An Improved Model for Fraser River Temperature Predictions

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1997

Canadian Technical Report of Fisheries and Aquatic Sciences 2172

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Canadian Technical Report of Fisheries and Aquatic Sciences

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Cat. No. FS-97-6/2172 ISSN-0706-6457

Correct citation for this publication:

Hollemans, P., and M. G. G. Foreman. 1997. An improved model for Fraser River temperature predictions. Can. Tech. Rep. Fish. Aq. Sci.: 2172, 27 p.

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ABSTRACT

Hollemans, P., and M. G. G. Foreman. 1997. An improved model for Fraser River temperature predictions. Can. Tech. Rep. Fish. Aq. Sci.: xx, yy p.

Investigations aimed at improving the accuracy of an existing finite difference temperature model for the Fraser River included both the reformulation of the governing equation and the implementation of several different numerical methods. The accuracies of these methods were initially tested using simple benchmark test cases. The most promising methods were then used in combination with observed atmospheric, flow, and temperature data to simulate temperatures in the Fraser River for 1993 and 1994. Model results were compared to observed temperatures by calculating root-mean-square differences. The reformulation of the governing equation and its temporal discretization were found to provide modest improvements to the Fraser River solutions. In contrast, implementing a finite element approach for the spatial representation improved the results in the Gaussian hill test case but decreased the accuracy of the Fraser River simulations. Finally, a new particle tracking algorithm was found to improve the results in all the simple test cases and to reduce the original RMS differences by as much as 26% and 23% respectively at the 1993 and 1994 Fraser River observation locations.

Keywords: temperature, Fraser River, particle tracking method

RÉSUMÉ

Hollemans, P., and M. G. G. Foreman. 1997. An improved model for Fraser River temperature predictions. Can. Tech. Rep. Fish. Aq. Sci.: xx, yy p.

Des enquètes visant au progrès de l'exactitude d'un modèle existant aux différences finies de température du fleuve Fraser comprenaient non seulement la réformulation de l'équation dominante, mais aussi l'implémentation de plusieurs méthodes numériques différentes.

Les exactitudes de ces méthodes furent analysées initialement avec des essais de base. Les méthodes les plus prometteuses ensuite furent utilisées jointes aux données atmosphériques, aux courants, et aux températures afin de simuler des températures dans le fleuve Fraser en 1993 et 1994. Des résultats du modèle furent comparés avec des températures en calculant des différences de la racine carrée de la moyenne des carrés. Nous constatâmes que la réformulation de l'équation dominante et sa discrétisation temporale pourvoyaient des améliorations modestes des solutions du fleuve Fraser.

Par contraste, l'implémentation de la façon d'éléments finis pour une représentation spatiale améliorait les résultats en tous essais de la courbe gaussienne mais diminuait l'exactitude des simulations du fleuve Fraser.

Pour terminer, nous constatâmes que l'algorithme suivant des nouvelles particules améliorait les résultats en tous essais simples et qu'il diminuait les différences RMS originales autant de 26% et 23% respectivement aux locations des observations en 1993 et 1994 du fleuve Fraser.

Mots-clés: température, fleuve Fraser, méthode pour suivre des particules

1 Introduction

The Fraser River is the largest Canadian river that empties into the Pacific Ocean (see Figure 1). With its intricate network of tributaries, the Fraser watershed drains approximately 230,000 km^2, or one quarter of British Columbia. The river originates in the Rocky Mountains near Jasper, Alberta, descends rapidly until it reaches Hope, and then spreads to a flat alluvial valley for the final 160 km of its 1370 km journey to the Strait of Georgia. Due to the accumulation of snow throughout the winter and its melting in the spring, typical discharges at Hope peak in May and June at about 7000 m^3/s (Thomson, 1981) and diminish to about 1000 m^3/s in the winter months. Of the total discharge at Hope, the major contributions come, on average, from the headwaters upstream of Shelley at 28%, the Thompson River at 40%, and the Quesnel River at about 12%. Smaller tributaries such as the Nechako, Chilcotin, and West Road Rivers all contribute less than 10% each.

Although the threat of flooding has led to the development of a river flow and elevation prediction model by the Department of the Environment of the B.C. Provincial Government (River Forecast Centre, 1996), it has only been recently that the need for a parallel temperature prediction model was also recognized. River temperatures at Hope often rise to about 20°C during the summer and early autumn while those in tributaries such as the Quesnel, West Road, and Nechako Rivers, whose flows are slower and depths are shallower than those in the Fraser, can be warmer. Such temperatures can have dramatic biological consequences. Annual pre-spawning mortalities of migrating Fraser River sockeye salmon are strongly correlated with river temperatures (Gilhousen, 1990). When the water is too warm, the metabolic rate of the salmon increases and their energy reserves rapidly deplete, causing them to die before reaching their spawning grounds. Temperatures above 24°C can cause acute thermal shock (Bouck et al., 1975) leading to death in only a few hours, whereas sustained exposure to temperatures between 22°C and 24°C for several days can also be lethal (Servizi and Jensen, 1977). Lesser temperatures, though they may not lead to mortality, can also cause sufficient stress that salmon fertility is significantly decreased.

The possibility that water temperatures in the Fraser River will increase in future years is likely, given various proposals for water withdrawals, industrial heat inputs, logging, and other human activities. Given these expectations, a river temperature model was developed to supply fisheries management with quantitative predictions so that thermal-induced stress and/or mortality could be estimated, and mitigative procedures could be taken. One proposal is to design water impoundments that could supply cooling water to assist salmon migrations at critical times and locations in the Fraser River system. Another proposal (that has been implemented) involves limiting the commercial fisheries in the Strait of Georgia during periods of high river temperatures to ensure that a larger percentage of the salmon run enters the river and the desired number of spawners still reach their natal streams. In

