Model Development and Estimation of Short-Term Impacts of Dam Removal on Dissolved Oxygen in the Klamath River

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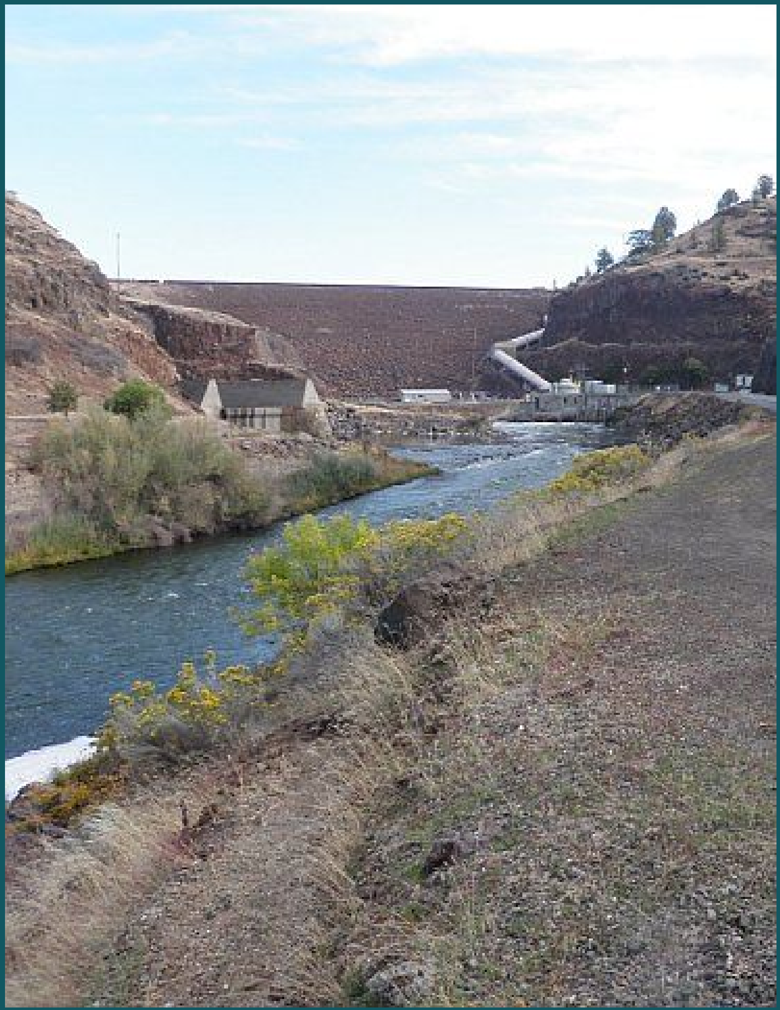
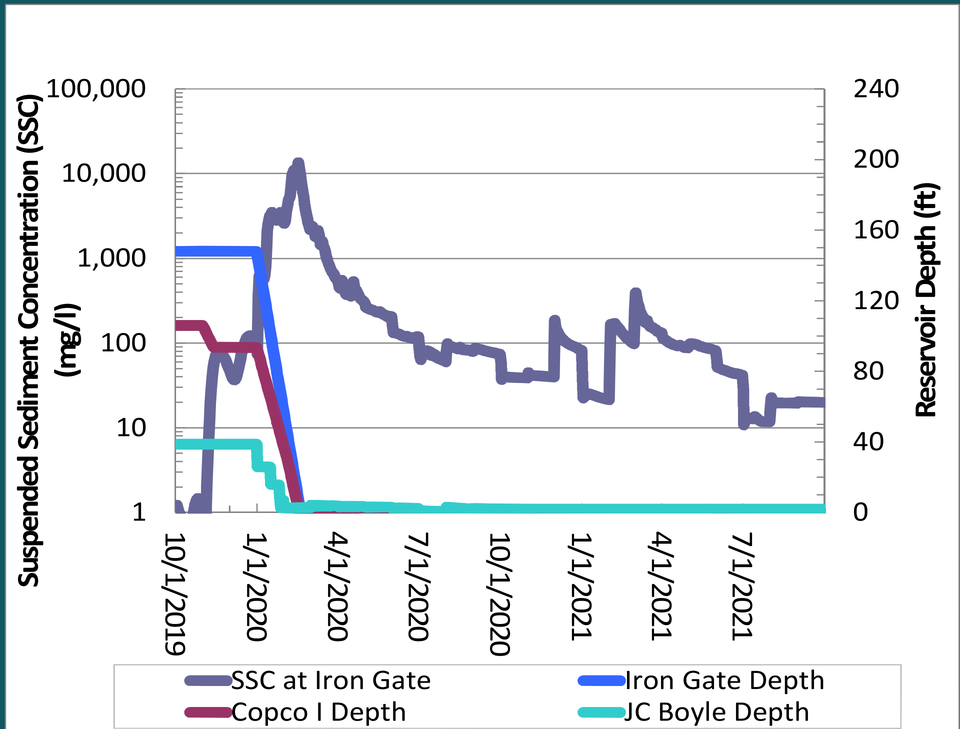
STUDY PURPOSE

