CHARACTERIZING THE INTERNAL WAVE FIELD IN A LARGE MULTI-BASIN RESERVOIR

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Abstract. Internal waves have a profound effect on outflow temperatures from hypolimnetic withdrawal facilities constructed in dammed reservoirs. The problem of characterizing the internal wave field is not a trivial one particularly in large multi-basin reservoirs with irregular bathymetries. Such difficulty is manifested in Nechako Reservoir, British Columbia, Canada, which constitutes a series of lakes connected by flooded riverine sections. Knewstubb Lake, the basin adjacent to the dam, is irregular in shape and connects to the next basin upstream, Natalkuz Lake, through a constriction and sill. As observed at thermistor moorings in both Knewstubb and Natalkuz lakes, the internal wave field in the reservoir is complex due to interaction of wave modes within and between lake basins. A three dimensional hydrodynamic model, ELCOM, is employed to simulate the internal seiching and wave motions in response to recorded wind events over several weeks during summer. The size (200 km long), complexity and lack of bathymetric information prohibited modeling of the entire reservoir. By modeling progressively larger regions of the reservoir we have determined the extent of the domain required for satisfactory reproduction of the dominant wave patterns near the dam.

1. Introduction

Nechako Reservoir is a large water body in central British Columbia, Canada (Figure 1). Water was impounded in the reservoir through the construction of Kenny Dam in the early 1950s together with other smaller saddle dams. Nechako Reservoir constitutes several lakes connected by flooded riverine sections. The reservoir resembles a hollow ring extending approximately 196km east to west and 75km north to south. With total thalweg length in excess of 430km and surface area of 910km^2, the total reservoir storage is 23.8km^3. At the west end of the reservoir, tunnels discharge 130m^3/s to a 1000MW power generation station [1].

Kenny Dam is not provided with a withdrawal facility; however, a spillway 80km east of the dam releases excess flood water in addition to base flow for fish habitat conservation and other domestic uses. As such, the 9km stretch of the Nechako River downstream Kenny Dam is no longer supplied with upstream flow and is only sustained by local drainage. The region downstream of the spillway was excessively scoured and altered as a result of the artificially high inflows during the past decades [1].

A water release facility is proposed at Kenny Dam. The withdrawal facility provides the benefits of restoring the ecology downstream of the dam as well as the spillway to a pre-impoundment state. The facility, referred to as the Cold Water Release Facility (CWRF), is planned to release surface water, deep water, or a mixture of both. Such flexibility is desired to maintain temperatures downstream of the dam at levels un-stressful to migrating and spawning fish. In particular, the facility would be used to release 170m^3/s at temperatures below 10°C during the hot summer period; from July 20th to August 20th [2]. Towards this target, the invert of the deep offtake is proposed at 63m below the normal operating water level where the total depth at the dam is 85m. The basin directly upstream of the dam, Knewstubb Lake, constitutes of two perpendicular basins, Knewstubb and Big Bend Arms extending E-W and Knewstubb Mid-reach extending N-S. At its south end, Knewstubb Mid-reach is connected to the next basin upstream, Natalkuz Lake, through a constricted sill, the Narrows (Figure 1).

The ability of the CWRF to supply cold water, less than 10°C, is affected by several factors including the seasonal evolution of the thermocline, displacement of the 10°C caused by wind-induced internal motions, and selective withdrawal layer thickness. Seiching and internal waves can lower the 10°C isotherm from its equilibrium level down towards the deep offtake. At a critical level, the established withdrawal layer may encompass water warmer than the threshold compromising the ability to satisfy target temperatures downstream. An aggravated case can be envisioned if strong winds depress the 10°C isotherm to the level of the sill, thereby isolating the hypolimnion of Knewstubb Lake from that of Natalkuz and limiting the supply of cold water.

