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River mixing characteristics in the Northwest Miramichi River (NB) and associated metal concentration following a discharge by Heath Steele Mines in 1991

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ABSTRACT

St-Hilaire, A., and D. Caissie. 2001. River mixing characteristics in the Northwest Miramichi River (NB) and associated metal concentration following a discharge by Heath Steele Mines in 1991. Can. Tech. Rep. Fish. Aquati. Sci. 2367: 29p.

Numerous studies have shown that water quality can have a significant impact on fish and on population density. One of the most important physical process by which water quality is altered is river mixing. In New Brunswick, a number of important salmon rivers are also sustaining mining industries in their drainage basin. The risk of potential adverse impact of the mining industry on salmonid habitat is always present. This becomes increasingly critical in areas immediately downstream of the confluence of rivers where one is impacted by mining activities.

This study present the results of a river mixing model (RIVMIX) on the Northwest Miramichi River (located in central New Brunswick), downstream of the confluence of the Tomogonops River. The calibration of the RIVMIX model was carried out using specific conductance as a conservative tracer. This was possible given the marked contrast in specific conductance between of the two studied rivers. With the calibration of RIVMIX, important river mixing coefficient (i.e. dispersion coefficient) was estimated for Atlantic salmon rivers. Once calibrated, the RIVMIX model was used to reconstruct the distribution of heavy metal concentrations following a spill of mine water, which occurred in the Tomogonops River in the winter of 1991.

Result from RIVMIX showed that the distribution of heavy metals in the Northwest Miramichi River varied laterally in the first 1.3 km downstream of the confluence. Immediately downstream of the confluence, high concentration of metals was observed on the true left bank of the Northwest Miramichi River. When the plume extended from bank to bank, results showed that concentrations of Copper and Zinc exceeded lethal levels for Atlantic Salmon (*Salmo salar*) in the Northwest Miramichi River.

RÉSUMÉ

St-Hilaire, A., and D. Caissie. 2001. River mixing characteristics in the Northwest Miramichi River (NB) and associated metal concentration following a discharge by Heath Steele Mines in 1991. Tech. Rep. Fish. Aquati. Sci. 2367: 29p.

De nombreuses études ont démontré l'importance de la qualité de l'eau pour l'habitat aquatique et les densités de population de poissons. Un des processus les plus déterminant en ce qui a trait à la qualité de l'eau est le mélange en rivière. Au Nouveau-Brunswick, un nombre élevé de rivières ayant une population de saumons Atlantique (*Salmo salar*) ont des bassins versants sur lesquels on retrouve des industries minières. Le risque d'impact négatif de l'activité minière sur les populations de saumon est toujours présent. Les biefs situés en aval de la confluence de deux rivières dont une a subi l'impact de l'activité minière sont particulièrement à risque.

Ce rapport présente les résultats d'un modèle de mélange en rivière (RIVMIX) appliqué à la rivière Northwest Miramichi (située au centre du Nouveau-Brunswick), en aval de la confluence de la rivière Tomogonops. Le calage du modèle RIVMIX a été fait à l'aide de données de conductivité de l'eau, (paramètre non-réactif). Ce calage a été rendu possible grâce à la différence marquée des valeurs de conductivité mesurées sur les deux rivières. Une évaluation du coefficient de dispersion typique pour les rivières à saumon de la région atlantique a aussi été faite. Après avoir été calibré, le modèle RIVMIX a été utilisé afin de reconstruire la distribution des concentrations de métaux lourds après un déversement d'effluent de mine qui s'est produit sur la rivière Tomogonops en 1991.

Les résultats des simulations avec RIVMIX ont démontré que la distribution des métaux lourds dans la rivière Miramichi varie latéralement sur les premier 1,3 km en aval de la confluence. Immédiatement en aval de la confluence, les concentrations près de la rive gauche étaient très élevées dans la rivière Northwest Miramichi. Une fois le panache étendu d'une rive à l'autre de la rivière, les concentrations de zinc et cuivre calculées par le modèle dépassaient le niveau mortel pour le Saumon de l'Atlantique (*Salmo salar*).

1.0 INTRODUCTION

The dilution and dispersion of heavy metals is an important concern for aquatic habitats. Mining sites are among some of the most critical point source and non-point sources of heavy metals in rivers. Not all chemicals behave similarly. For instance, Prusty *et al.* (1994) have studied the dispersal of metals from an ancient Zinc mine in the Tiri River (India). Their results on sediment chemical analyses showed that Cadmium (Cd) was more mobile than lead (Pb), Zinc (Zn) and Copper (Cu), while Zn tends to accumulate to greater concentrations in sediments.

In England, Boult *et al.* (1994) have shown that acid drainage from residual mining material is one of the major environmental impacts on Afon Goch, the primary stream of a small catchment. Their results showed a link between the erosive process and discharge. High discharges re-suspended contaminated sediments and higher heavy metal concentrations were observed in the stream. Zn, however, was shown to travel long distances in solution without being deposited or re-suspended. Boult *et al.* (1994) mentioned that results of mass balance studies may vary depending on the chemistry of the stream water and the influence of the local geochemistry. This was also observed in study by Cook and Cote (1972), which showed that the presence of humic acids above a threshold of 5 mg/L tended to double the concentrations of Cu and Zn to lethal levels for juvenile Atlantic Salmon (*Salmo salar*). In the Northwest Miramichi River, Zitko and Carson (1970) mentioned that humic substances have concentrations between 10-15 mg/L and can bind up to 1.5 mg/L of Cu or Zn.

The early life stages of salmonids appear to be most affected by high metal concentrations. Brown *et al.* (1993) have studied the affect of Cd on Rainbow Trout (*Oncorhynchus mykiss*) and Brown trout (*Salmo trutta L.*) over extended exposures periods. Adult survival rates were not significantly altered but eggs exposed to similar conditions failed to develop to the fry stage. High metal concentrations in both the water column and the substrate can affect the biota at various levels of the food chain. For instance, Miller *et al.* (1992) found a strong relation between measured Cu concentration in stream water and in benthic invertebrates. Zn concentrations from sediments were also related with Zn found in benthic invertebrates. They also found that White Sucker

(*Catostomus commersoni*) exposed to higher Zn concentrations had elevated concentrations in their bone tissue.

Thus, it can be seen that an understanding of mixing processes in streams (i.e. advection, dilution and dispersion characteristics) is of great importance in describing the potential impact of heavy metals pollution on aquatic habitat. In late winter of 1991, a broken pipeline released mine waters from Heath Steele Mine into the Tomogonops River. This study describes the mixing characteristics along a 2-km reach of the Northwest Miramichi River (New Brunswick) downstream of the confluence of the Tomogonops River. The main objective is therefore to implement a river mixing model (RIVMIX) and to perform a sensitivity analysis on a number of input parameters. After a brief overview of the location and hydrology of the river, a description of the model, field measurements and results will be given.

