USING COMPUTATIONAL FLUID DYNAMICS TO ADDRESS FISH PASSAGE CONCERNS AT THE GRAND FALLS-WINDSOR HYDROELECTRIC DEVELOPMENT

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ABSTRACT

The study of out-migration survival of Atlantic salmon at Abitibi-Consolidated Company of Canada's Grand Falls-Windsor Hydroelectric Development began in 1997 as a result of replacing the penstocks used to divert water to the generating station with a power canal. A fish bypass diversion system was implemented within the power canal utilizing a behavioral louvre system. The efficiency of the system to divert the migrating smolt was low when the power canal first commenced operation in 1997 and after a new 30 MW Unit was installed in 2003. Physical modeling was conducted at the University of Waterloo between 1997 and 2002 to test improvements to the system, which led to increased efficiencies of fish passage before the new unit was installed. However, recent results of the physical modeling, including the new unit, did not detail the extent of changes required to the system to increase fish bypass efficiency. This prompted Abitibi to retain SGE Acres Limited to test the existing canal configuration (including new unit) and various alternatives using a Computational Fluid Dynamics model (***FLOW-3D***), before implementing recommendations from the physical model.

RÉSUMÉ

L'étude de la survie durant la migration vers la mer du saumon atlantique au complexe hydroélectrique de Grand-Sault-Windsor d'Abitibi Consolidated a débuté en 1997, dans la foulée du remplacement par un canal usinier des conduites forcées utilisées pour la dérivation de l'eau vers la centrale. Un système de déviation du poisson constitué de registres à lattes activés par le poisson et d'une échelle à poissons a été mis en place dans le canal. Au début de l'exploitation du canal et après l'installation, en 2003, de la nouvelle turbine Beeton de 30 MW, le système de déviation des saumoneaux en migration demeurait peu efficace. Des travaux de modélisation physique ont été réalisés à l'Université de Waterloo de 1997 à 2002 afin d'examiner l'effet de différentes améliorations au système. Ces travaux se sont soldés par une augmentation de l'efficacité du passage des poissons. Toutefois, les résultats récents de la modélisation physique, portant notamment sur l'effet de la turbine Beeton, ne précisaient pas l'ampleur des modifications nécessaires pour entraîner une augmentation de l'efficacité. L'Abitibi Consolidated décidait donc de retenir les services de SGE Acres Limited pour mener des essais, à l'aide d'un modèle de dynamique des fluides numérique (Flow-3D), sur la configuration actuelle du canal et différentes solutions de rechange avant de mettre en application les recommandations découlant de la modélisation physique.

1. INTRODUCTION

In December 2004, Abitibi Consolidated Company of Canada (Abitibi) engaged SGE Acres Limited (SGE Acres) to investigate alternatives for increasing the effectiveness of the Grand Falls Power Canal Fish Bypass Diversion System. The study included

- setting up a computational fluid dynamics model (***FLOW-3D)*** to represent the existing condition of the power canal,
- simulations of the existing condition for various flows,
- review of model results to confirm model is representing overall canal hydraulics,
- simulation of various alternatives to increase fish bypass efficiency, and
- selection of a preferred alternative.

The above work was completed in April 2005. Abitibi then re-engaged SGE Acres in July 2005 for follow-up work after the collection of physical data in the power canal by Environment Canada in June 2005. The follow-up work included

- review of Environment Canada measurements and comparison with ***FLOW-3D*** model results, and
- additional simulations to determine impacts other potential changes to the canal could have on overall canal hydraulics.

This paper documents the original analysis conducted in 2004 and 2005, and the follow-up work conducted in 2005 and 2006. The essential problem is to improve the flow conditions near the fish bypass entrance and along the louvre line. As the physical model results clearly showed, the local hydraulics are dependent on the configuration of the entire power canal, as well as the local hydraulics around the fish bypass entrance. Given the hydraulic complexity of the problem, the importance of finding a good solution, and the potential capital and operating expenses of implementing solutions, it was decided that the best approach would be to use the ***FLOW-3D*** model. Short of constructing another large-scale physical model, or using trial-and-error in the field, the ***FLOW-3D*** model was the only approach that could provide timely and accurate results.

