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APPLICATION OF TWO TRANSPORT MODELS TO A REGULATED RIVER

by

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Abstract

Two one-dimensional mathematical models, one describing the sediment interaction and the other the transport of a pollutant or a tracer, are applied to a short-term regulated river. The results show that it is possible to use the described modeling procedures in such a case. Sediment interaction models have been rarely used and pollution transport models never before in Finland in similar conditions. Also outside Finland these types of models are usually applied to steady state conditions only.

1. *Introduction*

From the viewpoint of energy economy, hydroelectricity has the important advantage of being able to level off peaks in the consumption of energy. The power plant may be operated for only part of the day, the flow past or through the power plant being small at other times. This »short-term regulation» causes rapid changes in the water-level and flow in the river. This influences the water quality of the river. The sudden variations of water quality under varying flow conditions were studied by using a modeling system. We will here present an application of a sediment interaction model and a one-dimensional pollution transport model to the short-term regulated Nurmonjoki river.

2. *Effects of river regulation*

The effects of short-term regulation on the quality of water, erosion and sedimentation were studied in 1982–1983 in some rivers downstream of power plants in the Pohjanmaa region (Fig. 1).

The erosion of the river bed was clearly observable in the Nurmonjoki river, for example the shores have been eroded for about 5 km downstream of the powerplant. In this part of the river the sudden variations of flow can cause transport of more than 15 t/d of sediment during the summer while the corresponding transport of suspended solids downstream of this 5-km strech is below 1 t/d. The sediment mixes in the water at high flow velocities and it increases the concentration of suspended solids in the river water. The other qualities of the water change in relation to the materials included in the suspended solids. The erosion of the river bed is greatest during the summer, when the banks, which are liable to erosion, are not frozen.

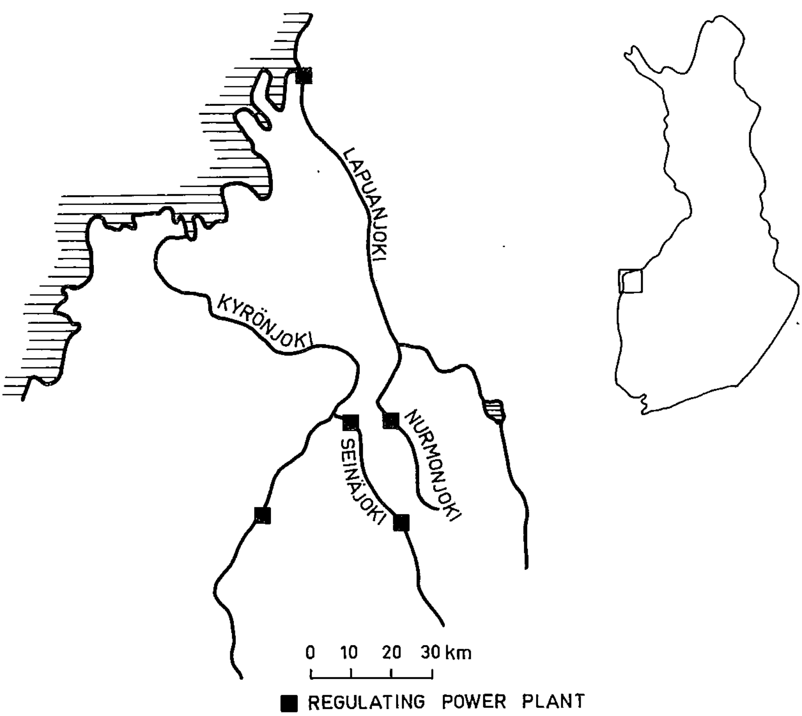


Fig. 1. Short-term regulated rivers in the Pohjanmaa region.

As a consequence of short-term requlation, the degree of dilution of the washout and the waste waters entering the river downstream of the power plant is changed. The substances accumulated in the water at low flow velocities give rise to locally increased concentration.

The waste waters from the town of Seinäjoki, which are discharged into the regulated river, give rise to transient changes in water quality.

