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Simulation of the Impact of Combined Sewer Overflow on Rivers

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Niels Bent Johansen, Thorkild Hvitved-Jacobsen and Poul Harremoës

Combined sewer overflows can in some cases cause critical oxygen concentrations in small rivers. The traditional design criteria for the overflow structures is not specificly related to this effect. By combination of a long historical rain series, a runoff model and a river quality model, it has been possible to achieve operational design diagrams for overflow structures. The diagrams are statistically based and relate the independent parameters for the catchment, the overflow structure and the river to the effect in question, the oxygen concentration.

Introduction

Modelling of the urban runoff process has grown into an accepted tool in water-quality management and planning during the last ten years. Much effort has been put into development of different types of models. An integrated part of the models is computation of overflow volumes and loads to the receiving waters from the combined sewer system. Status today is that many alternatives, from simple manual to complicated computer based methods, exist for these computations (Arnell et al. 1983). It is another fact that the resulting effect of these overflows to the receiving waters is of very high interest and the number of investigations and computation methods which has been developed in this field is very limited. The practise today is to design the overflow structures based on the number of overflows per year or the dilution coefficient between rain-water runoff and dry-weather flow at the time the overflow starts to operate. The values are selected without any specific consideration for the relation to the effect in the receiving waters in question.

The improvements made during recent years to the treatment of the daily flow of wastewater to the receiving waters can make combined sewer overflow the dominating source of pollution to rivers and lakes. It is therefore important that today's practise be changed, so that future investments in improvement of the sewer system will reduce the discharged pollution to a level which is in accordance with the capacity of the receiving waters, giving the preset water quality. The necessary basis for a change like that is an effective computational tool which links the characteristics of the catchment and overflow structure with the receiving water characteristics resulting in immediate answers to the question: Is it tolerable for the receiving waters to build a given overflow structure in a given catchment?

The method described in this paper can be a valuable tool in answering these questions for the most sensitive receiving waters, the small rivers. It is not unfamiliar that the overflow from large rain events can reduce the oxygen level to practically zero in such cases.

Basic Computational Principle

Fig. 1 illustrates the basic principle for the computational procedure. Based on a long rain series a series of overflow events are computed by a runoff model for the specific structure and catchment. By a receiving water quality model these overflow events are transformed into resulting minimum oxygen levels for the rivers in question. Based on rank order statistics the empirical distribution function for the minimum oxygen level can be obtained.

From these functions it is possible to read the minimum oxygen level for a given return period. By comparison of this actual curve to standard curves the overflow structure can be evaluated as acceptable/non-acceptable. In this quite complicated procedure many simplifications must be introduced to the ideal computational components. This is described in detail in Spildevandskomiteen (1984) and Hvitved-Jacobsen (1984). In the following paragraphs the basic characteristics of the computer models will be described.

Runoff Model

The overflow volumes and load of pollutants are computed by the runoff model SAMBA, Johansen et al, (1983); Johansen et al. (1983a); Spildevandskomiteen (1984).

The basic features of this model are:

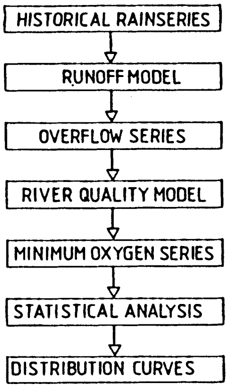

Fig. 1. Basic principle for computation of minimum oxygen level from overflow to rivers.

- Computation of runoff volume by means of initial loss and runoff coefficient for paved areas.
- Pipe hydraulics are computed by means of a modified time-area model, where the time of concentration (and thereby the time area curve) is computed for each specific rain event.
- Computation of overflow from basins and overflow structures by means of constant interceptor capacity.
- Computation of pollutografs by a simple mixing between pollution transported by dry-weather flow and pollution transported by rainwater runoff. The concentration of each component is assumed to be constant during the event. Furthermore, only the total quantity of pollutant discharged in an event is of importance – not the distribution within the event.
- Complete mixing between dry weather flow and rain-water runoff when the overflow is operating.

It is evident that the model expresses a simplification of the complete theory for the processes involved in the runoff transformation. However, comparisons to other types of hydraulic models shows that it gives practically the same overflow volumes as a kinematic wave model (ILLUDAS), Johansen (1981) and comparisons to measurements shows close agreement between measured and computed values, Johansen et al. (1984).

