Three Dimensional Computational Flow Modeling and High Resolution Flow Surveys for Fisheries Environmental Studies on the Upper Columbia River.

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ABSTRACT

In the area downstream of hydroelectric plants, river water circulation patterns represent an important environmental parameter for fish habitat. On the Canadian sector of the Columbia River, white sturgeon use deep eddy pools, which occur both as natural habitat and as features immediately downstream of dams. Adult sturgeon exhibit a preference for deeper water habitats, specifically areas having reduced flow speeds, generally < 0.5 m/s (1.6 feet/s). Two particular sturgeon habitat areas are located downstream of the Hugh A. Keenleyside Dam and in the Waneta Eddy, at the confluence of the Columbia and Pend d'Oreille rivers, immediately downstream from the Waneta Dam on the latter river.

For the purposes of environmental assessment studies, ASL has conducted detailed flow measurements downstream of both these dams. These studies have involved a two pronged approach: (1) development and implementation of a three-dimensional, finite-difference hydrodynamic computational model capable of resolving complex eddy patterns and vertical shears in river flows; and (2) field measurement methodologies based on acoustic doppler current profiling instrumentation and real-time high accuracy navigation systems, through which maps of the river circulation, in three dimensions, can be obtained over periods of about one hour. Both the computational modeling and field measurement procedures allow high resolution representation of the full three dimensional flow field to scales ranging from 5 to 25 m in the horizontal and about 1 m in the vertical.

High resolution field measurement data sets are used to calibrate, and separately, validate the computational models for the plant discharges in effect during the measurement programs. The computational model can then be applied to determining the effects of other plant discharges, in support of the process to obtain the necessary regulatory approvals. Results from the high resolution model studies, and the related flow surveys, are presented for the areas downstream of the Keenleyside and Waneta Dams.

INTRODUCTION

The portion of the Columbia River in British Columbia, Canada from the Lower Arrow Lake to the U.S./Canada border (Figure 1) is strongly influenced by three major dams: the Keenleyside Dam on the Columbia River, the Brilliant Dam (on the Kootenay River just upstream of the confluence with the Columbia River) and the Waneta Dam (on the Pend d'Oreille River just upstream of the confluence with the Columbia River). These dams were built many years ago and plans are either underway or under development for expansion of electrical generation capacity at all three sites.

Under the terms of the 1961 Columbia River Treaty between the United States and Canada, the Hugh A. Keenleyside Dam was built in 1968 to provide control of water levels for downstream portions of the Columbia River. The Keenleyside Dam, which is owned and operated by BC Hydro and does not generate electricity, is located at the downstream end of the Lower Arrow Lake. Columbia Power Corporation and the Columbia Basin Trust, through their Arrow Lakes Power Company joint venture, are just now completing construction of a 185 MW power plant, the Arrow Lakes Hydro Generating Station (Arrow Lakes GS), alongside the existing Keenleyside Dam. The new power house has been constructed approximately 400 m downstream of the existing dam and is fed by a 1 km approach channel whose entrance is upstream of the Keenleyside Dam.

The Waneta Dam, owned by Teck Cominco Ltd., is located on the Pend d'Oreille River just upstream of its junction with the Columbia River (Figure 2). In the mid-1990's, environmental studies were conducted in support of the proposed upgrade project for this plant by Teck Cominco. More recently, Columbia Power Corporation has begun studies in support of a possible separate hydroelectric plant to be operated downstream of the Waneta Dam on the Pend d'Oreille River.

