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THE IMPACT OF COMBINED SEWER OVERFLOWS ON THE DISSOLVED OXYGEN CONCENTRATION OF A RIVER

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Abstract—As described in the preceding paper by Harremoës (Harremoës, *Water Res.* **16**, 1093–1098, 1982) it is important to distinguish between removal and degradation of organic matter for non-steady-state discharges to rivers. These effects were investigated to determine the impact of combined sewer overflows on the dissolved oxygen concentration of a small river. Two different effects on the DO-concentration in the receiving river were observed during and after the passage of the bulk of combined sewage discharged at an existing outlet:

1. An immediate effect caused mainly by degradation of the soluble BOD-fraction in the water body and by direct absorption and degradation of organic matter at the bottom.
2. A delayed effect caused by degradation of adsorbed soluble, colloidal and fine particulate organic matter. After the passage of the bulk discharge a delayed effect on the DO-concentration in the river would be observed. This delayed effect lasted 12–24 hours after the discharge event.

Only 4% of the discharged organic matter was degraded during passage of the investigated stretch of the river, approx. 4 km. On the other hand about 35% of the discharged organic matter was removed by transfer to the bottom sediments. The rest was carried past the stretch of river investigated. This results in a rate of adsorption from the water phase of $k = 9\ \text{m day}^{-1}$. The deposited organic matter was degraded with a first order reaction rate of $K_4 = 0.75\ \text{day}^{-1}$.

NOMENCLATURE

A = Index for an upstream station
B = Index for a downstream station
b = Width of river, m
BOD = Biochemical oxygen demand, mg l^{-1}
C = Concentration of dissolved oxygen, mg l^{-1}
C_s = Saturation concentration of dissolved oxygen, mg l^{-1}
COD = Chemical oxygen demand, mg l^{-1}
DO = Dissolved oxygen, mg l^{-1}
h = Water depth, m
k = I' order rate of adsorption from water phase, m day^{-1}
K_1 = I' order rate of degradation in water phase, day^{-1}
K_2 = Reaeration constant, day^{-1}
K_4 = I' order rate of degradation in the sediments, day^{-1}
K_r = Rate of total degradation in the river, day^{-1}
L_b = Amount of adsorbed organic matter per unit area of bottom, g COD m^{-2}
N = Transport of adsorbable organic matter during discharge, g COD
P = Production in the river, $\text{g O}_2\ \text{m}^{-2}\ \text{day}^{-1}$
R_{tot} = Total respiration in the river, $\text{gO}_2\ \text{m}^{-2}\ \text{day}^{-1}$
SS = Suspended solids, mg l^{-1}
t = Time after discharge, days
t_h = Residence time from point of discharge, min
u = Velocity in river, m s^{-1}
x = Distance from point of discharge, m
ϵ_z = Vertical diffusion coefficient, $\text{m}^2\ \text{h}^{-1}$.

INTRODUCTION

During recent years in Denmark municipal wastewater has been increasingly treated with attention mostly to dry weather flow. Since 1974 such efforts have been demanded by the Danish Environmental Protection Act, which states the environmental considerations to be observed.

The relative importance of storm overflows from urban areas as a source of pollution to the aquatic environment is therfore increasing. Discharge from a combined sewer system into a river is a special, but very important case. The problem is often that a town of 1000–10,000 inhabitants discharges untreated, but diluted municipal wastewater from storm overflows into a stream with a natural flow of $25\text{–}500\ \text{l s}^{-1}$. During intensive storms the flow may for short periods increase several hundred percent.

With The Water Pollution Control Committee as coordinator and financial support from The National Agency of Environmental Protection an investigation is being carried out to determine the effects on the receiving stream of storm overflows from a combined sewer. The hydraulic, physico-chemical and biochemical parts of this investigation are being carried out by the University of Aalborg, while the biological part is in the hands of the Freshwater Laboratory of the Agency of Environmental Protection. The investigations were scheduled to take place from 1978 to 1981. A preliminary report has been prepared, Hvitved-Jacobsen *et al.* (1979). The most important part of the investigations deals with the effect of the combined sewer overflows on the dissolved oxygen concentration of the receiving stream.

