Understanding reservoir temperature dynamics with distributed temperature sensing and modeling at Shasta Lake, California

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INTRODUCTION

Stress on California's salmon fisheries as a result of recent drought drives a need for effective temperature management in California's Sacramento River. Cool temperatures downstream of Shasta Dam are required for Chinook salmon spawning and rearing. To acquire a more complete understanding of the thermal resources available to water managers, distributed temperature sensing (DTS) technology has been used at Shasta Lake in a pilot deployment from August 2015 to the present.

BACKGROUND

Field Site – Shasta Lake, California

- Shasta Dam was constructed in 1945 by United States Bureau of Reclamation (USBR) on the Sacramento River in California (Figure 1).
  - Dam construction blocked access to native spawning habitat with cold water temperatures
  - Warm temperatures below the dam impact salmon spawning and rearing downstream (Bartholow et al. 2001)
  - Winter-run Chinook salmon are considered endangered under the Endangered Species Act (ESA; NMFS 2009).
  - Central Valley Regional Water Quality Control Board adopted a late summer/fall discharge temperature objective of 13.3°C (56°F)
  - Recent drought emphasizes the need for efficient temperature management to maintain endangered species populations

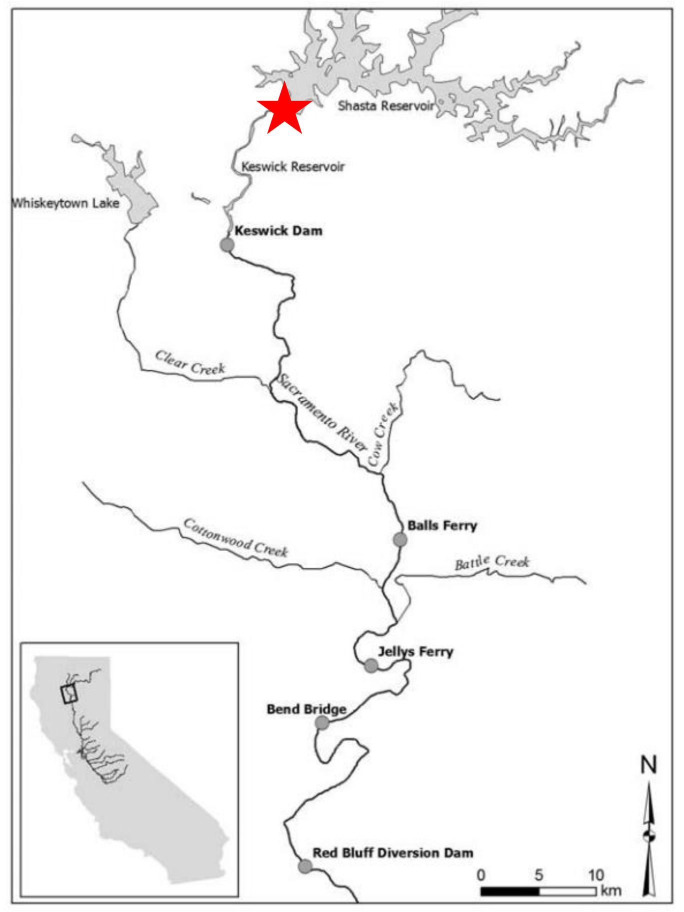

Figure 1: Field site marked with a red star along the Sacramento River, California. (Danner et al. 2012)

Temperature Mitigations at Shasta

- A temperature control device (TCD) was installed in 1997 to restore and sustain downstream thermal habitat for salmon spawning
  - TCD enables intake of water at four depths
  - Five gates exist laterally at each depth
  - TCD allows for temperature management based on thermal structure of reservoir

