PHYSICAL AND MATHEMATICAL MODEL STUDIES OF PUMPED STORAGE RESERVOIR HYDRODYNAMICS FOR DETERMINATION OF ENVIRONMENTAL EFFECTS

by

DANNY L. KING

and

THOMAS J. RHONE

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by Danny L. King
Chief, Hydraulics Branch
and Thomas J. Rhone
Head, Applied Hydraulics Section
Division of General Research
U.S. Bureau of Reclamation
Denver, Colorado U.S.A.

SYNOPSIS

Twin Lakes are two, connected high mountain lakes in Colorado. Both lakes stratify in summer, with very similar temperature profiles and are dimictic, with spring and fall mixing. The lower lake is very productive and sustains a large population of freshwater shrimp (Mysis relicta) which is the primary food source for a valuable lake trout fishery. A large portion of the reservoir bottom is covered with a very fine rock material, known as glacial flour. The Mount Elbert Pumped Storage Powerplant, now under construction, is located on the shore of the lower lake.

Recognition of potentially adverse environmental effects led to initiation of a major study of Twin Lakes. The study includes comprehensive biological assessment of pre-operation conditions, with the necessary, associated study of lake thermal regime and hydrodynamics. A mathematical model was used for prediction of normal seasonal stratification patterns and, in conjunction with physical models, for evaluation of destratification effects of plant operation.

Resume

Twin Lakes sont deux lacs unis dans le haut montagne en Colorado. Tous les deux stratifient en été avec profils de la temperature très semblable. Ils sont dimictique avec mélangement en printemps et en automne. Le lac aval est très fécond et il sustenit une grande population des crevettes d'eau douce (Mysis relicta) qui sont l'alimentation primaire pour un pêcherie de truite arc-en-ciel de grande valeur. Une grande partie du fond de lac est couvertée avec un matériaux très fin de roche qui s'appelle "farine de glacier". La station de pompage et turbinage, Mount Elbert, maintenant en construction, est situé sur la côte du lac aval.

La connaissance d'un effet potentiel adversé á l'environment a mené au debut d'un étude majeur des Trin Lakes. L'étude comprend une évaluation biologique compréhensive des conditions avant le mis en marche de l'installation avec l'étude associé et necessaire du régime thermal du lac et des hydrodynamiques du lac. Un modèle mathematique a été employé pour la prediction des caracter-normals de la stratification thermal, et, en conjonction avec les modèles experimentals, pour l'evaluation des effets de la destratification par l'operation de la station.

Introduction

Twin Lakes, two interconnected high-mountain lakes, are located at an elevation of about 9,000 (2,740m) feet in central Colorado. The lakes, modified by the addition of pumped storage, are a major feature of the Bureau of Reclamation's (USBR) Fryingpan-Arkansas transmountain diversion project. The dimictic lakes (mixing twice annually) contain a combined maximum volume of 170,000 acre feet (210,000,000 cubic meters), with a total surface area of about 3,000 acres (1,200 ha). The lakes are nearly 100 feet (30m) deep, have a total length of about 4 miles (6.5 km), and a width of about 1-1/2 miles (2.4 km). The bottoms of the lakes are covered with a deposit of pulverized rock of glacial origin (median size on the order of 0.005 mm), known as glacial flour, which is resuspended with only minor disturbance. The lake fishery is noted for the presence of very large lake trout (15 pounds (6.7 kg) weight and 36 inches (91 cm) in length), which feed during certain life stages on a freshwater shrimp (Mysis relicta) which was artifically introduced to the lakes in 1957 and which has become very abundant.

The Mt. Elbert pump-storage plant, now under construction on the northwestern shore of the lower lake (figure 1), will have an initial capacity of 100 megawatts, and an ultimate capacity of 200 megawatts following addition of a second unit, 3 years after the first. Present plans call for initial power generation in 1977.

During the pumping mode, with one unit, 3,090 ft^3/s (87.5 m^3/s) will be lifted to an 11,000 acre-foot (13,600,000 cubic meters) forebay reservoir located approximately 500 feet (150m) above the lakes. Generation will release 3,600 ft^3/s (102 m^3/s). These discharges will be doubled with two units operating. The operational plan calls for 8 hours generating in the afternoon and evening, followed by 9 hours pumping during the night, then a rest period of 7 hours. This cycle will occur during weekdays, with a 2-day rest period on weekends.