Rapid changes of acidity caused by sulphate washout and involving death of fish have been noted in the river Kyrönjoki. The situation has been attributed to a change in the dilution of the sulphate washout in the river. The longitudinal dispersion levels off the sudden variations of the water quality in the regulated river system. In the following, the two main effects of river regulation will be studied using a modeling system.

3. *The study area and methods*

The Nurmonjoki River is a small river, whose discharge is regulated by a water power plant. The river is about 20 m wide and has a bottom slope of slightly less than 10^{-3}.

During the study in August and November 1982 the mean daily discharge was 1–2 m^3/s. For power production reasons the water volume was discharged on one, two or three occasions each day, the peak discharge being about 12 m^3/s each time. Between these periods of power production the discharge was kept at 0.1 m^3/s.

On September 21–23 and November 9–10, 1982, the particulate matter carried with the river flow and that caught by traps near the river bottom were measured at two to four cross-sections along the river.

The flow velocities needed were obtained from an implicit one-dimensional unsteady flow model, which computed both the discharge and the stage at all the grid points at 15-min intervals. The flow model was calibrated against water level recorders at x = 4400 m and x = 18520 m. The measured and modeled water levels agreed well.

The dispersion coefficient was calibrated by means of a tracer experiment. During the tracer experiment, which lasted from the 24th to the 27th of August, the mean discharge was 1.7 m^3/s, but this water volume was discharged on three occasions each day. The whole amount of the tracer (Rhodamine, conc. 40 %) was injected at x = 0 m, the outlet of the power plant, upon maximum discharge and concentrations were observed at four locations along the river, the first one at location x = 2650 m and the last at location x = 10380 m.

4. *Interaction between river bed and water body*

The results of the study are obtained with a sediment interaction model similar to that of VIRTANEN, HUTTULA and SARKKULA (1982). The change in particulate matter ($\partial c_i/\partial t$) is a result of

1 inflow from upstreams ($+c_{i-1}Q_{i-1}/V_i$)
2 outflow to downstreams ($-c_i Q_i/V_i$)
3 erosion from the bottom ($+b \cdot u_i/H_i$)
4 increased erosion during the flow transients ($+p \cdot b \cdot \Delta u_i^+/H_i$)
5 settling to the bottom (detention to vegetation etc.) ($-c_i \cdot w/H_i$)

i.e.
$$\frac{\partial c_i}{\partial t} = + \frac{Q_{i\text{-}1}}{V_i} c_{i\text{-}1} - \frac{Q_i}{V_i} c_i + \frac{b}{H_i}\left(u_i + p\,\frac{\Delta u_i^+}{\Delta t}\right) - \frac{w}{H_i} c_i \tag{1}$$

where c_i is the particulate content in segment i, V_i is the respective water volume, u_i the flow velocity, H_i the mean water depth, w the settling velocity, b the erosion coefficient and p the pulse factor. $\Delta u_i^+ = (|u^t - u^t - \Delta t| + u^t - u^{t-\Delta t})/2$ is the increase (but not decrease) in u during the last time step Δt. The river section is subdivided into finite segments ($i = 1,...N$) at the locations of sediment observations. Eq. (1) is solved with Δt = 0.5 hours by using finite differences centred in time.

The volumes V_i, depth H_i and velocities u_i are approximated from the unsteady flow model. For the model parameters w, b and p – assumed to be constant – the following values are suggested by the observations of September 1982: w = 30 md^{-1}, b = 125 mg cm^{-2}d^{-1} (m/s)$^{-1}$ and p = 10 hours. Using these parameter values, the model validity is tested with the observations of November 1982 (Fig. 2).