Evaluate potential influences of suspended sediment concentrations upon dissolved oxygen levels in the Klamath River following the proposed dam removal at J.C. Boyle, Copco 1 and 2, and Iron Gate Reservoirs.



BACKGROUND

- High organic content of sediment deposits (Shannon & Wilson Inc. 2006, GEC 2006)
- High suspended sediments (7,000–14,000 mg/L) anticipated for first 2–3 months following reservoir drawdown (USBR 2011)



USBR 2011

APPROACH

- Develop a 1-D reach-scale model using modified Streeter-Phelps DO sag to predict corresponding dissolved oxygen levels in the river, based upon:
  - suspended sediments during and after reservoir drawdown
  - channel geometry
  - tributary inflows
- Employ direct sampling for empirical determination of oxygen-demand characteristics of reservoir sediment deposits.

KEY ASSUMPTIONS

- Concurrent removal of four dams
- 85-90% (6.3-11.2 mg/L) DO saturation needed for fish (CA objectives)
- 5.5-11 mg/L DO needed for aquatic life (OR objectives)

Photo courtesy of USBR

1-D REACH-SCALE MODELING

- Formulation of modified Streeter-Phelps:

$$\frac{dO}{dt} = k_a\left(O_{sat} - O\right) + \frac{dIOD}{dt} + \frac{dBOD}{dt} - k_b/d$$

O	= Dissolved oxygen concentration (mg/L);
O_{sat}	= Saturated concentration of dissolved oxygen (mg/L)
IOD	= Concentration of ultimate initial oxygen demand (mg/L);
BOD	= Concentration of ultimate biological oxygen demand (mg/L);
k_a	= Stream reaeration rate (d^{-1});
k_b	= Bed sediment oxygen demand ($g\text{-}O_2/m^2\text{-}d$);
d	= Average flow depth (m); and
t	= Time (d)

1-D REACH SCALE-MODELING

- IOD - 1st order, rapid chemical reaction of iron and manganese sulfides, with decay constant k_i
- BOD - 1st order, biological reaction, typically exerted more slowly with decay constant k_d