Potential environmental effects include: (1) destruction of the summer thermal stratification, (2) resuspension of the glacial flour with associated high turbidity, and (3) entrainment of fish and passage through the pump-turbines. These factors could be expected to have direct adverse effects on the freshwater shrimp and the lake trout as well as direct or indirect effects on other biota. Secondary effects on the resort and recreation industry would result. Recognition of these potentially adverse environmental effects led to initiation of a major study of Twin Lakes. The study includes comprehensive biological assessment of pre-operation conditions, with the necessary, associated study of lake thermal regime and hydrodynamics. The studies described in this paper were aimed at identifying the magnitude of these environmental effects and possible solutions to predicted problems.

Mathematical Model Studies

A Corps of Engineers modification of a model developed by Water Resources Engineers, Inc. (WRE) was used to simulate thermal stratification in Twin Lakes. In the model, the reservoir is divided into horizontal slices with diffusion and advection of heat and mass occurring vertically between the slices and inflows and outflows entering and leaving the slices according to elevation and density. Climatological data along with inflow and outflow temperatures form the basis for a heat budget calculation. The model is heavily dependent upon an effective diffusion coefficient which consolidates all the effects of diffusion including and in addition to molecular diffusion. The model has been previously verified using data from two very different USBR reservoirs and an effective diffusion coefficient from a third, a Corps of Engineers reservoir.

A coefficient from another Corps of Engineers reservoir was applied to Twin Lakes, with climatological and hydrological data collected at the site during 1974. Figure 2 compares the predicted temperature profiles with those actually measured. The agreement was determined to be sufficient for this analysis. The next step was to superimpose plant operation on the natural state of the lakes, with additional inflow and outflow points designated to represent generating and pumping. The computer program was also modified to include a routine for increasing or decreasing the temperature of water in the forebay according to the calculated equilibrium temperature. The diffusion coefficient was varied from that used in the verification run (0.25 m^2/sec or 2.7 ft^2/sec) to progressively higher values which caused decreasing strength of stratification until finally development of stratification was precluded for a coefficient of 1.5 m^2/sec or 16.2 ft^2/sec. Because the question remains as to whether this number was truly representative of the effect of the jet, the analysis is continuing.

Physical Model Studies

Figure 3 shows the three physical models used in this study. A distorted (1.84 vertical, 1:6,000 horizontal) thermally stratified tabletop model was used to demonstrate and approximate the possible destratifying effects of plant operation.

A second distorted, thermally stratified, rigid bed model (1:100 vertical, 1:600 horizontal) was used to study destratification effects and circulation patterns in detail. The model included both lakes, the connecting channel, the inflow and outflow channels, and the Mt. Elbert plant. Plant operation was controlled by a minicomputer which also scanned thermistors, applied calibration corrections, and printed temperatures. The thermistors were placed in vertical strings at several locations in the lower lake and at one location in the upper lake. The latter was used primarily to monitor any heat exchange between the model and the ambient laboratory air, since the upper lake is unaffected by plant operation. Velocities in the model were measured with an electromagnetic current meter, and circulation patterns and jet movement were determined by single-frame photography of dye clouds.

A third undistorted (1:100), homogeneous model was used to examine the near field characteristics of the jet and to develop the design of the tailrace channel. The bed was formed with sand to allow easy modification. Velocities were measured with a miniature propeller meter and the electromagnetic current meter.

Results

The table-top model showed that the jet leaving the plant during the generating mode stayed close to the west shore, then turned eastward when it reached the south shore of the lower lake. The model suggested that, beginning with a well-defined stratification, the lake would be only very weakly stratified after about 30 days of either one-unit or two-unit operation. Movement of the glacial flour was indicated.

Operation of the larger distorted model suggested the following conclusions:

(1) Cold [6° C (43° F)] forebay (generating) water introduced into an isothermal or mildly stratified lake (average temperature 12° - 15° C or 54° - 59° F) cooled the entire lake and caused a stratification (10°C (50° F) bottom to 15° C (59° F) near surface) in 12 days of one unit test operation. Test operation included 5 days with 8 hours generating, 9 hours pumping, and 7 hours rest followed by 2 days rest, then 5 days further operation.

(2) Starting with the stratification formed in (1) and operating in the same mode, except generating with 15° C (59° F) water, did not destroy the pattern of stratification but tended to warm the entire lake about 1° C (1.8° F). Length of this operation was 5 days.

(3) Two-unit operation in a similar sequence as (1) and (2) showed similar results, figure 4. Another two-unit test showed a resultant warming of the lake in that the final temperature profile was warmer than the starting profile.

(4) The temperature profile in the area within 600 feet (183m) of the plant was rapidly affected by each generating phase but was restored by the subsequent pumping cycle. The greater the distance from the plant, the less evident was this trend. Water temperatures in the plant penstocks during the pumping were usually approximately the same as found in the lake at the elevation of the bottom of the intake channel.