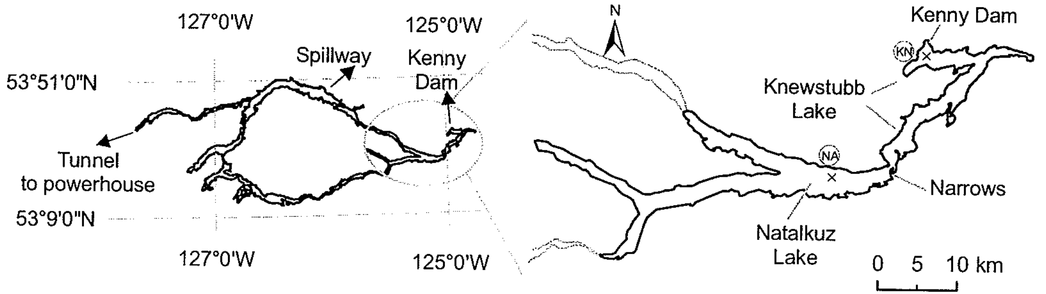

Figure 1: Left: Map of Nechako Reservoir showing Kenny Dam, the spillway, and tunnel to the powerhouse. Right: The two basins immediately upstream of Kenny Dam, Knewstubb and Natalkuz Lakes, connected through the Narrows. xKN and xNA shows the locations of moorings in Knewstubb and Natalkuz Lakes, respectively.

Recently, Anohin et al, 2006, [3] investigated the effect of internal waves on the water quality withdrawn from Lake Burragorang, Australia. Based on field data analysis, these authors concluded that internal waves were the dominant process in determining the temperature and turbidity of hypolimnetic withdrawals. Thus, to predict *a priori* the performance of the proposed CWRF under various scenarios, it is important to successfully characterize the internal wave field in the reservoir. This is not a trivial task owing in part to its complex irregular shape – particularly near the dam, and in part to the modulation of the waves by exchange flow between the interconnected basins. Here, we attempt to describe internal wave structure by means of 3D hydrodynamic numerical modeling supported by a small suite of field measurements.

2. Methodology

2.1. *Hydrothermal Observations*

Thermistor-chain data are available from two moorings deployed in Knewstubb (KN) and Natalkuz (NA) Lakes in 1994, from day 174 to 285 (Figure 1). At the two moorings, wind speed and direction are also available for the same period [4]. The wind fields at the two locations are very similar with a dominant wind direction from W-SW particularly during strong wind events. The 10°C isotherm fluctuated between 15m and 30m depth but was consistently out of phase at the two moorings.

2.2. *The Numerical Method*

The Estuary and Lake Computer Model (ELCOM), developed by the Center for Water Research, University of Western Australia, is a three dimensional hydrodynamic and transport model distinctively useful in modeling basin-scale internal waves in stratified water bodies; [5] and [6]. This capability is achieved using a vertical mixed-layer scheme as opposed to other turbulence closure schemes. ELCOM has been demonstrated to accurately capture the depth of the surface mixed-layer which is required for successful modeling of basin-scale internal waves. ELCOM employs a structured rectangular grid wherein cells containing the free-surface and bottom in any column can partially fill the respective layers.

2.3. *Model Development*

The vast size of Nechako Reservoir inhibited modeling of the entire domain at the required resolution and for the needed periods. The model was applied to several domains of different extents wherein the largest covers Knewstubb and Natalkuz Lakes being the two basins most influential to the CWRF (run-A). A non-uniform bathymetric grid was generated as the base of ELCOM simulations (Figure 2). Directly upstream of the dam, the first few grid cells are of fine resolution, 50m x 50m, the spacing increases by 8% from one cell to the next up to a maximum of 200m. Moving south towards the Narrows, the cell size is gradually reduced down to 50m x 50m. West of the Narrows, the spacing increases by 8% to a maximum of 1km and is fixed at this size to the end of the domain. In the vertical, a fine spacing (0.5m) is utilized for the top 30m. Below that, layer thicknesses increase gradually by 10% to a maximum of 4.5m at the deepest level. Utilizing the same grid, run-B excludes Natalkuz from the simulation sealing the Narrows at Knewstubb side. Furthermore, run-C excludes Knewstubb mid-reach, only extending over Knewstubb and Big Bend Arms with a closed boundary south of the junction with the mid-reach.