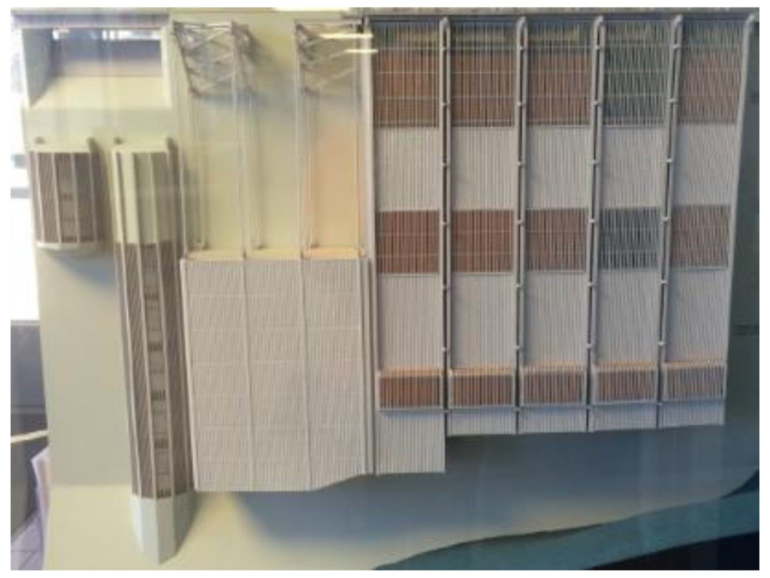

Figure 2: Model of the TCD on the upstream side of the dam

OBJECTIVES

- Understand thermal resources within Shasta Lake year round for Chinook salmon spawning and rearing
- Evaluate thermal hydrodynamics of water flowing from the reservoir through dam intakes and discharging through penstocks
- Understand influence of dam operations on thermal structure and the reservoir's cold pool storage directly upstream of the dam

METHODS

Distributed Temperature Sensing Technology (Hausner et al. 2011)

- DTS allows for high resolution temperature data along fiber optic cable
  - Temperature resolution up to 0.05°C
- Laser pulses are sent down the cable with a known speed of light
- Raman backscatter, a result of molecular vibrations, is measured and used as a proxy for temperature:

$$T(z) = \frac{\gamma}{\ln\frac{P_S(z)}{P_{aS}(z)} + C - \Delta\alpha z}$$

Where:

- γ, C, and $\Delta\alpha$ are calibration parameters
- $P_S(z)$ and $P_{aS}(z)$ are the power of Stokes and anti-Stokes backscatter frequencies
- z is the distance along the cable

Previous DTS Applications in Hydrologic Systems

- Antarctic ice shelf stability (Kobs et al. 2014)
- Convective mixing in Devil's Hole in Death Valley, California (Hausner et al. 2012)
- Heat generation in salt-gradient solar ponds (Suarez et al. 2014)
- Stream dynamics (Selker et al. 2006)

Current Pilot Deployment at Shasta

- DTS system installed just upstream of Shasta Dam (Figure 3)
- DTS instrument is located inside Shasta dam
- Cable extends from the instrument down the side of the TCD to the water (Figure 4)
- Fiber optic cable is 3/8" diameter with an outer shield of stainless steel braid
  - Tensile strength is ~1000lbs
  - Cable was secured to a buoy line to account for fluctuating reservoir levels
- Measurements recorded every 12.5 cm of cable
- Temperature resolution is 0.05°C
- Measurements along entire cable are taken every ¼ hour

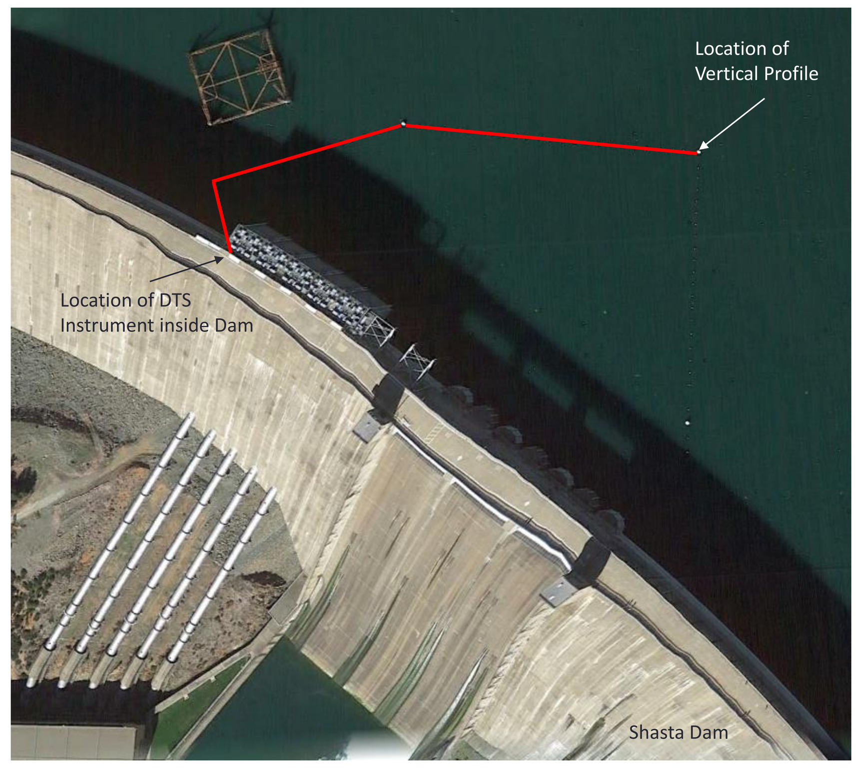

Figure 3: Plan view of cable deployment at Shasta Lake. Red line indicates path of cable.