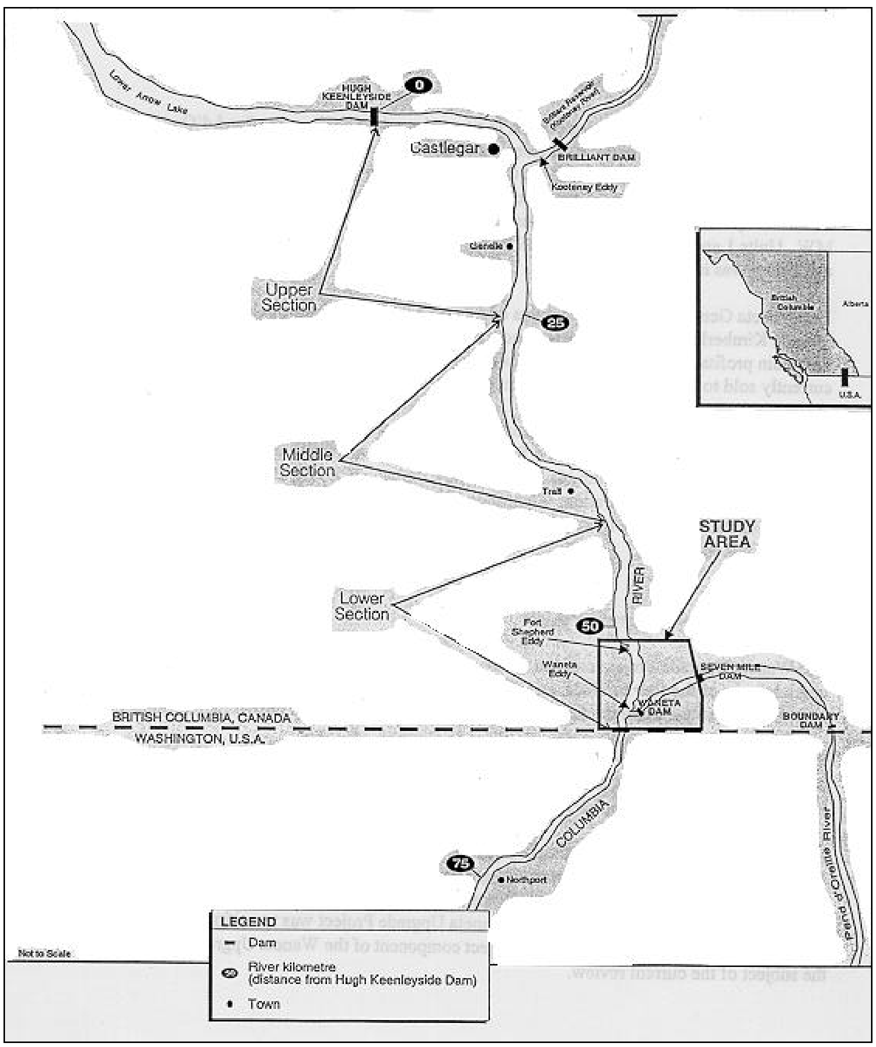

Figure 1: A map of the Columbia River from the US/Canada border to the Lower Arrow Lakes.

For the upgrade of the existing Waneta Dam, the Waneta Expansion Project, and for the new Arrow Lakes Hydro GS beside Keenleyside, environmental studies have been conducted over the past several years in support of regulatory approval requirements. These studies have addressed a wide range of environmental issues, including water quality and fish impacts in the areas downstream of the existing dams. Within the overall region, there are important habitat areas for white sturgeon fish, as well as a variety of sportfish, including kokanee, trout, whitefish and walleye.

White sturgeon are a particularly important species within the region. At the adult stages, these fish are known to exhibit a preference for river areas that are deep and characterized by relatively low flows, while during spawning the sturgeon make use of high flow areas to aid in dispersal of eggs for improving survival probabilities. The most important spawning area in the region is the Waneta eddy area, located at the confluence of the Columbia and Pend d'Oreille rivers (see Figure 2).

White sturgeon habitat is known to include deep eddy pools, which occur both as natural habitat, as is the case with the Waneta Eddy and in backwater areas immediately downstream of dams (as is the case with the Keenleyside Dam). The preference of white sturgeon for deeper water and areas having reduced flow speeds, has been associated with flow speeds of less than 0.5 m/s, for the purposes of environmental assessment (B.C. Environmental Assessment Office, 1998).