2. SYSTEM DESCRIPTION

Abitibi owns and operates a hydroelectric facility located in Grand Falls-Windsor for the primary purpose of supplying power to their pulp and paper mill located at the same site. The general arrangement of the station is shown in Figure 1, and should be referred to for locations of structures noted throughout the paper.

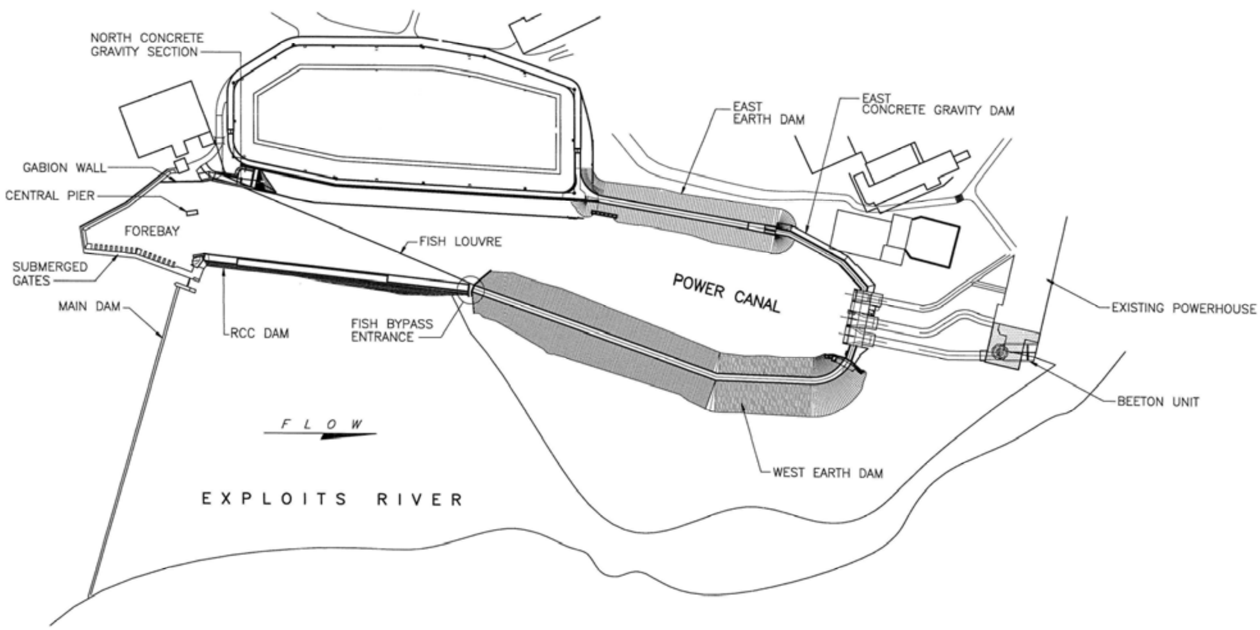


Figure 1. General Arrangement

Table 1 below indicates unit and flow capacities provided by Abitibi in 2004 for the scenarios studies. These flows were adopted for the original scope of work, while measurements conducted by Environment Canada are discussed further in the paper.

Table 1. Grand Falls Hydroelectric Development Unit Capacities and Flows

Unit	Installed Capacity (MW)	Firm Flow (m^3/s)	High Flow (m^3/s)
Beeton Unit	30	104	104
Unit 4	27	107	143
Unit 5/8	16	0	67
Total	73	211	314

3. MODEL SETUP AND CALIBRATION

This section provides a description of the Grand Falls Power Canal ***FLOW-3D*** model setup, and a comparison of the results with prototype data and physical model data available prior to the collection of data by Environment Canada in June 2005. The ***FLOW-3D*** model is distributed and supported by Flow Science Incorporated, of Santa Fe, New Mexico. This program simulates the dynamic behavior of fluid in three dimensions through a solution of the complete Navier-Stokes equations simulating free surface flows, including transitions between supercritical and subcritical flow within a single model setup.

Physical data for the power canal were required to set up a 3-dimensional shape of the power canal that could be imported to the ***FLOW-3D*** model. Dimensions of each physical component were based on information available from previous work conducted by SGE Acres for Abitibi. However, detailed information on the power canal bathymetry was not available; therefore, Abitibi contracted Red Indian Surveys Limited (RIS) as a part of this study to conduct a detailed bathymetric survey of the power canal in December 2004.