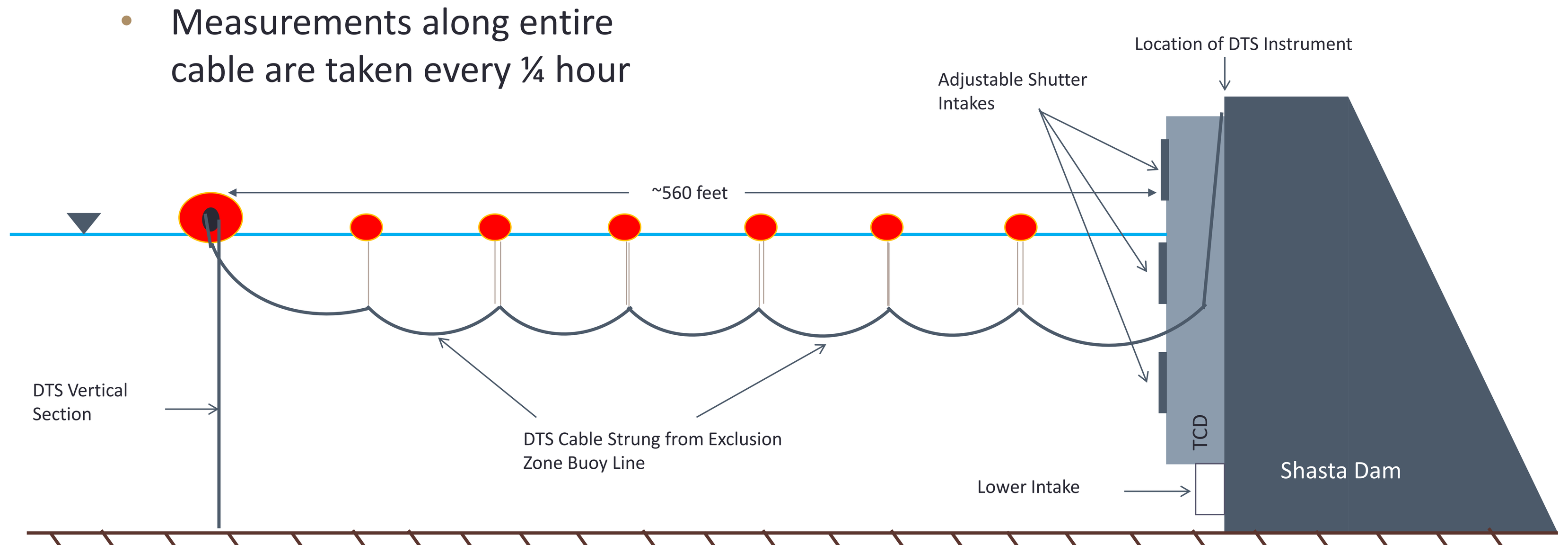

Figure 4: Schematic of DTS cable from a side view of the dam (not to scale). The DTS instrument is located just inside the dam at the top of the TCD. The cable extends from the device, outside and down the west side of the TCD to the water. It then follows along the exclusion zone buoy line (orange circles) and down from the water surface to through the vertical water profile.

PRELIMINARY DATA

DTS Data Obtained

- Since the deployment in August 2015, DTS has successfully captured the shift in thermal structure of the reservoir (Figure 5)
  - August through September show sharp thermal stratification
  - September through November show a weakening of stratification and decline of the reservoir's thermocline
  - November to December show fall mixing and loss of stratification
  - Late December through March show isothermal conditions