2.0 GEOGRAPHICAL AND HYDROLOGICAL SETTING

The study was carried out in the Northwest Miramichi River (Figure 1). It is part of the Miramichi River basin and one of the most important salmon rivers in eastern New Brunswick with a drainage area covering 14,000 km^2. The Northwest Miramichi River, has a drainage basin of 3,900 km^2. It is the second most important salmon river of the Miramichi system. The study area was on the Northwest Miramichi River from the confluence of the Tomogonops River to the confluence of the Portage River. The sub-basin of the Northwest Miramichi River ending at the confluence of the Portage River covers an area of 899 km^2.

Heath Steele Mines operates two mines in the area of interest. The treated effluent drains into the Tomogonops River. In late winter of 1991, a broken pipeline released mine waters into the Tomogonops River:

> "Water quality monitoring by Heath Steele demonstrated substantial increases in zinc and copper concentrations in the Tomogonops River at the time of the mine water discharge." (Schiefer *et al.*, 1992).

Biological analysis performed after the mine water released demonstrated the potential for some mortality of Atlantic Salmon eggs and fry and Brook Trout (*Salvelinus fontinalis*) fry (Schiefer *et al.*, 1992). Given the importance of the potential impact of such a spill, it was decided that a better understanding of the mixing characteristics of the Northwest Miramichi River was required.

Environment Canada has a gauging station (station 01BQ001) on the Northwest Miramichi River at approximately 15 km downstream of the study site (Figure 1). The gauging station has a drainage area of 948 km^2. Based on historical data (1963-1997), maximum monthly flow occurs in May (69.8 m^3/s) while the minimum monthly flow occurs in January (8.13 m^3/s), which is similar to September (8.71 m^3/s). Hydrologic conditions for the year of interest (1991) were characterized by an annual mean flow of 25.8 m^3/s, close to average condition of 20.8 m^3/s (1963-1997). Monthly means in February and March of 1991 were of specific interest for this project because they correspond to the months where mine water was released and flowed into the Northwest Miramichi River. Monthly flows were below average for both February and March, 1991. February showed a discharge of 4.93 m^3/s compared to the monthly mean of 8.70 m^3/s. March was also lower than average with a discharge of 7.67 m^3/s compared to the mean of 9.74 m^3/s.

3.0 METHOD

3.1 River Mixing

As a conservative substance is carried downstream, its concentration and distribution are affected by a number of physical processes, which include advection, mollecular diffusion, turbulent diffusion, differential advection and secondary circulation.

Advection refers to the movement of mass caused by currents (i.e. water velocities). Molecular diffusion is the term used to describe the movement of molecules from areas of high concentration to low concentration. The turbulent diffusion is the result of the fluctuating (i.e. variation from the mean) component of velocity. Turbulent flow can be in all directions whereas advective flow moves in the downstream direction. Differential advection is caused by non-uniformity in flow streamlines (e.g. midstream vs stream edges). Portions of a dissolved substance will thus travel faster depending on their location within the water column and along a transect. Finally, secondary circulation refers to flow, which is perpendicular to the main direction of the current, as is often developed in meanders, for instance.

River mixing has been an ongoing topic of research for many years. Among the first mathematical models were developed during the 19th century by Fick (Fisher et al, 1979). Some of the diffusion processes described above are more important than others. For instance, molecular diffusion is orders of magnitude smaller than turbulent diffusion and hence, is usually omitted when the conservation of mass is described for a river or stream. The general advection-diffusion equation for the distribution or gradient of concentration of a substance is given by Elhadi *et al.* (1984):

[1] $$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} + w\frac{\partial C}{\partial z} = \frac{\partial}{\partial x}\left(\varepsilon_x \frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(\varepsilon_y \frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial z}\left(\varepsilon_z \frac{\partial C}{\partial z}\right)$$

where:
C = concentration of a tracer (natural or injected);
t = time;
x = longitudinal coordinate;
y = vertical coordinate;
z = lateral coordinate;
u, v, w = velocity in the x, y and z directions;
ε_x, ε_y, ε_z = turbulent diffusion coefficients in the x, y and z directions ;

The terms on the left hand side of equation [1], with velocities u,v and w are advective terms, while the terms on the right hand side are diffusive terms. In cases where the depth is small compared to stream width or no significant gradient of concentration is present with depth, the terms in the y direction can be dropped, as concentrations are considered to be depth-averaged. In order to further simplify equation [1], the case of a steady release of a constant concentration of a conservative substance (steady-state) can be used as an approximation (i.e. $\partial C/\partial t = 0$).

To account for the non-cartesian nature of stream morphology, Yotsukura and Sayre (1976) developed a natural coordinate system in which the x-axis follows the right bank and includes three mutually perpendicular axes (Figure 2). In this coordinate system, coefficients (m_x and m_z) are introduced to account for longitudinal variability in stream width (Figure 2).

Equation [1] can also be further simplified by using the so-called cummulative discharge, defined as:

[2] $$q_c = \int_0^z m_z h u dz$$

where : q_c = cummulative discharge (m^3/s)

h = water depth (m)

The value of q_c ranges form zero on the right bank to the total discharge Q on the left bank.

Using these simplifications, depth average, natural coordinate system, cummulative discharge and assuming a steady state condition, a simplified version of equation [1] can be obtain (Elhadi et al, 1984):

[3] $$\frac{\partial C}{\partial x} = \frac{\partial}{\partial q_c}\left(m_x h^2 v_x \varepsilon_z \frac{\partial C}{\partial q_c} \right)$$

The one-dimensional case (i.e. depth-averaged and laterally-averaged) has a simple analytical solution of the form :

[4] $$C = \left(\frac{M}{Q}\right)\left(\frac{2}{\sqrt{2\pi}}\right) k \exp^{\frac{-\eta^2}{2k}}$$

where: C = concentration of a tracer (natural or injected);

M = mass of injected tracer per unit time;

Q = total river discharge;

k = factor of diffusion ;

η = ratio of cumulative discharge(Q_c) to total discharge (Q), which ranges from zero on the right bank to unity of the left bank.

The factor of diffusion k is not constant in rivers and streams. To simulate turbulent processes, it takes the following form:

[5] $$k = uh^2 m_x \varepsilon_z$$

where: u = velocity;
h = depth;
m_x = longitudinal curvilinear coordinate;
ε_z = dispersion coefficient.