The ***FLOW-3D*** model set up included the 3-dimensional shape as noted above, but required further input parameters to specify the mesh size in the model. ***FLOW-3D*** requires that the model be subdivided into a mesh to allow the computation of the hydraulics within the smaller blocks of the mesh. This mesh size is dependent on the overall dimensions of the problem and the desired accuracy. The smaller the mesh size, the more accurate an answer; however, the longer the simulation time. To optimize the setup between run time and accuracy, a combination of mesh blocks with varying mesh densities was chosen. Based on this mesh density it took approximately 40 hours to simulate 1000 seconds of real time in ***FLOW-3D***.

In an effort to determine if the ***FLOW-3D*** model was accurately reproducing the overall hydraulics in the power canal, a number of simulations were conducted in ***FLOW-3D***. The results of these simulations were then compared with available prototype data measured in the power canal and results of previous physical model studies conducted at the University of Waterloo, since at this point Environment Canada had not conducted the velocity profile measurements in the power canal. Review of the information available for comparison indicated that information was limited and that the data set was quite small. A detailed comparison between ***FLOW-3D*** results, and prototype data and physical model data was therefore of limited use.

FLOW-3D model results were reviewed with Abitibi staff to determine if the model is accurately representing the overall hydraulics in the power canal. During the review, Abitibi staff indicated that there are a number of phenomena simulated in ***FLOW-3D*** that have been seen to occur in the power canal. Some examples are as follows.

- Distribution of velocities along the intake gates varies with lower velocities having been observed in the upper portion of the power canal inside the forebay intake gates.

- Rotating currents, or boils, have been observed to occur in the power canal.

- Eddies and zones of reduced velocity have been observed to occur in the power canal downstream of the fish bypass entrance.

- Relatively small head loss has been observed to occur at the upper forebay intake gates.

- Pulsations along the RCC dam have been observed to occur in the power canal, which leads to dynamic velocities upstream of the fish bypass entrance.

The ***FLOW-3D*** simulations for each of the flow scenarios simulated showed the above phenomena and based on these observations it was decided that the ***FLOW-3D*** model gives a good representation of the overall canal hydraulics and could be used to test alternatives for improving the efficiency of the fish bypass diversion system.

4. MODELING OF PROPOSED IMPROVEMENTS

The objective of any modification to the existing configuration is to have increasing velocities along the louvre line towards the fish bypass entrance. Since earlier physical model studies had shown that a berm placed between the central pier and gabion wall could be effective, it was decided to test this configuration. Another potentially effective way identified during the course of the work by SGE Acres to increase velocities near the fish bypass entrance was to remove some of the flashboards along the RCC dam near the fish bypass entrance. The impact of this would be to draw more flow over the RCC dam, thus increasing the velocities near the fish bypass entrance and changing the direction of flow along the louvre line towards the fish bypass entrance. Taking this into consideration, the following alternatives were selected for investigation.

- Construct berm between central pier and gabion wall (refer to Figure 1 for location).
- Remove portion of RCC dam flashboards near fish bypass entrance (refer to Figure 1 for location).

The above alternatives were simulated in ***FLOW-3D*** for the firm flow case and a fish bypass flow of 4.5 m^3/s, and the results were compared with the existing configuration. As can be seen in Figure 2, the velocities for the RCC configuration are increased near the fish bypass entrance compared to both the proposed berm configuration and existing configuration. It can also be seen in Figure 2 that the velocities are lower near the fish bypass entrance for the berm configuration.