River Quality Model

The river quality model is based on the assumption that the dominating process is the delayed oxygen consumption i.e. the removal of the organic substances from the water phase by absorption and sedimentation takes place without consumption of oxygen. The organic matter becomes fixed to stationary objects. In this fixed position the organic matter is subsequently degraded with a delayed oxygen consumption exerted on the water passing by. (Hvitved-Jacobsen and Harremoës 1982; Harremoës 1982; Hvitved-Jacobsen 1982; Miljøprojekter nr. 36 1981).

The oxygen concentration in the river can be expressed by Eqs. (1) to (3)

$$C = \bar{C} + \Delta C \frac{\beta}{\Delta\beta} - \frac{L'_o}{K_2/K' - 1}\left(e^{-K' t_h} - e^{-K_2 t_h}\right) \tag{1}$$

$$K' = \frac{k}{h} \tag{2}$$

$$L'_o = K_4 \frac{P}{Q_{ov}+Q_b} e^{-K_4 t} \tag{3}$$

where

C – Oxygen concentration
$\bar{C}$ – Mean daily oxygen concentration in the river
ΔC – Maximum daily fluctuation in oxygen concentration
β, $\Delta\beta$ – Constants giving the scale of the daily fluctuations (Simonsen and Harremoës 1978)
K_2 – Reaeration constant
t_h – Residence time in the river from the point of outlet
t – Time from passage of the polluted plug
k – 1' order removal constant for adsorption or sedimentation
h – Water depth
K_4 – 1' order degradation constant for organic matter fixed to stationary objects
P – Total load of organic matter during one overflow event, expressed as COD
Q_{ov} – Flow passing the overflow weir
Q_b – Baseflow in the river.

Several assumptions have been made deriving this equation (Hvitved-Jacobsen 1984):

- Constant width, depth, velocity and slope in the river reach in question.
- No longitudinal dispersion.
- The overflow duration is small compared to the period in which the effect acts on the river.
- Constant flow over the weir and constant baseflow in the river.

Computations

By means of the presented models a number of alternative configurations have been computed. The basic rainseries is the series from the town of Odense, with 1,571 events recorded during 33 years (Spildevandskomiteen 1984a). Table 1

Table 1 – Independent parameters.

Parameter	Symbol	Value
Concentration in dry weather	L_d	450 g COD/m^3
Concentration in rainwater runoff	L_r	120 g COD/m^3
Reaeration constant	K_2	3d^{-1}
Degradation const. for fixed organic matter	K_4	2.5 d^{-1}
Removal constant	k	1.5 m/d
Interceptor capacity	a	0.1; 0.3; 1.2; 2.6 μm/s
Full flow runoff time	t_f	5; 10; 30 min.
Intensity of dry weather flow	q_s	0.04; 0.2 μm/s
Impervious area	F_r	1; 5; 25 ha
Maximum oxygen fluctuation	ΔC	0; 4 g/m^3
Storage volume	V_b	0; 3; 10 mm
Baseflow in the river	Q_b	0.05; 0.1; 0.3 m^3/s
Water depth	h	0.1; 0.2; 0.5 m

shows the independent parameters with the selected values or range of values.

By introducing dependency between some of the parameter the total number of independent combinations was reduced to 576. For each event the oxygen profile in time and space (expressed by t and t_h) was found by varying t and t_h in the interval $0 \leqslant (t, t_h) \leqslant 23$, giving 576 combinations. In the end Eqs. (1) to (3) had been computed app. 14 mill. times.

An example of the result of such a computation is shown in Fig. 2. It is clearly seen that the oxygen concentration reaches zero for t_h from 1 to 10 and t from 0 to 5. For a given section in the river e.g. $t_h = 5$ the oxygen level will be zero from the polluted plug passes ($t = 0$) to 5 hours after the plug has passed. Thereafter the oxygen level slowly raises and for $t = 23$ it has not regained the original value.

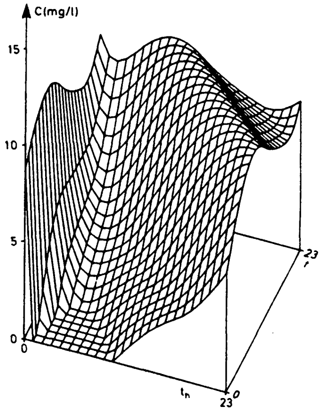

Fig. 2. Resulting oxygen profile from a discharge of 127 kg COD to a river with $\dot{Q}_b \equiv 50$ l/s. The discharge took place at appr. 1pm in July.