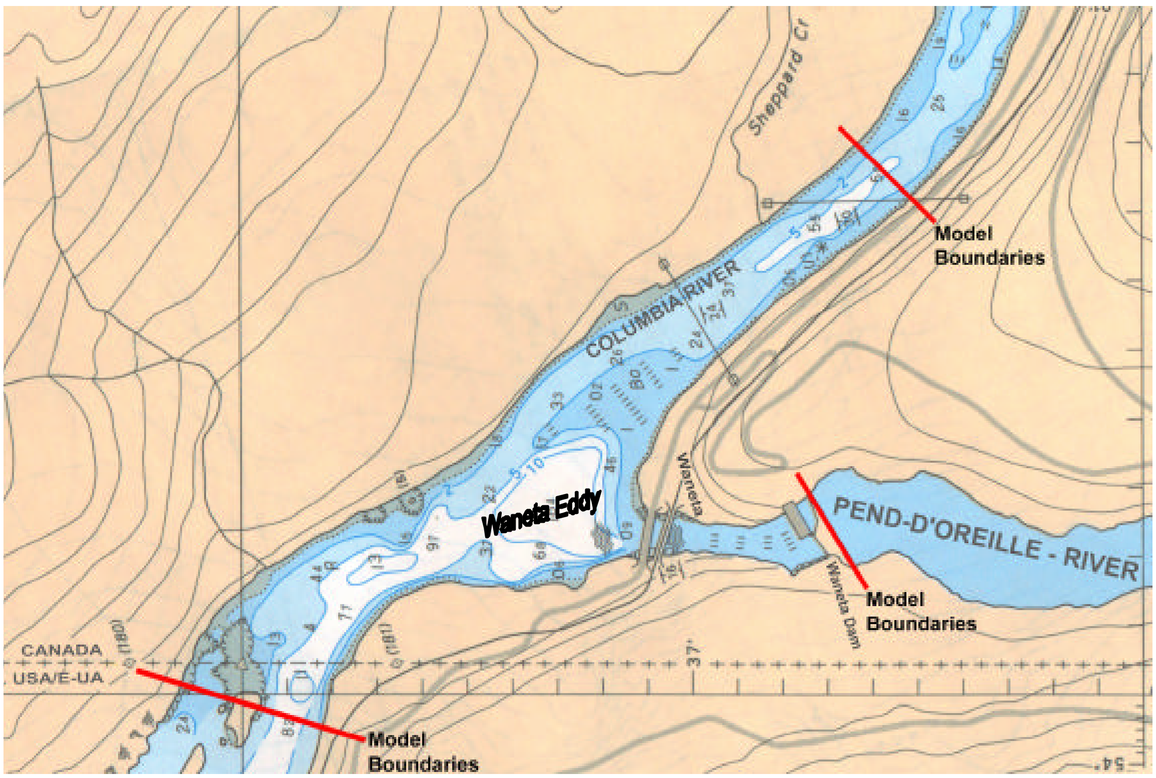

Figure 2: A map of the confluence of the Columbia and Pend d'Oreille Rivers, showing the numerical model boundaries, the Waneta Dam and Eddy and the road and rail bridges over the Pend d'Oreille River (based on Canadian Hydrographic Service, Chart #3055).

For the purposes of the environmental studies, water flow patterns are an important fish habitat parameter. In response to the need for high resolution and accurate representations of river flow patterns on the Columbia River, especially in areas downstream of existing and proposed dams, ASL Environmental Sciences has been developing advanced observational and numerical computational methods. These methods are described in the remainder of this paper.

HIGH RESOLUTION FIELD MEASUREMENTS

Early Use of Non-Intrusive Acoustic Flow Meters at Hydro Dams

ASL Environmental Sciences pioneered much of the early use of non-intrusive acoustic flow measurement techniques at hydroelectric dams (Birch and Lemon, 1993 & 1995). Obstacles that had to be overcome included the magnetic disturbance due to the dam that made conventional compass measurements of current direction highly unreliable. The solution was to obtain the current meter direction reference from a gyrocompass, usually on the surface, but for one survey, submerged along with the doppler current meter.

ASL has conducted studies of flow circulation at hydroelectric dams since 1991. During the early 1990’s the focus was on forebay and tailrace circulation studies at dams along the lower Columbia River, often for fish diversion projects but also for discharge measurements.

Three Dimensional Detailed Flow Surveys on Rivers Downstream of Dams

In the mid 1990’s, activities expanded to include the Canadian portion of the Columbia River, particularly the environmental effects, to sturgeon habitat primarily, of proposed powerhouse upgrades to the Keenleyside and Waneta dams.

In order to work in the shallow, often turbulent rivers associated with the hydroelectric dams on the Columbia River, new techniques had to be developed. The doppler current meter (early models were often very bulky) had to be attached to small river boats, and since the boat was often different each time, the mounting arrangements needed to be flexible/adaptable. A typical boat mount, shown in Figure 3, allows the instrument to pivot out of the water when not in use. In areas of turbulent flow, a fairing is fitted around the instrument to reduce vibration and turbulence around the transducer head. However, even this cannot prevent data loss, due to signal attenuation, in areas of high bubble concentration often experienced directly downstream of a dam discharging significant flows.

The doppler current meters used (generally RD Instrument’s 600 kHz BroadBand or 1200 kHz Workhorse) have bottom tracking capability, enabling the subtraction of the boat velocity from the measurements to determine the absolute current velocity profiles. As mentioned, if necessary, a surface gyroscope is used to provide directional reference in areas of magnetic disturbance. If the disturbance is due to the vessel itself, then a KVH digital compass is used which can be calibrated in the field to correct for such disturbances.