$$\frac{dIOD}{dt} = -k_i IOD \qquad \frac{dBOD}{dt} = -k_d BOD - k_s BOD$$

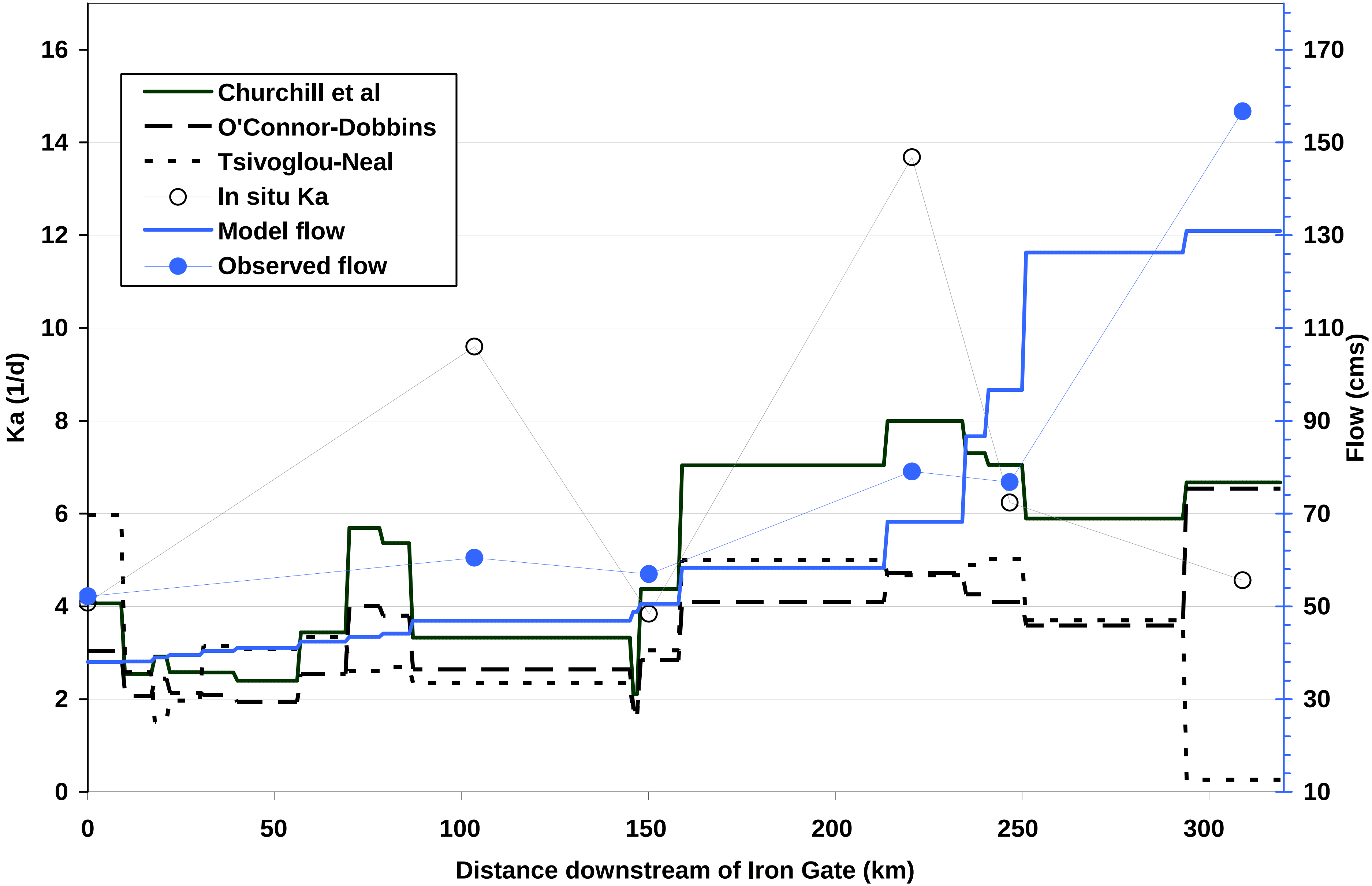
⬇

$$\frac{dO}{dt} = k_a\left(O_{sat} - O\right) - k_i IOD - k_d BOD - k_s BOD - k_b / d$$

MODEL PARAMETER ESTIMATION

- Stream re-aeration rate (k_a) based on reach-specific comparisons of
  - O'Connor and Dobbins (1958) $k_a = 5.026 \frac{U}{H^{1.67}}$
  - Churchill et al. (1962) $k_a = 3.93 \frac{U^{0.5}}{H^{1.5}}$
  - Tsivoglou and Neal (1976) $k_a = k' \frac{\Delta H}{\Delta X} U$
  - *In situ* summer measurements by Ward and Armstrong (2010)
- Empirical rate estimates typically under predicted *in situ* re-aeration