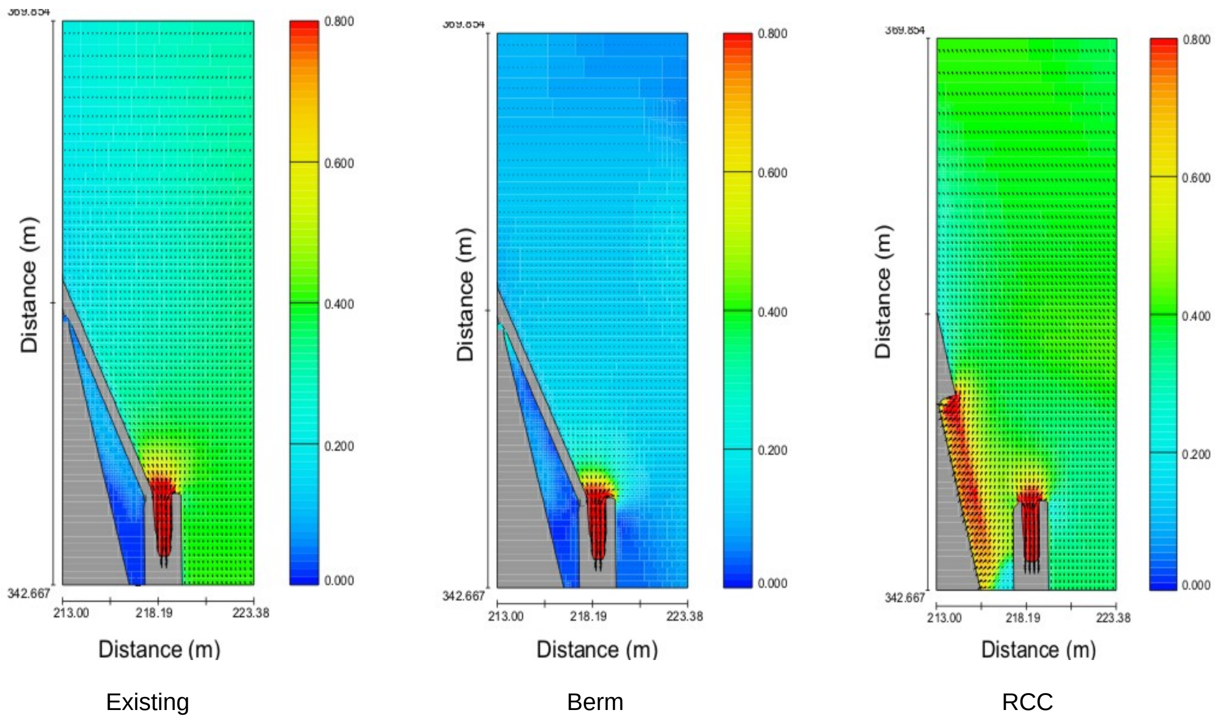


Figure 2. Comparison of ***FLOW-3D*** Results near Fish Bypass (Velocity Magnitude Contours in m/s)

Based on this analysis, it was decided that the better option for increasing the effectiveness of the fish bypass diversion system of the two cases investigated would be the RCC configuration. This case shows improvement over the existing configuration, and berm configuration, when considering increases in velocity near the fish bypass entrance. Subsequent to completing this analysis, this recommendation was made to Abitibi, and the structural modifications were conducted under a separate scope of work and completed prior to the 2005 monitoring program. The results of the 2005 monitoring program indicated an increase in fish bypass efficiency and increased guidance near the fish bypass entrance. However, the program did show that there was some loss of guidance approximately midway along the louvre line indicating some additional potential for improvement (loss of guidance was not a result of the RCC change).

Abitibi decided after the 2005 monitoring program that it was important to further investigate the loss of guidance at the midway louvre line area; however, before doing this, additional physical data were required to further validate the model beyond the anecdotal comparison discussed earlier. The collection of physical data, comparison of this data to the ***FLOW-3D*** model results, and the investigation of loss of guidance at the midway louvre line area are discussed in the following sections.

5. PHYSICAL DATA COLLECTION AND MODEL VALIDATION

Abitibi contracted Environment Canada to conduct detailed velocity measurements in the power canal June 2005. Site surveys were conducted on June 7th and June 8th for both firm flow and high flow conditions, respectively. To compare with the ***FLOW-3D*** results, Environment Canada's measurements were at consistent locations that could be compared directly with the model results.