In Denmark as elsewhere, several investigations have been carried out during recent years in order to determine the content of pollutants in the run-off water, e.g. Harremoës (1977) and Johansen (1974). Few investigations deal with the impact on the receiving water bodies (Horner *et al.*, 1977; Pitt *et al.*, 1977; Smith *et al.*, 1978; Meinholz, 1980). Those investigations, however, do not describe in detail the processes involved in the oxygen consumption. The primary objective of this investiagion is to get a better understanding of the impact on the water quality of the receiving streams. The results are intended to be used as a basis for guidelines for the protection of the water quality of the receiving waters from stormwater discharges and combined sewer overflows.

INVESTIGATED AREA

The investigation was carried out in river Skravad, a small triburary to the river Skals located in the middle of Jutland, Denmark (Fig. 1). The total length of river Skravad is 15 km and the part investigated has a length of approx. 4 km, and on average a width of 2.5 m and a depth of 0.25 m.

About 5.5 km upstreams from the confluence with river Skals the stream receives biologically treated wastewater from Møldrup sewage treatment plant. From Møldrup township, which has a combined sewerage system and covers an area of about 70 ha, the storm overflows discharge through a ditch to river Skravad just downstream from the outfall from the sewage treatment plant (Fig. 2).

Møldrup has about 1000 inhabitants and some industrial activities, among them a dairy and a small abattoir. This means a base discharge of BOD amounting to a population equivalent of 2000.

Apart from the outfall from the sewage treatment plant the river Skravad receives water from drainage and surface run-off from rural areas only. This has been an important argument for the choice of river Skravad as investigation area.

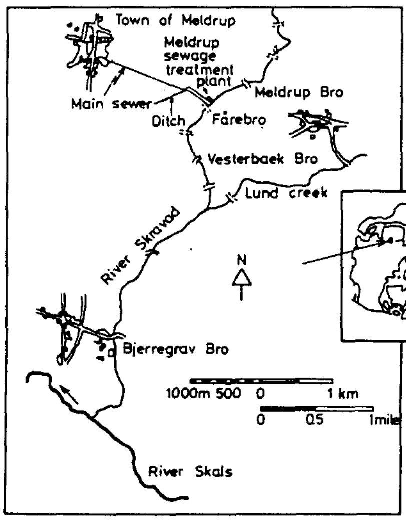

Fig. 1. Map of the investigated area, river Skravad. The position of this area on the map of Denmark is shown.

The investigation started in autumn 1978 at which time the following characteristics were found:

Rate of stream reaeration $K_2(20) \sim 10\,\text{day}^{-1}$
Total respiration $R_{tot} \sim 2.5\,gO_2\,m^{-2}\,\text{day}^{-1}$
Production P $\sim 0.3\,gO_2\,m^{-2}\,\text{day}^{-1}$
Biochemical oxygen demand $BOD_5 < 2$–$3\,mgO_2\,l^{-1}$

Determination of K_2, R_{tot} and P was carried out by means of the twin curve method (Simonsen & Harremoës, 1978). At dry-weather flow there is little variation in the DO-concentration throughout the day and night, e.g. 9–10 mg l^{-1} with a saturation value of 11.0–12.5 mg l^{-1}. Favourable oxygen conditions exist even though the stream receives treated wastewater. This is due to the fact that the dilution at the point of discharge is greater than about 15 and because of the high reaeration coefficient.

Apart from short periods with growth of aquatic plants during summer the DO-concentration throughout day and night exceeds 6 mg l^{-1}. With respect to the oxygen conditions the stream investigated can thus be characterised as favourable for a diverse flora and fauna and trout are often observed in the stream. It is therefore to be expected that occasional overflows would have a relatively minor effect on the water quality. However, the objective of this investigation is to obtain general information on what happens due to an abrupt discharge of diluted waste water, not whether the effects are more or less serious in this particular case.