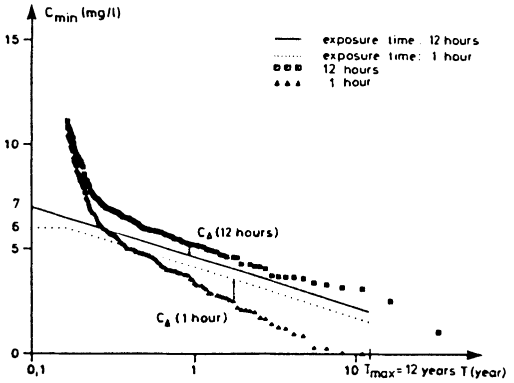

Fig. 3.
Distribution functions for a given min. oxygen level on 1-hour and 12-hour basis. By means of standard curves C_Δ, the minimum of the difference of the actual curve and the standard curve can be computed.

Results

For each of the independent combinations the minimum-mean oxygen levels for a 1-hour (C_{min} (1hr)) and for a 12-hour (C_{min} (12 hr)) period was computed by a moving average method. By rank order statistics a return period can be assigned to each value of C_{min} (1 hr) and C_{min} (12 hr). Eq. (4) expresses the relationship between rank (lowest value has rank m = 1 etc.) and return period

$$T = \frac{N}{M} \tag{4}$$

T – Return period
N – Observation Period (33 years for the rainseries from Odense)
m – Rank of C_{min}

For each independent combination curves like Fig. 3 can be obtained. It is seen that the minimum oxygen concentration for 12-hour exposure time is higher than the concentration for the 1-hour exposure time. In the figure is shown proposed standards for trout fishing water. (Hvitved-Jacobsen 1984). The standards express that in the rare events it is permissible to have lower oxygen concentrations than in the more frequent events. The difference C_Δ (T) between the actual curve and the standard curve can be computed for each value of T. The minimum of C_Δ is then an indicator of whether the conditions in the river are acceptable or not.

By plotting C_Δ as a function of the independent parameters as shown in Fig. 4 an operational diagram for evaluations of the effect of combined system overflows on rivers is achieved. A total of 16 diagrams have been produced, each with 9 curves relating C_Δ to a and V_b for each value of Q_b and h. Fig. 4 examplifies that an overflow structure with a = 0.1 µm/s and V_b = 0 mm will give unacceptable conditions (C_Δ is negative) in a river with Q_b = 50 l/s. Even addition of a storage volume of 10 mm will not give acceptable conditions. If the value of a was raised to 0.2 µm/s and 10 mm storage was kept the outlet could be accepted.

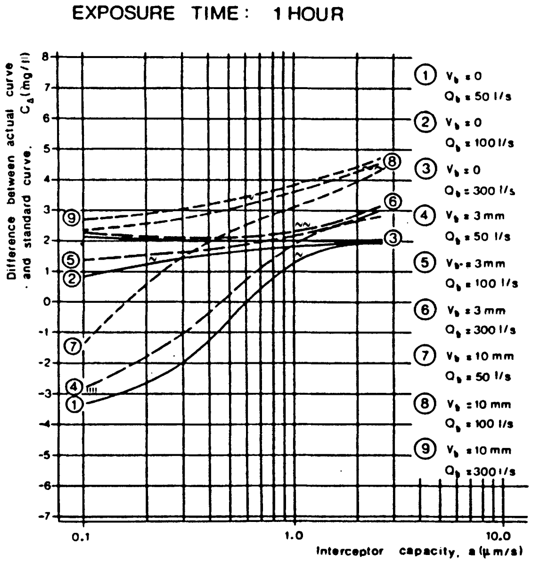

Fig. 4.

Diagram for evaluation of effect on river quality from overflows. $t_f \equiv 5$ min; $qs = 0.2$ μm/s; $F_r = 1$ ha; $\Delta C \equiv 4$ g/m^3.

Conclusions

It has been demonstrated that by combining a runoff model and a river quality model it is possible on the basis of historical rain series to make an effective tool for statistical evaluation of combined system overflows to rivers. By the method it is possible to exchange the old empirical design criteria for overflow structures, dilution coefficients and overflow frequencies, by effect related diagrams based on the physical and biological phenomena involved in the process.

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Address:
Niels Bent Johansen,
COWICONSULT, Consulting Engineers and Planners,
45 Teknikerbyen,
DK-2820 Virum,
Denmark.

Thorkild Hvitved-Jacobsen,
Environmental Engineering Laboratory,
Department of Civil Engineerng,
University of Aalborg,
57 Sohngaardsholmsvej,
DK-9000 Aalborg, Denmark

Poul Harremoës,
Department of Environmental engineering,
Building 115,
Technical University of Denmark,
DK-2800 Lyngby,
Denmark.