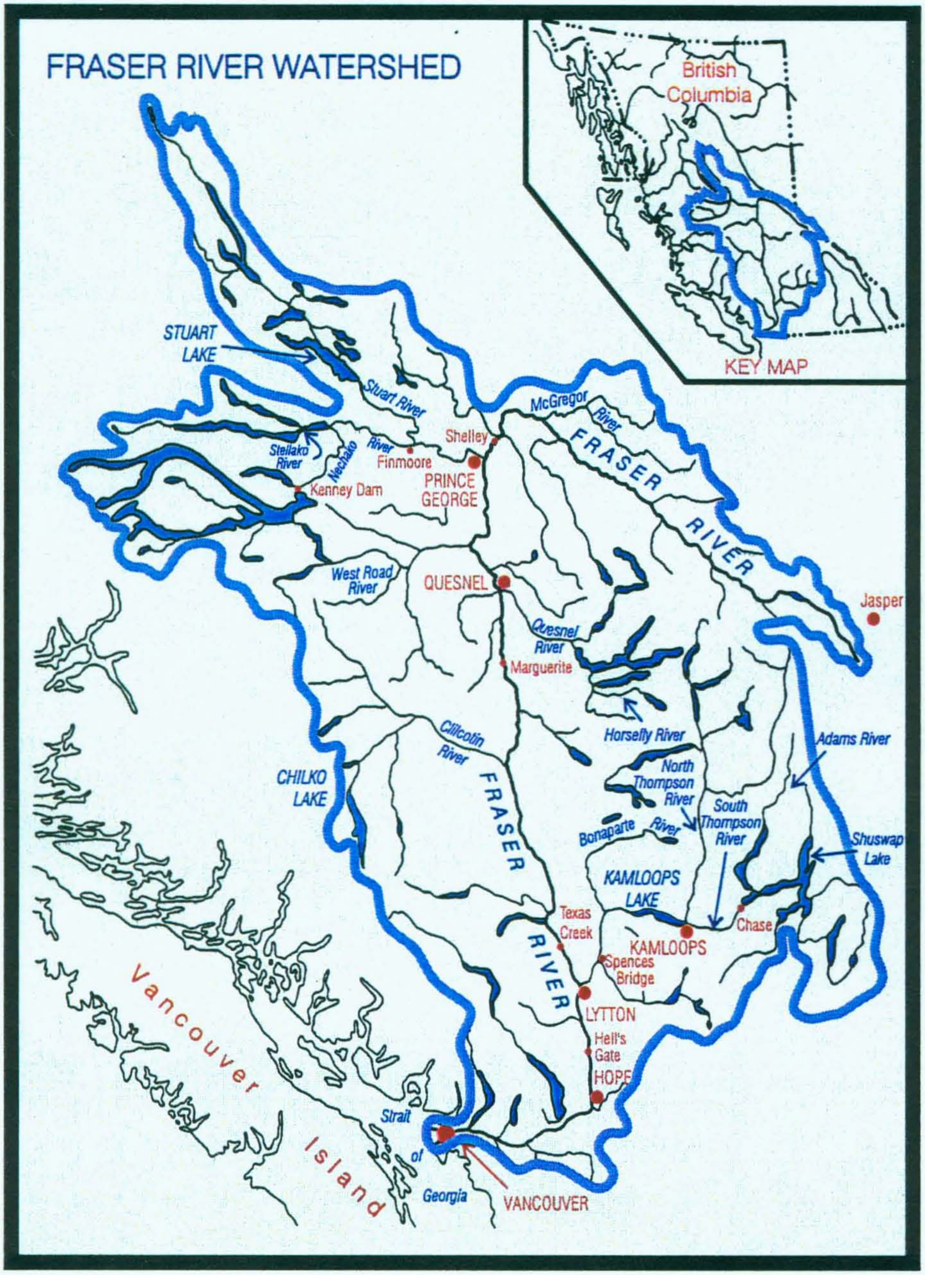

Figure 1: The Fraser River watershed.

1995 and 1996, the river temperature model was used to assist in setting such regulations. Ten-day predictions were issued twice a week during the salmon migration period of June through October and they played an important role in the decision to close the commercial fishery briefly in July 1995.

Although the 1995 predictions were, on average, accurate to within 1°C, there is an obvious need to improve this accuracy and provide even better estimates of salmon mortality and thermal-induced stress. This paper describes the development of one such improvement to the numerical technique. For the interested reader, the report by Hollemans (1994) describes the equations and software used in the existing Institute of Ocean Sciences' River Temperature Model (IOSRTM) while the paper by Foreman et al. (1997) gives a more general overview of the model and its results for 1993 and 1994. In brief, the model simulates river temperatures using a fairly simple one-dimensional advective transport scheme. The headwater boundary conditions are forced using recorded temperatures and heat is allowed to enter or leave the river through atmospheric heating and cooling, and through tributary inputs. The model is currently applied to the Fraser River between Shelley and Hope, and to the Thompson River from Chase to the confluence with the Fraser at Lytton (see Figure 1). In this region, the flow and velocity values needed by the transport equation are supplied by a separate one-dimensional flow model developed by Quick and Pipes (1977). This flow model overcomes the difficulties associated with a river system where there exist large ungauged lateral inflows and limited data, by employing a technique (Quick and Pipes, 1976) based on routing coefficients and parameters that are calculated from existing river stage-discharge and stage-velocity measurements taken by Water Survey of Canada (WSC). Though the Quick and Pipes routing model is over twenty years old, the development of a more advanced two- or three-dimensional model that would permit the simulation of horizontal and vertical channel variations is limited by the lack of river survey data. The Fraser and Thompson Rivers are not navigable above Hope and little bathymetric data are available. Only at five gauging stations along the two rivers has WSC performed the necessary measurements to establish the flow versus width relationships required by a routing model.

The organization of this paper is as follows. The existing model is introduced in Section 3, while in Section 4 attempts to improve the accuracy of the existing temperature model by either changing the governing equation or replacing the numerical algorithm are described. In Section 5 the development of a new particle tracking algorithm is described after the initial model improvements were found to fall short of expectations. The application of this new algorithm to the 1993 and 1994 Fraser River simulations is described in Section 6 and all results are summarized and discussed in Section 7. In the early stages of development, a few simple tests were devised in order to benchmark the various improvements. These tests, along with a brief introduction to the 1993 and 1994 hindcast runs are described in Section 2.

2 Test Cases

Several simple tests for assessing the accuracy of numerical solutions to the transport equation are given by Baptista et al. (1995). We decided that a *Gaussian wave test* similar to that mentioned in Baptista et al. (1995), and a *step function test* would be most useful for measuring the amount of numerical diffusion inherent in a prospective scheme and revealing any other numerical artifacts that might arise in the solution. The first test involves forcing the headwater boundary with a Gaussian temperature time series and observing how this profile changes as it travels down the river. The velocity and transport of the river are held constant so that the time evolution of the theoretical Gaussian wave can be calculated easily and root-mean-square (RMS) differences between the modelled and true temperatures can be used to evaluate the accuracy of the numerical advection schemes. In a similar fashion, the step function test uses headwater temperatures that change suddenly, rather than gradually, as in the Gaussian test. Both these tests are performed with constant velocity and volume transport values that approximate the real Fraser River near Shelley in early May. The two plots in Figure 2 show sample Gaussian and step tests for which the shape of the disturbance is perfectly preserved. Other similar tests, such as the *hill test* and *sine-wave test*, were also devised but not used as extensively during the new model development. The hill test (or square-wave test in Oran and Boris (1987)) forces the headwater boundary with a square-wave function in time, while the sine-wave test uses a sine function. In particular, a sine-wave with a period of one day provides a reasonable approximation of the actual Fraser River headwater temperatures at Shelley.

It should be pointed out that because tributary temperatures can differ significantly from those in the mainstem river, temperatures in the one-dimensional Fraser model can have abrupt changes. For example, between July 10 and September 13, 1994, the average temperatures in the Nechako River were 3.6°C warmer than those of the Fraser just above their confluence at Prince George. As the Nechako flows are about 40% of the Fraser's at this point, the relatively quick mixing of these two rivers causes a virtually immediate increase of 1.1° in the Fraser temperatures. The ability to handle these discontinuities is critical to the success or failure of any numerical technique applied to this problem. Consequently, a *tributary test* was also devised to help check that tributary inputs were handled correctly by prospective new models. The analytical solution in this case performs a simple mixing calculation based on the mainstem and tributary temperatures and flows, in order to determine the temperature of the river downstream of the confluence.

Note that in all these simple tests, the river is considered to be insulated from atmospheric heating or cooling. In order to test the model under realistic conditions, a final test was to hindcast the Fraser River temperatures for 1993 and 1994 by using observed atmospheric, flow, and tributary data. The hindcasted temperatures were compared to observed values

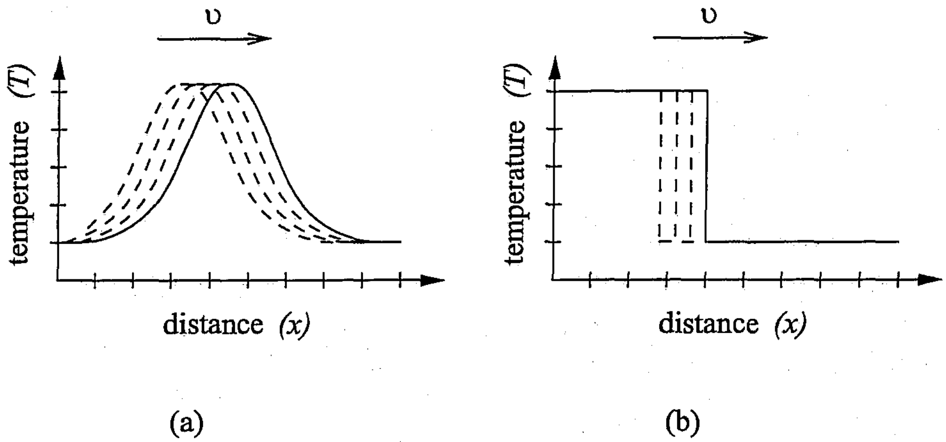

Figure 2: Simple test solutions: (a) a Gaussian wave, (b) a step function. Each signal maintains its shape as it travels down the river with velocity v. Dashed lines indicate previous positions.

at various locations along the river and RMS differences were calculated. This test gives the best indication of how the model will perform in future temperature prediction runs. Further details are provided in Section 6.