OXYGEN CONDITIONS DURING DISCHARGE OF COMBINED SEWER OVERFLOWS

From a theoretical point of view the classical Streeter–Phelps model is able to describe the deoxygenation and physical reaeration in streams during steady-state conditions. The model can be further developed by considering more processes and improving the description of these.

During dry-weather periods approximately steady-state conditions often prevail, and removal of organic matter from the water body will be equivalent to the amount of BOD oxidized whether the degradation takes place in the water phase or at the bed.

During non-steady-state situations, for instance during discharge of combined sewer overflows, the concentration of organic matter will increase in the water phase. Removal of organic matter from the water body will increase too and will exceed the actual degradation at the bottom. This again implies a subsequently increased degradation at the bottom and a delayed oxygen demand after the passage of the bulk discharge. Therefore, the non-steady-state condition requires distinction between an immediate and a delayed effect on the DO-concentration. The preceding paper by Harremoës describes these processes in detail (Harremoes, 1982).

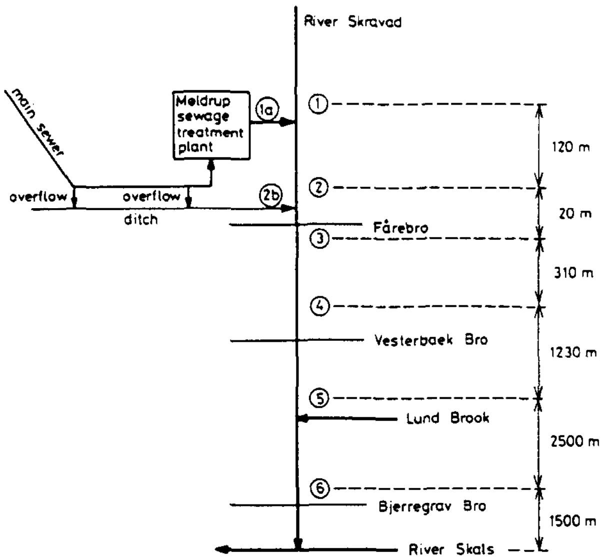

Fig. 2. Schematic representation of the investigated part of the river Skravad. Stations for sampling and DO-concentration measurements are shown.

After overflow from a combined sewer the DO-concentration in the receiving water results from:

(I) Mixing of combined sewer overflow and water from the receiving stream.

(a) Different DO-concentration of the mixing components (quality).

(b) Variation in discharge of the mixing components (quantity).

(II) The DO-influencing processes in the stream. Among the various processes which reduce the DO-concentration in a stream oxygen consumption by degradation of organic matter is expected to be the most important one. A distinction must be made between:

(a) An immediate oxygen consumption which is assumed to be due to: degradation in the water body; absorption by benthic organisms. Both processes are mainly due to degradation of dissolved organic matter.

(b) A delayed oxygen consumption caused by: degradation of adsorbed soluble, colloidal and fine particulate organic matter; degradation of settled particulate matter.

METHODS

Since the purpose of the investigation is primarily to examine the stream response to the combined sewer overflow, the processes mentioned under (II) of the previous section are of special interest.

The investigations were carried out by means of artificial overflows. The day before the artificial overflow was to take place, water from the river Skravad and raw waste water from Møldrup in proportions 10:1 was pumped into a reservoir of 370 m^3 at the wastewater treatment plant. On the day of investigation this mix was discharged through a ditch into river Skarvad (Fig. 2).

The artificial overflows were carried out to resemble existing overflows hydraulically as well as in their quality characteristics. The following data characterize the artificial overflow of 9 November 1978:

Duration of overflow: 70 min

Discharged quantity of water: 215 m^3

Flow in ditch before overflow: 10 l s^{-1}

Maximum flow in the ditch during overflow: 110 l s^{-1}

Flow in river Skravad just upstream of the outlet from the ditch: 120 l s^{-1}

DO-concentration in the ditch during overflow: 4.5–6.5 mg l^{-1}

DO-concentration in river Skravad just upstream of the outlet from the ditch: 10.5 mg l^{-1}

Quantity of BOD in the discharged water: 15 kg BOD_5.