The model resolution is smoothed down by several integrations and approximations. First of all, the model results are longitudinal averages (over a 1...1.3 km distance), transverse averages (10...50 m width) and vertical averages (0.2... 4 m depth). Therefore, it is not surprising that not all of the details of local observations (*e.g.* trapped area was about 10 cm by 25 cm) are reproduced by the model. In particular, the true accumulation on the river bottom is more abundant than that estimated by the vertical average concentration (model), indicating a clear gradient in the vertical concentration profile. In addition to this, the model can be improved by *e.g.* taking into account the particle size distribution, the dependence of the parameter values on local properties, and perhaps by a more accurate description of advection and dispersion. However, in the present form

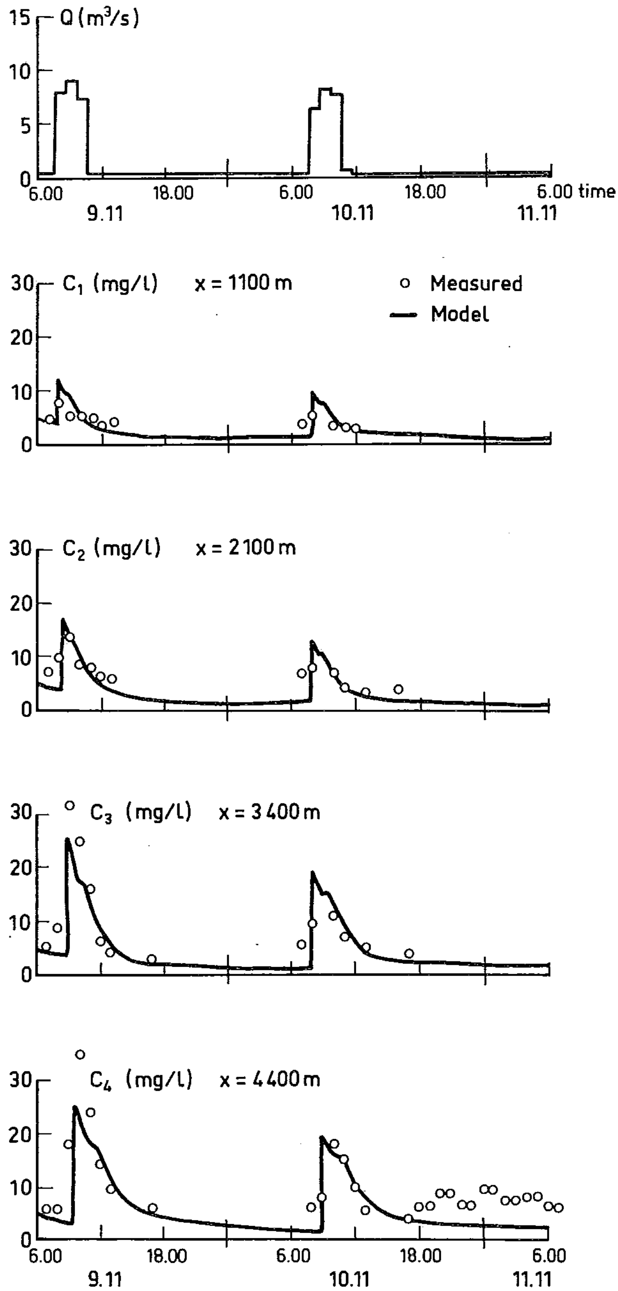


Fig. 2. Concentration of particulate matter.

the model structure is extremely simple, general and easy to handle. In this respect, the results are highly satisfactory and very useful for practical prediction purposes.

5. *The pollution transport model*

Mathematical models of pollution transport in rivers are usually applied to steady state conditions. The reason is, of course, that flow conditions usually do not change, or change very little, during the time in which mixing takes place. Another reason may be the numerical technique used in several models. According to Cunge *et al.* (1980), the calculation of the convection part in some models requires that the Courant number is close to unity, in order to minimize the numerical diffusion or dispersion introduced by the model itself. The Courant number C_r is obtained from the relation $C_r = U \cdot \Delta t/\Delta x$, where U is the flow velocity, Δt the time step and Δx the distance between the computational points. This numerical diffusion can be much greater than the actual physical diffusion, if the Courant number is chosen incorrectly. If, however, the discharge of the river is regulated, the assumption of steady flow during the tracer experiment may not be valid. In fact, one can easily imagine a situation where, at a certain moment, the discharge is at a minimum at the upstream end and the preceeding peak discharge has just arrived at the downstream end of the stretch. Such a situation, with varying flow conditions and consequently varying Courant number, requires special attention for the computation of the convection part of the total transport.