To this point, all ***FLOW-3D*** simulations were based on flows provided by Abitibi, as presented in Section 2. Although the main reason for conducting the velocity measurements was for the ***FLOW-3D*** model validation, another key reason was to compare actual flow measurements in the canal with Abitibi's estimates. The total canal flow based on Environment Canada's measurements is approximately 180 m^3/s and 280 m^3/s for the firm flow and high flow conditions, respectively. Since these estimates of flow differ from the ones provided by Abitibi previously used to conduct the ***FLOW-3D*** modeling, the model had to be re-run with the revised Environment Canada flows to allow a direct comparison of measured and modeled velocity profiles. Table 2 provides the revised flows for ***FLOW-3D*** modeling based on Environment Canada's measurements. It should be noted that for comparison the Abitibi total flow noted in Table 2 includes the Fish Bypass and RCC flow for direct comparison with Environment Canada's total flow estimate.

Table 2. Revised Flow Scenarios

Unit	Firm Flow (m^3/s)	High Flow (m^3/s)
Fish Bypass Flow	4	4
RCC Flow	8	8
Beeton Unit	90	106
Unit 4	78	97
Unit 5/8	0	65
Total Canal Flow (Environment Canada)	180	280
Total Flow (Abitibi)	223	326

Before re-simulating with the revised flows, the ***FLOW-3D*** geometry file was updated with additional bathymetry collected by Environment Canada. The original geometry file bathymetry was based on data collected by RIS, and since additional data was now available from Environment Canada's surveys, the two data sets were combined to increase the detail of the bathymetry. Figure 3 shows the revised ***FLOW-3D*** geometry file, which includes bathymetry data from both RIS and Environment Canada. Figure 1 can be used to identify the key components of the model.

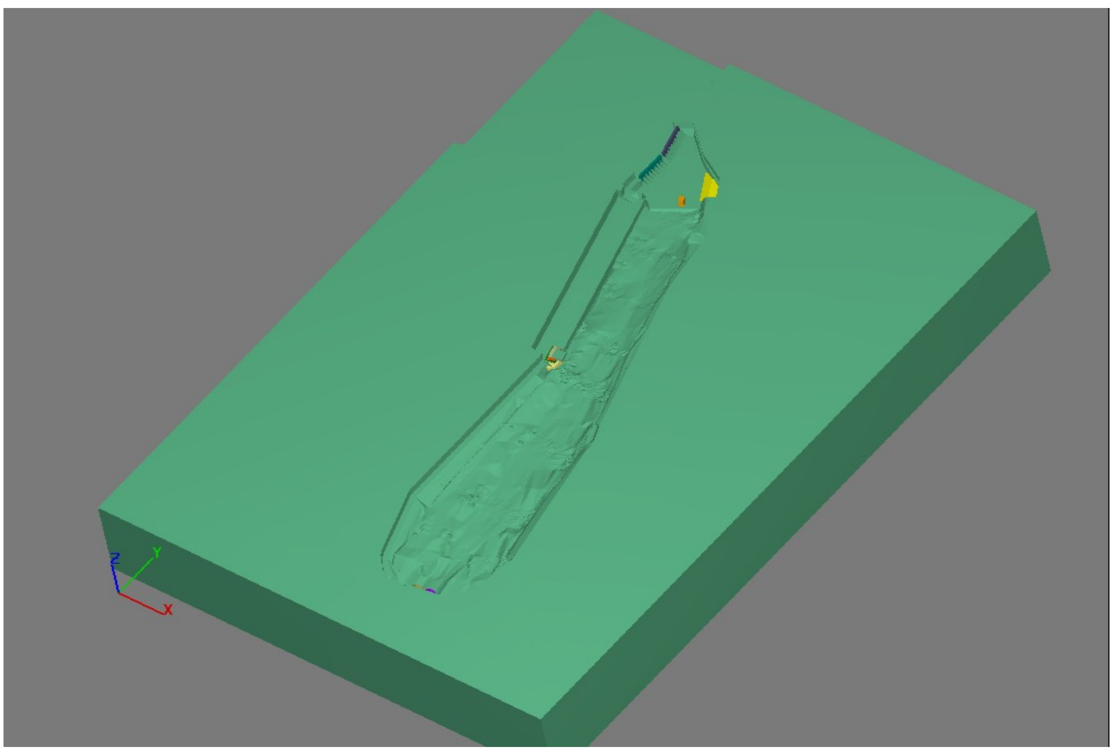


Figure 3. ***FLOW-3D*** Geometry File

Using the revised flow estimates and geometry file, the ***FLOW-3D*** model was re-run for both the firm flow and high flow conditions. Velocity profiles from both Environment Canada measurements and the model were produced for a number of cross sections in the power canal. The velocity distribution and magnitude modeled with ***FLOW-3D*** matched reasonably well to that measured by Environment Canada, as shown in Figure 4 for a sample cross section. This validates the model results with physical data, along with the previous anecdotal data comparison; thus, the model can be considered to accurately represent the overall hydraulics in the power canal.