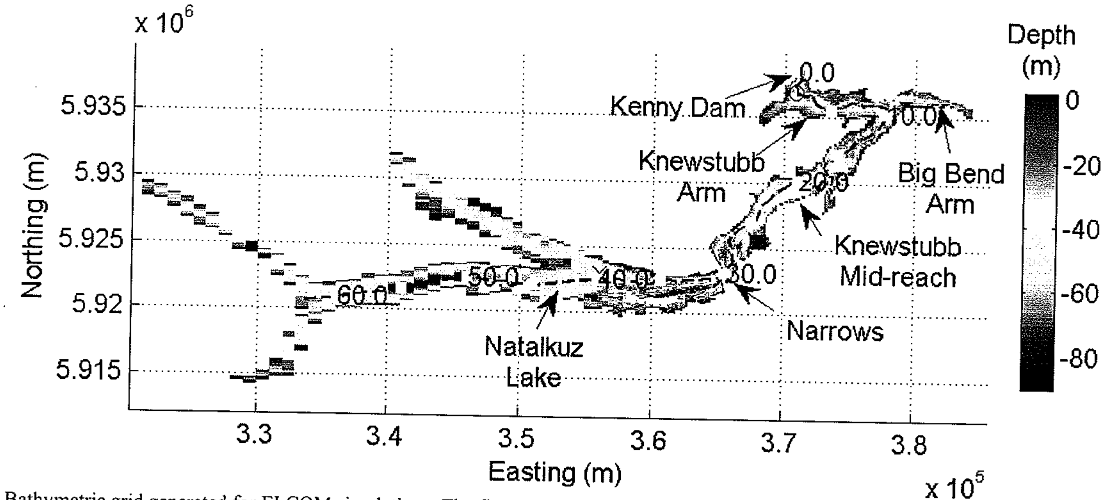

Figure 2: Bathymetric grid generated for ELCOM simulations. The fine resolution is apparent close to the Dam and within the Narrows while coarser cells are obvious at the west end of the domain. The dashed black line represents a curtain along the thalweg for which ELCOM results are illustrated later. The curtain is marked at 5km intervals originating from the dam with distance along the thalweg labeled every 10km.

Measured wind speed and direction at both the KN and NA moorings are used to force the model. Wind measurements from KN are applied on Knewstubb and Big Bend Arms while measurements from NA are applied over the rest of the domain. In ELCOM, surface wind stress is parametrized using a bulk formulation employing a coefficient of drag. The coefficient is adjusted in ELCOM to 1.63×10^3 instead of 1.3×10^3 to account for wind speed being measured 3m above the water as opposed to 10m.

The domain is initialized using thermistor data from both KN and NA moorings. Temperature-depth profiles are specified at the mooring location and interpolated to all grid cells for initial temperatures. First, interpolation is carried on vertically in a linear fashion then horizontally using the inverse distance-weighted method with a power of two. Generally, simulations are started after extended periods of calm weather when isotherms at KN mooring were at approximately the same level as at NA mooring. Ideally, this implies that forced motions are negligible and free internal oscillations are almost damped. Consequently, the start-from-rest assumption becomes acceptable and the period of model spin-up (affected by the specified initial conditions) is reduced.

2.4. *Limitations and Assumptions*

Although ELCOM can handle heat exchange through the air-water interface, thermodynamic fluxes were not incorporated in the simulations. The scope set for ELCOM in this study makes it unessential to do so. Only short-termed simulations were attempted to explain the effect of internal waves on the CWRF outflow. The longest ELCOM simulation runs for only 15days. At this time-scale, incorporating thermodynamics was deemed unnecessary and inconsequential to the results.

A turbulent benthic layer was specified as the bottom boundary condition over the entire domain with a drag coefficient of 0.005. This imposed boundary includes mixing induced by bottom stirring in the mixed layer model, [6] and [7], and as such is particularly useful in the vicinity of the Narrows were the thermocline is very close to the bottom. The actual drag coefficient is expected to be high since Nechako Reservoir was not logged prior to the impoundment. Well preserved underwater trees likely induce ample mixing particularly as they penetrate the oscillating thermocline entraining warmer water and mixing it with cold water when the thermocline reverses its vertical motion and the associated horizontal currents are reversed as well.

3. Model Application

3.1. *Model Validation*

The model was first validated for the period between day 225.5 and 240. Simulation results from run-A are in good agreement with measurements at the thermistor chains (Figure 3c and 3d). In particular, the model is successful in capturing the vertical mode 2 waves observed at Natalkuz mooring (Figure 3d). At both KN and NA moorings, higher isotherms are better replicated than lower ones. For instance, at KN, the simulated 14°C isotherm is highly correlated to the observed isotherm with a coefficient of 0.93. The correlation coefficient for the 6°C isotherm drops to 0.62. This vertical discrepancy in the model performance can be ascribed to the poorly resolved drag induced by underwater trees and to the step-wise representation of deep bathymetry of the original narrow river valley.