Figure 3: The acoustic doppler current profiler flow meter attached to an aluminium work boat used for flow surveys.

The bottom track feature of the RD Instrument doppler current meters enables the instrument to determine the vessel location relative to the starting point. However cumulative errors in position arise (due to small inaccuracies in the BT velocity; ±1 cm/s) resulting in errors of up to tens of meters over a typical survey transect (order of 1-2 km). Therefore, the vessel position is determined using differential Global Positioning (GPS). The differential signal is obtained either from a stand-alone base station at the site, or from a satellite feed. The accuracy of these positions is generally 1-2 meters, and these are used to plot the locations of the current meter velocity data.

The grid pattern used for a typical survey generally involves 25 to 50 meter line spacing. A helmsman's display (Nav-Log™, by Terra Remote Sensing) allows the boat operator to steer the vessel along the pre-determined transect lines. The velocity data are also ensemble averaged over typically 25 m elapsed distance, resulting in evenly spaced vector plots. After ensemble averaging the accuracy of the current velocities is typically ± 1 cm/s. The figure below illustrates the current velocity in the tailrace of the Keenleyside Dam. Note the detail in the structure of the circulation, with four eddies evident, the smallest (E4) having a scale of only about 60 m across.

A circulation survey of a 700 m long section of the Columbia River generally requires 1 to 2 hours. Often moored doppler profilers are also used at selected locations to obtain a measure of the time variability of the flow. These high frequency profilers have small blanking zones and bin sizes well suited to the shallow water environment.

3-D doppler current profilers provide detailed current flow data previously unattainable. As well as the horizontal flow, they also measure the vertical component of flow velocity. Often the vertical flow is insignificant, however flows being drawn down into the upper portion of a turbine intake at one dam (Rocky Reach) were inclined 18° down from horizontal.

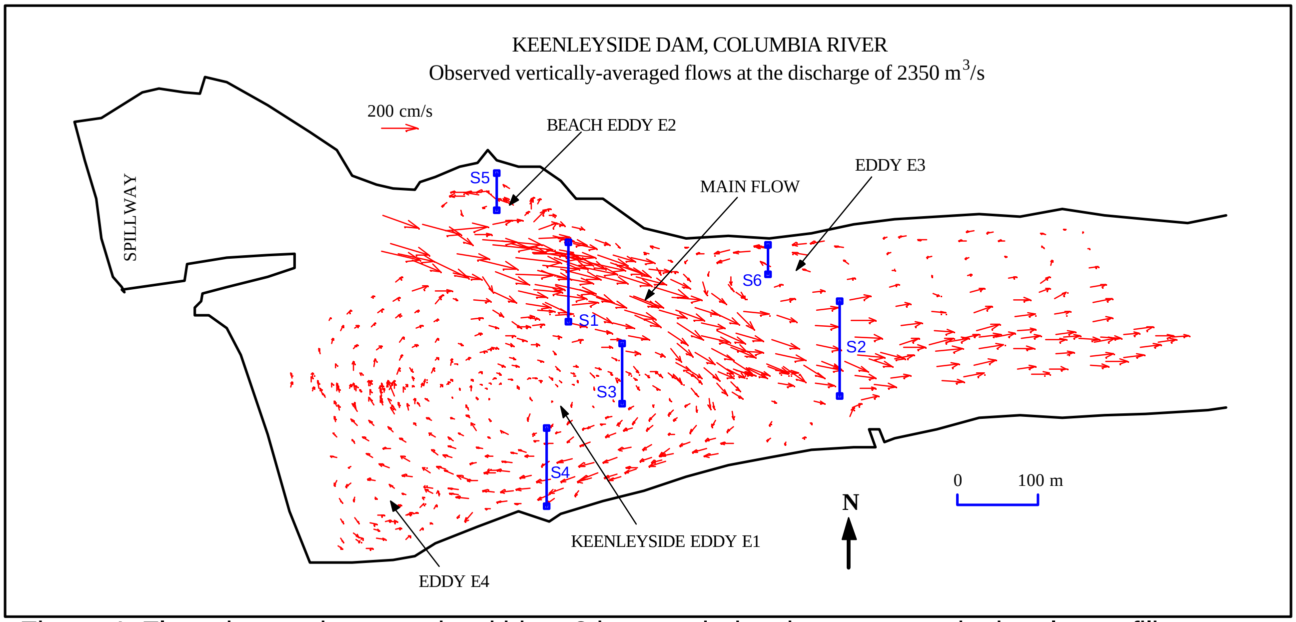

Figure 4: Flow observations, made within a 2 hour period, using an acoustic doppler profiling current meter in the area downstream of the Keenleyside Dam under Columbia River flow discharge levels of 2350 m^3/s.