The transport of a conservative tracer in one dimension is described by the equation

$$\frac{\partial}{\partial t}(AC) + \frac{\partial}{\partial x}(AUC) - \frac{\partial}{\partial x}\left(AK\frac{\partial C}{\partial x}\right) = 0 \qquad (2)$$

where C and U are the cross-sectional average concentrations and velocities, respectively, A is the flow area, K the longitudinal mixing coefficient, and t the time and x the longitudinal co-ordinate. It is divided into two parts, a convection part and a diffusion part. The pure convection of a concentration is given by the equation

$$\frac{\partial}{\partial t}(AC) + \frac{\partial}{\partial x}(AUC) = 0 \qquad (3)$$

The diffusion equation is given by

$$A \frac{\partial C}{\partial t} = \frac{\partial}{\partial x}\left(AK \frac{\partial C}{\partial x}\right) \tag{4}$$

Equations (3) and (4) are solved with finite difference methods.

Equation (3) is solved with the explicit »two-point fourth-order method» developed by HOLLY and PREISSMANN (1977). In this method not only the concentrations are assumed to be convected, but also the concentration gradients, whereby it is possible to obtain fourth order accuracy of the numerical scheme, using information from only two computational points. Holly and Preissmann demonstrated that this method introduced very little numerical diffusion or dispersion compared with some other methods. In their case the Courant number varied between 0.25 and 1.0.

The diffusion equation is solved with an explicit centred scheme according to CHEVEREAU and PREISSMANN (cf. CUNGE *et al.* (1980)). For each time step, equation (3) is first solved for the whole river stretch, and the concentrations thus obtained are then used as initial conditions when solving the diffusion equation. In the present simulation, concentrations measured at the location x = 2650 m were used as input concentration values. The input values of the concentration gradient were obtained from the measured time curve of the concentration through the expression

$$\frac{\partial C}{\partial x}(t) = -\frac{1}{U}\left(\frac{\partial C}{\partial t}\right)_{x=2650} \tag{5}$$

Because the flow conditions varied greatly in both time and space, the discharge being 0.1...12.5 m^3/s at x = 0 m and 0.4...2.9 m^3/s at x = 10.380 km, the intensity of mixing must also vary considerably. Therefore, the diffusion coefficient K was computed at each point; according to HESS and WHITE (1975)

$$K = a \cdot U \cdot A/B \tag{6}$$

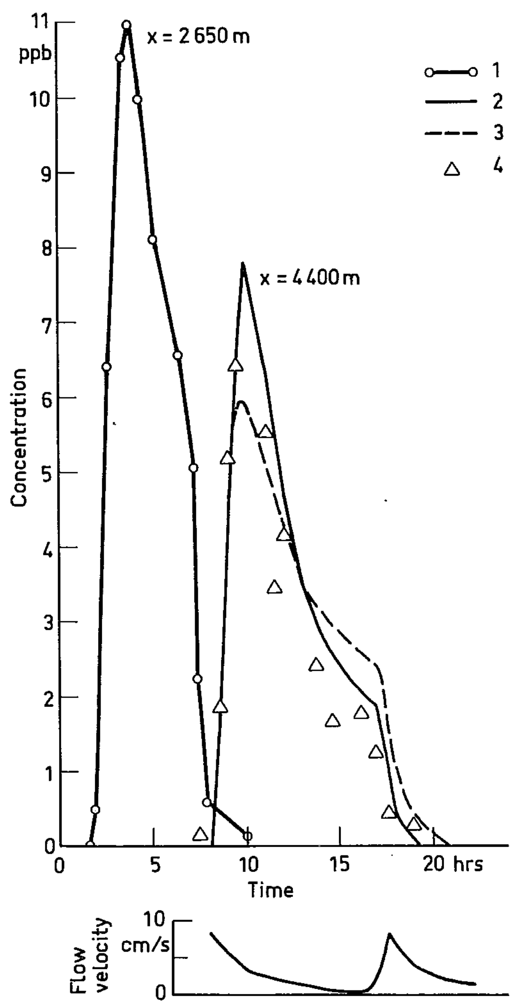
where a is a coefficient and B the surface width of the river. In the simulation a time step of 150 s and a mean distance step of 103 m were used.