3 The Existing Model

The existing model was originally developed by Triton Environmental Consultants (1995) for their simulations in the Nechako River. It is based on heat transport models developed by Edinger et al. (1974). The governing heat budget equation (see Edinger et al., 1974; and Foreman et al., 1997) is

$$\frac{\partial(hT)}{\partial t} + \frac{\partial(QT)}{\partial A} = \frac{H_{net}}{\rho c_p} + \frac{Q_{tr}T_{tr}}{dA} \tag{1}$$

where h is the hydraulic depth (m), T is the temperature (°C), Q is flow (m^3/s), A is the cumulative surface area (m^2), H_{net} is the atmospheric heat exchange (W/m^2), ρ is the density of water (kg/m^3), c_p is the specific heat capacity of water at constant pressure (J/kg °C), Q_{tr} is the tributary flow (m^3/s), and T_{tr} is the tributary temperature (°C). The discretization that was adopted by Triton for this equation is the following *backward Euler* (Celia and

Gray, 1992), *upwind* scheme

$$\frac{(hT)_j^{n+1} - (hT)_j^n}{\Delta t} + \frac{(QT)_j^{n+1} - (QT)_{j-1}^{n+1}}{A_j^{n+1} - A_{j-1}^{n+1}} = \frac{(H_{net})_j^{n+1}}{\rho c_p} + \frac{(Q_{tr}T_{tr})_j^{n+1}}{A_j^{n+1} - A_{j-1}^{n+1}} \quad , \tag{2}$$

where subscripts j and n denote discretized space and time indices such that $f_j^n \equiv f(j\Delta x, n\Delta t)$. In particular, the space and time increments $\Delta x = 10000$ m and $\Delta t = 3600$ s were chosen to coincide with those of the flow model. Equation 2 is easily re-arranged to solve for the unknown T_j^{n+1} values. The flow model provides all the Q and v values while the difference in cumulative area is calculated as

$$A_j^{n+1} - A_{j-1}^{n+1} = \frac{1}{2}(w_j^{n+1} + w_{j-1}^{n+1})\Delta x, \tag{3}$$

and w, the river width (m), is calculated as

$$w = aQ^b. \tag{4}$$

The site specific width constants, a and b, are computed from regression analyses based on WSC measurements, and the depth, h, is calculated as

$$h = \frac{Q}{wv}. \tag{5}$$

Finally the tributary values Q_{tr}^n and T_{tr}^n are assumed to be known for all j and n, and T_j^n is assumed to be known at $n = 0$. Further details are available in Foreman et al. (1997).

The finite difference model given by Equation 2 was used for the 1993 and 1994 Fraser and Thompson River hindcast runs that were described in Foreman et al. (1997). The results from these runs provided the impetus for the improvements to the governing equation and numerical algorithm that are presented in the next section.

4 Improvements to the Model

4.1 Governing Equation

One problem with the Triton formulation of the governing equation is that its derivation assumes the river width w to be constant in time (Hollemans, 1994). Although this is a reasonable approximation, it should certainly be more accurate to allow the river width to vary in both space *and* time. Another problem with Equation 1 is that the cumulative area, A, is treated as an independent variable. In order to implement a finite element (Section 4.3) and other prospective methods, it is more meaningful to have space, x, and time, t as the independent variables. The derivation in this section addresses both of these problems.

The derivation of a new governing equation follows. Assuming that the river can be represented by a one-dimensional incompressible flow, the material derivative for the temperature, T, is then

$$\frac{DT}{Dt} = \frac{\partial T}{\partial t} + v\frac{\partial T}{\partial x}. \tag{6}$$

Assuming that the only heat exchange occurs at the atmosphere/river interface, we also have

$$\frac{DT}{Dt} = \frac{H_{net}}{\rho c_p h}. \tag{7}$$

In order to derive a continuity condition, consider a river section of length Δx and volume V. The change in volume, ΔV, during a time interval Δt is governed by the flow characteristics, such that

$$\Delta V = [Q(x,t) - Q(x+\Delta x, t)]\Delta t. \tag{8}$$

Thus,

$$\frac{\Delta V}{\Delta t} = \left[\frac{Q(x,t) - Q(x+\Delta x, t)}{\Delta x}\right]\Delta x, \tag{9}$$

and letting Δx, $\Delta t \to 0$, we get

$$\frac{\partial V}{\partial t} = -\frac{\partial Q}{\partial x}dx. \tag{10}$$

If the total volume is then calculated as $V = wh\,dx$, we have

$$\frac{\partial (wh)}{\partial t} + \frac{\partial Q}{\partial x} = 0. \tag{11}$$

Combining this continuity condition with Equations 6, 7 and the relation $Q = whv$ then yields

$$\begin{aligned} wh\frac{\partial T}{\partial t} + Q\frac{\partial T}{\partial x} + T\left[\frac{\partial(wh)}{\partial t} + \frac{\partial Q}{\partial x}\right] &= \frac{wH_{net}}{\rho c_p}, \\ \text{or} \quad \frac{\partial(whT)}{\partial t} + \frac{\partial(QT)}{\partial x} &= \frac{wH_{net}}{\rho c_p}. \end{aligned} \tag{12}$$

Finally, by adding a tributary term analogous to that in Equation 1, the new governing equation is

$$\frac{\partial(whT)}{\partial t} + \frac{\partial(QT)}{\partial x} = \frac{wH_{net}}{\rho c_p} + \frac{Q_{tr}T_{tr}}{dx}. \tag{13}$$

This equation is consistent with Equation 1 when the river width is constant in time.

When Equation 13 is approximated with a backward Euler, upwind discretization and applied to the Gaussian and step tests, the results are identical to those produced with the Triton model. This is because the river width is constant in time for both these tests. However, when this new method was applied to the 1993 and 1994 hindcasts, the RMS differences became only marginally smaller than those obtained with the Triton model. Thus, a slight accuracy improvement is attained when w is not assumed to be constant in time.

4.2 Temporal Representation

A further accuracy improvement can be expected if the first-order backward Euler time-stepping is replaced with a second-order approximation such as the Crank-Nicolson (Burden et al., 1978) scheme. Since for an equation of the form

$$\frac{\partial}{\partial t}f(x,t) = g(f,x,t), \tag{14}$$

a backward Euler scheme is potentially implicit, the move to Crank-Nicolson does not present any further complications. However a minor problem does occur with the atmospheric heating term because the net atmospheric heat exchange, H_{net}, depends on the water temperature, T, through a non-trivial formula (see Foreman et al. (1997), Equations 2-8). In order to overcome this difficulty, $H_{net}(T^{n+1})$ is simply approximated as $H_{net}(T^n)$ when using an implicit solution of Equation 1 or 13.

