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MOUSE TRAP: MODELLING OF WATER QUALITY PROCESSES AND THE INTERACTION OF SEDIMENTS AND POLLUTANTS IN SEWERS

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ABSTRACT

A water quality model has been developed with the objective to describe the water quality processes in sewer systems. The model has the capability of simulating both dissolved and sediment attached pollutants. This paper describes the modelling approach for the water quality processes and it demonstrates a small application of the water quality model to a gravity sewer operating under aerobic conditions. The application shows that the transport of dissolved substance in sewers can be accurately described and that the water quality processes are simulated with acceptable results.

KEYWORDS

Advection-dispersion, mathematical model, MOUSE TRAP, sewer, water quality.

INTRODUCTION

As the knowledge of pollutant transport and water quality processes in sewers develops there is a simultaneous need for the establishment of state of the art modelling tools for the overall management of sewer systems. Predictions of pollutographs for combined sewer overflows as well as predictions of pollutant loadings to sewage treatment plants will be valuable information to managers of urban sewer systems. At present simplified models are used in the urban pollution management as there has been a lack of knowledge of the pollutant transport and water quality processes in sewers. However, the state of the art knowledge enables us to establish mathematical expressions for the main processes involved. The pollutants are carried through the sewer system both as dissolved matter in the water phase and attached to the sediments. Both of these transport processes must be included in the modelling of water quality processes. Sediment transport processes are important in relation to in-pipe erosion and deposition of sediment attached pollutants as well as to the retention of sediments with attached pollutants in basins and overflow structures. A new deterministic modelling tool called MOUSE TRAP has been developed in order to describe the transport of sediments , dissolved and sediment attached pollutants together with water quality processes in sewers. MOUSE TRAP is based on the MOUSE package developed by the Danish Hydraulic Institute, (Lindberg et al., 1986). The MOUSE package contains descriptions for the run-off from both pervious and impervious catchments and a pipe flow model which solves the full St. Venant equations for looped sewer systems. This paper focuses on the water quality module of MOUSE TRAP and presents a case study which applies the advection-dispersion and the water quality module.

THE MOUSE TRAP MODULES

The modules in MOUSE TRAP all work in full integration with the MOUSE model offering the same facilities for results presentation and data transformations. Results are easily transferred to a river model such as MIKE11 for studies of the impact from combined sewer overflows on the water quality in the river. There are four new modules are embraced in MOUSE TRAP : Surface Runoff Quality (SRQ), Sediment Transport (ST), Advection - Dispersion (AD), and Water Quality (WQ). The SRQ module describes the transport processes on catchment surfaces whilst the ST, AD and WQ modules describe the processes in the pipe system. The ST, the AD and the WQ modules all run in parallel with the hydrodynamic module of the MOUSE system. These modules can be used individually or in combination except for the WQ module which is coupled to the AD module. The basic mechanisms and equations involved in the SRQ, ST and AD modules have previously been described (Mark, 1992; Mark et al., 1993).

THE WATER QUALITY MODULE

The in-pipe water quality module (WQ) is comprised of a suite of submodules to describe the biological and physical reaction processes of multicompound systems. These include the degradation of organic matter, bacterial fate, exchange of oxygen with the atmosphere, and oxygen demand from eroded sewer sediments. The WQ module is directly coupled to the transport modules AD and ST. This means that the calculation of transport of dissolved and suspended components within the flow is carried out simultaneously with the calculation of the effects of the biological processes. A facility for describing the diurnal variation of foul flow discharges and concentrations of user-specified foul flow components is available for usage with the WQ module. The WQ module simulates a variety of processes related to oxygen demand, as represented by either BOD or COD, dissolved oxygen (DO) and bacterial fate. At present, the model operates under aerobic conditions. Figure 1 shows the biochemical processes in sewers which are modelled in relation to DO, BOD/COD. Three state variables are used in the submodule to describe the BOD/COD - DO relations. The degradation of organic matter (expressed as BOD or COD) in sewers under aerobic conditions will be carried out by heterotrophic micro-organisms. The heterotrophic micro-organisms are considered to grow both in suspension and in the biofilm attached to the pipe walls. The biofilm attached to the walls and any sediment on the invert are modelled as one compartment, while the flowing sewage is modelled as a second compartment. Oxygen consumption is modelled in each of the two compartments using current knowledge concerning biofilm kinetics and activated sludge processes within the biofilm/sediments and flowing sewage respectively. It is assumed that oxygen supply is the limiting factor for the degradation of dissolved organic matter in the biofilm. This means that the diffusion of DO from the water phase into the biofilm determines the actual degradation of dissolved organic matter in the biofilm. This assumption will be valid for most sewer systems due to low oxygen concentrations and good supply of easy degradable organic matter creating a thick biofilm. However, heavy rainfall may flush the biofilm away and the assumption will fail. Inclusion of the oxygen consumption in biofilm is optional in the model. Suspended heterotrophic organisms are responsible for the degradation of dissolved organic matter in the water phase. The heterotrophic biomass constitutes a certain fraction of the suspended BOD/COD (0.5 - 1). The degradation of dissolved organic matter by this group of microorganisms can be modelled by the use of a fixed fraction of suspended organic matter as the biomass. This estimated biomass is then applied in a temperature dependent half saturation expression involving dissolved oxygen, dissolved organic matter and the biomass.