The model was first tested for numerical diffusion by setting a = 0, *i.e.* a condition of no diffusion, whereby the peak concentration will theoretically pass unaffected down the river. The peak concentration computed at the locations x = 4400 m, x = 7970 m and x = 10380 m was 95 %, 80 % and 66 % of the initial peak at x = 2650 m. This observed numerical diffusion is by no means insignificant, but still it is remarkably low, if we take into consideration that the

Courant number varied in the range 0.012...0.935. By refining the grid one could apparently further reduce this numerical diffusion, because, as HOLLY and PREISSMAN (1977) point out, the accuracy depends not only on the Courant number, but also on the size of Δx compared with the size of the concentration distribution.

In the field test simulation two different values of a were tested. For $a = 10$, K got a value in the range 0.1...3.8 m^2/s, and at the location $x = 4400$ m it seems to give a fairly good correspondence with the measured data. With $a = 25$ ($K =$

a)



b)

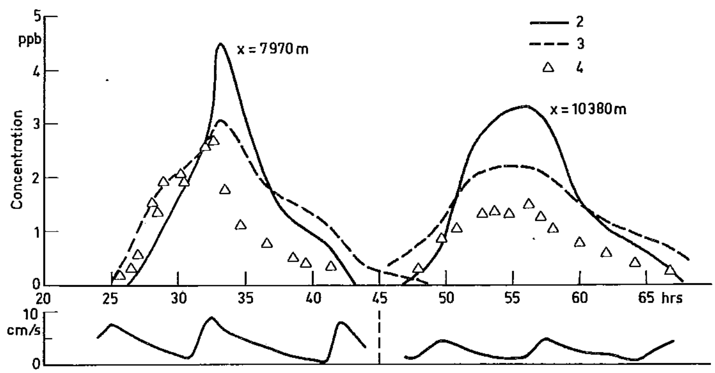


Fig. 3. a) and b). Tracer concentration distribution:
1 = initial concentration distribution, 2 = concentration distribution with a = 10, 3 = concentration distribution with a = 25, 4 = measured concentrations. Below the concentration curves the corresponding computed flow velocities are shown.

0.2...9.4 m^2/s), the best agreement is obtained at the locations x = 7970 m and x = 10380 km. The results are shown in Fig. 3. The steep arrival of the tracer was simulated quite well, whereas the tail was simulated with less accuracy. The field data indicate a less elongated tracer cloud than is predicted by the model. This indicates that the true diffusion is smaller than that computed. On the other hand, this would mean higher measured peak concentrations as compared with the predicted ones, which is not the case. One reason for the decline of the measured peak concentrations is probably adsorption of the tracer on the vegetation and the bottom gravel. This assumption is supported by the fact that while 65 % of the initial amount of tracer was recovered at x = 2650 m, only 33 % was recovered 3 days later at x = 10380 m, when using measured concentrations and computed discharges. It is also possible that the relatively simple expression used for the varying diffusion coefficient is not adequate and that it needs refining.

6. *Conclusions*

1. It is possible to compute the transport of a tracer in a water course which is heavily regulated, by using the above modeling system, provided that an unsteady flow model is used to get the necessary flow data for the transport model. The problem of the adsorption of a large amount of tracer makes it difficult to judge the merits of the model on the basis of the field test alone, especially concerning the formulation used for the computation of the diffusion coefficient.

But the moderate numerical diffusion demonstrated by the model indicates its value as a computational tool even during varying flow conditions.

2. The amount of particulate matter in the water body can be computed with a simple model to obtain useful results for practical purposes.

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