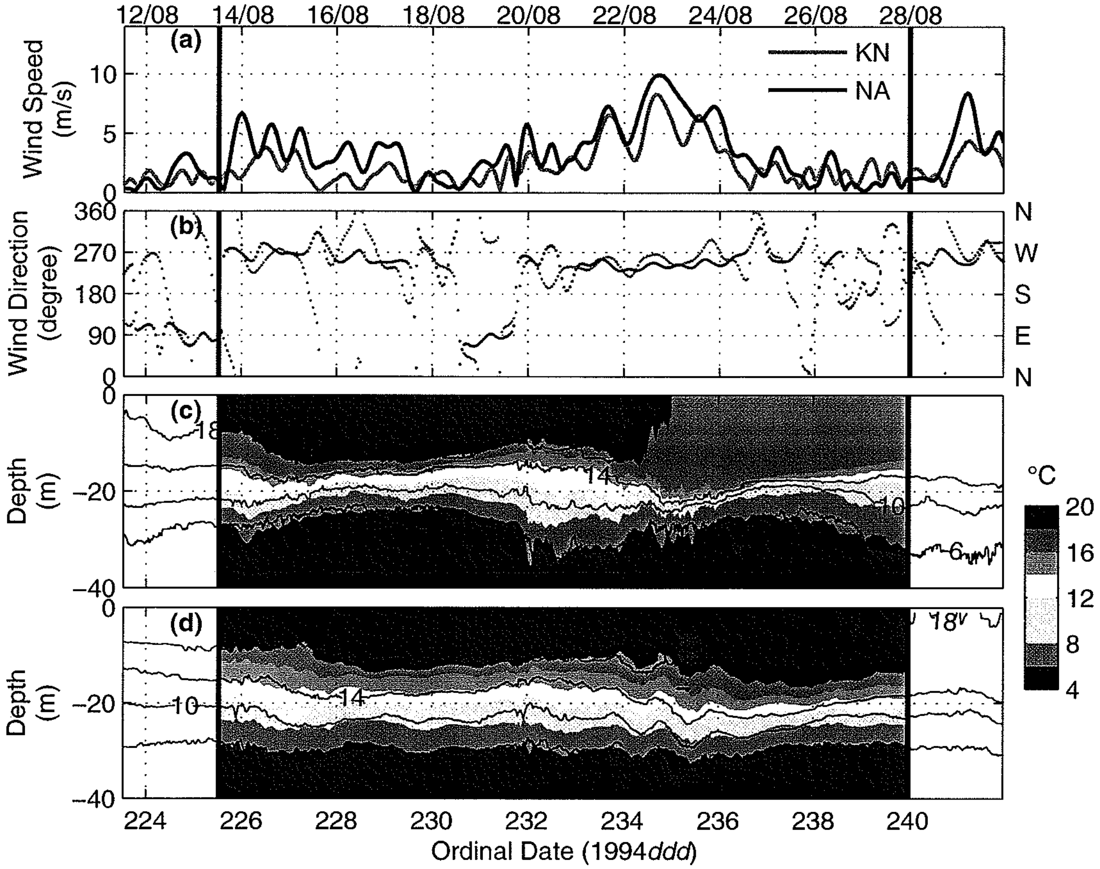

Figure 3: Forcing with measured and simulated isotherm response. Upper two panels show a) wind speed and b) direction measured at KN and NA met stations. Comparison of simulated (color fill) and measured (black solid lines; 6, 10, 14, and 18°C) isotherm levels for run-A. c) Knewstubb mooring. d) Natalkuz mooring. Wind data is low-pass filtered with a cutoff of 12 hours using a Butterworth filter.

3.2. *Wave Decomposition*

The 10°C isotherm from the three simulations, run-A, -B, and –C are compared to that observed at KN mooring (Figure 4). The mean and standard deviation of the 10°C isotherm is given in Table 1. Run-A shows the best agreement with the mooring data while, as might be expected, the smaller domain runs produce less agreeable results.

Table 1: Basic statistics of the 10° isotherm for the different series.

Series	Mean (m)	Standard deviation (m^2)	Correlation to KN (at no lag)
KN	23.8	1.86	1.00
Run-A	22.8	1.19	0.85
Run-B	21.3	1.38	0.33
Run-C	20.8	0.56	0.32

Run-C, with the smallest domain, doesn't capture the low frequency motion propagating from Knewstubb Mid-reach and beyond. The three crests of the 10°C isotherm on days 233.87, 234.90, 235.77 (indicated by arrows in Figure 4) are obviously local features excited by the wind blowing over Knewstubb and Big Bend Arms (refer to Figure 3c and 3d for wind forcing). The period of this wave is approximately 24hrs, which is the estimated period for the fundamental oscillation of the basin comprised of Knewstubb and Big Bend Arms. The average depth of the 10°C isotherm is essentially the initial depth with the abovementioned oscillations superimposed on it. Progressing to runs B and A, the 10°C isotherm trend indicates the same locally induced waves are superimposed on lower frequency waves propagating from Knewstubb Midreach and Natalkuz Lake, respectively.