Equation [4] only allows for the description of a longitudinal (along the river reach) distribution of concentration. The results from this equation do not allow for a two-dimensional investigation. Therefore, the mixing zone (e.g. the plume with varying concentrations) can only be characterized longitudinally and laterally using a numerical solution of equation [3]. Numerical methods were therefore used to solve equation [3] for a two-dimensional (longitudinal and lateral) domain.

3.2 The River Mixing Model

Many hydrological models and hydrochemical models have been developed over the past decades. Dzombak and Ashraf Ali (1993) described two general categories of models: the so-called "One-step models" and the "two-step models". In the one-step model approach, only one set of differential equations is used and a numerical solution is applied. The two-step model approach is more flexible because it allows for changes in the chemical compositions (i.e. the dissolved chemicals are not necessarely conservative). The transport equations are separated from the chemical reaction equations at each time step.

The river mixing model RIVMIX (Krishnappan and Lau, 1982) uses the one-step approach. Because of the variability of the factor of diffusion (k), the analytical solution is not used but a numerical scheme is implemented to solve equation [3]. RIVMIX uses the finite difference numerical scheme (Stone and Brian, 1963).

The input parameters required by the software as well as the output are shown in Table 1. The model is coded in FORTRAN IV and can be run on an IBM PC. The model produces a set of grid points at each section of interest, as well as for a selected number of equidistant sections in the region between the input sections. Depths and velocity profiles are interpolated for each grid point either from the collected data or, in the case of velocities, from the discharge or continuity between transects. The concentration is calculated at each grid point from a numerical solution of equation [3].

RIVMIX requires a dispersion coefficient (ε_z) for each modelled section. Estimation of ε_z can be carried out based on the hydraulic characteristics of each section (Krishnapan and Lau, 1982). Data required to estimate ε_z include the average section velocity, discharge and the model grid size. The values of ε_z were estimated during the calibration of RIVMIX.

3.3. Physical measurements

The RIVMIX model requires a number of input parameters: longitudinal distances, water depth and velocities, as well as concentrations measured at the first transect for initial conditions. In the present study specific conductance was used to obtain some data on the distribution of chemical concentration laterally.

Longitudinal distances between sections were measured from the true left bank of the river, starting at the confluence of the Tomogonops River (Table 2). The instrument used was an Electronic Distance Meter (Model Citation CI-410) with a standard deviation of 10 mm / 1000 m. Longitudinal distances on the true right bank were extrapolated using a 1:10 000 scale topographic map of the area (map # 21P/04Y3 from NBGIC).

The model also required depth and velocity distribution at each transects as input parameters. Depths and velocities were measured on two occasions (September 08 and 13, 1994). Depths were measured in cm and ranged between 6 cm and 53 cm. Sampling intervals at each transects (B, C, D, E and F; Figure 1) were carried out at every 0.5 m to insure a minimum of 20 points per section. Sampling station A was at the confluence of the two rivers and did not constitute a river mixing transect (i.e. no mixing had occurred at this location). Velocities were measured using a Marsh McBirney flow meter (model 201D, precision of ± 2% of full scale). Data from the September 13 sampling were used for model calibration, except for section B, which was only sampled on September 08. Data at section B were modified to reflect the flow and concentration condition of September 11.

Discharges were calculated from depths and velocities measured at different transects on September 13, 1994. Discharge data from Environment Canada's gauging station on the Northwest Miramichi River was prorated to section A of the study site for comparative purposes. Following the comparison of field sampling vs gauging station discharge, a fix value of discharge was selected to carry out the river mixing model.

Specific conductance measurements were taken with YSI SCT Model 33 at every 0.5 m along sections B, C, D, E and F on September 13. In order to analyze the dilution characteristics of the two river systems (i.e. Tomogonops and Northwest Miramichi Rivers), water samples were taken upstream of the confluent, on both rivers. Known volumes of Tomogonops and Northwest Miramichi waters were mixed in various proportions and specific conductance was measured to obtain the dilution relation. The established dilution curve was then used to calculate percentage of Tomogonops water from the specific conductance measurements taken on sections B, C, D, E, and F. The percentage of Tomogonops water was then used in the application of RIVMIX. This provided for a direct assessment of the mixing characteristics of the river reach in percentage of water, which can also be used for any conservative trace elements (e.g. Zn and Cu).

A concentration profile at the first modelled section (i.e. section B) was required as initial conditions in the RIVMIX model. Specific conductance measurements from section B were converted to percentage of Tomogonops water and they were used as initial conditions.

4.0 RESULTS

The RIVMIX model was used to simulate percentages of Tomogonops water within the Northwest Miramichi River at sections C, D, E and F on September 13 using the initial condition at section B. Specific conductance of different volumes of water between the two rivers was measured to establish specific conductance vs percentage of water. The dilution curve was obtained and the results are shown in Figure 3. By mixing water from the two rivers, it was observed that an almost linear relation was obtained during the two sampling dates (September 08 and 13).

Based on the information on discharge from the gauging station and measured field discharges, a value of 3.1 m^3/s was selected to run the RIVMIX model. Also RIVMIX requires values of dispersion coefficient (ε_z), which were estimated for each section. Results showed values between 0.01 and 0.015 (Table 3). In the calibration, it was decided to keep ε_z values as constant as possible between reaches to have an overall dispersion coefficient. This is especially useful to allow for modelling downstream of section F.

Two types of simulations were carried out. First, the RIVMIX model was run to verify its accuracy against measured field data (i.e. measured vs. observed concentrations). Once the model was calibrated using observed concentrations (i.e. % of Tomogonops water as calculated from specific conductance) it was run to estimate chemical concentrations. The validated model was then used to reconstruct Cu and Zn concentrations, which occurred in the study reach during the mining spill of the winter of 1991. Finally, a sensitivity analysis was performed to verify the impact of modifying the value of the transverse dispersion coefficient (ε_z).

4.1 Validation of RIVMIX with field data

As a first step in validating the RIVMIX model, simulations were carried out using percentage of Tomogonops water from dilution curves (Figure 3). Simulated concentration profiles (percentage of Tomogonops River water) for sections C, D, E and F were compared with field measurements (Figure 4). Good agreement was observed between measured and modelled (predicted) values at all sections, even in the downstream sections such as E and F, which were further to initial conditions (section B). Results indicated that at 400 m below the confluence of the two rivers, the left bank of the Northwest Miramichi River still experienced close to 90% of Tomogonops River water (Figure 4a). By mid-stream, the influence of the Tomogonops River was no longer present. At a distance of over 1 km (station E) the concentration on the left bank of the Northwest Miramichi River was still close 50% (Figure 4c). A higher deviation between predicted vs observed concentration was observed at station C compared to other stations. The best agreement using RIVMIX was observed at station D and F with a high level of association between the two series. Results from the last station (F) indicated that the concentration on the left bank was still close to 50% and that mid-stream concentration was in the order of 20% (Figure 4d). At this last station, Tomogonops River water was reaching almost to the right bank of the Northwest Miramichi River. At this station for a distance greater than 20 m from the right bank, the concentrations were in the order of 2% to 5% of Tomogonops River water (Figure 4d).