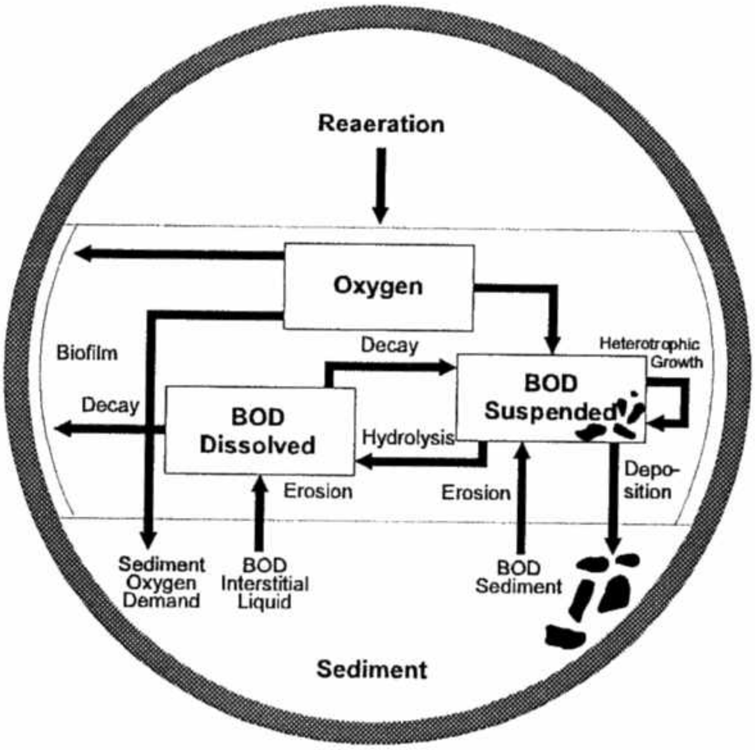

Figure 1. Water quality processes modelled in MOUSE TRAP.

Hydrolysis converts the suspended organic matter into dissolved substrate. This process, as described by (Henze et al., 1986), is a first order temperature dependent reaction including a hydrolysis constant. Suspended organic matter is also produced in sewers due to the growth of heterotrophic organism. This process can be modelled by applying a yield constant to the degradation rate of dissolved organic matter in the water phase. The oxygen consumption from eroded sediment is modelled as a constant value multiplied by the sediment volume eroded. The reaeration of the sewer is modelled by the use of a reaeration coefficient multiplied by the oxygen deficit. The reaeration coefficient is determined by a formulation where the coefficient is a function of local physical conditions (Pomeroy and Parkhurst, 1973). The bacteria Escherichia coli (E. coli) is normally considered non-pathogenic, but is very often used as an indicator for faecal pollution. The bacterial model distinguishes between two groups of coliforms: "Total coliforms" and " Faecal coliforms". "Total coliforms" may include a wide range of bacterial genera, of which many are not specific of faecal contamination. Further, a third group of bacteria is included in the model - Streptococci bacteria. The bacteria submodule assumes a temperature dependent first order decay of the three groups of bacteria.

MATHEMATICAL FORMULATIONS OF THE WATER QUALITY PROCESSES

The mathematical formulation of the most significant processes concerning the water quality are described in the equations below. BOD is used as the unit for oxygen demand.

