TECHNICAL PAPER

Title:	**Use of Physical Model and 3D Numerical Models to Design a Selective Withdrawal Intake**
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Use of physical model and 3D numerical models to design a selective withdrawal intake

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ABSTRACT: Most of the releases from a stratified reservoir in Western USA are through a hydroelectric power plant, which withdraws water from a relatively shallow arm of the reservoir. Much of the cold water both enters the reservoir and is stored in a second but deeper arm of the reservoir located about 6 km from the intake for the hydroelectric plant. The plant releases flow to downstream reservoirs and stream channels, where the water temperature is an issue in terms of cold-water fisheries. Extensive modeling studies have been performed to design a modified intake to enhance the selective withdrawal of cold water. The models included a distorted physical model, and several 3D numerical models. Selective withdrawal options included floating curtains, and an offshore submerged intake structure connected to the existing intake by a pipeline.

This paper will focus on the efforts to calibrate the physical model.

1 INTRODUCTION

1.1 *Problem Description*

A stratified reservoir in the Western USA has a surface area of 11,800 hectares, a storage volume of 1400 million cubic meters, and a maximum depth of 25 m. The reservoir configuration is shown in Figure 1, and consists of two lobes.

Inflows to the reservoir are distributed approximately 40% into the western lobe, 30% into the eastern lobe and 30% through a series of cold water springs, with most of the spring inflow into the northern end of the eastern lobe, which is 3+ meters deeper than the western lobe. Most of the outflow from the reservoir (up to 60 m^3/s) is through a hydroelectric plant located as shown on the southern shore of the shallower western lobe. A 6 km long narrow incised channel, about 3m deep and 25-35m wide, connects the intake to the cooler water in the eastern lobe. The remainder of the outflow, typically 1 m^3/s, is through a low level outlet at the south end of the eastern lobe. The large hydroelectric plant outflow is released into a narrow, partially stratified reservoir, about 8km long, with a surface area of 700 hectares, and a volume of 33 million m^3. At present the releases from the downstream reservoir exceed 20ºC in August about 90% of the time. The objective of these studies is to determine how to minimize and preferably eliminate flow releases exceeding 20ºC from the downstream reservoir. Since typical warming through the downstream reservoir is 1-2ºC, the intent is to restrict the temperature of the hydroelectric releases to less than 18ºC.

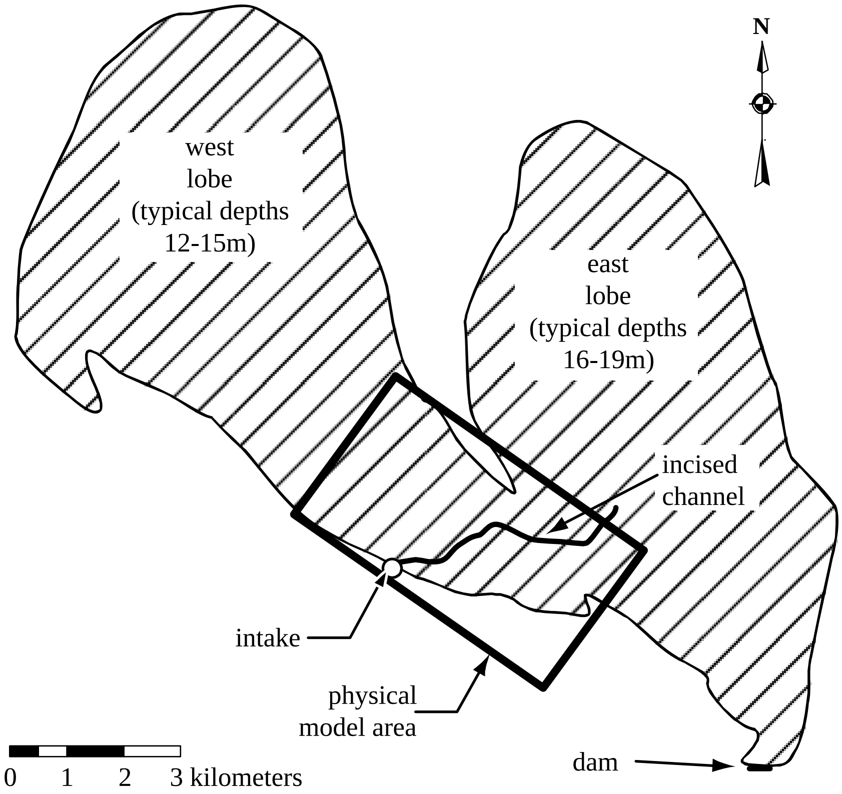

Figure 1. Map of stratified reservoir including outline of physical model.

1.2 *Study Objectives*

The primary objective of the study is to determine if a modified hydroelectric intake can selectively withdraw cold water and keep peak summer return temperatures below 18ºC for normal outflows of 45 m^3/s, and if possible for peak outflows of 60 m^3/s.