4.2 Metal concentrations

In order to reconstruct the chemical plume during the winter spill of 1991, data on Cu and Zn were obtained from previous study (Schiefer *et al.* 1992). Tomogonops River water at the mouth showed concentrations of 0.48 mg/l of Cu and 7.2 mg/l of Zn. Simulation of the plume for Cu and Zn concentrations, from known initial values at section B, was carried out. This will show the distribution of heavy metals in the study reach of the Northwest Miramichi River. Results for metal concentrations of Cu on February 23, 1991 are presented for stations C, D, E and F (Figure 5). Results for Zn are presented in Figure 6. Concentrations of Cu near the left bank of the river varied from 0.43 mg/l (station C, Figure 5a) to 0.24 mg/l (station F, Figure 5d). Concentrations of Cu near the right bank remained low for all sections in the study reach. Values of 0.02 mg/l of Cu were monitored at station F near the right bank (Figure 5d). Zn concentrations near the left bank of the Northwest Miramichi River varied between 6.4 mg/l (station C, Figure 6a) and 3.5 mg/l (station F, Figure 6d). Similar to Cu, Zn concentrations near the right bank remained low for all sections in the reach.

4.3 Sensitivity analysis: Dispersion coefficient

Model outputs were produced with values of ε_z at half and twice the initial value (0.01). The results show that initial values at the true left bank are 20% lower for an ε_z of 0.02 and 20% higher for an

ε_z of 0.005. This difference diminishes to less than 10% in the middle of the section of the river, which means that the most affected results would be at the river edge. Such results showed that although the values of ε_z are important, a slight deviation from the selected value of 0.01 will not drastically change the output of the model.

5.0 DISCUSSION AND CONCLUSION

5.1 Mixing zone and dispersion coefficient

It can be seen from Figure 4d (Station F) that the mixing zone extends further downstream than the study reach at 1.13 km from the confluence of the Tomogonops River. The water from the Tomogonops River has not fully mixed with the water from the Northwest Miramichi River at section F. A fully mixed river section would exhibit a more or less constant conductivity across the river and, therefore, a constant percentage of Tomogonops river water. The distance between the point source (Station B, 148 m downstream of Tomogonops River) and section F is 1310 m. Our data indicates that for low discharge events (3.1 m^3/s in this case), the mixing zone extends beyond the study area, perhaps even beyond the confluence of the Portage river (Figure 1). However, within the study region, mixing has occurred as shown by comparing Figure 4a and Figure 4d.

To run RIVMIX, dispersion coefficients (ε_z) were estimated for each river reach. Values were in the order of 0.01 and 0.015 (Table 3). Such dispersion coefficients (ε_z) were in the order of magnitude of those observed in the literature for similar river conditions (Elhadi *et al.* 1984). For instance the Northwest Miramichi River was on average 40.3 m wide in our study reach with a mean depth of 0.29 m and mean velocities of 0.30 m/s. The resulting shear velocity was calculated at 0.089 m/s. Such information indicates that dispersion coefficients of 0.010-0.015 can be applied in river mixing studies of Altantic salmon river similar to the Northwest Miramichi River.

5.2 Precision of the model.

Results in Figures 4 show that the model provided a good overall description of the mixing process for the river reach of interest. Given the good agreement between observed and modelled concentration (% of Tomogonops River water), Cu and Zn concentrations across the Northwest Miramichi River should be reflective of the conditions that occurred during the spill of the winter of

1991. Metal concentrations available from Schiefer *et al.* (1992) were spot surface samples while the model produces values for each grid point across a section of the river. It was not possible to compare our results with their observations. For instance, Schiefer *et al.* (1992) measured a Cu concentration of 0.03 mg/l, 8 km downstream of our study area, on 23 February 91. The values measured at section F show Cu concentrations varying between 0.23 and close to 0 mg/l, with values near 0.10 mg/l in the middle of the section. Although the lack of information does not allow for a quantitative estimate of the accuracy, the dilution pattern provided by the RIVMIX model output is in the expected range.

The Cu and Zn concentrations modelled remained high near the true left bank of the Northwest Miramichi River. Even at section F near the far bank (right bank), Cu concentration were higher than the 0.015 mg/l suggested by Miller *et al.* (1992) as a tolerable limit. Similarly, Zn concentrations near the left bank remained above 3 mg/l, which is higher than 0.15 mg/l, a level associated with dangerous concentrations of Zn in the liver and kidneys of fish (Miller *et al.* 1992). Our study showed that the metal concentrations would have been lower that critical values on the right bank of the Northwest Miramichi River, only in a very short distance downstream of confluence of the two rivers. Downstream of section F, the level of concentration of Cu and Zn would have exceeded tolerable limits from bank to bank until other rivers significantly diluted the concentrations.

Toxicity studies reported by Schiefer *et al.* (1992) show incipient lethal levels for young Atlantic salmon to be 0.048 mg/l Cu and 0.6 mg/l Zn. It can thus be seen from the model outputs that these concentrations were exceeded on February 23, 1991 in each river section in our study reach. Results also show concentrations of Cu and Zn below the lethal concentrations near the right bank, but only for first 1.3 km of the Northwest Miramichi River downstream of the Tomogonops River.

5.3 Limitations of the model

RIVMIX is a model which can be implemented with a limited amount of initial data. Its source code is simple and relatively easy to follow and use. Our limited data set showed model to be in good agreement with field observations. However, this study showed some of the limitations of the model. It should be remembered that the option which would allow the model to be used without a velocity distribution at each selected section does not seem to model the hydraulic properties of the river as well as the case where velocities are known.

Another important limitation is that the hydrodynamics of this model do not enable the user to properly represent the impact of tributaries along the main river. It would have been interesting to quantify the influence of Portage River, which would normally have pushed the plume from the true left bank towards the middle of the Northwest Miramichi River in this specific case. The only way to achieve such a study with the present model would be to use the concentrations of section F (the last section upstream of Portage River) and re-inject them as initial concentrations for a new set of sections downstream of Portage River. This would be a very crude approximation and would only model the dilution process accurately while the mixing would not necessarily represent accurate results. In order to obtain a better representation of the mixing processes in such a situation, a two-dimensional model using a finite-element scheme can be used (Boudreau *et al.* 1994).