Throughout the whole period of investigation it was observed that the DO-concentration curves during day and night in dry-weather situations at Stas 2–6 had nearly the same shape. This proved to be very useful for the evaluation of DO-variations caused by the overflow. The DO-concentration curves at the various stations were thus assumed to be identical in such a way that they could be brought to cover each other through (1) change in concentration level and (2) adjustment of time corresponding to the time of travel between the stations.

The effects on the DO-concentration in the stretch affected by the overflow was calculated by comparing the concentration curves at Stas 3–6 with that of Sta. 2, which can be regarded as unaffected (Fig. 3).

It has been demonstrated that no difference between results from simulated overflows as compared to results from real discharges can be detected (see a later section).

IMMEDIATE EFFECT IN THE RIVER

As previously mentioned, the immediate oxygen consumption takes place during the passage of the bulk discharge due to degradation in the water phase and absorption at the bed.

Figure 3 shows the response to an artificial overflow carried out on 8 November 1978 between 12.00

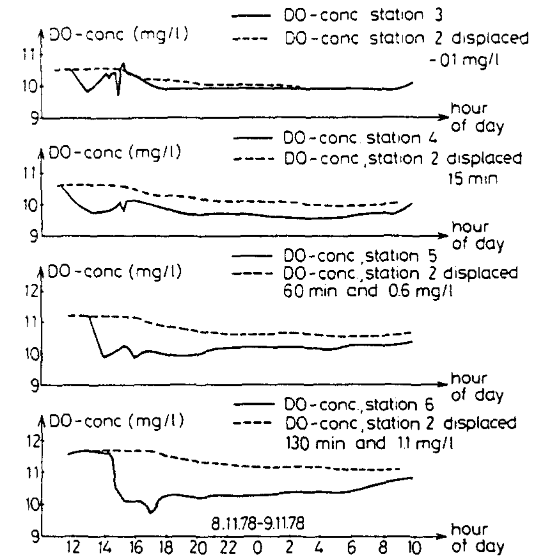

Fig. 3. DO-concentration at Stas 3–6 before, during and after a discharge compared to expected DO-concentration if no discharge had taken place (curve transferred from Sta. 2).

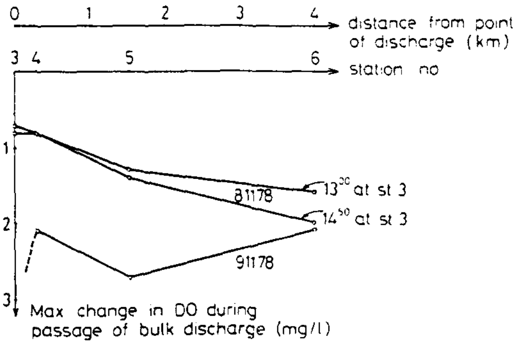

Fig. 4. Maximum difference in DO-concentration between the actual value during passage of bulk discharge and expected value assuming dry weather flow only.

and 15.30 h. The overflow discharge was moderate. The maximum flow in the ditch was $50\,l\,s^{-1}$ and the flow was greater than $20\,l\,s^{-1}$ for only half and hour. The DO-concentrations at Sta. 3 shows the effect on the stream immediately downstream of the outlet from the ditch where the mixing with the stream water takes place. The flow in the river upstream of the ditch was $120\,l\,s^{-1}$.

The immediate oxygen depletion within the 4 km stretch between Stas 3 and 6 can be perceived by following the two minima on each of the observed DO-concentration curves. These minima appear at 13:00 and 14:50 h at Sta. 3 and at 15:10 and 17:00 h respectively at Sta. 6. The difference between the measured DO-curve and the curve transferred from Sta. 2, corresponding to the assumed variation with no overflow, gives the variation in oxygen depletion caused by the overflow.