Comparisons of Churchill et al. 1962, O'Connor and Dobbins 1958, and Tsivoglou and Neal 1976 reaeration models estimated using July 2001 observed flows and compared with July 2001 *in situ* estimates by Ward and Armstrong (2010)



MODEL PARAMETER ESTIMATION

- Oxygen saturation (O_{sat}) using Duke and Masch (1973)

$$O_{sat} = \left(14.652 - 0.3898\ T + 0.006969\ T^2 - 5.897 \cdot 10^{-5} T^3\right) \times \left(1 - 6.97 \cdot 10^{-6} E\right)^{5.167}$$

- Sediment oxygen demand rate (k_d) estimates based on laboratory experiments 0.5–2.0 g-O_2/m^2-d (Thomann 1972) and *in situ* Klamath River measurements 0.6 g-O_2/m^2-d (Ward and Armstrong 2010)

MODEL PARAMETER ESTIMATION

- Temperature adjustments to rate constants using Arrhenius relationship

$$k(T) = k_{20C}\,\theta^{T-20}$$

- Oxygen-demand initial values and rates (IOD, BOD, k_i, and k_d) empirically determined for reservoir sediment deposits

PHASE I SAMPLING - NOVEMBER 2009

Photos courtesy of USBR

PHASE I LABORATORY ANALYSES

- DO depletion tests with sediment sub-samples (BOD_5, $CBOD_5$, BOD_{30})
- Native water
- Mass additions (0.5, 2, and 8 g) in 300 mL BOD bottle
- Temperatures: 4 and 20 °C