As part of the circulation surveys of key sturgeon habitat on the Columbia River, we produce maps of the extent of the preferred low current near-bottom flow regime. The changing extent of this area, depending on powerhouse upgrade designs for example, can then be used to determine the expected impact, if any, on the sturgeon. The numerical model capability developed within ASL and discussed below, along with detailed field measurements, have together proven to be very effective in predicting changes to this low-flow regime.

Flow Measurements in Very Shallow River Segments

Some rivers are too shallow or inaccessible for manned boats. In such cases the doppler current meter is attached to a small unmanned boat. The boat (see Figure 5) is manoeuvred using lines to shore, and a GPS mounted on the boat records its position.

In October 2001, this flow measurement technique was applied to the lower section of the Pend d'Oreille River near the Waneta Eddy area (Figure 2). Current data were collected in water depths as little as 1m, and under current speeds exceeding 4 m/s. Typical results are shown in Figure 6.

NUMERICAL MODELING

Since 1999, ASL has been actively developing a three-dimensional computer model that is capable of simulating water circulation in complex river regimes with a very high horizontal resolution. Unlike the two-dimensional numerical models often used in earlier environmental assessment studies, the 3-D model computes the vertical profiles of water flows throughout the modeled area. The complex flow structure, consisting of up to four eddies as revealed in the detailed observations available at Keenleyside Dam, provided the opportunity to test the ASL 3-D finite difference numerical model. Previous two-dimensional models applied, by others to this area, were not able to resolve the three smaller eddies.

Figure 5: A small unmanned vessel, prior to use, which supported a 1200 Khz acoustic doppler current profiler for measuring flows on the lower Pend d'Oreille River (shown in background) in October 2001.

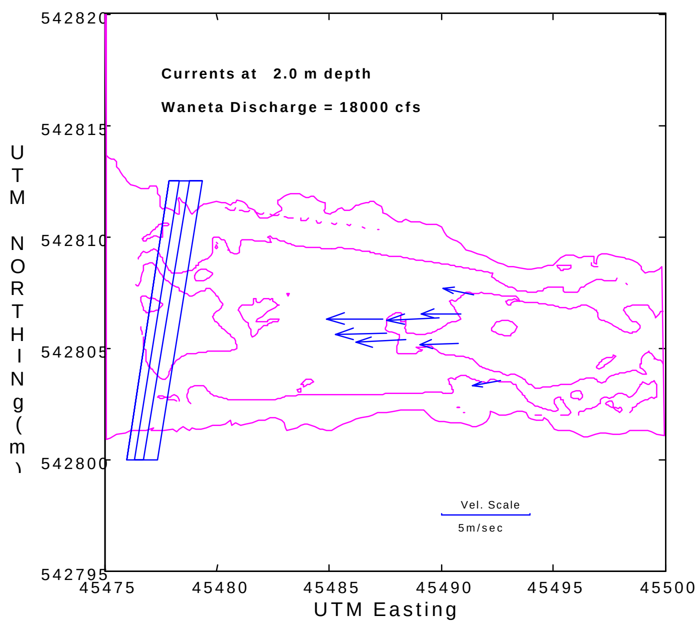

Figure 6: Plot of the horizontal component of the current velocity at 2.0 meters depth. The discharge through the Waneta Dam was 18000 cfs or 510 m^3/s. Each velocity is an average of several minutes worth of data, while the current meter was held steady in the flow.

ASL Model Description

The ASL model is based on the fundamental dynamical equations of fluid hydrodynamics for circulation including such natural forces as pressure heads, buoyancy, wind stress and drag arising from shoreline and bottom. The model uses the hydrostatic approximation and solves for the time-dependent, three-dimensional velocities (u, v, w) (Jiang, 1999). The boundary conditions of the zero momentum flux (wind stress) at the water surface and the shear stress at the bottom in terms of quadratic law were employed. At the upstream boundary, the discharge was specified and the resulting currents were oriented to the same direction as the spillway. A semi-implicit finite difference method is applied in the model. The numerical solution method has the advantages of a minimum degree of implicitness, good stability and consistency, and high computational efficiency at a low computational cost.