Because of the high atmospheric reaeration rate very low values of the DO-concentration are not likely to occur. During an artificial overflow the following day, 9 November with a greater DO-depletion at Sta. 3, the resulting maximum depletion at Sta. 6 was still around $2\,mg\,l^{-1}$ (Fig. 4), even though the BOD_5 mean value was around $30\,mg\,l^{-1}$ during the passage of the bulk discharge.

Based on the measurements from 9 November when the stream temperature was 9°C, the following parameters were calculated for the passage of the bulk discharge:

Rate of degradation in water phase: $K_1 = 0.15\,day^{-1}$

Rate of total degradation in the river: $K_r = 0.9\,day^{-1}$.

K_1 was measured using a BOD-bottle while K_r is based on the measured oxygen sag curve. These values imply that only about 4% of the total BOD discharge was degraded immediately while the bulk discharge passes from Stas 3 to 5. The difference between K_r and K_1 shows the importance of degradation of organic matter at the river bottom.

DELAYED EFFECT IN THE RIVER

The delayed effect on the DO-concentration is due to the degradation at the bed of settled particulate matter and/or adsorbed organic matter. This is shown in Fig. 3, when the delayed effect appears after 16:00 h at Sta. 3 and 15, 60 and 130 min later at Stas 4, 5 and 6 respectively, corresponding to the pertinent time of travel from Sta. 3. Measurements with tracer (rhodamin B) indicate that the observed effect cannot be due to the delay of polluted water in the dead-zone volume of the stream. Depending on the actual adsorption, sedimentation, desorption and resuspension, the observed delayed effect on the DO-concentration will vary from one discharge event to another. The flow conditions in the stream may also be important. Typically though, the delayed effect had a duration of 12–24 h.

The total respiration (R_{tot}) of the stream determined immediately prior to the simulated overflow on 8 November 1978 showed a decrease in the downstream direction. This is due to the effluent from the sewage treatment plant, the effect of which tapers off with distance downstream of the outlet. The values of R_{tot} determined immediately after the overflow had passed on 8 and 9 November 1978 show a much slower decrease (Fig. 5).

The relative importance of adsorption versus sedimentation is determined from a mass balanced between Stas 3 and 5. Only SS, COD_{tot}, COD_{filt} and COD_{part} are taken into account (Fig. 6). The latter is defined as the difference between the COD of a non-filtered and a filtered sample:

$$COD_{part} = COD_{tot} - COD_{filt}.$$

For the period of passage of the bulk discharge on 9

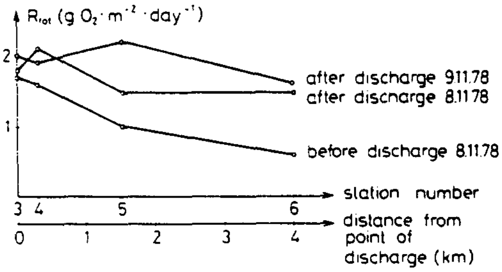

Fig. 5. Total respiration in river Skravad before and after discharge on 8–9 November 1978.

November 1978, the following results were obtained (Fig. 7):

ΔSS = eroded − removed
= output − input = 5 kg SS 70 min^{-1}
ΔCOD_{tot} = eroded − removed
= output + degraded − input = −14 kg COD 70 min^{-1}
ΔCOD_{part} = eroded − removed
= output − input = −3 kg COD 70 min^{-1}.

Thus a certain net erosion takes place. The eroded matter, however, has a much lower COD than the deposited matter as ΔCOD_{part} is negative (10–15 mgO_2 g^{-1} dry matter vs around 1000 mgO_2 g^{-1} dry matter) but only insignificant quantities of particulate organic matter are exchanged at the bottom. Due to the relatively steep slope of bed (0.2%) it is not surprising that no sedimentation in the river will take place.

According to the mass balance organic matter is mainly removed by adsorption at the bottom of soluble, colloidal and fine particulate matter:

$$\Delta COD_{filt} = \Delta COD_{tot} - \Delta COD_{part} = -11 \text{ kg COD } 70 \text{ min}^{-1}.$$

The delayed DO-consumption is therefore most likely due to degradation of the adsorbed fractions.

