow into the river.

Having derived the polluto-graphs for the CSO, the next step was to simulate the effect of these polluto-graphs in the river.

**River model**

An initial simulation using the InfoWorks RS model was made to simulate the pollutants in the river with no storage tanks, see Figure 5. This simulation showed
two pollutant disturbances in the outlet: the first peak is due to the southern Lambro overflow, which is the nearest to the catchment outlet; the second derives from the combined effect of the two northern overflow discharges. The hydraulic effects, in terms of discharge and velocity variations, of the northern overflows are not evident due to the attenuation of the flows in the river.

Next, the normative criteria were used to size the storage tanks for each CSO. Then the InfoWorks RS model was re-run with the storage tanks at the CSOs. The resulting river quality is shown in Figure 6.

The hydraulic simulation with the storage tanks showed only one increase in the flow and pollutants in the outlet of the Lambro River even though there are three overflows into the catchment. Again the southern Lambro overflow, which is the nearest to the outlet, dominates the peak flow.

The pollutants levels in the figures are conservative as the chemical and biological decay processes are not simulated during the short duration of the overflow event (the pollutants reach the overflow outlet within 4 h).

However, of greater interest is the comparison of the size of each storage tank calculated using the law (D.L. vo 152/2006), and using the model to retain the first flush volume (see Table 5). With the model, the storage tanks were sized in order to discharge in the river water with the same pollutant concentration already existing in the river. This assumption is quite strict, but with dynamic modelling a number of criteria can be selected and the carried out solutions correctly evaluated.

In this case, the required size of the Bevera storage tank calculated with the law is larger than that calculated using the model. A comparison of the sizes for the Lambro up-stream CSO tank shows the law requires a slightly larger tank than the model. However, a comparison of the Lambro down-stream tank sizes shows that the law significantly under-estimates the size of the tank needed to retain the first flush.

The carried out differences obviously depend on the different catchments characteristics.

The volumes computed using the normative criteria depend only on the extent of the urban catchment. They do not consider important factors such as: the typology of the storage tank, if it is built on-line or off-line, the behaviour of the network and the shape or the kind of urbanisation of the catchment. However, it was noted that although the number and density of people living in the catchments upstream of each CSO are different (see Tables 3 and 4), there was no apparent correlation between the number of inhabitants and the rate of pollution. Hence the law would appear to be correct in not requiring that particular factor to be considered in sizing the CSO storage tank.
Table 5. First flush volume calculated with the normative criteria and the modelling results.

<table>
<thead>
<tr>
<th>Law</th>
<th>Bevera</th>
<th>Lambro upstream</th>
<th>Lambro downstream</th>
</tr>
</thead>
<tbody>
<tr>
<td>525 m³</td>
<td>1750 m³</td>
<td>1750 m³</td>
<td></td>
</tr>
<tr>
<td>51 m³</td>
<td>1710 m³</td>
<td>3131 m³</td>
<td></td>
</tr>
</tbody>
</table>

Conclusions

This paper used a case study to evaluate the efficiency of the Italian law that defines the normative criteria for designing CSO storage tanks, aiming to limit pollution of water bodies. The study found that the current law, which is based on an effluent standard approach, can significantly underestimate the size of the CSO storage tanks needed to prevent pollution. An alternative is to change the law to use a stream standard approach and require the CSO tanks to be sized based upon the volume and concentration of the pollutants at the CSO. By using a dynamic model of the river, the study showed that it was possible to provide a more accurate estimate of the size of the CSO storage tanks required to prevent pollution. This approach was further justified by a lack of reliable literature data that can be used to determine the effect of CSOs to river water quality and hence allow for a reliable evaluation of the required changes to the size of CSO storage tanks.

List of symbols

- $a$: parameter of the DDF curve [mm h$^{-1}$]
- $h$: rainfall depth [mm]
- $h_{\text{average}}$: mean altitude of the catchment [m asl]
- $h_{\text{outlet}}$: altitude of the catchment outlet [m asl]
- $i$: rainfall intensity [mm h$^{-1}$]
- $n$: parameter of the DDF curve [dimensionless]
- $t$: time [seconds, hours or days according with the phenomenon]
- $\text{wash}$: numerical parameter [dimensionless]
- $A$: catchment area [ha or km$^2$] according with the formula
- $\text{Acc}$: storing up coefficient [kg ha$^{-1}$ day$^{-1}$]
- $\text{Arra}$: washing coefficient [m$^{-1}$ day$^{-1}$ (wash$^{-1}$)]
- $C$: afflux coefficient [dimensionless]
- $\text{Disp}$: disappearance coefficient [day$^{-1}$]
- $H$: mean elevation of the catchment referred to the outlet [m]
- $L$: length of the main reach in the catchment [km]
- $Ma$: mass accumulated in the catchment [kg ha$^{-1}$]
- $Md$: mass of pollutant washed away by the rainfall [kg ha$^{-1}$]
- $Q$: discharge [m$^3$ s$^{-1}$]
- $T$: return period [years]
- $Tc$: concentration time [h]
- $\vartheta$: rainfall duration [h]

References