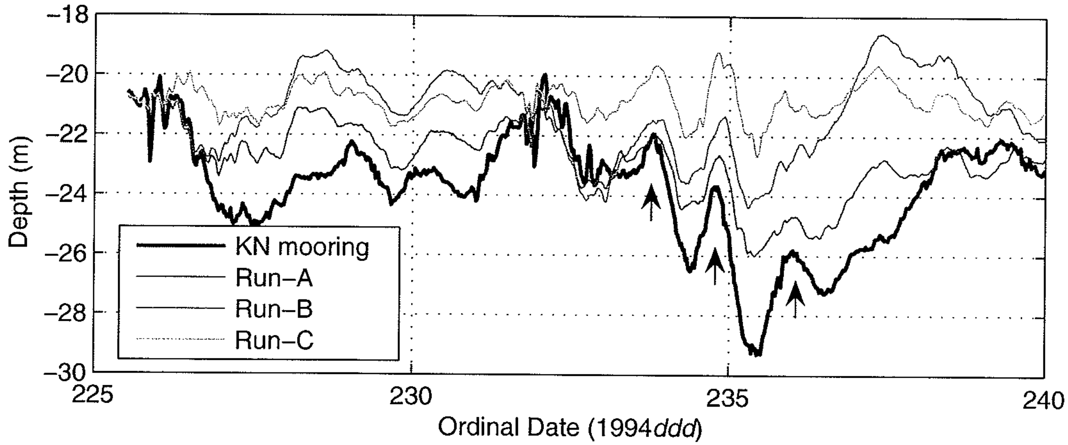

Figure 4: Simulated depths of the 10°C isotherm versus observed depths at Knewstubb Mooring. Arrows indicate the three wave crests referred to in the text.

The 10° isotherm depth is correlated at both moorings with a value of 0.7 (Figure 5). The linearly-detrended low-pass filtered depth, with a cutoff of 48hrs to remove locally excited motions, is correlated more strongly with a value of 0.8. This strong correlation is associated with a lag of 40hrs of Knewstubb isotherm behind Natalkuz. Over the 38km separation distance between the two moorings, the lag is equivalent to wave celerity of 0.25m/s. This celerity value reasonably matches the celerity estimated for the fundamental oscillation in Knewstubb and Big Bend Arms; 0.19m/s. Thus, it is evident that this long wave originates in Natalkuz basin, travels through the Narrows and Knewstubb Mid-reach, and is strongly detected at KN. The spatial structure of the wave is described below as obtained from the simulation results.

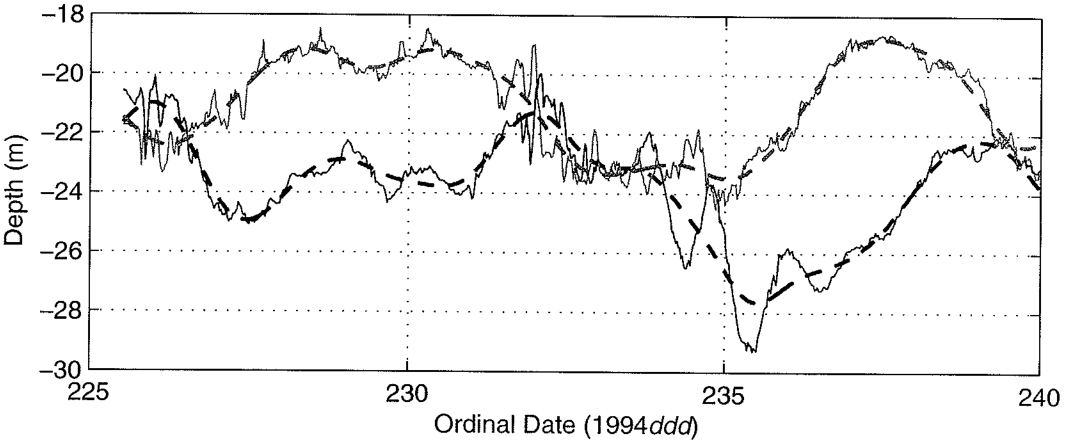

Figure 5: 10°C isotherm depths from KN (blue) and NA (red) moorings versus time. Dashed lines show low-pass filtered series with a 5th order Butterworth filter.