Degradation of BOD_{dis} in biofilm. The degradation of dissolved BOD/COD in biofilm is described as a standard ½ order reaction combined with a temperature dependent oxygen diffusion and removal:

$$BOD_{degra,biofilm} = \Theta^{temp-20} \cdot \sqrt{2D \cdot k_{of}} \cdot DO^{1/2} \cdot A_{biofilm}/V \tag{1}$$

Θ = temperature coefficient
D = diffusion coefficient of oxygen in water at 20°C (m^2/s)
k_{of} = removal of oxygen in biofilm at 20°C ($g/m^3 \cdot s$)
$A_{biofilm}$ = area in pipe covered with biofilm (m^2)
V = water volume (m^3)

The value of D is 20.0 (Jansen, 1983; Andreasen, 1979) and k_{of} has been measured to 3.0 (Gujer et al., 1990; Arvin and Harremoës, 1990). Degradation of BOD_{dis} in biofilm is only activated when modelling oxygen consumption in biofilm.

Degradation of BOD_{dis} in suspension. The degradation of dissolved BOD/COD carried out by suspended heterotrophic is described as:

$$BOD_{degra,susp} = K_s \cdot \Theta^{temp-20} \cdot BOD/(BOD+k_{m,BOD}) \cdot DO/(DO+k_{m,DO}) \cdot k_b \cdot BOD_{susp} \tag{2}$$

K_s = μ_{max}/Y_{max} (Max growth rate at 20 °C / Max yield constant) (day^{-1})
$k_{m,BOD}$ = half-saturation constant, BOD dissolved (g/m^3)
$k_{m,DO}$ = half saturation constant, DO (g/m^3)
k_b = fraction of active heterotrophic organisms in BOD_{susp}

In the literature μ_{max} and Y_{max} vary from 3.0 to 13.2 day^{-1} and from 0.6 to 0.7 kg VSS/kg BOD, respectively (Hence et al., 1986). The values for $K_{m,BOD}$ and $k_{m,DO}$ which are used as fixed half-saturations in the model are 8 g BOD/m^3 and 0.3 g DO/m^3 (Hence et al., 1986; Arvin and Harremoës, 1990), k_b varies from 0.5 to 1.0.

Hydrolysis of BOD_{susp}. Hydrolysis of suspended matter is described as a temperature dependent 1st order reaction:

$$BOD_{hydro} = \Theta^{temp-20} \cdot k_{hl} \cdot BOD_{susp} \tag{3}$$

k_{hl} = 1st order decay constant at 20°C (day^{-1})

The value of k_{hl} is in the range of 0.05 - 0.10 day^{-1}.

Growth of heterotrophics (BOD_{susp}). The growth of heterotrophics depends on the BOD degradation in the water phase:

$$BOD_{growth} = Y_{max} \cdot BOD_{degra,susp} \tag{4}$$

Reaeration of waste water. The reaeration is calculated by multiplying the reaeration coefficient by the oxygen deficit:

$$\mathrm{REAR} = K1 \cdot (1 + K2 \cdot u^2/(g \cdot d_m)) \cdot (s \cdot u)^{K3}/d_m \cdot (C_s - DO)$$

$K1, K2, K3$ = reaeration constants
u = flow velocity (m/s)
g = gravity constant (m/s^2)
d_m = hydraulic mean depth (m)
C_s = oxygen saturation concentration (g DO/m^3)

APPLICATION OF MOUSE TRAP ADVECTION - DISPERSION AND WATER QUALITY MODULES

The MOUSE TRAP Advection-Dispersion and Water Quality Modules have been calibrated and validated against measurements on an intercepting gravity sewer.

Description of the gravity sewer. The gravity sewer is located in the Northern part of Jutland, Denmark. It transports waste water from the city of Dronninglund to the sewage treatment plant in Asaa. The waste water organic loading to the gravity sewer in terms of Person Equivalents (PE) is 4350 PE. The pipeline is a one string system with no other waste water discharge or infiltration along the sewer. The sewer is a concrete pipe with a diameter of 500 mm. 70 manholes are placed on the sewer stretch with a spacing of approximately 70 m. The average slope of the sewer is 2.72‰. Further details on the physical characteristics of the sewer as well as physical and biological measurements that are used in this paper are reported in (Raunkjær, 1993). The physical setup as represented in the MOUSE system is shown in Figure 2.