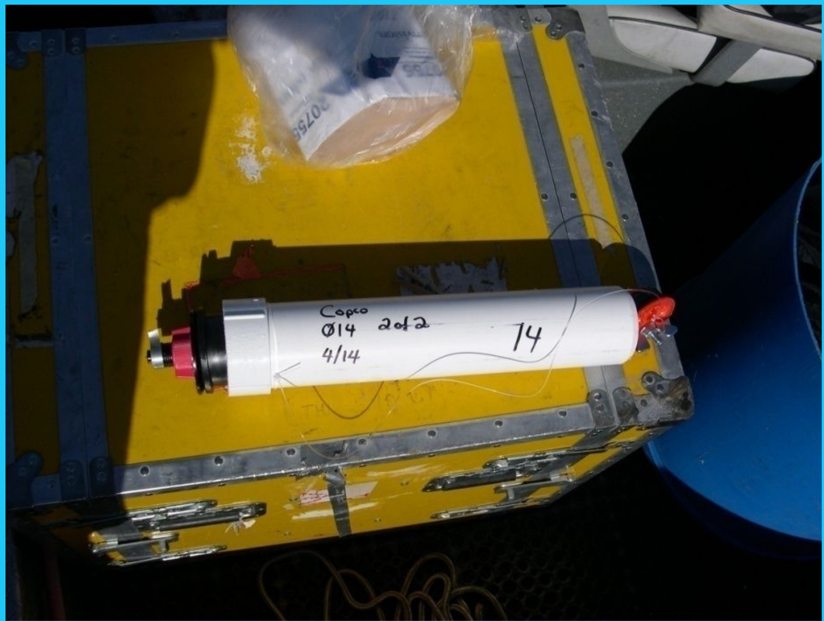
Photo courtesy of USBR

PHASE II SAMPLING – APRIL 2010

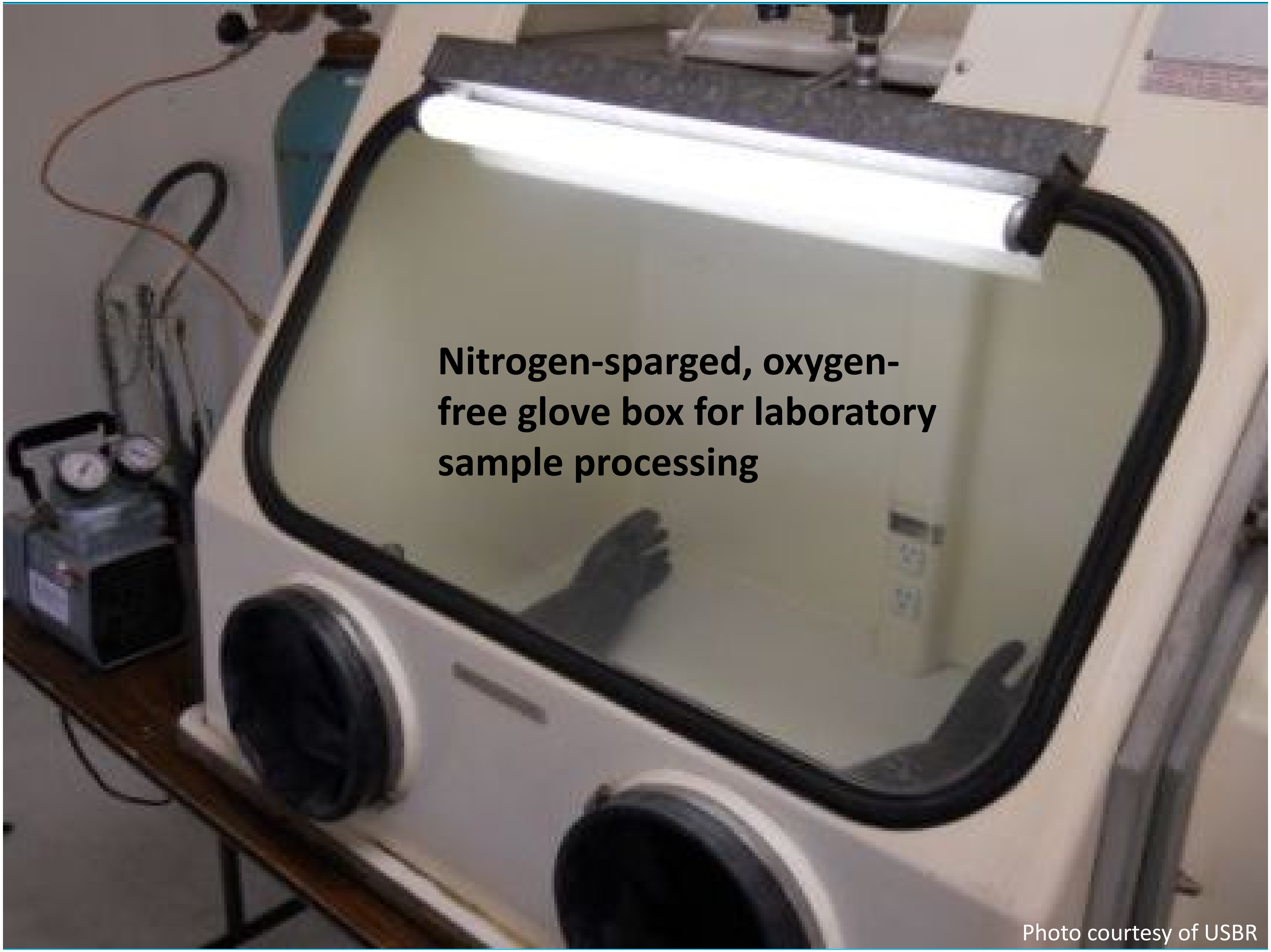
- Capitalize on diver inspections of dam structures to collect additional samples
- Refined sample handling to prevent oxidation of sediments and allow evaluation of IOD that may have been missed during Phase I
- Divers with 3” push tubes capped at depth to prevent oxidation