3.3. *Spatial Structure*

On day 235.0, the spatial structure of the thermocline is inferred from the excursions of the 10°C isotherm in response to the strong wind forcing. Since thermodynamic fluxes are excluded from simulations, the volume of water colder than 10°C is conserved except for mixing. The temperature stratification is diffused by vertical mixing, altering the isotherm equilibrium level from its initial value. In the model runs, the depth of the 10°C isotherm at the beginning of the simulation is essentially the initial equilibrium level as a consequence of the start-from-rest assumption. Assuming mixing is negligible, the simulated isotherm depth at later times is compared to this initial level (Figure 6).

In run-C, as the junction is sealed from the south and Knewstubb and Big Bend Arms are modeled as a single contained basin, the 10°C isotherm rises above its equilibrium level on the dam side and depresses below the equilibrium level on the opposite side. In run-B, the 10°C isotherm is completely lowered below the equilibrium level throughout Knewstubb and Big Bend Arms with the same tilt as run-C. The cold volume of water displaced downward in the two arms flows into Knewstubb Midreach and raises up the 10°C isotherm in the Midreach. The 10°C isotherm within Knewstubb and Big Bend Arms is further depressed in run-A than in runs -C and -B. The isotherm is also depressed down in Knewstubb Midreach from its run-B level. Nevertheless, in both basins, the isotherm retains the same local tilts predicted by the previous runs except a short distance downstream the Narrows. The cold water displaced by lowering of the isotherm in Knewstubb Lake upwells at the west end of Natalkuz. The exchange flow between Knewstubb and Natalkuz Lakes is subject to internal hydraulic control at the end of the Narrows as evident by the abrupt change in isotherms levels at 30 and 37km. Observing the evolution of the spatial structure from Run-C through Run-A indicates a relatively linear superposition of oscillations generated in Knewstubb and Big Bend Arms and waves propagating from the Midreach and Natalkuz Lake.

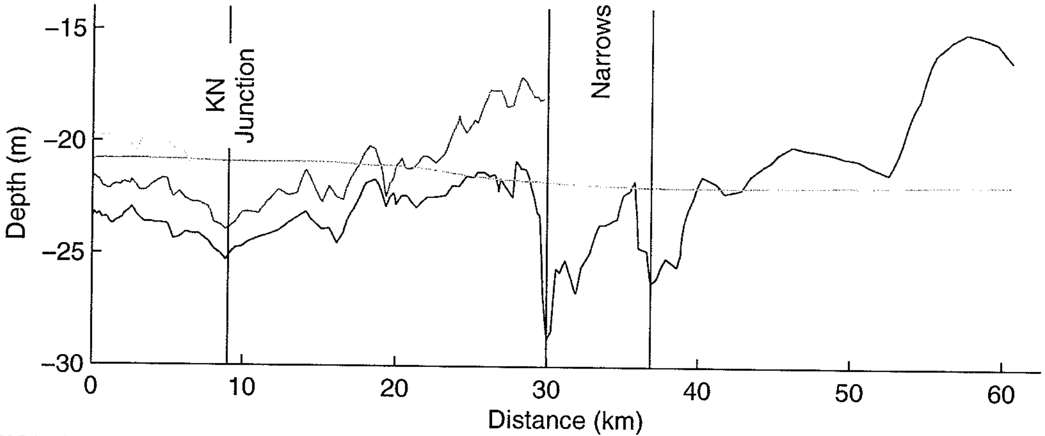

Figure 6: 10°C isotherm depth along the thalweg on day 235.0. Blue, red, and green lines are for runs A, B, and C, respectively. Initial isotherm level is indicated by grey line. Black vertical lines indicate features along the thalweg.

4. Conclusions

The thermal structure of part of Nechako Reservoir has been modeled numerically. By simulating domains of different extents, the internal wave field observed at Knewstubb mooring is decomposed to oscillations originating locally within Knewstubb and Big Bend Arms and to longer waves propagating from Knewstubb Midreach and Natalkuz Lake. For the domain including Knewstubb and Natalkuz Lakes, simulation results show good agreement with thermistors chain data from the two moorings. On average 80% of the internal wave structure at KN mooring can be explained through modeling Knewstubb and Natalkuz Lakes only.

Acknowledgments

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