It should also be remembered that the available data only allowed modelling of low flow events. Concentration data for flood events were not available and therefore the model could not be tested for such conditions.

5.4 Conclusion

The application of the RIVMIX model on the Northwest Miramichi River has shown that, although there are limits to the information that can be obtained, the model is an easy tool to use. It enables the user to obtain relevant information such as the length of the mixing zone as well as concentration profiles within the mixing zone. Results for a low discharge and high initial concentrations (23 February 1991) on the Northwest Miramichi River show that Cu and Zn concentrations were higher than lethal levels for portions of each section within the study reach. Results also showed that at over 1 km downstream of the confluence of the Tomogonops River, the Northwest Miramichi River still showed a significant gradient in concentrations from the left bank to the right bank. In conclusion, this study did not only reconstruct the metal concentration gradient during the mining spill of the winter of 1991, it also established an important parameter, i.e. dispersion coefficients in river mixing studies. Dispersion coefficients of rivers in general are not very well known and such data is important in future studies.

6.0 ACKNOWLEDGMENTS

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Table 1. Inputs and outputs for RIVMIX.

INPUTS	OUTPUTS
Number of sections	All the inputs are printed as outputs
Distance between sections along both banks	Intermediate calculations at grid points
Cross-sectional characteristics (depths or velocity and depths)	Concentration distribution at grid points
Value of ε_z for each region	Concentration flux between sections
Desired numbers of stream grid points	
Initial distribution of concentrations	

Table 2. Distance downstream from the confluence of the Tomogonops River and longitudinal distances between sections and river banks.

Station	Section	Reach	TRB (m)	TLB (m)
0+00	A			
0+148	B			
		B-C	240	238
0+388	C			
		C-D	400	373
0+788	D			
		D-E	270	245
0+1058	E			
		E-F	252	285
0+1310	F			

TRB = true right bank; TLB = true left bank.

Table 3. Calculated dispersion coefficient (ε_z) for each section in the Northwest Miramichi River.

River reach	ε_z
B-C	0.010
C-D	0.015
D-E	0.010
E-F	0.010

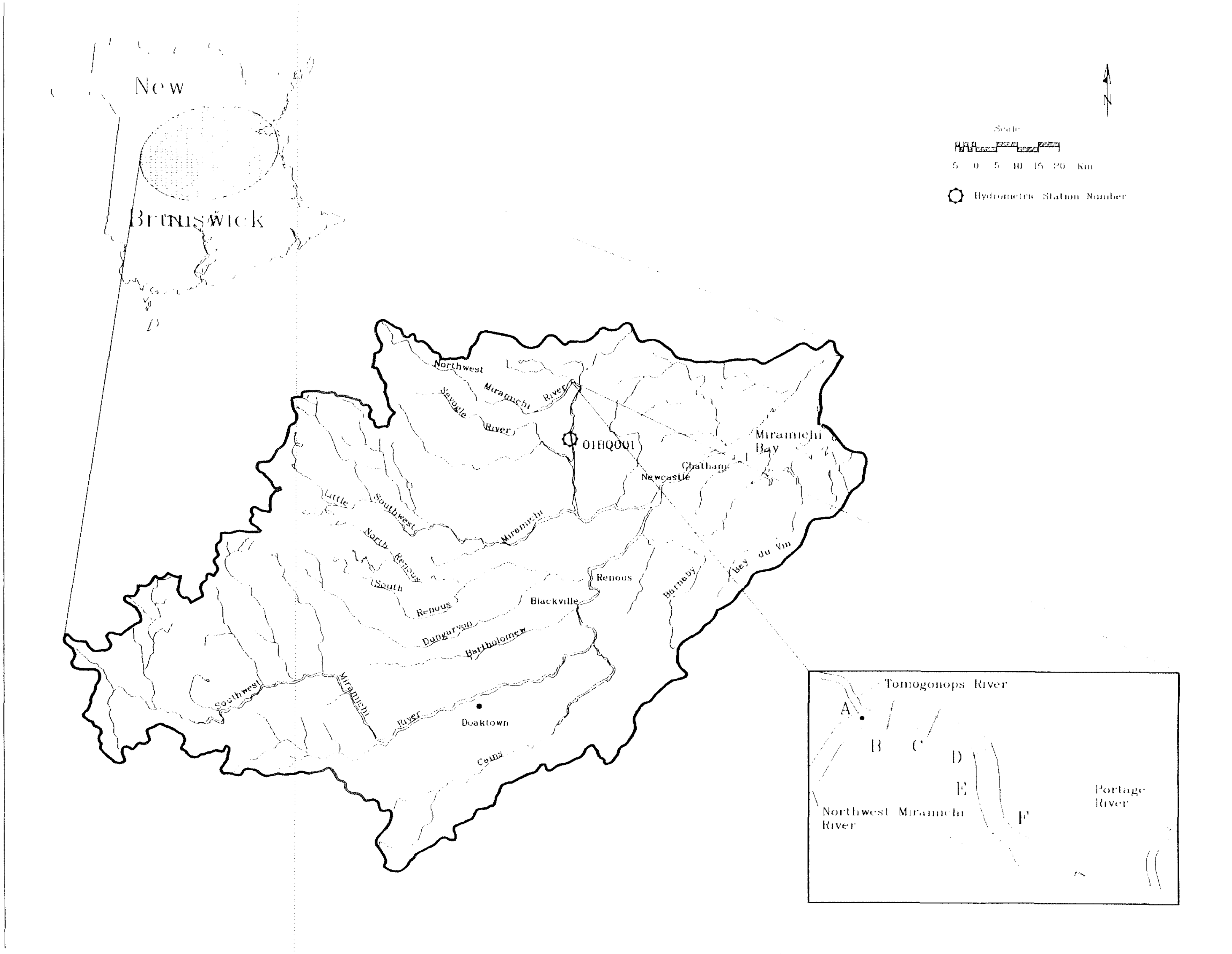

Figure 1. Map of the Miramichi River showing the study site on the Northwest Miramichi River downstream of the Tomogonops River