A secondary objective is to determine the impact of the intake modifications on release temperatures for a range of release flows.

1.3 *Approach*

The approach was to develop a series of models including:

- A distorted physical model of the area around the hydroelectric intake, including the incised channel connecting the intake to the cooler water in the eastern lobe
- A numerical model of the entire lake
- A numerical model of both the distorted physical model, and an undistorted version of the physical model

The models were used to evaluate the performance of the intake modifications over a range of environmental conditions, including both flows and density stratification.

1.4 *Deliverables*

The study deliverables were to include both the proposed intake modifications and a validated numerical model for future design modifications and flow simulation.

2 MODELS

2.1 *Selection of Models*

A distorted physical model was selected for the following reasons:

- Simulating stratified flow through a long channel typically requires a distortion of approximately 5 to compensate for the increased friction (both interfacial and bed) in the model compared to the prototype.
- Available test basins were such that a distorted model allowed a more representative area of the reservoir to be reproduced with flows in an acceptable range of Reynolds Numbers.

The area covered by the model is shown in Figure 1.

The numerical model used was a 3D Unsteady and Unstructured Reynolds-Averaged Navier-Stokes (U^2RANS) solver. The primary model user was one of the model developers with extensive experience in using the model, and worked at the institute where the physical modelling was performed, allowing for close interaction between the physical and numerical modelling.

2.2 *Physical Model*

As shown in Figure 1, the physical model covered an area approximately 5km by 3km, including the incised channel connecting the intake to the cool water in the deeper eastern lobe. The horizontal scale ratio was 1:220 and vertical scale ratio was 1:40. The bottom and sides of the model basin were heavily insulated, and cooling coils were installed in the bottom of the model. Separate warm and cold water inflow systems were installed which allowed (along with the cooling coils) a high degree of control over the temperature stratification in the model. Extensive field bathymetric data were obtained to allow detailed reconstruction in the model of the incised channel and the topography around the intake. A model filling process was developed by trial and error that allowed typical temperature profiles for the three summer months, June, July and August, to be routinely imposed in the model. Flow and temperature measurement systems were installed that allowed instantaneous readout of flows and temperatures into and out of the model, plus temperature profiles at 6 locations in the model. The time-history of temperatures at the hydroelectric intake was recorded, so that the response of the system to intake modifications could be determined as soon as it occurred. Dye injection was used to examine the stratified flow behavior along the incised channel, particularly in vicinity of the intake.

2.3 *Scaling*

A major uncertainty in using a distorted stratified model is how to scale the flows into and out of the model. The standard approach for the case where the density stratification is the same in model and prototype is to use Froude similarity. For a horizontal scale of 1:220 and vertical scale of 1:40, the flow ratio is 1:55,656. However, this is only correct when the flow direction is parallel to the bed. In our case, the flow near the intake dives towards the bed. In the distorted model, with standard Froude scaling, initial tests indicated that the model was withdrawing cooler bottom water, even though field data indicated a relatively uniform (top to bottom) withdrawal. This was because the vertical component of the velocity was ‘under-scaled’, and it was necessary to re-evaluate the flow scale ratio. For an undistorted model, with a horizontal scale ratio of 1:40, the flow scale ratio is 1:10,119. Due to the fact that far from the intake the flow is parallel to the bottom, but near the intake vertical velocity components are significant, the flow scale ratio is expected to be between the above two values, and generic tests were developed to determine the appropriate ratio.

2.4 *Scaling Test Program*

The generic test program consisted of constructing an idealized intake, or ‘test box’, in both distorted and undistorted form, and placing it in the model (see Figure 2) so that it is exposed to the same temperature profile as the hydroelectric intake. Two types of intakes were constructed. Both cases included the incised channel and intake tower. In one case, the sidewalls of the test box penetrated the water surface, while in another case the sidewalls stopped short of the surface to simulate the underwater ridges in the prototype. Tests were performed for a range of flows for both the existing intake condition, and an intake with a skimmer curtain in front of it. Over a wide range of tests a consistent scale ratio of about 1.5-1.7 was found to apply, i.e. increasing the distorted Froude flow ratio by approximately 50-70% resulted in the same intake temperature as the undistorted intake. Figure 3 shows typical results. The horizontal scale Q/Q $_0$ is the ratio of the flow through the hydroelectric intake to the design flow rate of 45 m^3/s. A numerical model of the 'test box' resulted in a similar value of the scale ratio.