Comparing the Model Results with Observations – Keenleyside Dam

The first version of the ASL River 3-D numerical model was developed and tested for the area of the Columbia River downstream of the Keenleyside Dam. In order to test and determine the validity, the ASL river model was adapted to simulate the currents and the associated eddies using two independent data sets observed by ASL Environmental Sciences during 10:56-12:40 PST, 9 April 1997 and 13:45-16:25 PDT, 27 August 1997, respectively.

The model domain is a 3 km long section of the Columbia River below the Keenleyside Dam. The bathymetry for the model domain was derived from three sources: (1) a topographic survey around the Keenleyside Dam conducted in 1993 by British Columbia Hydro and Power Authority; (2) ADCP water depth data (Fissel and Billenness, 1997); and (3) hydrographic chart # 3056 published by the Canadian Hydrographic Service in 1991. Note that the resolution of the bathymetric sounding points was coarse, especially in the downstream half of the model domain.

The domain was discretized using spatial steps ?x=?y=15 m and ?s=0.1, with the total number of rectangular cells $M \times N \times K$= 200×46×10=92,000. Figure 7 shows the numerical mesh in the horizontal plane within the modeled domain. Time steps of ?t= 1.5 s during high discharge and ?t= 6 s during low discharge were adopted based on stability constraints resulting from the numerical scheme involving a back-tracing formulation. The lowest layer near the bottom was 0.05H above the bed and the highest layer near the surface was 0.05H below the instantaneous water surface.

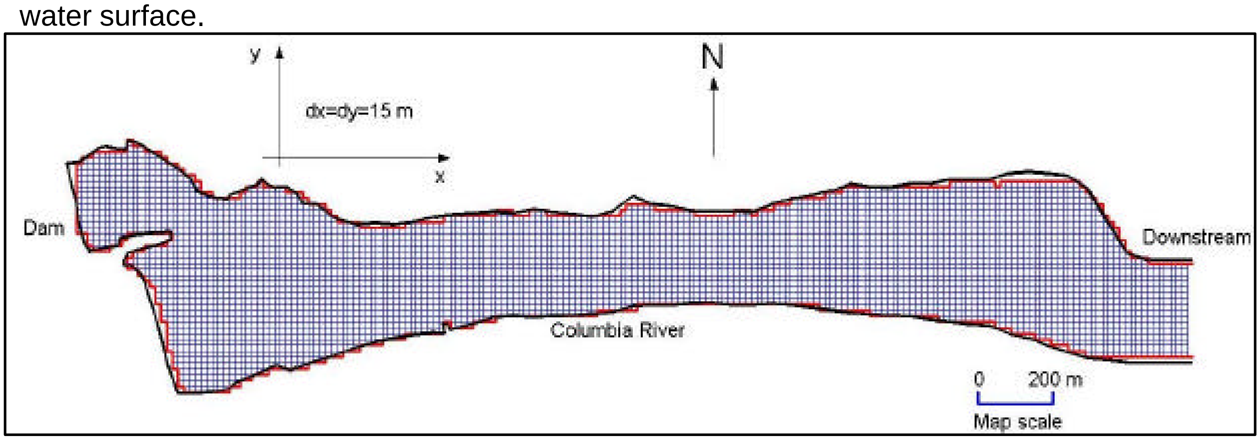

Figure 7: The 15 m by 15 m horizontal grid mesh used for the three dimensional numerical model.

The initial conditions for the model runs were as follows: (1) All velocities were set equal to zero; and (2) water elevation at each grid point was set to be constant. The model was run until a stable flow was obtained, which took about 3 hours using a Pentium III 500 MHz desktop computer. The stable results were then outputted for calibration and validation.

At the downstream open boundary, constant water elevation was prescribed (Table 1). At the spillway, the discharge was specified (Table 1) and the currents were oriented to the same direction as the spillway.

Calibration and validation are two distinct steps in a modeling study and they serve separate objectives. Calibration is the process of tuning a particular model by altering various parameters in order to obtain the best fit between simulated and observed results for a specific problem. Validation is the demonstration that the calibrated model provides good results when compared against data, which is independent from that used in the calibration stage (Reeve and Hiley, 1992). In the model application of the Keenleyside Dam, the ADCP current data set of 9 April 1997 was used to calibrate the model and that of 27 August 1997 was used to test the validity of the model (Table 1).