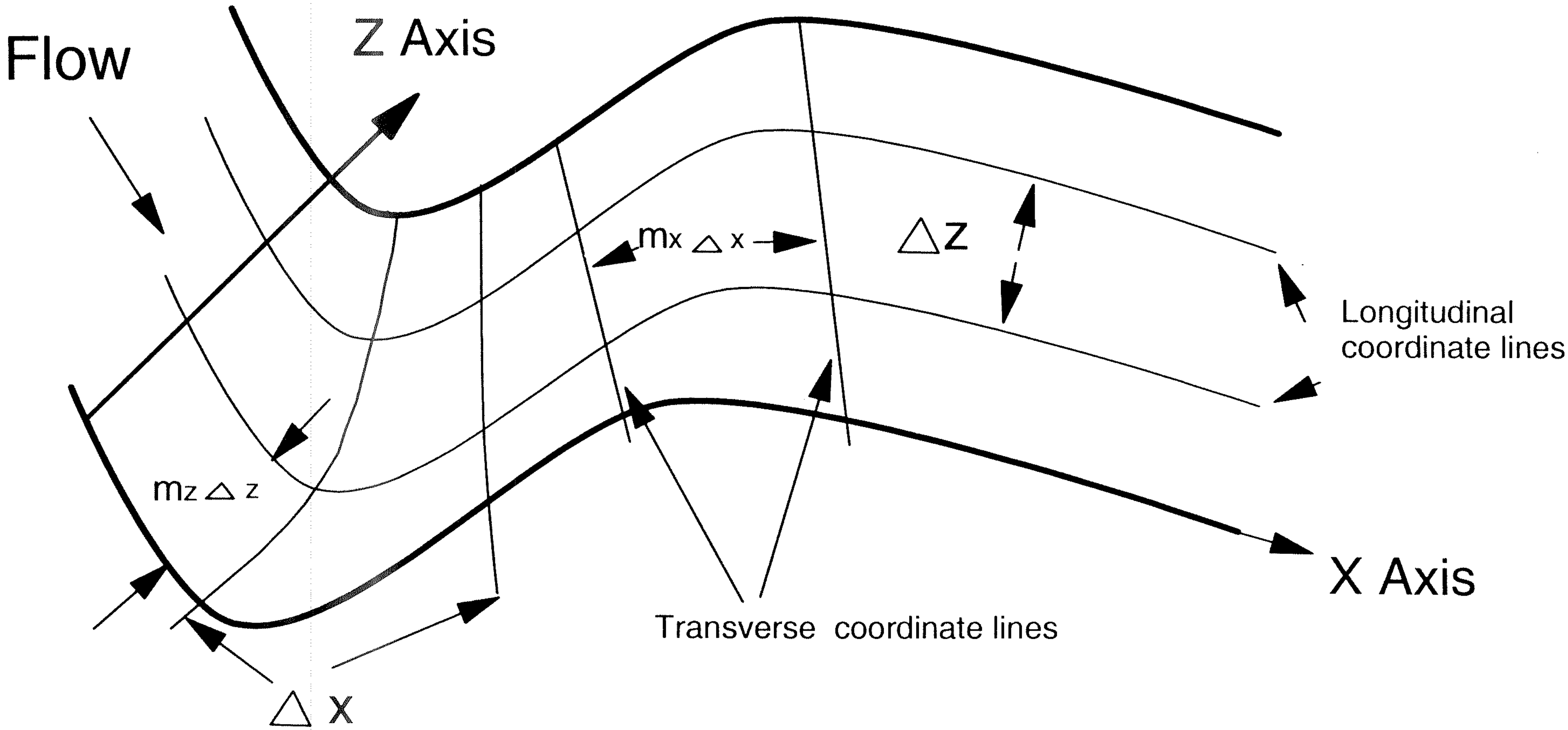

Figure 2. Natural Coordinates system. The x-axis is the True Right Bank (from Elhadi et al. 1984).

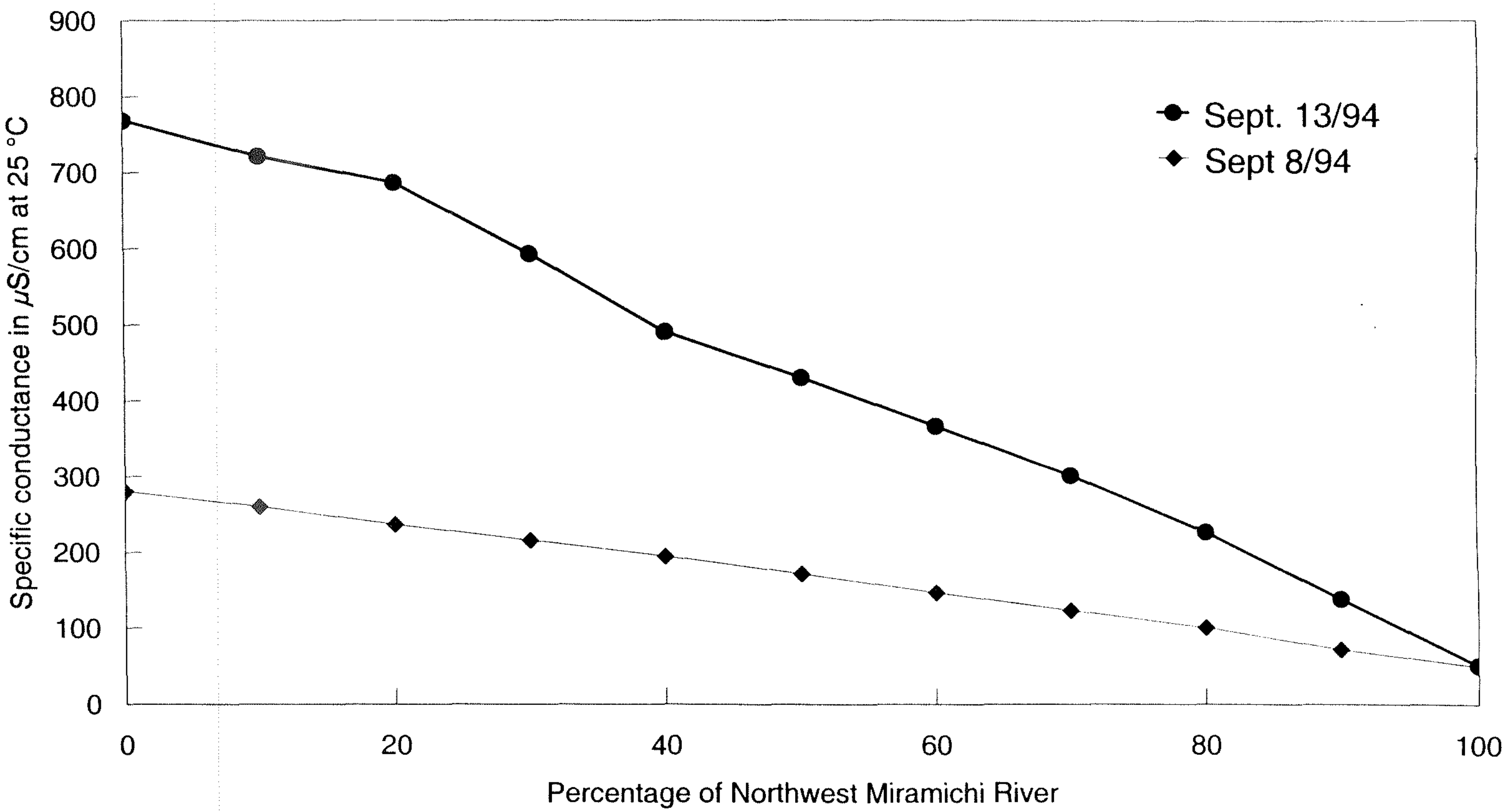

Figure 3. Specific conductance in relation to dilution ratios between Northwest Miramichi and Tomogonops Rivers.