Photo courtesy of USBR

PHASE II SAMPLING – APRIL 2010



Photos courtesy of USBR

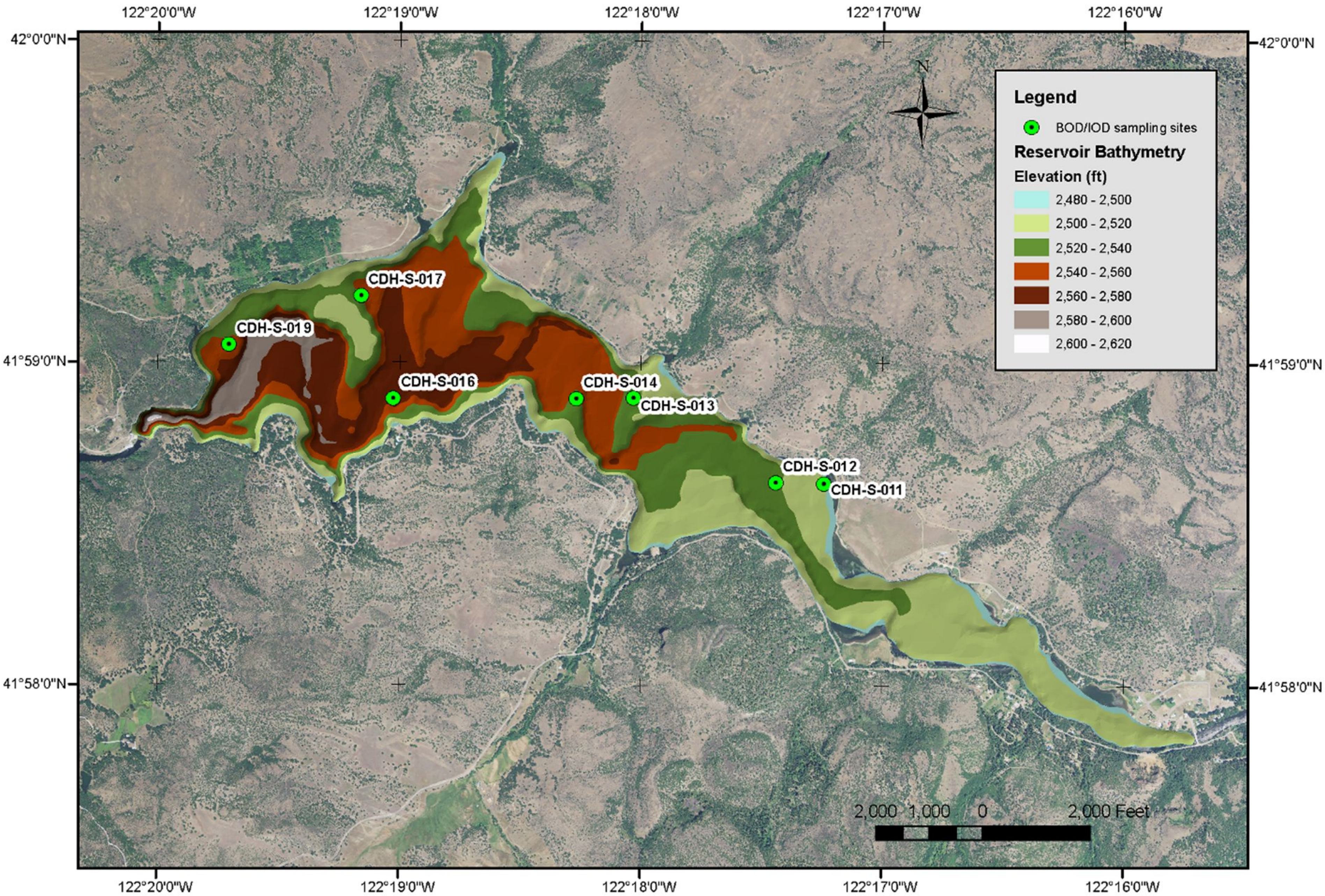

Nitrogen-sparged, oxygen-free glove box for laboratory sample processing
Photo courtesy of USBR