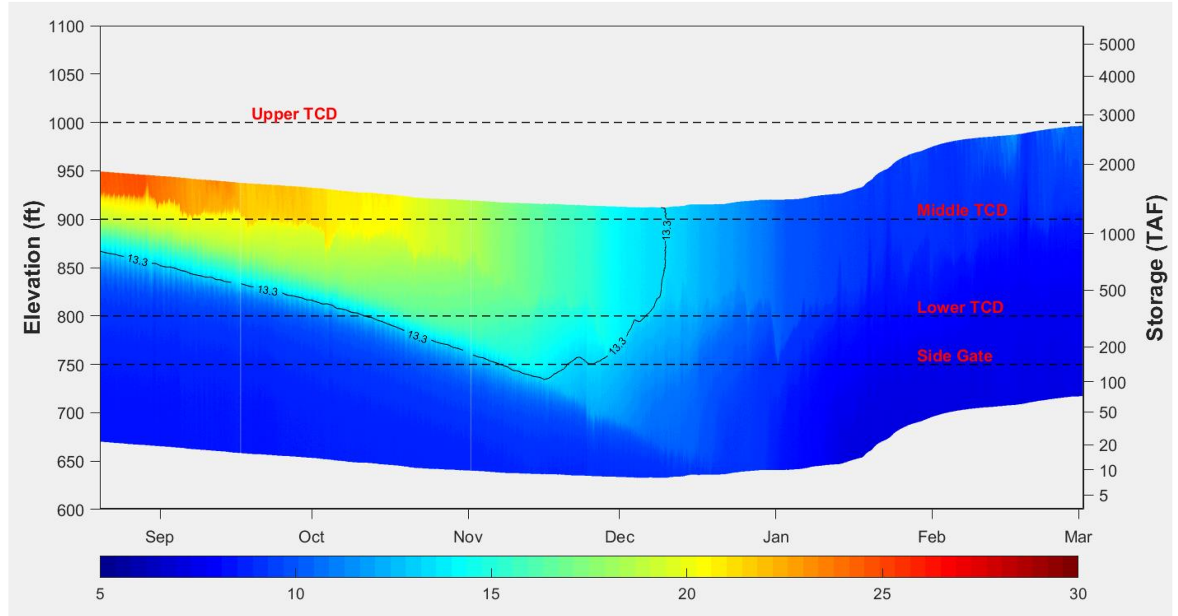

Figure 5: Temperature data obtained from DTS pilot installation at Shasta from August 19th, 2015 through March, 2016 (adjusted for reservoir elevation). Critical temperature of 13.3°C is shown in black. A fixed length of cable is plotted, so the water surface and the bottom of the plot move up and down as the reservoir water surface rises and falls.

FUTURE WORK

- Use high resolution data from DTS to calibrate and build a computational fluid dynamics (CFD) model of the TCD intakes
  - CFD model will be built using modeling software *Fluent* by ANSYS
- Use CFD model to examine changes in reservoir dynamics as a result of dam release operations
  - Examine lateral mixing within TCD based on the lateral position of open gates at each level
- Use model in a predictive mode to help inform reservoir operations for effective temperature release for salmon spawning and rearing downstream

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REFERENCES

Bartholow, J.; Hanna, R., and Saito, L. 2001. Simulated Limnological effects of the Shasta Lake temperature control device. *Environmental Management* (27) 609-626.

Danner, E. M., Melton F. S., Pike, A., Hashimoto H., Michaelis, A., Rajagopalan, B., Caldwell, J., DeWitt, L., Lindley, S., and Nemani, R. 2012. River temperature forecasting: a coupled-modeling framework for management of river habitat. *IEEE Journal of Selected Topics in AppliedEarth Observations and Remote Sensing*, 5(6) 1752-1760.

Hausner, M. B., Suárez, F., Glander, K. E., van de Giesen, N., Selker, J. S., Tyler, S. W. 2011. Calibrating Single-Ended Fiber-Optic Raman Spectra Distributed Temperature Sensing Data. *Sensors* (11) 10859-10879.

Hausner MB, Wilson KP, Gaines DB, Tyler SW. 2012. Interpreting seasonal convective mixing in Devils Hole, Death Valley National Park, from temperature profiles observed by fiber-optic distributed temperature sensing. *Water Resour. Res.,* (48) W05513.

Kobs S, Holland DM, Zagorodnov V, Stern A, Tyler SW. 2014. Novel monitoring of Antarctic ice shelf basal melting using a fiber-optic distributed temperature sensing mooring. *Geophysical Research Letters* 41(19) 6779-6786.

NMFS, National Marine Fisheries Service, 2009. Biological Opinion and Conference Opinion on the Long Term Operations of the Central Valley Project and State Water Project, National Marine Fisheries Service.

Selker, J. S., L. Thevenaz, H. Huwald, A. Mallet, W. Luxemburg, N. Van de Giesen, M. Stejskal, J. Zeman, M. Westhoff, and M. B. Parlange 2006. Distributed fiber-optic temperature sensing for hydrologic systems, *Water Resour. Res.*, (42) W12202.

Selker, J., Van de Giesen, N., Westhoff, M., Luxemburg, W., and Parlange, M. B., 2006. Fiber Optics Opens Window on Stream Dynamics, *Geophys. Res. Lett.* (33) L24001.

Suarez F; Ruskowitz JA, Childress AE, Tyler SW. 2014. Understanding the expected performance of large-scale solar ponds from laboratory-scale observations and numerical modeling. *Applied Energy* (117) 1-10.