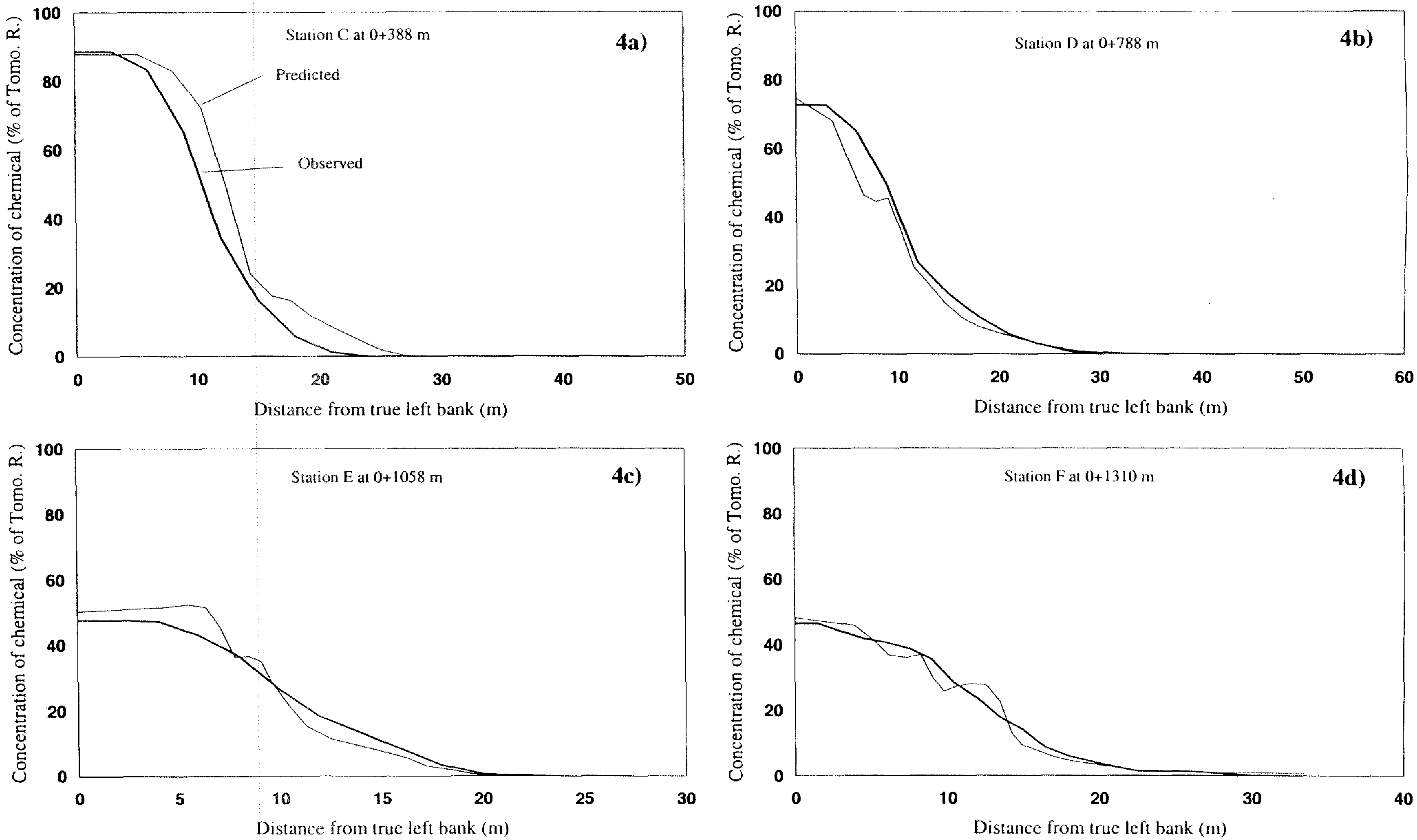

Figure 4. Measured and simulated percentage of Tomogonops River water at each station on the Northwest Miramichi River, September 13, 1994. a) station C at 0+388m; b) station D at 0+788 m; c) station E at 0+1058 m and d) station F at 0+1310 m.