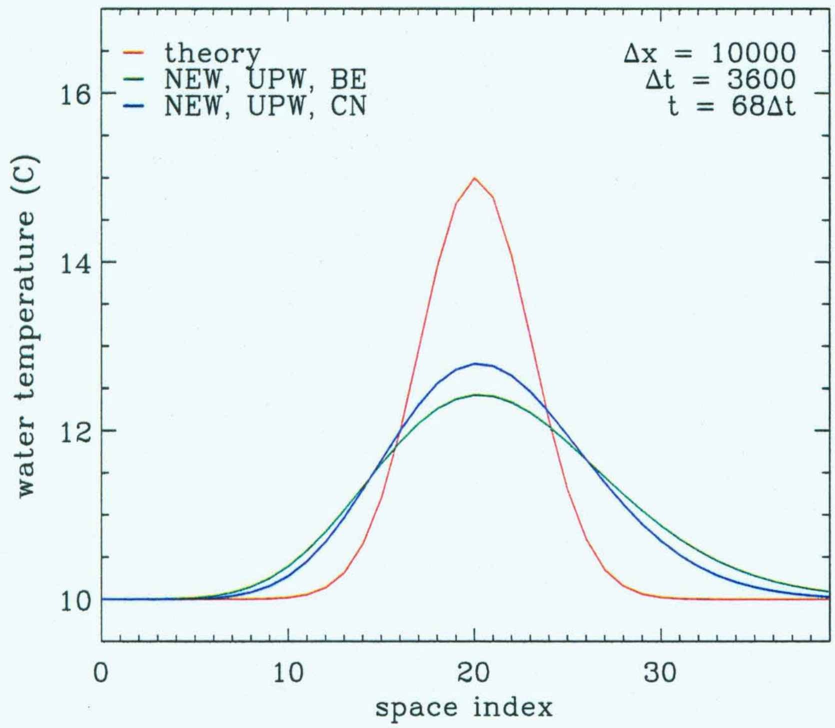

Figure 3: Gaussian test solutions for finite difference discretizations of Equation 13 with backward Euler and Crank-Nicolson time stepping. Model and theoretical results are shown after 68 one hour time steps.

The following equation is a Crank-Nicholson, upwind version of Equation 13

$$\frac{(whT)_j^{n+1} - (whT)_j^n}{\Delta t} + \left[\frac{(QT)_j - (QT)_{j-1}}{\Delta x}\right]_n^{n+1} = \left[\frac{(wH_{net})_j}{\rho c_p}\right]_n^{n+1} + \left[\frac{(Q_{tr}T_{tr})_j}{\Delta x}\right]_n^{n+1}, \quad (15)$$

where (square) brackets denote the temporal averaging $[f]_n^{n+1} \equiv \frac{1}{2}(f^n + f^{n+1})$. Figure 3 shows a noticeable improvement in the Gaussian test results when switching to Crank-Nicolson from the original backward Euler time stepping.

4.3 Spatial Representation

A finite element spatial discretization was also implemented to determine if it would provide further improvements over the previous finite difference solutions. Its application is described as follows. Assume that the variables in Equation 13 can be approximated as

$$w(x,t)h(x,t)T(x,t) \simeq \sum_{i=1}^{N} w_i(t)h_i(t)T_i(t)\phi_i(x) \tag{16}$$

$$Q(x,t)T(x,t) \simeq \sum_{i=1}^{N} Q_i(t)T_i(t)\phi_i(x) \tag{17}$$

$$S(x,t) \equiv \frac{Q_{tr}(x,t)T_{tr}(x,t)}{\Delta x} + \frac{w(x,t)H_{net}(x,t)}{\rho c_p} \simeq \sum_{i=1}^{N} S_i(t)\phi_i(x) \tag{18}$$

where the subscript i denotes the node number, N is the total number of nodes, and the $\phi_i(x)$'s are linear Lagrange basis functions. Substituting these approximations into Equation 13, the residual becomes

$$R(x,t) \equiv \frac{\partial}{\partial t}\left[\sum_{i=1}^{N} w_i(t)h_i(t)T_i(t)\phi_i(x)\right] + \frac{\partial}{\partial x}\left[\sum_{i=1}^{N} Q_i(t)T_i(t)\phi_i(x)\right] - \sum_{i=1}^{N} S_i(t)\phi_i(x). \tag{19}$$

By applying Galerkin conditions to this residual,

$$\int_{\Omega} R(x,t)\phi_j(x)\, dx = 0, \quad \forall j \in (1,2,...N) \tag{20}$$

where Ω is the entire spatial domain, a matrix equation (written in standard subscript notation) of the form

$$A_{ij}\frac{\partial}{\partial t}\left[w(t)h(t)T(t)\right]_j + B_{ij}\left[Q(t)T(t)\right]_j = A_{ij}S_j(t) \tag{21}$$

emerges. Finally, implementing Crank-Nicolson time stepping yields the following fully discretized matrix equation

$$A_{ij}\left[\frac{(whT)_j^{n+1} - (whT)_j^{n}}{\Delta t}\right] + B_{ij}\left[(QT)_j\right]_n^{n+1} = A_{ij}\left[S_j\right]_n^{n+1}, \tag{22}$$

which can be rearranged into the form

$$C_{ij}T_j^{n+1} = D_{ij}T_j^{n} + b_j \tag{23}$$

and solved for the vector T_j^{n+1}.

The preceding finite element discretization improves the model accuracy significantly for the Gaussian test function. If its solution were included in Figure 3, the temperatures would be indistinguishable from the analytical values. However, problems arose when the same finite element technique was used with the step function and hindcast tests. Specifically, the step function solution contained parasitic oscillations (also observed by Baptista et al. (1995)) that lagged behind the step wave front as it travelled down the river (see Figure 4). With the 1993 simulation, the FEM solution followed the same general trends as the Triton model predictions, but also had an oscillatory component that increased in amplitude toward the tail end of the river. The oscillations observed in the step function test are thought to explain this effect. The spatial discontinuities in temperature, inherent in the river at points where tributaries enter, act in the same way as the wave front in the step test.

In an attempt to reduce these oscillations, higher order (quadratic) basis functions were used in place of the linear Lagrange functions. Although this switch increased the accuracy even further for smooth temperature profiles such as with the Gaussian test, it did not decrease the generation of the oscillations associated with the step test. Given the inherent discontinuities in the Fraser River temperatures and the fact that a finite element method with linear or higher order basis functions assumes a continuous solution, further investigations with the finite element method were abandoned. Although an implementation with piecewise constant basis functions might prove to be more successful, it was not investigated.

5 A Particle Tracking Model

A particle tracking method was developed with the expectation that it would overcome both the numerical diffusion inherent in *any* finite difference or finite element method, and be able to handle spatial discontinuities without the generation of spurious oscillations. Its implementation is described as follows. Under a Lagrangian representation as discussed by Oran and Boris (1987), the river is divided into macroparticles of fluid or "nodes", at which the initial temperatures are known. These nodes are tracked numerically down the river and their temperatures are adjusted to account for tributary mixing and atmospheric heat exchanges. The fact that velocities in the river are always positive (ie. downstream) guarantees that the Lagrangian grid will not become tangled during the tracking process. Although the distance between adjacent nodes can change during their propagation down the river, no node is able to catch up to or pass another node. This eliminates the need for any grid remapping procedure that might act as a source of numerical diffusion (Oran and Boris, 1987). At the end of each time step, the temperature field is interpolated to a regular grid for comparison with the non-Lagrangian algorithms previously discussed.