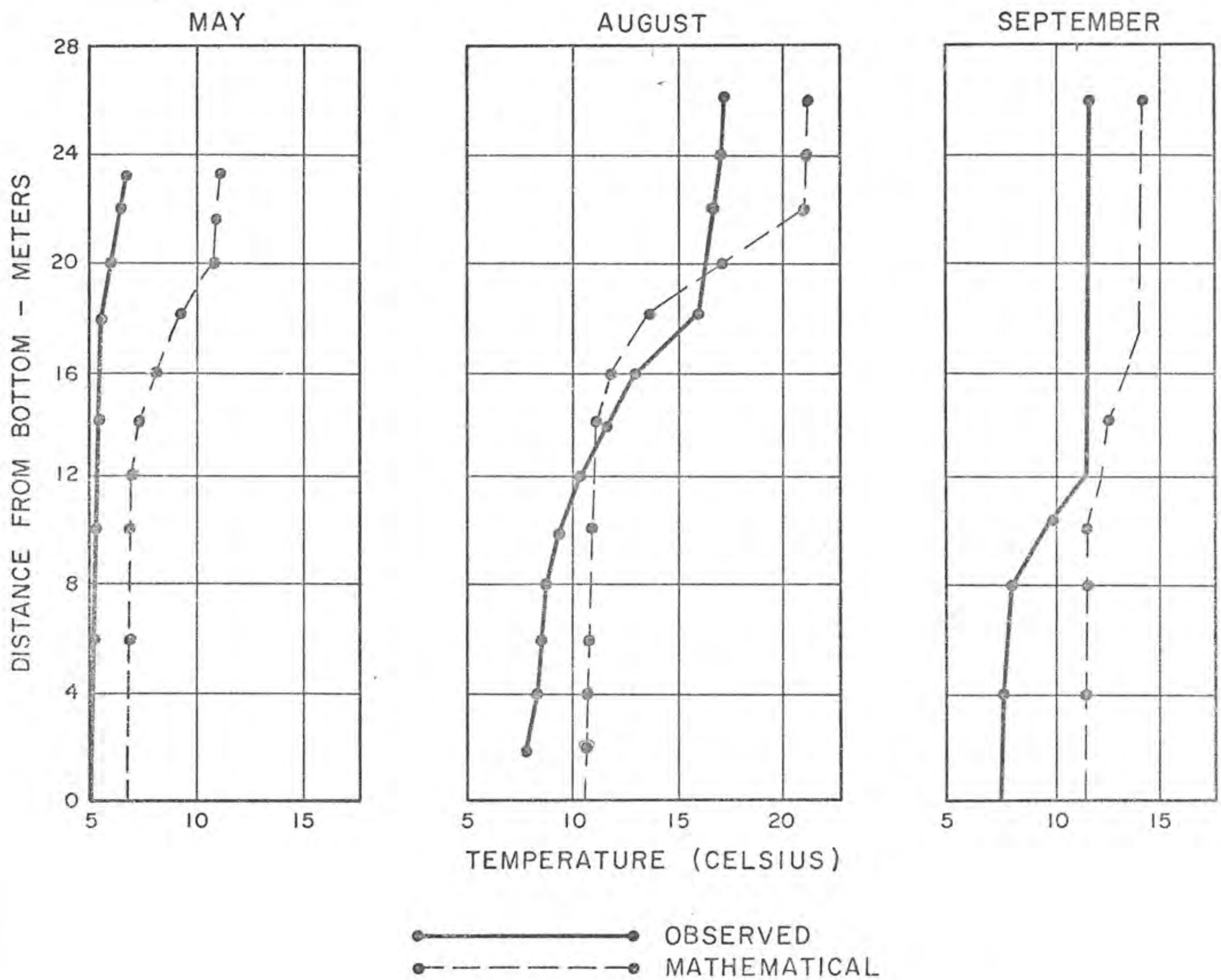
(5) Prototype conditions at initial operation will have considerable influence on the effects of plant operation. To determine this, the approximate time of year for initial startup and expected temperature of forebay reservoid water should be known. For example, if temperature conditions cause a diving jet, bottom materials will be disturbed and may continue to circulate in the lake. On the other hand, an initial surface jet may determine a different future. It is conceivable that the startup date might be set according to the expected effects.