Table 1: Data set and model runs

Model run	Date	Discharge at the spillway (m^3/s)	Water elevation above mean water level prescribed at downstream open boundary (m)	?t (s)
Calibration (with low discharge)	9 April 1997	425	0	6
Validation (with high discharge)	27 August 1997	2,350	3	1.5

The capabilities of the model, through comparison of the model and observed flow patterns are illustrated for at 2.9 m depth level for the 27 August 1997 flow observations (Figure 8). The 3-D numerical model clearly resolves three of the four observed eddies. Both the directions and the magnitudes agree very well over the full area of the large dominant clockwise eddy (E1).

The two counter-clockwise eddies near the dam are also well resolved by the model. For the beach eddy (E2), the model is in reasonably good agreement with observations, in view of the observational difficulty of realizing adequate spatial resolution for these comparatively strong flows. The model version of the eddy provides more detail than can be achieved in the observations. Eddy E4 is also well resolved, but the observations reveal slightly stronger flows.

The counter-clockwise eddy (E3), situated to the east further away from the dam, was only faintly evident in the model results. In contrast, the observational results reveal stronger flows, albeit with some high frequency variability that may reflect sampling problems. The capability of the numerical model to fully resolve this flow feature may be related to the coarse representation of the bathymetry in this area, with spacings between bottom soundings being considerably larger than the horizontal grid size of 15 m.

Interestingly, the model indicates a fifth eddy (E5) just to the north of the spillway. The flows were too turbulent here to measure with the doppler current meter.

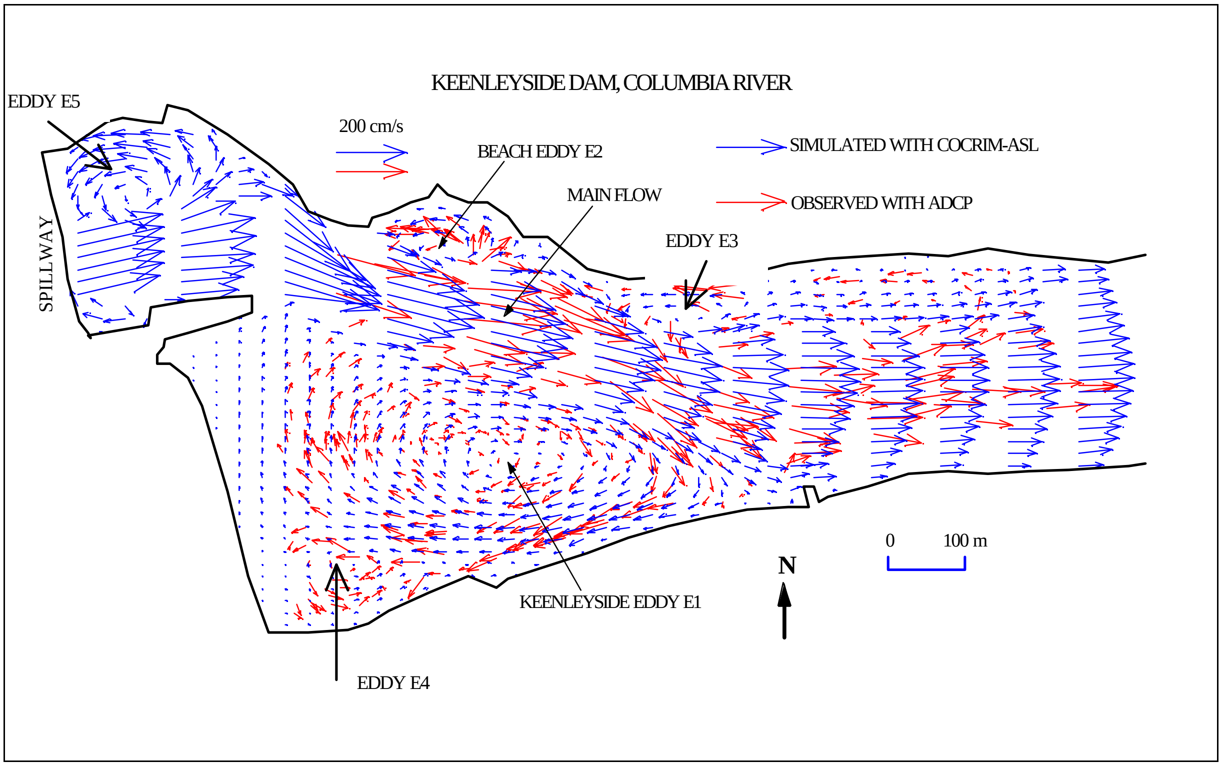

Figure 8: The red vectors show the near-surface flow measurements made in 1997, while the blue vectors are the 3-D numerical model outputs for the area downstream of the Keenleyside Dam on the Columbia River.