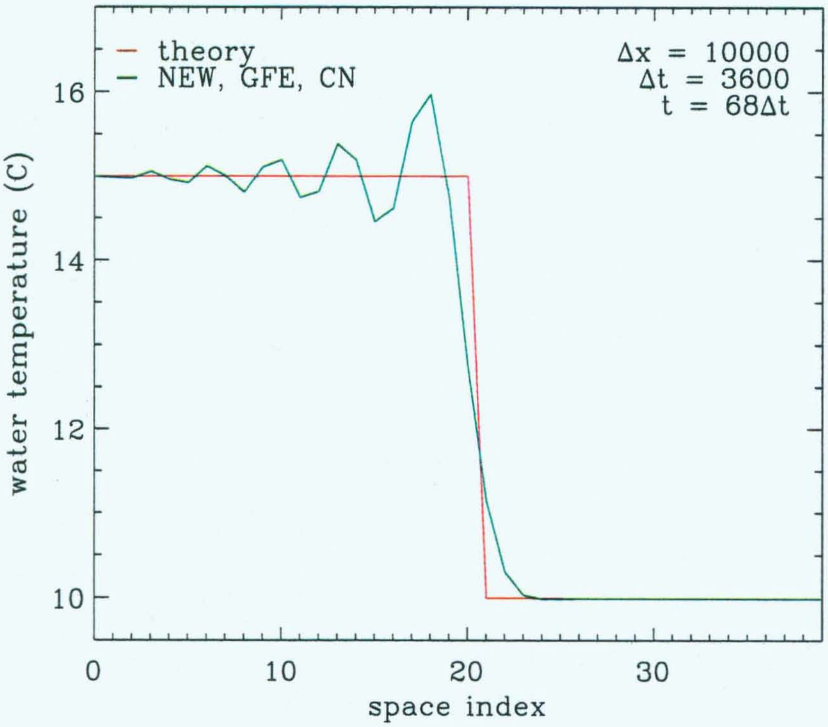

Figure 4: Theoretical and Galerkin finite element solutions for the step test. The results are shown after 68 one hour time steps.

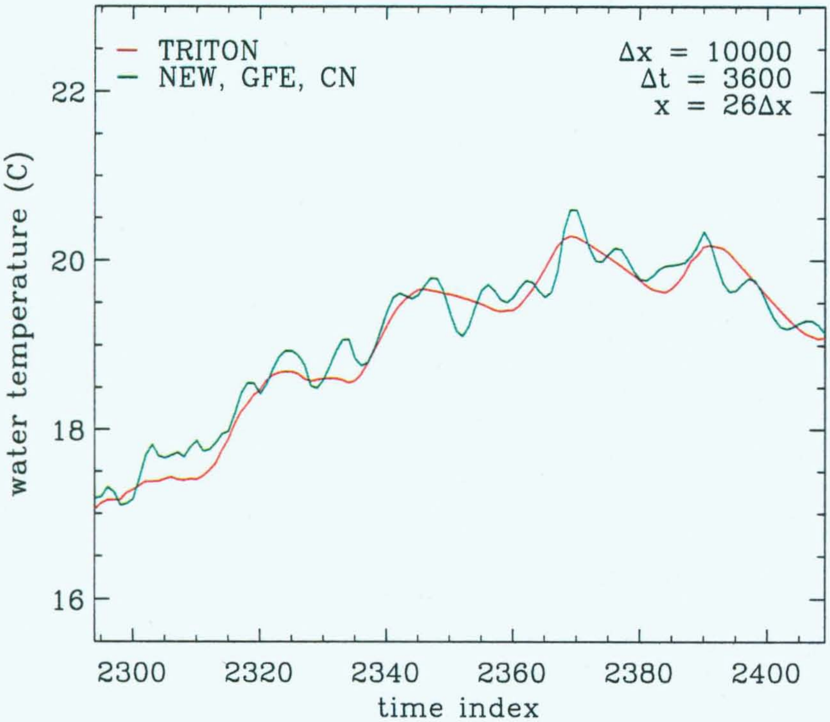

Figure 5: Triton and Galerkin finite element simulations for the Fraser River in 1993. The results are shown for the location 260 km downstream from Shelley.

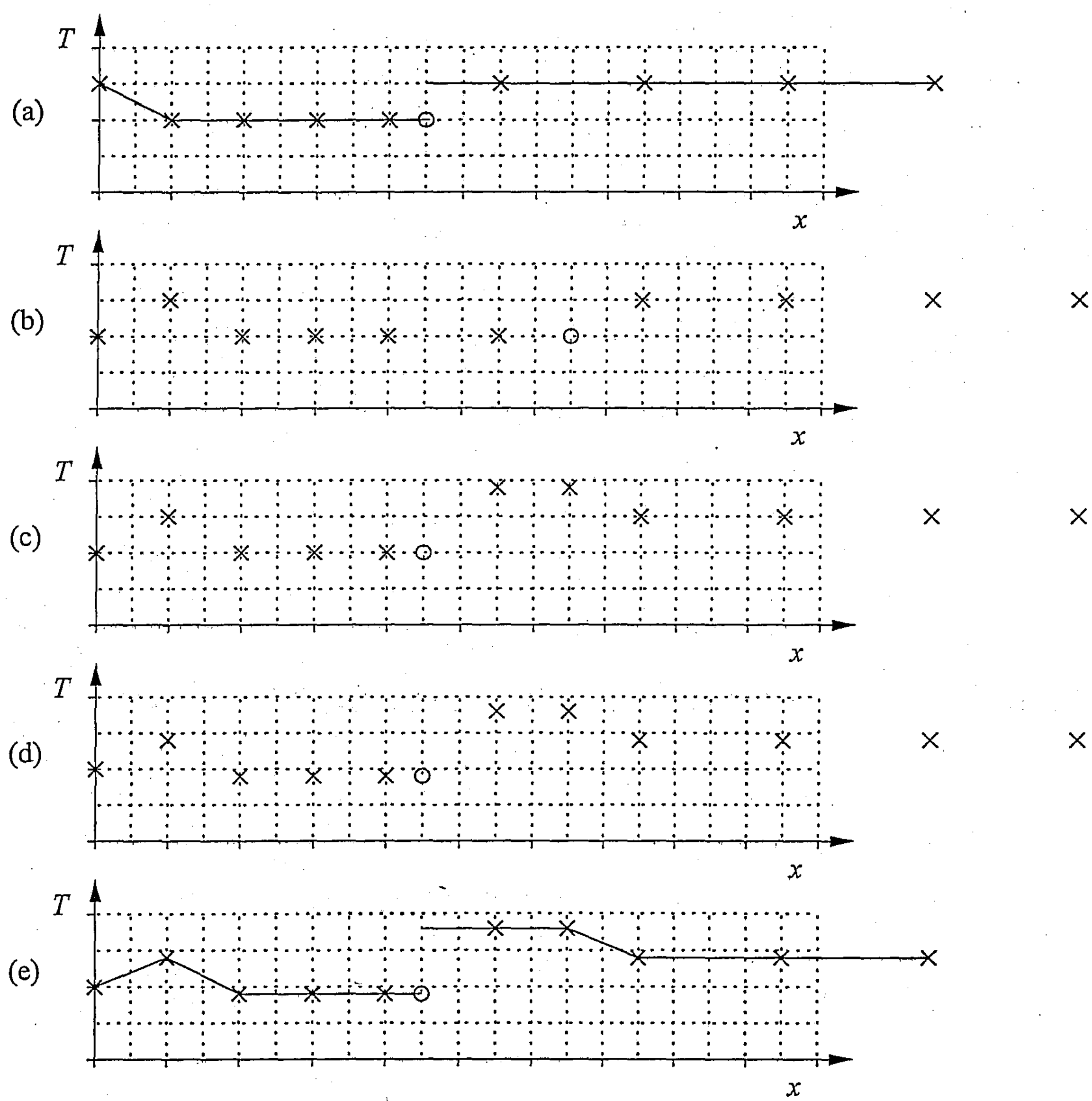

Figure 6: One time step in the particle tracking method. The × symbols represent regular temperature nodes and the ∘ symbols are temperature nodes associated with a tributary entrance location. (a) shows the grid at the start of the time step with a solid line to mark the fully interpolated temperature field. (b), (c), and (d) show the intermediate results of the algorithm after advection, a warming correction for tributary mixing, and a cooling correction for atmospheric heat exchange respectively. (e) shows the final configuration of the nodes with a new solid line for the fully interpolated temperature field.