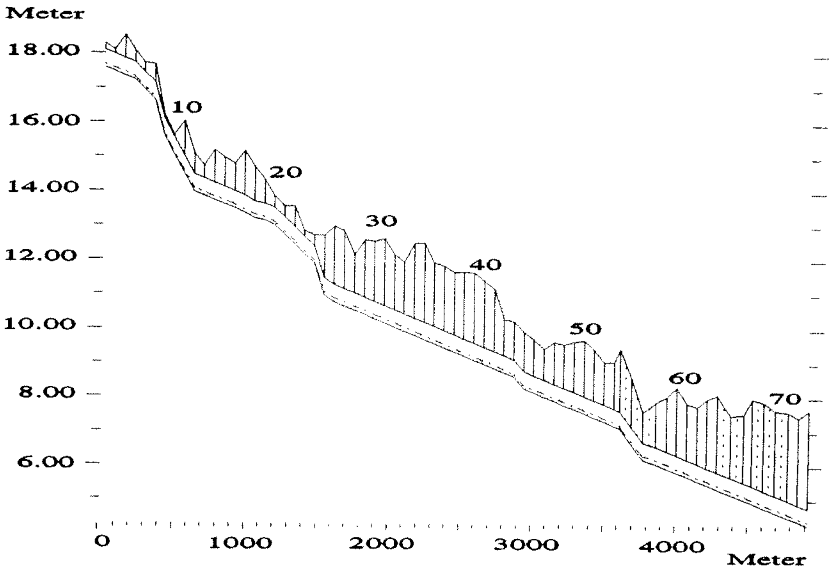

Figure 2. The MOUSE model of the Dronninglund-Asaa gravity sewer.

Hydrodynamic Basis. For all sample periods, changes in water levels were recorded at the inflow to the sewer (Raunkjær, personal communication). Based on this information together with estimated velocities the discharges into the pipe system were calculated (Table 1). Initial hydrodynamic conditions in terms of discharge and water levels for the system were generated by running the MOUSE hydrodynamic model. The initial conditions together with the boundary conditions (Table 1) were then used as the hydrodynamic input to the model.

Table 1. Discharges for the Dronninglund-Asaa gravity sewer.

Date	Discharge range [l/s]
September 30, 1991	9.3 - 16.7
September 10, 1992	11.6 - 16.7
September 17, 1992	8.3 - 17.3
September 22, 1992	11.6 - 17.7
March 25, morning, 1992	22.5 - 32.6
March 25, afternoon, 1992	18.9 - 25.9
April 1, morning, 1992	22.1
April 1, afternoon, 1992	21.3

Residence Time of Dissolved Substances. The MOUSE TRAP advection-dispersion module was verified against results from a Rhodamine experiment (Raunkjær, 1993). The results were residence times for dissolved substance measured at three manholes on the sewer stretch. The Rhodamine spectrum was also measured and it showed that dispersion occurred in the system. However, it is not possible to calculate a theoretical dispersion coefficient from the Rhodamine spectrum due to lack of data. Results from calibration of pipe roughness and dispersion coefficient from the event on 30 September 1991 can be seen in Figure 3. The degree of dispersion is in agreement with the observed data. The dispersion coefficient is found to be 1.5 m^2/s. The Rhodamine spectrum was only measured once, but for all other sampling dates the residence time was recorded by visual observation of the Rhodamine peak passing the manholes. The calibrated model was verified against these observations, see Figure 3. It can be seen that the simulated and observed residence times are in good accordance.

Water Quality Processes. The WQ module has been calibrated for three days in September 1992 (10, 17 and 22). The parameters of the calibrated model are shown in Table 2. The model has been calibrated by comparing simulated and observed data for dissolved oxygen, COD dissolved and COD suspended. The calibrated model was then validated using a new set of input data from March/April 1992. The underlying data used in the calibration period are different from the validation period, especially with regard to temperature, but also the level of DO is different. This can be seen in Table 3 where all input data are shown. The model simulates a variable DO concentration throughout the sewer system as illustrated in Figure 4. Peaks of DO are occurring several times while dissolved and suspended COD are increased and decreased respectively during the transport through the sewer.

By comparing Figure 2, which shows the profile of the setup, with the simulated DO (Figure 4), it can be seen that a strong coherence between the actual slope of the system and DO exists. This indicates that reaeration is a very important process for the site-specific oxygen concentration in the sewer system. The simulated COD dissolved and suspended versus the measured values are shown in Figure 5.