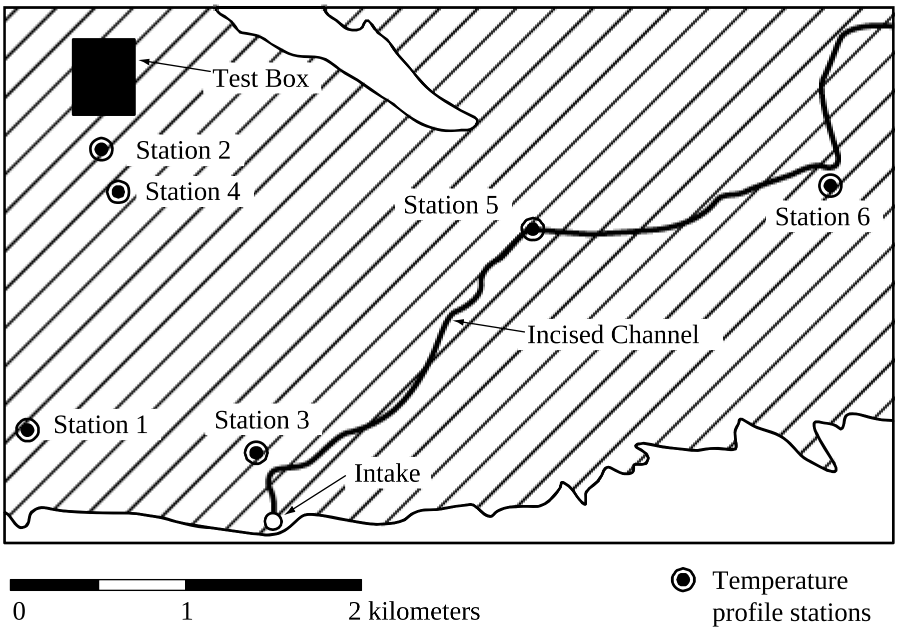

Figure 2. Physical model showing location of test box.

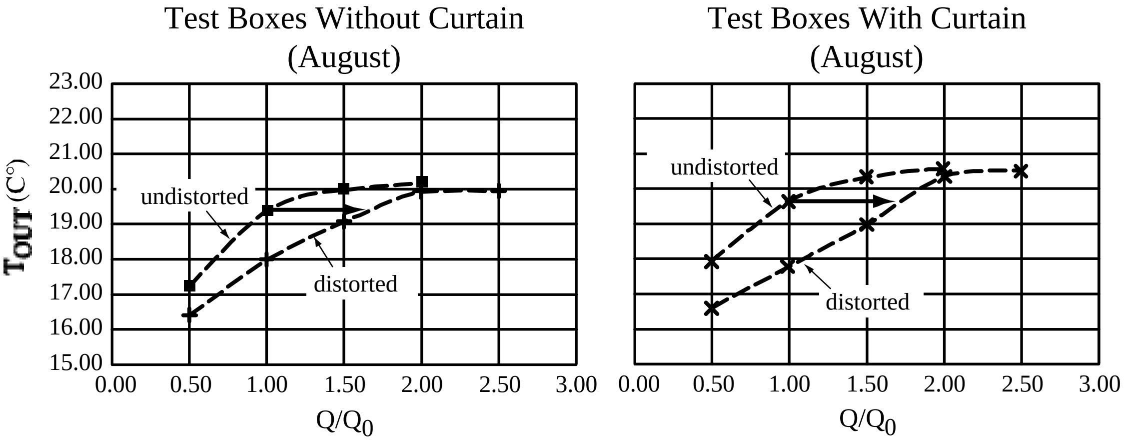

Figure 3. Flow scaling factor determined using the "Test Box".

2.5 *Hydraulic Model Validation*

Field data were available for three temperature profiles and a limited range of flow conditions. Figure 4 shows that increasing the model flow ratio by a factor of approximately 1.7 allows the model to accurately simulate prototype behavior.