Velocity distribution data were obtained in the channel between the plant and the lake for a distance equivalent to about 700 feet (214m) in front of the plant. Three channel configurations were tested in the 1:100 undistorted model; one was a direct extension along the plant centerline, the other two angled to the right toward the west shore of the lake. Velocity distribution readings taken during the generating cycle indicated the configuration of the draft tubes concentrated the flow toward the centerline of the plant and there was very little dispersion, thus giving the jet a higher energy flux at the point of entry into the lake. Bottom velocities seemed to be lower than intermediate depth and surface velocities. On the angled channels, the flow impinged on the left bank before turning and following channel alinement. There was also some return flow and dead water areas, particularly with one-unit operation. These trends were prevalent to the point where the excavated channel exited into the lake. Both one- and two-unit operation exhibited the same tendencies. Flow distribution was much better during the pumping cycle, particularly with the angled channels.

Based on these tests, an angled channel was designed and installed in both models for further investigation. Work is continuing at the time of this writing (February, 1975). Flow patterns, bottom velocities, tendencies for movement of the glacial flow, and destratifying effects are being more closely defined. The mathematical model is being refined for accurate simulation of the plant operation and computations are underway to compare the energy of the jet with the stability of the reservoir.


FOREBAY RESERVOIR AREA
UPPER LAKE
N
MOUNT ELBERT
POWER PLANT SITE
LOWER LAKE

FIGURE 1

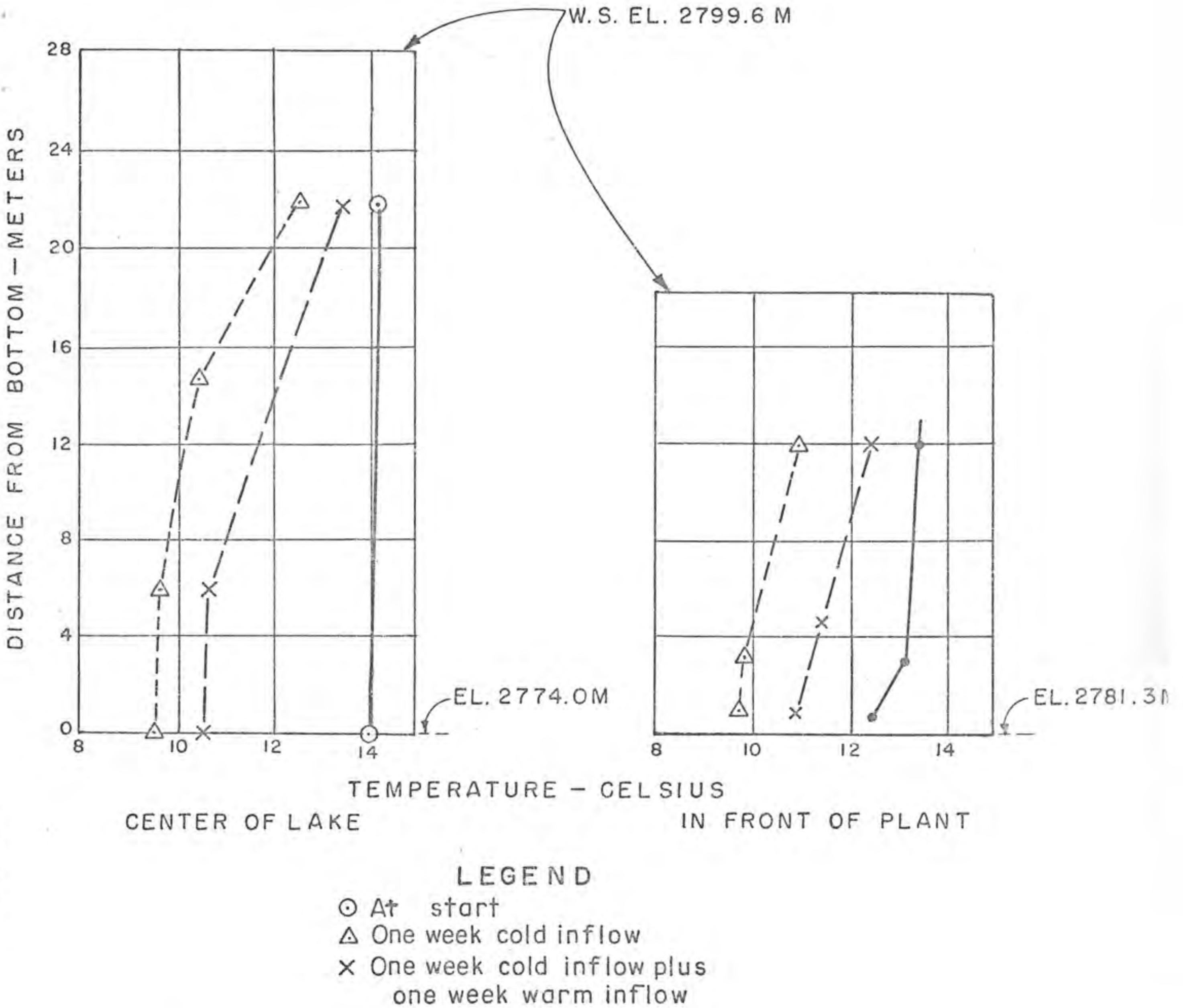


TEMPERATURE PROFILES

FIGURE 2


SMALL DISTORTED MODEL
V-1:84 H-1:6000
LARGE DISTORTED MODEL
V-1:100 H-1:600
UNDISTORTED MODEL
1:100

FIGURE 3



TYPICAL TEMPERATURE PROFILES IN MODEL

FIGURE 4

FIGURE CAPTIONS

Figure 1 - Twin Lakes, Colorado and major features.

Twin Lakes, Colorado et les installations principaux

Figure 2 - Typical temperature profiles and comparison with math model predictions

Profils caractéristiques de la temperature et une comparison avec les resultats de le modèle mathématique

Figure 3 - View of physical models

Les modèles experimentals

Figure 4 - Results from a representative test

Les resultats de un essai typique

FINAL RESULTS AND CONCLUSIONS ON PHYSICAL MODEL STUDIES OF PUMPED STORAGE RESERVOIR HYDRODYNAMICS

The channel selected for prototype installation angled 27 degrees to the right of the pumping-generating plant centerline. The physical dimensions of the channel are 60-foot (18.3 meters) bottom width and 3 to 1 side slopes. The invert is at elevation 9150 (2790 meters). At the end of the channel, where the channel enters the lake, a 5-foot (1.5 meters) high, 10-foot (3.0 meters) wide berm serves as an underwater barrier. The barrier is to encourage withdrawing water from a higher level during the pumping cycle and to influence the inflowing jet during the generating cycle so that it will have less tendency to move along the bottom of the lake.