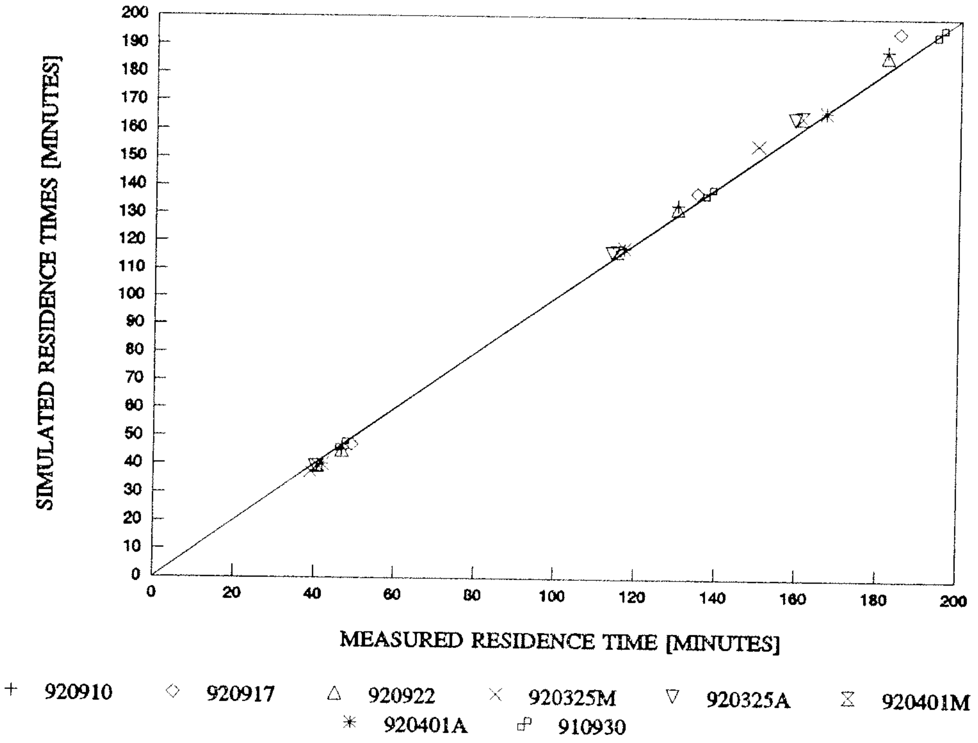

Figure 3. Measured versus simulated residence times.

Table 2. Parameter list for calibrated model.

BIOFILM

Oxygen removal constant = 3.000 (g DO/m3/s)

SUSPENDED HETEROTROPHICS

Max growth rate at 20°C = 11.000 (1/day)
Max yield constant = 0.650 (g VSS/g BOD)
Biomass = 0.850 (g VSS/g BOD)
Temperature coefficient = 1.090 (dimensionless)
K_m, BOD = 8.000 (g BOD/m^3)
K_m, DO = 0.300 (g DO/m^3)

HYDROLYSIS

Decay constant at 20°C = 0.075 (1/day)
Temperature coefficient = 1.090 (dimensionless)

In general there is partial agreement between measured and simulated concentrations throughout the whole sewer system. However, some of the measured values deviate strongly from simulated values, especially COD$_{susp}$ at 0.75 hour and COD$_{dis}$ at 3.2 hours.

In Figure 6 simulated and measured COD dissolved for all three calibration days are shown. It can be seen that an overall agreement between measured and simulated DO and COD (dissolved and suspended) exists. The discrepancy in an isolated simulation seems to be partly caused by the low number of data as all the simulated values are within the range of the measurements.

Table 3. Inflow data used in the WQ simulation

Date	Temperature	DO	Inflow concentration COD_{DIS}	COD_{SUSP}
September 10, 1992	15.30	0.50	243	197
September 17, 1992	15.05	0.70	191*	156*
September 22, 1992	15.40	0.40	204	142
March 25, morning, 1992	8.27	5.05	114	68
March 25, afternoon, 1992	8.55	4.00	150	146
April 1, morning, 1992	8.13	3.40	101	78
April 1, afternoon, 1992	8.75	2.30	194	222

* Modified value of dissolved COD, see text. Date source : (Raunkjær, 1993).