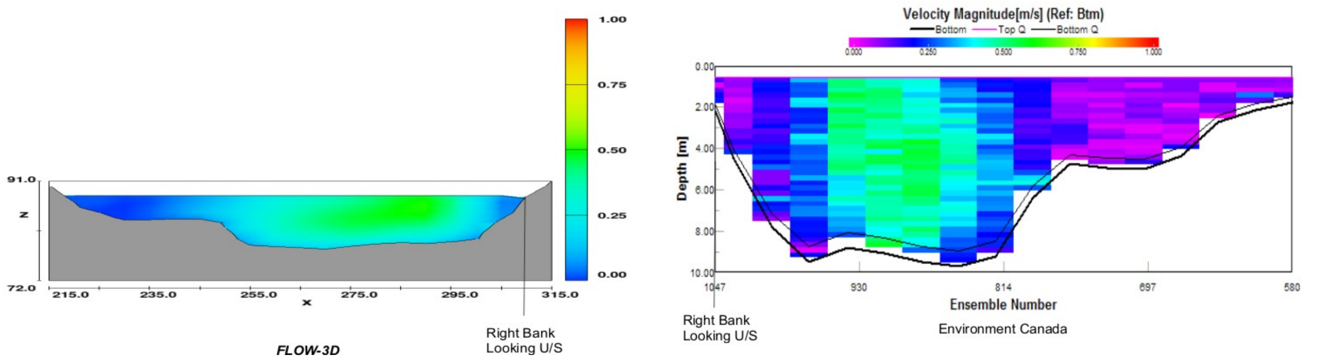


Figure 4. ***FLOW-3D***/ Environment Canada Sample Comparison (Velocity Magnitude Contours in m/s)

6. ADDITIONAL ANALYSIS

It was noted previously that when Abitibi implemented the proposed flow improvement by removal of flashboards at the RCC dam near the fish bypass, fish bypass efficiency increased during the 2005 monitoring program. However, it was also noted during this program, that although there was an overall increase in fish bypass efficiency, especially near the fish bypass entrance, fish guidance was still being lost midway along the louvre line. It was decided to review the results from the ***FLOW-3D*** model to determine why this loss of fish guidance was occurring and to simulate a number of alternatives that may help alleviate the problem.

Lotek Wireless Inc. (Lotek) conducted the monitoring program in 2005 and had indicated that the loss of fish guidance along the louvre line was observed at four of their antenna locations (Antennae 5-8). These antennae are roughly located midway along the louvre line. The results from the power canal existing configuration (including RCC configuration) ***FLOW-3D*** model setup for the firm flow condition were reviewed. To assess the potential for a hydraulic issue that could be leading to a loss in fish guidance, it is important to investigate not only the velocity magnitude at the specific locations, but also the directional velocities. The vertical direction is of particular interest since the fish may be carried downward under the louvre line. Figure 5 shows the velocity in the Z direction (vertical direction) cut along the louvre line.