The specific steps in the particle tracking algorithm are as follows:

Step 1 Initialize the Lagrangian grid with a number of temperature nodes using an initial temperature field, $T(x, 0)$, and the tributary entrance locations (Figure 6 (a)).

Step 2 Track each node for a time Δt from its original position to a new position using the known velocity field and a numerical integration algorithm such as Runge-Kutta (Press et al., 1992). Introduce a new temperature node at the head of the river using the known temperature time series for the headwaters, $T(0, t)$ (Figure 6 (b)).

Step 3 Insert a new temperature node at each tributary entrance location, and adjust the temperatures of all nodes that have moved downstream of the tributary location (Figure 6 (c)) with the mixing calculation

$$T_{mix} = \frac{Q_{up}T_{up} + Q_{tr}T_{tr}}{Q_{up} + Q_{tr}}. \tag{24}$$

T_{mix} is the mixed temperature, Q_{up} is the flow just upstream of the tributary, T_{up} is the upstream (previous) temperature of the node, Q_{tr} is the tributary flow, and T_{tr} is the tributary temperature.

Step 4 Adjust the temperature of each node (except for the headwater node) using an atmospheric heat exchange calculation (Figure 6 (d)) that follows from Equation 7,

$$T_{final} = T_{initial} + \frac{(H_{net})_{avg}}{\rho c_p (h)_{avg}} \Delta t. \tag{25}$$

T_{final} is the temperature after atmospheric heat exchange, $T_{initial}$ is the temperature after Step 3 above, $(H_{net})_{avg}$ is the time-averaged atmospheric heat exchange based on the previous node temperature, and $(h)_{avg}$ is the average river depth encountered by the node during its most recent track.

Step 5 Discard any temperature nodes that extend beyond the domain (Figure 6 (e)) and linearly interpolate the temperatures to a regular grid for output. Return to Step 2 for the next time iteration.

Due to the high accuracy of the particle tracking associated with Step 2, the shape of any temperature waveform produced at the headwaters in the simple test cases was found to be perfectly preserved with this algorithm. In particular, the sine-wave test shows the particle tracking method to be far superior to the original Triton model for propagating a periodic signal down the river. As seen in Figure 7, the accuracy of the Triton signal decreases rapidly with the distance from the headwaters, whereas the particle tracking method maintains the original wave amplitude. The next section compares the performance of the new tracking algorithm with the Triton model for the Fraser River hindcast tests.

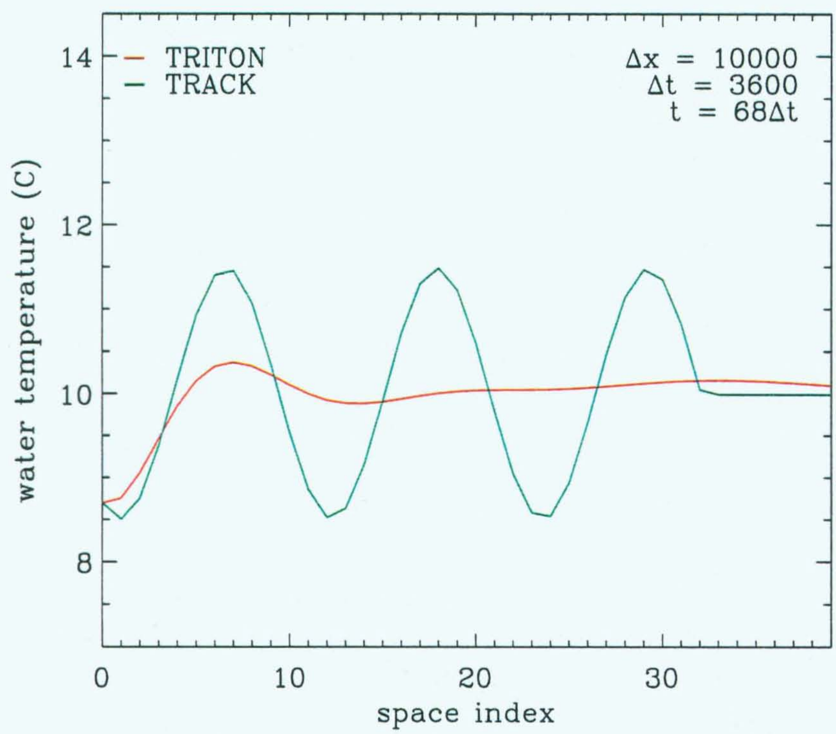

Figure 7: Triton vs. particle tracking in the sine-wave test. The results are plotted after 68 one hour time steps.

6 Simulated Temperatures for 1993 and 1994

An extensive electronic temperature monitoring network that was installed and maintained in the Fraser Watershed during the summers of 1993 and 1994 (Lauzier et al., 1995) provided data with which the previous temperature models could be tested and verified. (See Figure 4 in Foreman et al. (1997) for the observation locations.) The data loggers were programmed to store the average temperature over hourly periods and were located at positions that were deemed to be sufficiently well-mixed that the measurements would be representative of the particular chosen section of the river.

Meteorological data for 1993 and 1994 were supplied by the Atmospheric Environment Service, headwater and tributary flow data were obtained from WSC, and headwater and tributary temperatures were measured as part of the temperature monitoring program. Although the meteorological time series were complete, the river flow and temperature time series had occasional gaps that were filled by either linear interpolation or correlations with nearby stations.

As described in Foreman et al. (1997), the Triton model was evaluated by computing average and root-mean-square (RMS) differences between hourly simulated temperatures and the values observed at eleven locations along the Fraser River in 1993 and twelve in 1994. We repeated these 1993 and 1994 simulations with the new particle tracking algorithm. Figures 8 and 9, and Tables 1 and 2 summarize the results.

Figure 8 and Table 1 show the RMS differences between observed and modelled temperatures during the period of July 20 to September 21, 1993 when there were nearby temperature observations that could be used to force the headwaters at Shelley. (At other times, tenuous correlations with more distant sites had to be used.) Simlarly in 1994, limited headwater temperature observations restricted the RMS calculations to the period of July 10 to September 13. Figure 9 and Table 2 show these RMS values.

Tables 1 and 2 show that, with the exception of the RMS values arising from reach 64 in 1994, the particle tracking algorithm is consistently more accurate beyond reach 17 in both years. The average RMS improvements in 1993 and 1994 are 9.7% and 4.4% respectively, and maximum improvements of 26% and 23% occur in reach 39 for those same respective years. Given the increased damping that the Triton method imposes on signals propagating down the river, these improvements are not surprising. However the fact that both Figures 8 and 9 show the tracking method temperatures to be *less* accurate than those for the Triton model in the first 17 reaches was initially puzzling and required further investigation.