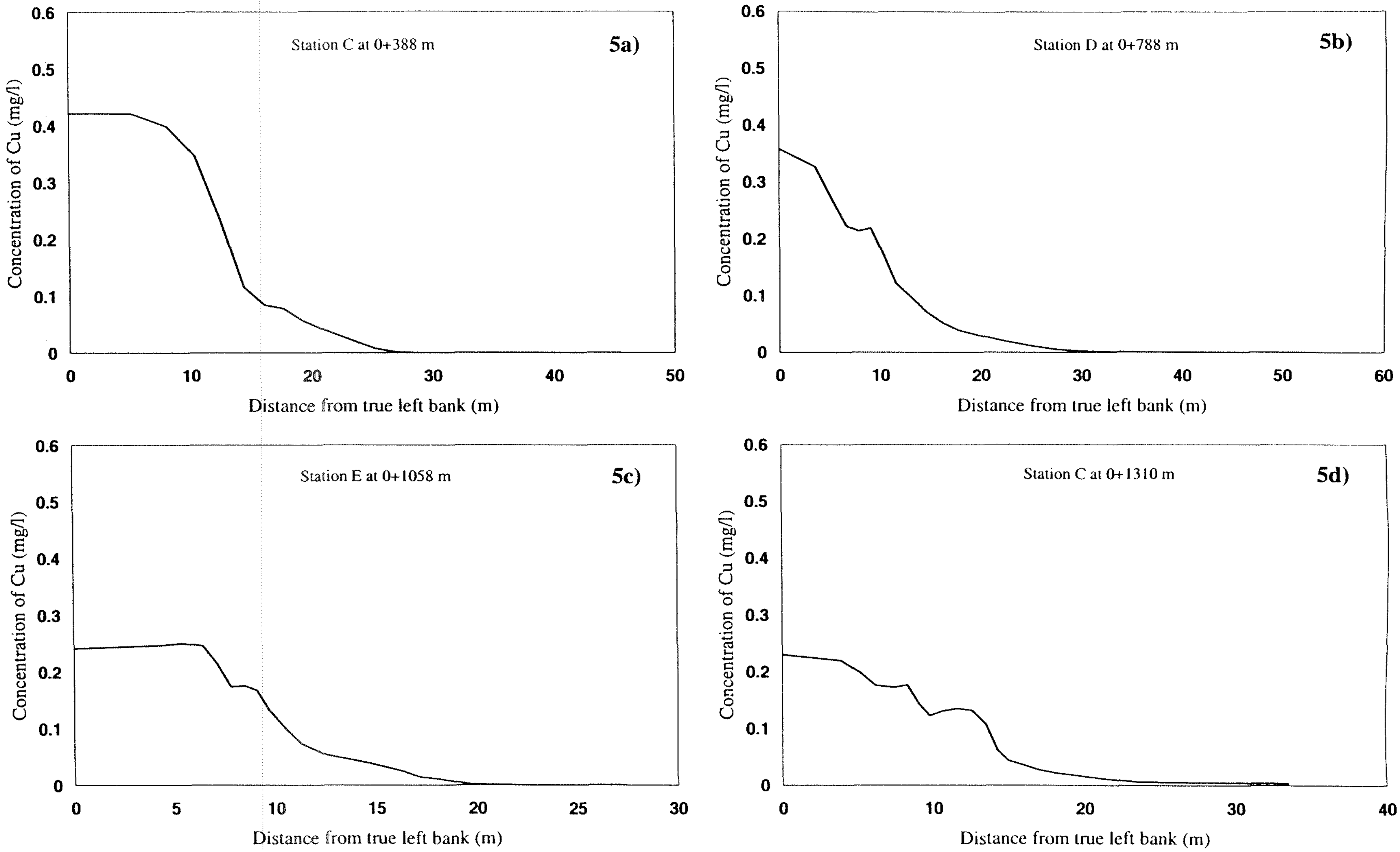

Figure 5. Simulation of Cu concentration during mining spill of Feb. 23, 1991 using RIVMIX at transects C, D, E and F on the Northwest Miramichi River (NB). The Cu concentration at the mouth of the Tomogonops River was at 0.48 mg/l (Schiefer et al. 1992) .

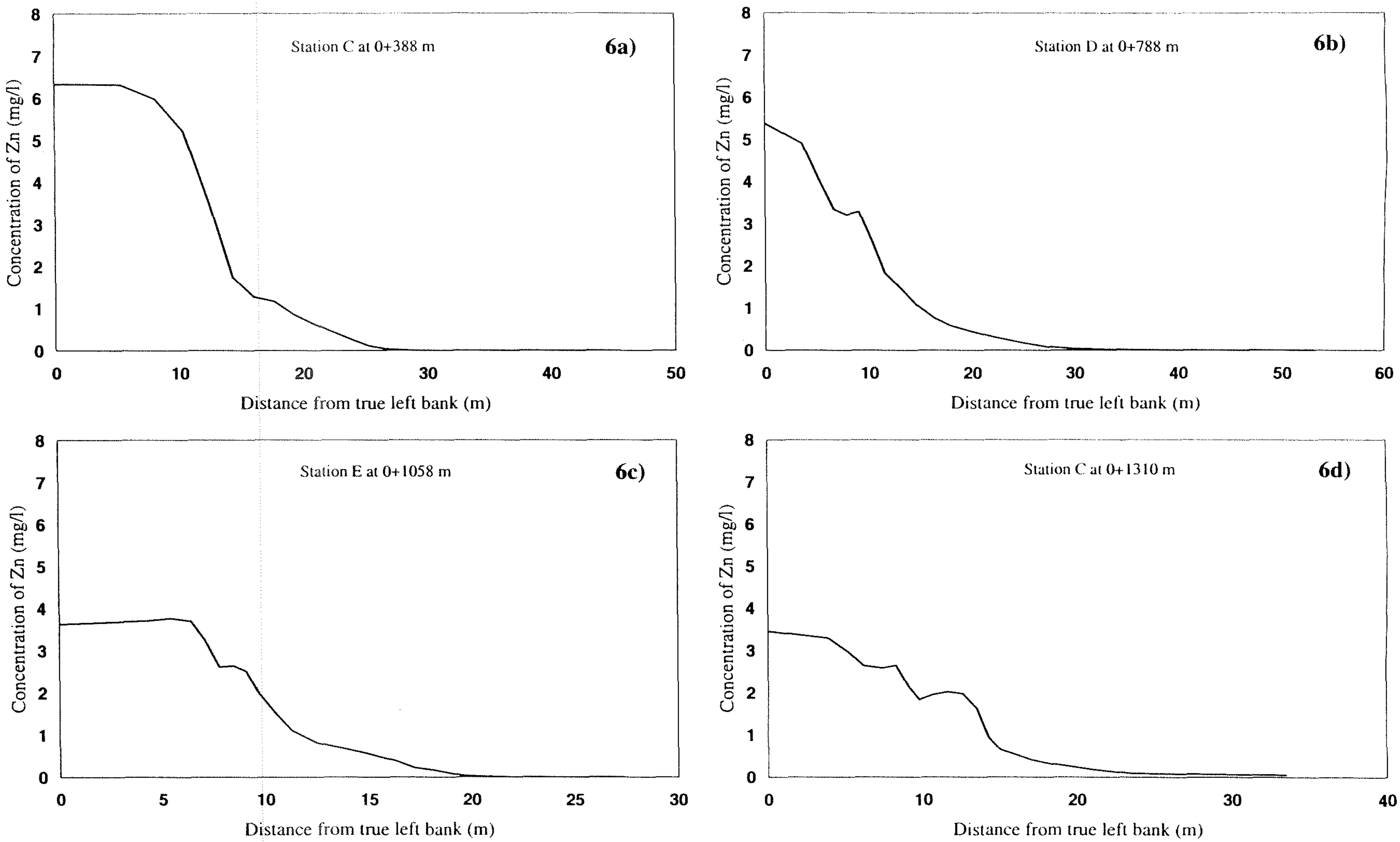

Figure 6. Simulation of Zn concentration during mining spill of Feb. 23, 1991 using RIVMIX at transects C, D, E and F on the Northwest Miramichi River (NB). The Zn concentration at the mouth of the Tomogonops River was at 7.20 mg/l (Schiefer et al. 1992) .