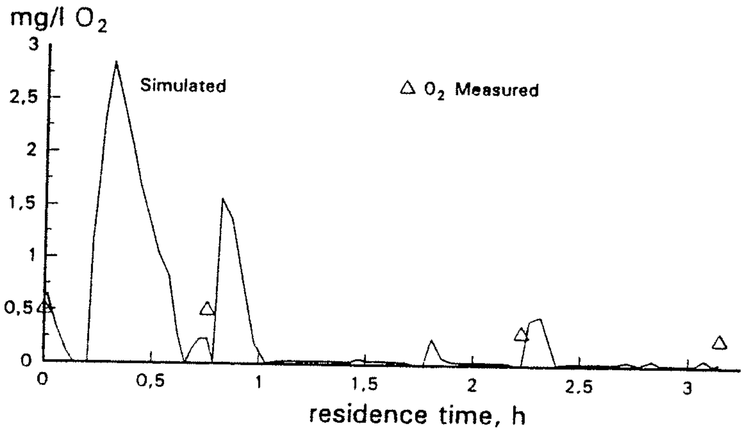

Figure 4. DO results from the calibration run , September 10, 1992.

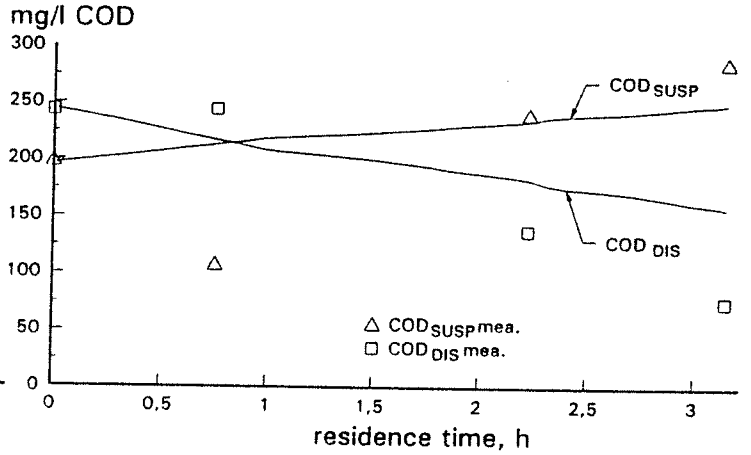

Figure 5. COD results from the calibration run , September 10, 1992.

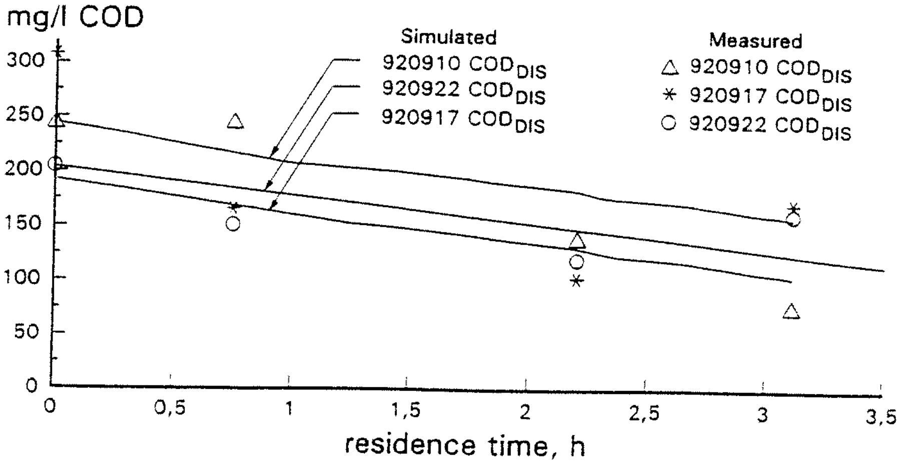

Figure 6. Simulated and measured dissolved COD for all calibration days.

In the simulation of September 17, 1993 the percentage of dissolved COD of the total COD has been changed to 55% instead of the extreme high percentage which has been reported (89 %, derived from : Total COD 347 mg/l, dissolved COD 308 mg/l). The reason for this change is that within a residence time of 50 minutes the dissolved COD concentration is reduced from 308 to 166 mg/l with a corresponding increase in suspended COD from 39 to 168 mg/l. These rates are considered much too high based on the experience of the authors, and the dissolved COD fraction is therefore changed to a value which is in accordance with the values in the other samples. For the other samples the dissolved fraction is approximately 55 % of the total COD. A reason for the observed uncertainties can be found in the measuring technique itself which implies that the variability in the input data as well as the calibration data is too high. In other words model results can never be better than the underlying data. In order to obtain a better calibrated model a larger and more accurate data base is neccesary, especially at the upstream boundary.