Removal of organic matter by adsorption is described by k which is the rate of adsorption from the

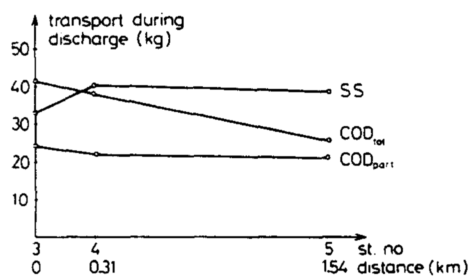

Fig. 6. Transport of COD and SS during the discharge on 9 November 1978. The quantities of substance transported during a dry-weather situation of some duration have been deducted.

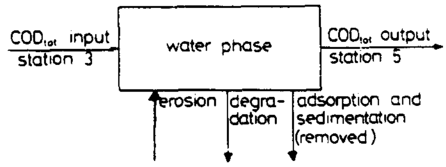

Fig. 7. Mass balance for the stretch between Stas 3 and 5 with COD_{tot} as an example.

water phase. This parameter is experimentally determined by:

$$L_b = -\frac{N_A - N_B}{(X_A - X_B)\cdot b} = \frac{k}{u\cdot h\cdot b}\cdot\frac{N_A + N_B}{2}.$$

The actual case results in $k = 9$ m day^{-1} as a mean value. The removal rate is thus $k/h = 36$ day^{-1}.

The adsorbed organic matter is assumed to be degraded by a first order reaction. The rate of degradation immediately after the passage of the polluted volume can be calculated from the following mass balance for DO considering atmospheric reaeration and degradation in the sediments:

$$u\cdot\frac{\Delta C}{\Delta x} = K_s(C_s - C) - \frac{K_4}{h}\cdot L_b.$$

This mass balance results in $K_4 = 0.75$ day^{-1}. It is remarkable that this value is extremely high compared to values from steady-state measurements, e.g. Velz (1970) states a K_4-value of 0.07 day^{-1}.

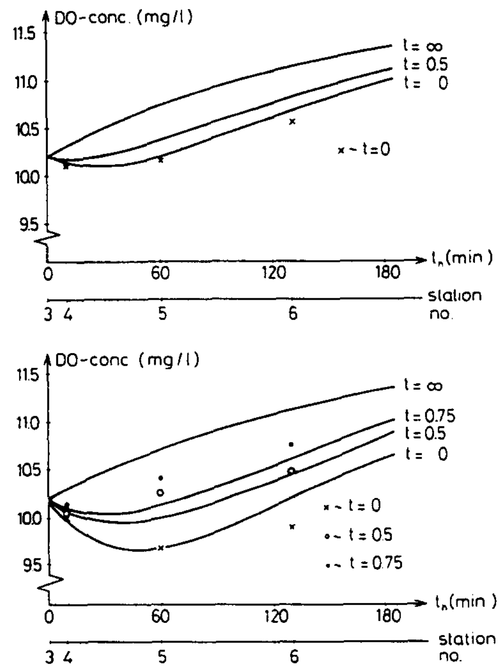

Fig. 8. Comparison between calculated and measured delayed effect on the DO-concentration in river Skravad 8–9 November 1978 (lower fig.) and 9–10 November 1978 (upper fig.). The curves show the DO-concentration at different times after termination of discharge. The curve for $t = \infty$ states the steady-state situation (dry weather).

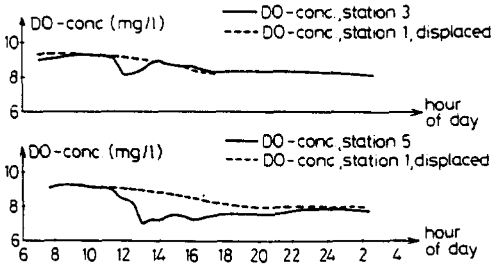

Fig. 9. DO-concentrations at the Stas 3 and 5 before, during and after discharge on 5 October 1978 compared to expected DO-concentration if no discharge had taken place (displaced curve from Sta. 1).