In 1993 the problem arose because, in the absence of direct observations at Shelley, the headwater temperature time series was created by simply using the recorded temperatures at reach 2. These temperatures were not adjusted to account for either timing differences

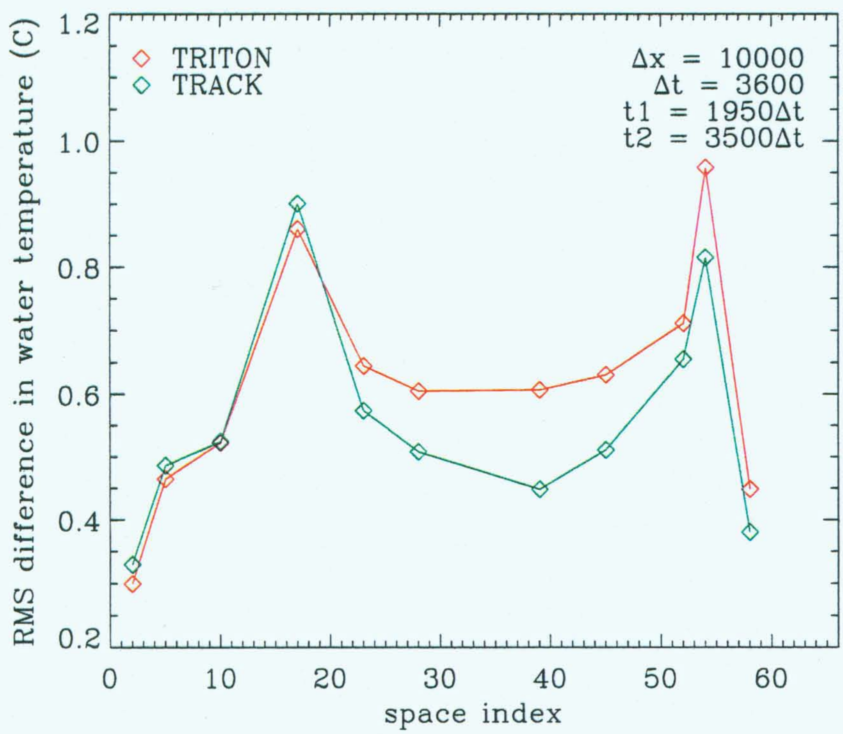

Figure 8: Root-mean-square differences between the 1993 observed temperatures and those simulated with the Triton and particle tracking models.

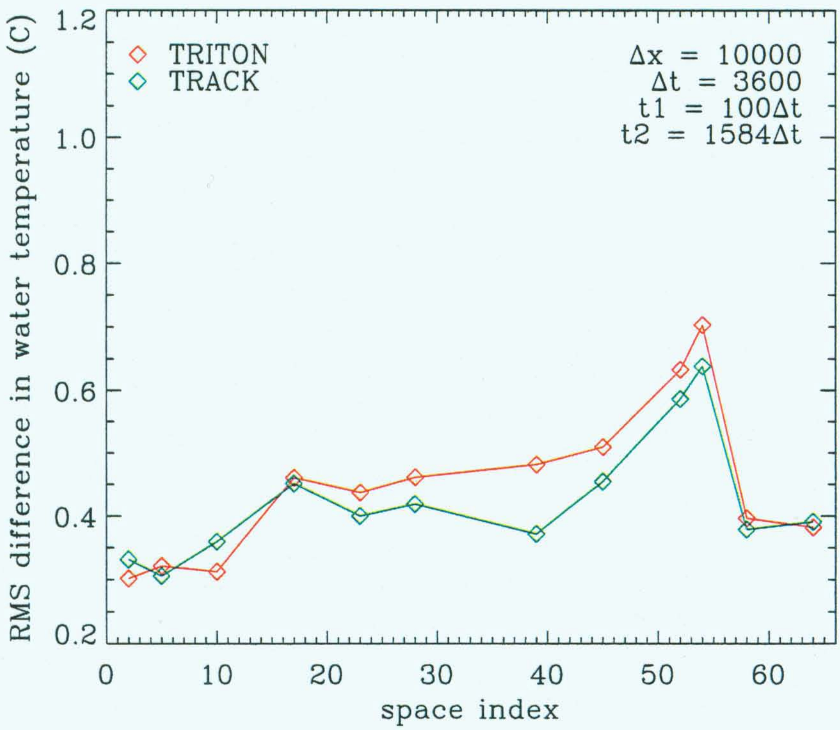

Figure 9: Root-mean-square differences between the 1994 observed temperatures and those simulated with the Triton and particle tracking models.

Table 1: Root-mean-square and average differences (°C) between the 1993 observed and modelled Fraser River temperatures. (Difference=observed-modelled)

	Triton		Particle tracking	
Reach	RMS	average	RMS	average
2	0.30	-.176	0.33	-.185
5	0.47	0.085	0.49	0.060
10	0.52	0.031	0.52	-.016
17	0.86	-.170	0.90	-.208
23	0.65	0.323	0.57	0.256
28	0.61	0.245	0.51	0.166
39	0.61	0.205	0.45	0.125
45	0.63	0.270	0.51	0.224
52	0.71	0.066	0.66	-.021
54	0.96	0.479	0.82	0.387
58	0.45	0.014	0.38	-.056
average	0.63	0.125	0.56	0.067

Table 2: Root-mean-square and average differences (°C) between the 1994 observed and modelled Fraser River temperatures. (Difference=observed-modelled)

	Triton		Particle tracking	
Reach	RMS	average	RMS	average
2	0.30	-.124	0.33	-.134
5	0.32	0.152	0.31	0.115
10	0.31	-.090	0.36	-.154
17	0.46	0.036	0.45	-.063
23	0.44	0.073	0.40	-.046
28	0.46	0.096	0.42	-.062
39	0.48	0.195	0.37	0.035
45	0.51	0.098	0.46	-.041
52	0.63	0.155	0.59	0.045
54	0.70	0.442	0.64	0.372
58	0.40	-.138	0.38	0.144
64	0.38	-.142	0.39	0.204
average	0.45	0.063	0.43	0.035

that arise due to downstream propagation, or for the atmospheric warming (or cooling) that would occur during that propagation time. Table 3 shows the root-mean-square and average differences between the 1993 observed temperatures and those hindcasted with versions of the Triton and the particle tracking algorithms that excluded the heat exchange contribution. Comparing Table 3 and Table 1 we see that, on average, atmospheric contributions warmed the river by about 0.175°C during the time required for a temperature signal to propagate from the headwaters to reach 2. As all the temperature time series contain 24 hour oscillations arising from daily fluctuations in the air temperature, solar radiation, and other components in the heat exchange term, it is relatively easy to estimate this propagation time. In particular, reach 2 time series plots that superimpose the observed temperatures and the particle tracking temperatures without this heat exchange term show the latter to be delayed by about about 6 hours. As seen in Table 3, this delay results in a RMS difference of 0.41°C. The analogous Triton temperatures have similar delays but their RMS value at reach 2 is slightly smaller due to increased damping of the 24 hour signal. Although the 1993 headwater temperatures should be adjusted to properly account for both this phase delay and the atmospheric warming, this was felt to be beyond the scope of the present study and has not been done.

The anomalous 1994 RMS values in the upper Fraser River reaches arose for different reasons. Although observed headwater temperatures were available for this year, they were only partially consistent with the reach 2 observations. In particular, comparing the two time series revealed that the peaks in 24 hour oscillations of the reach 2 temperatures were often clipped. (See Figure 10 for an example of similar clipping with the reach 5 observations.) This instrument problem would make the Triton simulations appear to be more accurate, as their 24 hour signals are damped more than those for the tracking method and are thus closer to the clipped observations.

The relatively large RMS discrepancies arising in reaches 17 and 54 with both methods (see Figures 8 and 9) are also disconcerting. Inspection of the 1993 observations for reach 17 reveals daily temperature oscillations of up to 2.5°C in amplitude at times when similar oscillations observed at the nearest upstream and downstream data-loggers were about 1°C. This certainly suggests a problem with the reach 17 observations. It is possible that the data logger may have been too close to the river surface and was influenced too strongly by air temperatures. Again further investigation is warranted but not directly relevant to this study.