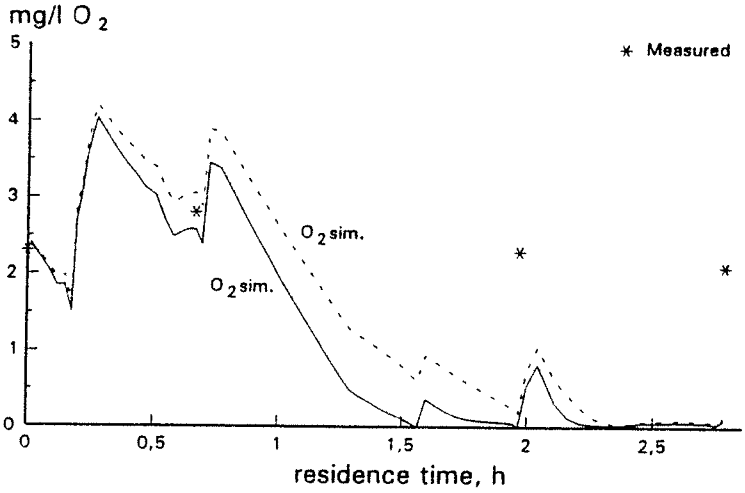

Figure 7. Validation results for dissolved oxygen April 1st, 1992, afternoon.

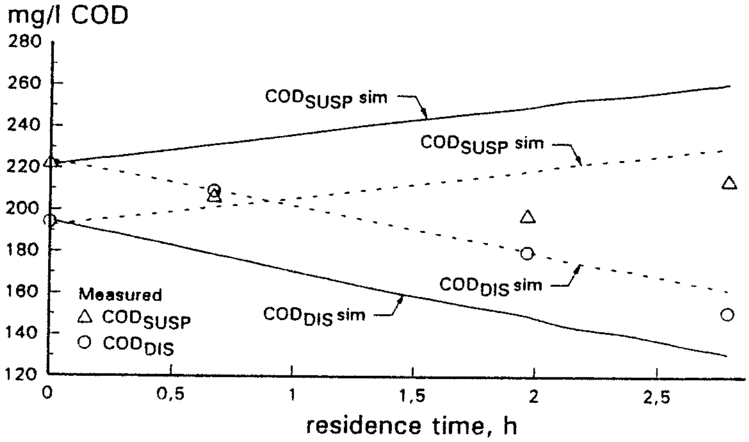

Figure 8. Validation results for COD April 1st, 1992, afternoon.

In Figures 7 and 8 results from the validation are shown. In general the model can only partly simulate the COD/DO dynamics in this period. The most significant difference from the September period is the water temperature (≈8.5 °C in March/April and ≈15 °C in September). The validation reveals that the model in its present form and with the existing data basis is not capable of modelling a "new" period without a preceding re-adjustment of the parameters. This could, however, be relevant if the biological community has changed during this period, or if the composition of the organic material not is the same. Further, in Figure 8 results from a simulation with a minor change in the percentage of dissolved COD of the input data (from 47% to 53%) show that the COD hereafter can be modelled very accurate (the dotted lines). This again shows that the data base for the simulation is of extreme importance.

CONCLUSIONS

In this paper the MOUSE TRAP water quality module and sediment interaction with pollutants has been presented. Further, the advection-dispersion and the water quality modules have been validated against measurements in a real gravity sewer. The results from the advection-dispersion validation show very good accordance between simulated and measured results. Hence, the advection-dispersion equation describes the transport of dissolved substances in sewers well. The presented water quality model, including a dynamic coupling with the advection-dispersion transport model, can simulate the variations in DO, COD_{dis}, and COD_{susp} in the studied sewer system. The whole model system would be a valuable tool for the overall management of sewer systems. The calibration of the model shows that the oxygen profile in the sewer is highly variable due to local hydraulic and physical conditions. The calibration further shows that the discrepancy between a few simulated and measured values is most likely due to inaccurate spot measurements. The subsequent validation for another period reveals that the underlying data set is of great importance for the reliability of the model results. Further work is needed in order to improve the capability of the model to describe the full range of biological processes in sewers and to get a full understanding of the applicability of the model.

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