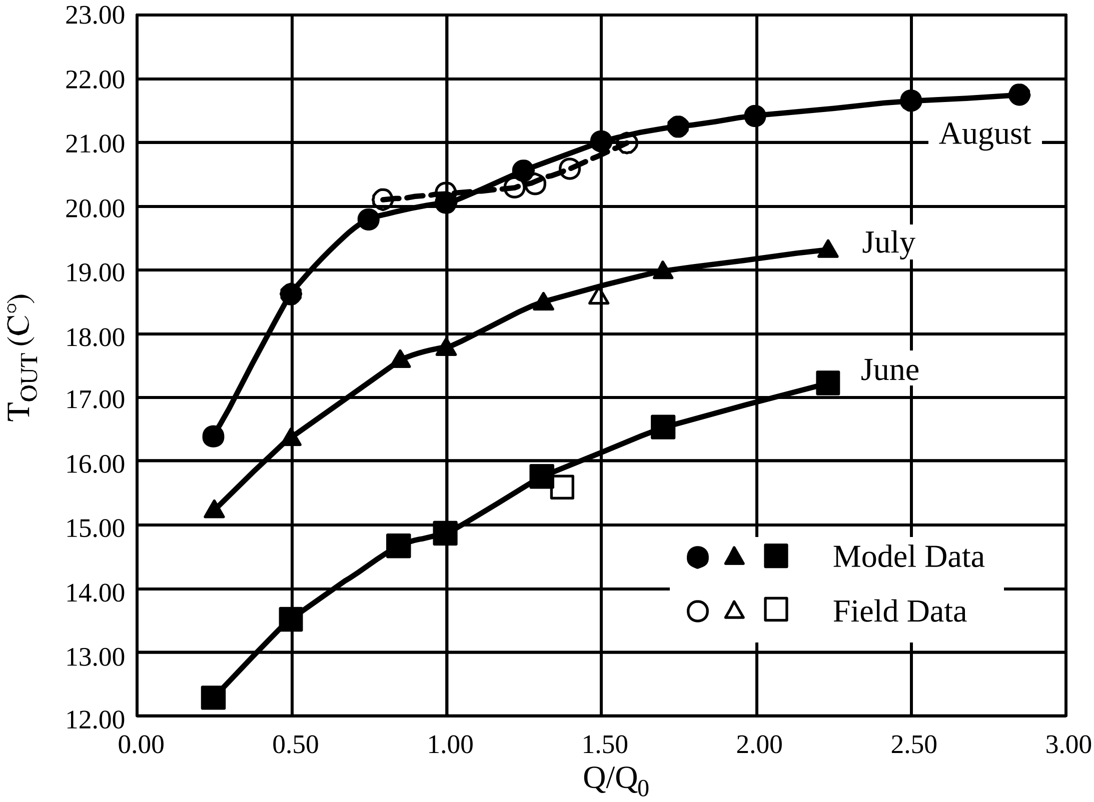

Figure 4. Comparison of physical model data and field data using a flow scaling factor of 1.7.

2.6 *Numerical Model Calibration and Validation*

A 3D numerical model of the entire reservoir was developed, and did a reasonable job of predicting both the outflow temperature and the temperature profiles in the deeper parts of the reservoir. However in the shallower areas of the model, the agreement between the predicted and measured temperature profiles was not as good.

3 INTAKE MODIFICATIONS

A range of intake modifications was considered including

- Curtain – this consisted of a curtain surrounding the intake so that the flow was withdrawn through a bottom opening, 2-3m high. Typical curtain dimensions were 700m long by 13m deep. The major opening under the curtain was about 280m from the intake tower.
- Levee removed – levees formed during the incised channel construction created an underwater berm approximately 1.5m high and affected the stratified flow towards the intake. Tests were performed with and without levees for a range of curtain lengths and depths.
- Offshore submerged intake – A submerged ‘hood’, about 30m square, was located abut 300m offshore in the incised channel, and connected to the existing intake by 4m diameter pipes. Several versions were tested.

4 RESULTS

4.1 *Physical Model*

Test results are given in Table 1, and show that the curtain with the levees removed gave the best results, with a temperature reduction during the critical month of August of over 5ºC. Similar results were obtained for June and July. The submerged 'hood', without levees, gave a reduction of ~ 3.5ºC.

Table 1. Effect of Intake Modification on Withdrawal Temperatures

Intake Condition	Withdrawal Temperature ºC	Temperature Reduction ºC
Existing	21	-
Curtain Without Levees	15.8	5.2
Curtain with Levees	17.5	3.5
Offshore Submerged Intake	17.6	3.4

4.2 *Comparison of Physical Model and Numerical Model*

Our early concepts involved developing a numerical model of the distorted physical model with the idea of calibrating / validating the numerical model against the physical model results. The numerical model would then be 'undistorted', i.e. the horizontal scale in the numerical model would be increased by a factor of 5.5, and the effect of the distortion could be directly assessed.

Comparisons between the physical and numerical model results were preformed both for the existing intake and for the intake with curtain (with levees). Initial results were not promising, but after considerable-refinement of the numerical model grid, in particular using a much finer vertical grid near the bottom, reasonable agreement was obtained. However, when the numerical model was 'undistorted', some unexpected behavior was observed, including a decrease in the withdrawal temperature as the withdrawal flow increased. Further changes to the numerical model e.g. reducing the time step by a factor of 10, improved the agreement with the results of the 'corrected' physical model. However, the combination of finer grid and smaller time steps led to such long run times on the available desktop computers, that the use of the numerical model to verify the scaling factor, observed in the physical model test, was discontinued before conclusive results were obtained.

5 CONCLUSIONS

- A consistent flow scaling factor was established for a distorted physical model of a stratified reservoir for a wide range of conditions
- The validated distorted physical model allowed a variety of intake options to be compared, and showed that temperature reductions in the outflow from the reservoir as high as 5ºC can be achieved.
- The use of a numerical model to confirm the scaling factor for the physical model was only partially successful.