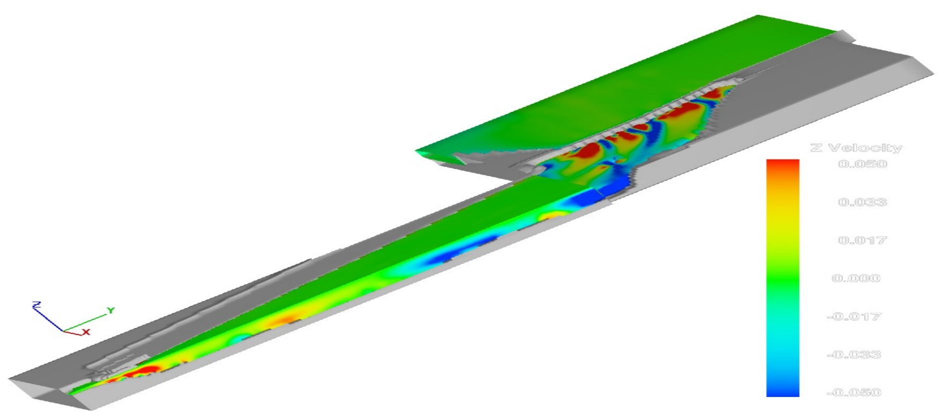
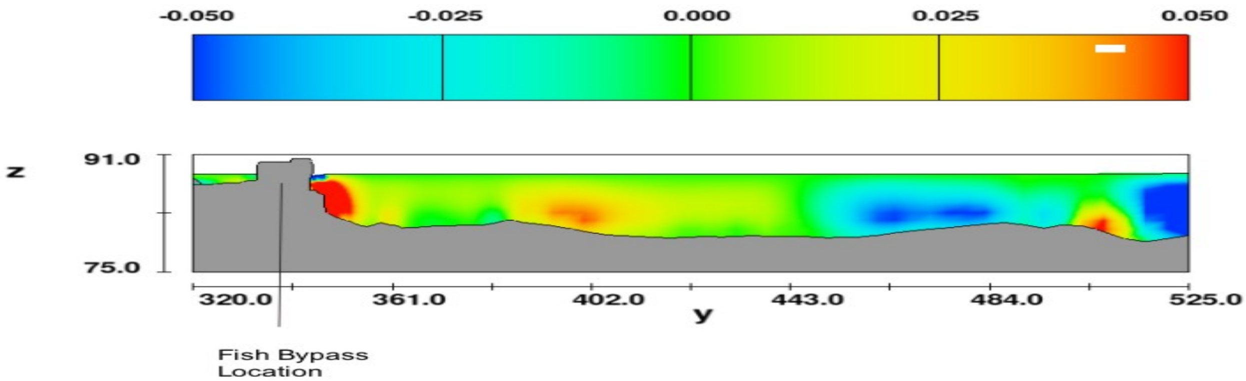


Figure 5. Z Velocity Contours along Louvre Line in m/s (Existing Configuration)

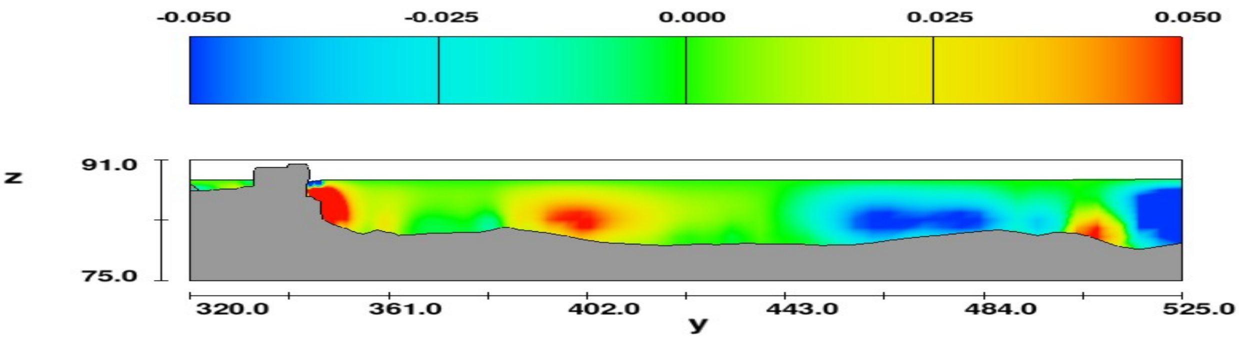
As can be seen in Figure 5, the Z direction velocity is negative or towards the canal bottom at approximately the same location (mid-louvre) where fish guidance was lost during the 2005 monitoring program. This was discussed with Lotek and it was determined that this negative velocity in the Z direction could be a contributing factor to the loss in fish guidance. Detailed ***FLOW-3D*** model outputs were reviewed and provided to Lotek in preparation for their 2006 monitoring program to assist them in trying to remove the loss of fish guidance midway along the louvre line. Although temporary measures will be made during the 2006 monitoring program, Abitibi would like to further investigate the loss of guidance to develop a permanent solution in the future.