PHASE II - LABORATORY ANALYSES

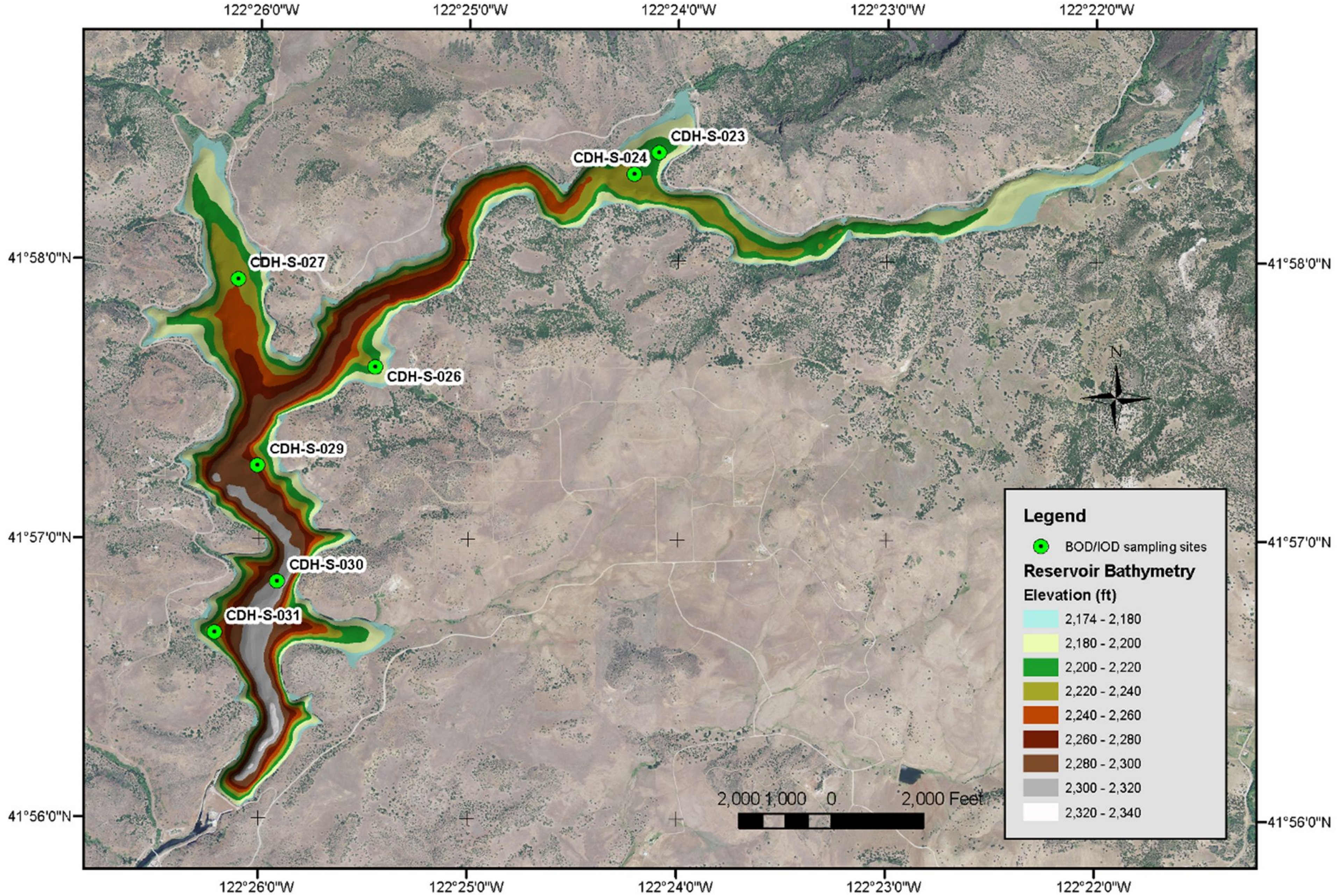
- DO depletion tests with sediment sub-samples (IOD [3-hr])
- Same conditions as 2009, but O_2-free conditions (i.e., source water, 0.5, 2, and 8 g sample mass, 300 mL BOD bottle, 4 and 20 °C)