This case study of a 3-D finite difference numerical model illustrates the overall capability of advanced numerical hydrodynamic models for complex riverine flow applications. The numerical model indicates that the inertial effect and horizontal turbulent diffusion are the dominant physical factors causing the eddies downstream of the Keenleyside Dam.

Higher Resolution 3-D Numerical Models

The ASL 3-D River model as implemented in the Columbia River study at the Keenleyside Dam, was further developed and refined for a modeling application now underway for the Waneta Expansion Project. This modeling study is being conducted in the Waneta area at the confluence of the Columbia and Pend d'Oreille rivers, with the model boundaries shown in Figure 2. This area has some very significant morphological and circulation features. The main channel of the Columbia River, on the northwest side of this area, features large flows through typical water depths of 3 to 5 m. Just upstream of the confluence of the two rivers, a large gravel bar occupies most of the width of the river, with the water depth over the gravel bar being only 1 m or less relative to chart datum. Immediately downstream of the gravel bar, at the river confluence, is an area of deep water, known as the Waneta Eddy. In this eddy feature, water depths are as much as 18 m or more and the water flows are comparatively weak (< 0.5 m/s) generally following a counter clockwise circulation pattern. Immediately to the south of the Waneta Eddy is the discharge from the Pend d'Oreille River into the Columbia River. Under most Pend d'Oreille discharge levels, the flow in the area at the shallow narrows under the road and rail bridges is very turbulent, with large standing waves present due to the supercritical flow regime. This area of highly turbulent, standing wave conditions extends downstream as far as the southeast corner of the deep portion of the Waneta Eddy. The modeling incorporates historical bathymetric and flow data from the mid 1990's and recently acquired data sets collected as part of Waneta Expansion Project studies in the summer and fall of 2001.

In the modeling study presently being carried out, the ASL River 3-D numerical model has been adapted to very high resolution having a horizontal element size, in initial testing at 5 by 5 m, and then subsequently increased to an even finer resolution of 3 by 3 m. The use of the 3 m horizontal resolution was found to provide satisfactory performance, especially in the demanding hydraulic conditions associated with the very strong flows of the Pend d'Oreille River discharge just downstream of the road and rail bridges. Other refinements were also made to the ASL river model for the purposes of the Waneta study, most notably using a nested sub-grid model of 1 by 1 m resolution to adequately simulate the outflows in the proposed expansion hydro plant tailrace, which was required to adequately represent the hydraulic conditions associated with some of the alternative engineering designs for the plant tailrace.

This 3-D very high resolution numerical model for the Waneta area is operated on a Pentium IV 1.9 Ghz computer. A typical model run requires about 20 hours of dedicated computer time.

CONCLUSIONS

Recently a three dimensional, finite-difference numerical model has been developed and tested using extensive flow measurement observations previously obtained in 1997 downstream of the Hugh A. Keenleyside Dam. The 3-D model was successful in realizing the main flow pattern as well as a complex structure of four eddies, although two of the weaker eddies were somewhat weaker in magnitude than was observed. Previously, at the time the observations were made, a 2-D numerical model was not able to replicate three of the four eddies. Moreover, the new 3-D numerical model provides good measures of the changes in water flows from surface to near-bottom, which cannot be addressed with 2-D numerical models.

The development and implementation of such models require accurate and high resolution field measurement methodologies to provide suitable calibration and verification flow survey data sets, as well as bathymetric data with suitable horizontal resolution. ASL has developed advanced flow measurement techniques, based on acoustic Doppler current profiling instrumentation and real-time high accuracy navigation systems, through which maps of the river circulation, in three dimensions, can be obtained over periods of about one hour.

The ASL 3-D River model is presently being applied to an even more demanding hydrodynamic regime, in the Waneta area at the confluence of the Columbia and Pend d'Oreille rivers just north of the Canada – United States border. In this model implementation, the horizontal grid size resolution has been greatly increased from linear dimensions of 15 m, as used in the Keenleyside model, to a grid size of 3 m and 1m for the Waneta modeling study.

The 3-D finite-difference numerical model provides an improved tool for river application around hydroelectric dams for environmental or engineering design purposes. The power of the computer model lies in its ability to predict flows in regions where data is sparse or expensive to obtain in order to fully resolve the horizontal scales of the flow features. Moreover, numerical models provide a cost effective means of undertaking "what if" studies to investigate the impact on river circulation patterns of the placement of a new dam or plant, or the effect of changing discharge levels or operational configurations.

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