The 1993 and 1994 observed temperatures at reach 54 might also be questionable. Tables 1 and 2 show that these temperatures were, on average, 0.48°C and 0.44°C warmer than the Triton simulated values, and 0.39°C and 0.37°C warmer than the particle tracking values. These averages are much larger than those at neighbouring stations. Moreover, the fact that these discrepancies are large for both methods and both years suggests a problem with either the observations themselves, or with model parameters (such as the flow/width relationships) that are common to both approaches. (For example, if a section of the simulated river were shallower and wider than it should be, the atmospheric heat exchange would receive too much weight and the downstream river temperatures would be adversely affected.) As before, the source of the accuracy problems at reach 54 is under investigation but not within the realm of the present study.

The fact that the relative accuracy of the particle tracking algorithm with actual observations was less impressive than similar evaluations with our simple benchmark tests can be attributed to two factors. The first, as we have just seen, involves problems either with the observations themselves, or in defining the model input time series or model parameters. The second is that unlike the simple benchmark tests, downstream advection is not the only factor contributing to actual river temperatures. The atmospheric heat exchange also plays an important role and its numerical representation is essentially the same for both the Triton and particle tracking simulations. Setting aside the fact that this representation might also be improved (another issue beyond the scope of the present study), it is interesting to view how much of a role this term plays. Table 3 shows that the 1993 RMS discrepancies increase significantly when the heat exchange term is removed from the model simulations. Viewing specific time series plots demonstrates that the precise role of this term varies at different locations and times. It can shift the low frequency component of the simulated temperatures up or down and thus cause mean discrepancies between observed and modelled time series. It can also cause phase shifts in the 24 hour signal. Figure 10 illustrates such an occurrence at reach 5 in 1993. The addition of the heat exchange term has clearly shifted the simulated temperatures back into phase with the observations. The fact that the observations seem to exhibit a clipping at the top of their 24 hour oscillations (similar to what was previously described for the 1994 reach 2 observations) is further evidence of problems that can exist with the observational time series. In short, the accuracy of real Fraser River simulations is dependent on several factors of which the numerical advection scheme is only one. Nevertheless, our application of the new particle tracking method to the 1993 and 1994 simulations has demonstrated that it is more accurate than the Triton method.

7 Summary and Discussion

The preceding presentation has described investigations aimed at improving the finite difference river temperature model developed by Triton Environmental Consultants (1994). These included the reformulation of new governing equations and their subsequent discretization with both finite difference and finite element methods, and the development of a new particle

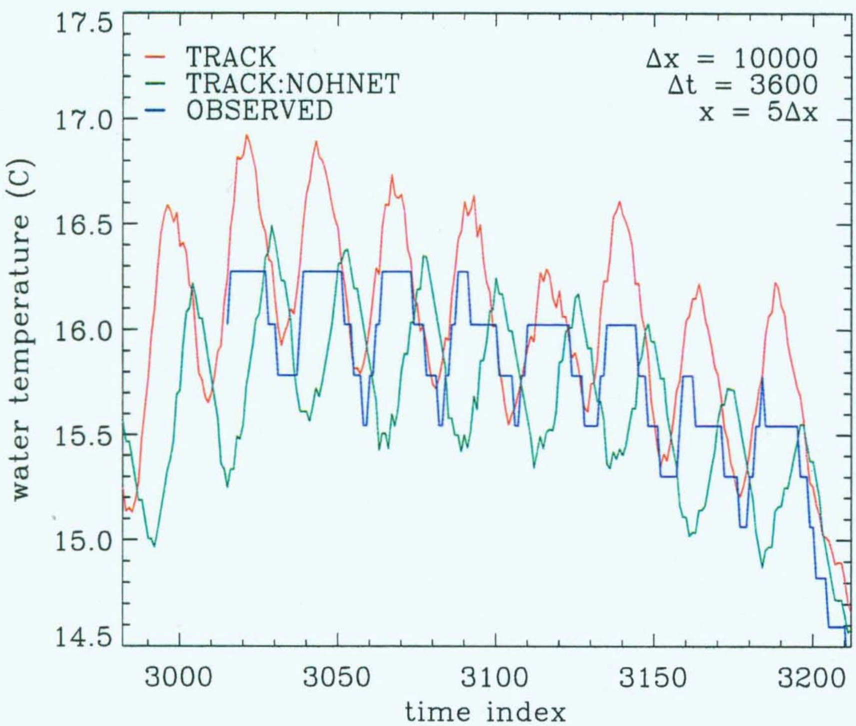

Figure 10: 1993 observed and modelled temperature at reach 5. Two model time series are shown; one with and one without the heat exchange term.

Table 3: Root-mean-square and average differences (°C) between the 1993 Fraser River observed temperatures and those modelled without the inclusion of the heat exchange term. (Difference=observed-modelled)

	Triton		Particle tracking	
Reach	RMS	average	RMS	average
2	0.31	-.002	0.41	-.010
5	0.63	0.332	0.71	0.314
10	0.86	0.485	0.83	0.449
17	1.24	0.559	1.32	0.536
23	1.37	1.079	1.31	1.020
28	1.40	1.100	1.32	1.027
39	1.47	1.156	1.38	1.077
45	1.37	1.151	1.36	1.104
52	1.35	1.159	1.24	1.070
54	1.81	1.605	1.69	1.511
58	0.97	0.798	0.89	0.730
average	1.16	0.857	1.13	0.803

tracking algorithm. These new techniques were initially tested with simple benchmark problems which illustrated the two common difficulties (Baptista et al., 1995) that often arise with numerical solutions of temperature advection problems, namely, (i) over-damping of the signal, and (ii) the generation of spurious waves near discontinuities or fronts. The original Triton model, employing a backward Euler time-stepping and an upwind discretization of the advective terms, was clearly seen to exhibit excessive damping of signals propagating downstream. Changing the time-stepping to a Crank-Nicolson formulation improved the accuracy slightly. Switching to a finite element spatial discretization and Crank-Nicolson time-stepping improved the model accuracy considerably for a propagating Gaussian temperature profile but caused the generation of parasitic oscillations with a step function signal. This is because our implementation of the finite element method assumed that the temperature profile could be represented as a linear combination of *continuous* piecewise linear or quadratic basis functions. As the Fraser River temperatures will have discontinuities due to the input of warmer and/or cooler tributaries, such an assumption is clearly invalid and the cause of the spurious oscillations.

In order to overcome both these difficulties, a particle tracking method was developed and found to be very accurate for both the Gaussian and step function test cases. In particular, it displayed neither the excessive damping nor parasitic oscillation problems that plagued the other techniques. This method was also applied to actual Fraser River hindcasts in 1993 and 1994 and the RMS discrepancies between the model and observed temperatures were computed. Apart from the first 17 reaches, the particle tracking model temperatures were found to be more accurate than those computed with the Triton model. Average RMS improvements were found to be 9.7% and 4.4% in 1993 and 1994 respectively, and maximum improvements of 26% and 23% were seen in reach 39 for those same respective years. Although the RMS differences were consistently higher for both methods and both years at two of the observation sites, inspection of the time series suggested that this was due to poor model parameterizations or problems with the observations at those locations. In summary, the new particle tracking algorithm has provided a satisfactory improvement over the existing Triton technique. The new technique will be implemented for the 1997 prediction season in order to provide more accurate estimates of river temperatures and their impact on migrating sockeye salmon.

Application of this particle tracking method to a river system that flows through a lake, such as the Thompson River, may require some modification. The dynamics of Kamloops Lake (see Figure 1) can be much more complicated (e.g., Carmack, 1979;, Hamblin, 1978; Foreman et al., 1997) than those represented by Equation 13. In order to deal with such cases, it is preferable to consider the lake thermodynamics separately and treat output from the lake as if it were the headwaters of a new river. Flow and temperature input to the lake can be used in a mixing calculation (that might also include wind forcing) that in turn produces the necessary output flow and temperature to force the downstream portion of the river. Although such a scheme has yet to be applied and tested for Kamloops Lake and the Thompson River, we are hoping to do so before the 1997 prediction season.

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