During the course of the study, a number of alternatives had been discussed as potential configurations to the power canal that may have a positive effect on overall canal hydraulics. It was decided that since these alternatives were of interest, there would be merit in simulating these configurations in ***FLOW-3D*** and investigating the impacts on velocities midway along the louvre line. The alternatives included smoothing the upstream corner of the RCC dam near the forebay gates to help distribute the flow as it enters the power canal, and removing the central pier to remove turbulence at the upstream end of the louvre line.

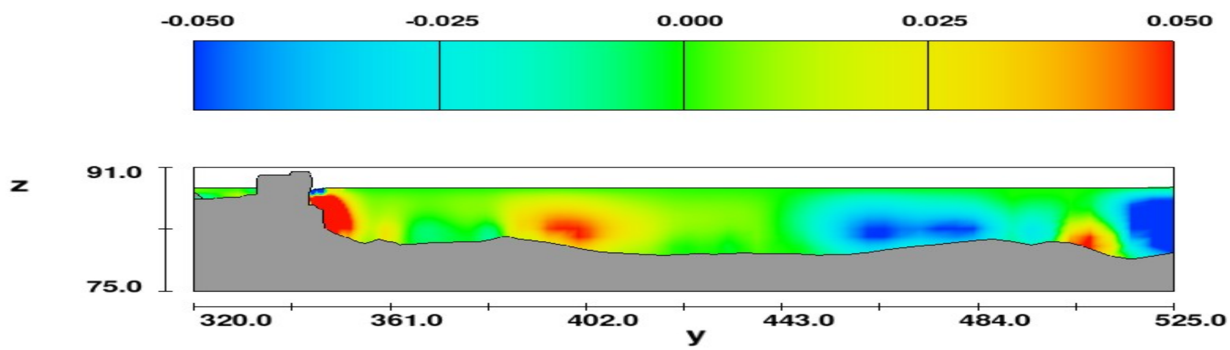
These alternatives were modeled for the firm flow condition with the RCC configuration in place. Figure 6 provides Z direction velocity profiles along the louvre line for both the smoothed corner and removal of central pier configurations, as compared to the existing configuration. It can be seen from these plots that the negative Z velocity along the louvre line suspected to be an issue for loss of fish guidance is still present for all configurations. Based on this, implementing these configurations would not likely help reduce the loss of fish guidance.



Existing



No Pier



Smoothed Corner

Figure 6. Z Velocity Contours along Louvre Line in m/s

It was noted during the review of these results, however, that a small outcrop along the bottom of the canal upstream of the negative Z velocity zone could be contributing to this phenomenon. It was decided to continue with temporary measures for the 2006 monitoring program, but there may be potential for a more permanent fix if this outcrop could be removed. It was recommended that ***FLOW-3D*** be used to simulate this configuration to determine if there would be positive effects on canal hydraulics, especially along the louvre line. Abitibi decided to wait until after the 2006 monitoring program before addressing this possible improvement.

7. CONCLUSIONS

a) The study showed that ***FLOW-3D*** can model the overall power canal hydraulics and is an effective tool for investigating alternatives for increasing the effectiveness of the fish bypass diversion system.

b) The model results matched both anecdotal observations by Abitibi staff and actual physical data recorded in the power canal by Environment Canada.

c) The RCC configuration simulation results showed the potential for increased velocity magnitudes near the fish bypass entrance leading to the potential for an increase in fish bypass diversion efficiency. This was confirmed during the 2005 monitoring season when the RCC configuration was in place and fish bypass efficiency increased, especially near the fish bypass entrance.

d) Model results when compared with results from Lotek on location of loss of fish guidance along the louvre line indicated that negative Z (downward) velocities could be leading to loss in fish guidance.

e) There is no impact on negative Z velocities along the louvre line for the options of the smoothed upstream corner on the RCC dam or removal of central pier configuration.

f) Results indicted that a small outcrop on the bottom of the power canal could be leading to the negative Z velocities experienced midway along the louvre line.