The velocity distribution measurements, in the undistorted model, indicated that during the pumping cycle most of the flow entered the channel from along the north shore of the lake. The flow was evenly distributed and the velocity was about 1.2 feet (37 cm) per second.

During the generating cycle flow was not evenly distributed near the plant but had attained an adequate distribution when it entered the lake where average velocities were usually less than 1.0 foot (30 cm) per second. Velocities were slightly higher from mid-depth down.

Temperature measurements in the lower lake (made in the distorted model) showed the same tendency as in the earlier tests. Stratification was not affected by two-unit operation although there was a tendency for the ambient temperature to be affected by the temperature of the generating flow. Over a 2-week operating period cold water inflow lowered the lake temperature and warm water inflow increased the temperature but the gradient remained essentially the same.

Time lapse motion pictures of colored water inflow showed movement of the generating influent generally toward the southeast and the pumping cycle intake generally originating along the north side of the lake. There was noticeable (but not appreciable) flow along the west side of the lake during the pumping cycle. This was not apparent during the velocity measurements in the undistorted model.

Dye tracers placed in the bottom of the lake in the vicinity of glacial flour deposits prior to operation did not move during the initial 2 or 3 days of operation but were gradually assimilated into the surrounding water.

Nineteen days of simulated operation did not affect the temperature in the upper lake.

A configuration in which a 1-mile (1.6 km) long canal carried flow from the plant into the upper lake was also studied. This canal had an 80-foot (24 m) bottom width and 3 to 1 side slopes. The invert was at elevation 9150 (2790 meters). No velocity measurements were made but alinement modifications were made to correct an adverse vortex condition at the plant.

Temperature measurements showed that the stratification in the upper lake would be affected by plant operation. Cold water inflow reenforced the stratification and increased the gradient; warm water inflow moderated the stratification and generally warmed the lake. There was no indication of severe bottom sediment movement in the lake but there was circulation along the north and west shores that could disturb the bottom material.

This configuration had only minor influence on temperatures and stratification in the lower lake. Most of the effect was noted in the vicinity of the channel between the two lakes. When colored water was used for the generating flow a small quantity of the colored water entered the lower lake, most of which flowed back into the upper lake during the pumping cycle.

In summary, the angled channel into the lower lake will provide satisfactory flow conditions, minor bottom disturbance, small changes to the natural stratification patterns, and a warming or cooling trend in the ambient lake temperature, depending on the temperature of the inflowing water.

A long channel into the upper lake provided conditions that left the lower lake virtually unchanged but did make significant changes in the stratification and temperatures in the upper lake.