It is assumed, that the value of the vertical diffusion coefficient ϵ_z is approx. $10\,\mathrm{m^2\,h^{-1}}$. This means that the dimensionless quantity $k \cdot h/\epsilon_z \simeq 0.01$ is rather small and the removal from the water phase can be simplified to an exponential equation.

The necessary conditions for the use of the simple rate constants mentioned in the preceeding paper by Harremoës are thus fulfilled. With values of k and K_4 obtained, the effects on the DO-concentration can be followed as time passes (Fig. 8). As k and K_4 have been assumed constant, variations due to differences between day and night have been disregarded. The critical value of DO is seen to occur within a short distance of the point of discharge according to the high removal rate for adsorbable organic matter.

RESULTS FROM REAL OVERFLOWS

So far only measurements in connection with artificial overflows have been reported. Throughout the period of investigation, however, continuous observations of the DO-concentration in the stream and other pertinent parameters were carried out, although less intensively. Figure 9 shows the variations in DO-concentration at Stas 3 and 5 as compared to the variation in Sta. 1 during a natural overflow on 5 October 1978 from 10:00 to 16:00 h. The maximum discharge in the ditch was $170\,\mathrm{l\,s^{-1}}$ at 13:20 h. These results seem to agree quite well with the results obtained by means of artificial overflows with respect to both maximum depletion and timewise distribution of DO.

Figure 10 is a further illustration of the immediate and the delayed effect on the DO-concentration. It shows the DO-concentration at Sta. 6 during 5 consecutive days and nights. The period contained 2 overflow events. The immediate as well as the delayed effects are readily observed.

CONCLUSIONS

Combined sewer overflows to the investigated river Skravad have been demonstrated to result in two different effects on DO-concentration: An immediate effect and a delayed effect. The immediate effect takes place while the bulk discharge passes the river. The delayed effect is due to degradation of organic matter fixed to the bed by adsorption (see the preceding paper by Harremoës). Results have been obtained from natural as well as artificial overflows.

In the river investigated the immediate effect takes place by degradation in the water phase and by absorption at the bottom. The delayed effect is due mainly to degradation of organic matter adsorbed to the bed. It is possible to describe the delayed effect on the DO-concentration by the amount of adsorbed organic matter and a subsequent first order degradation at the bottom.

Due to the delayed effect, the oxygen depletion extends over a longer period than just the duration of the overflow. In the investigated river the oxygen concentration returns to dry weather conditions within 12–24 h.

The purpose of the investigations was to elucidate the effects on the DO-concentration of a receiving stream resulting from combined sewer overflows and not the importance of these discharges to the river in

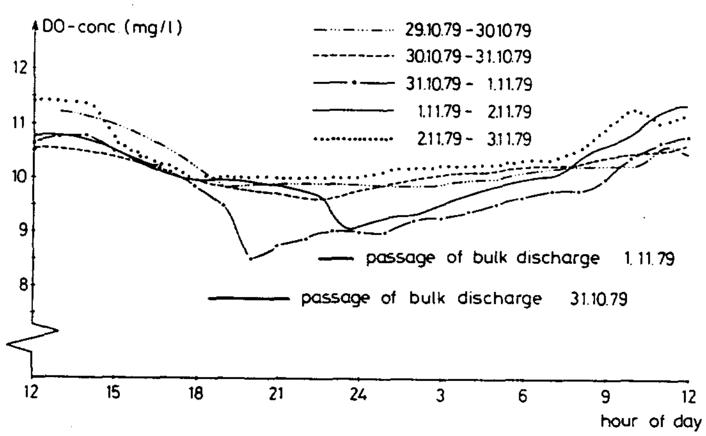

Fig. 10. DO-concentrations at Sta. 6 in the period 29 October–3 November 1979. Duration of passage of bulk discharge on 31 October 1978 and 1 November 1978 is indicated.

question. The investigations will continue and streams of different quality will be included.

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