Photos courtesy of USBR

COPCO 1 RESERVOIR 2009-2010 SAMPLING LOCATIONS



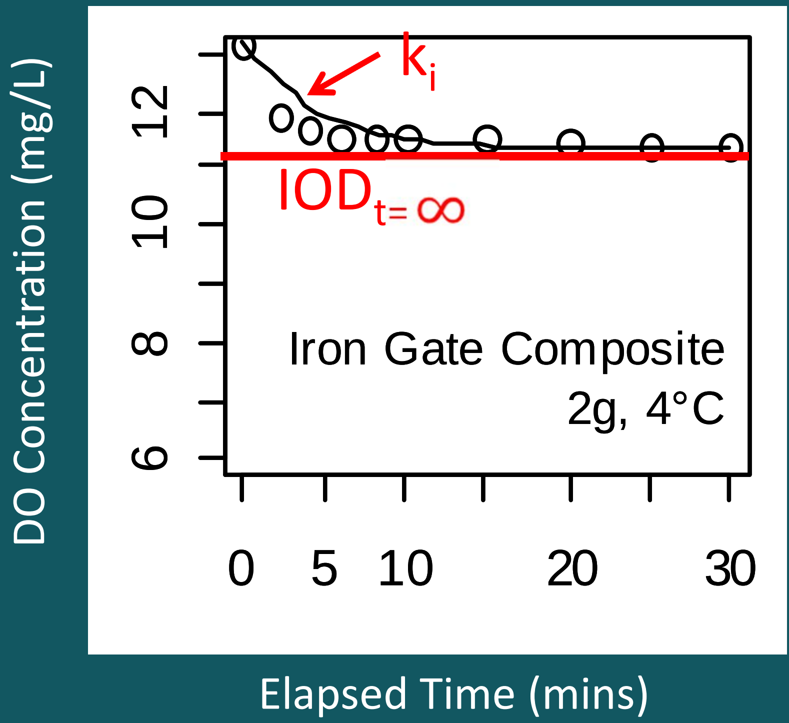
IRON GATE RESERVOIR 2009-2010 SAMPLING LOCATIONS

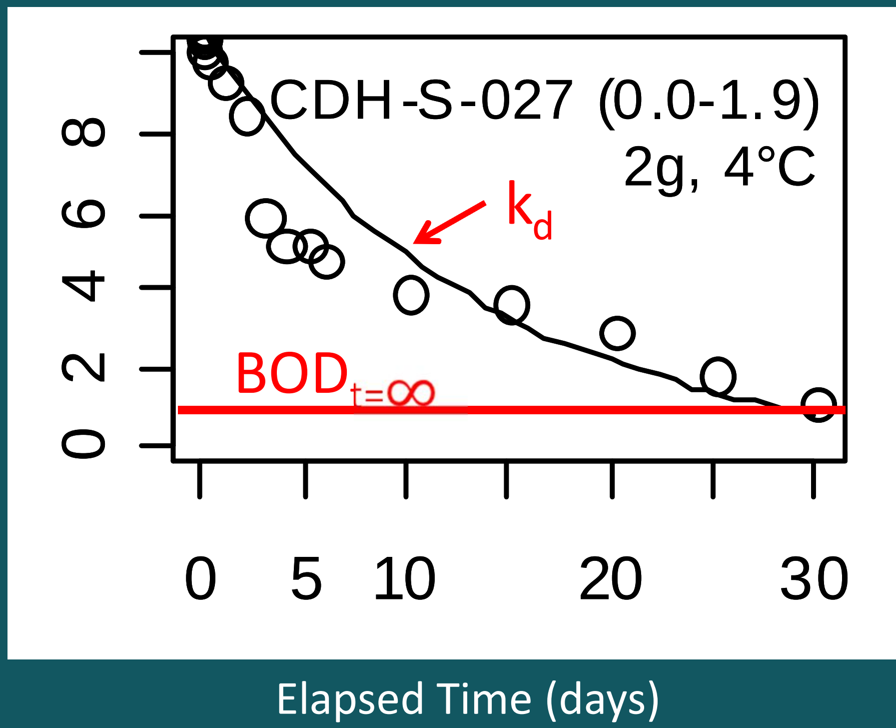


ANALYSIS

Oxygen demand estimates from sediment core samples:

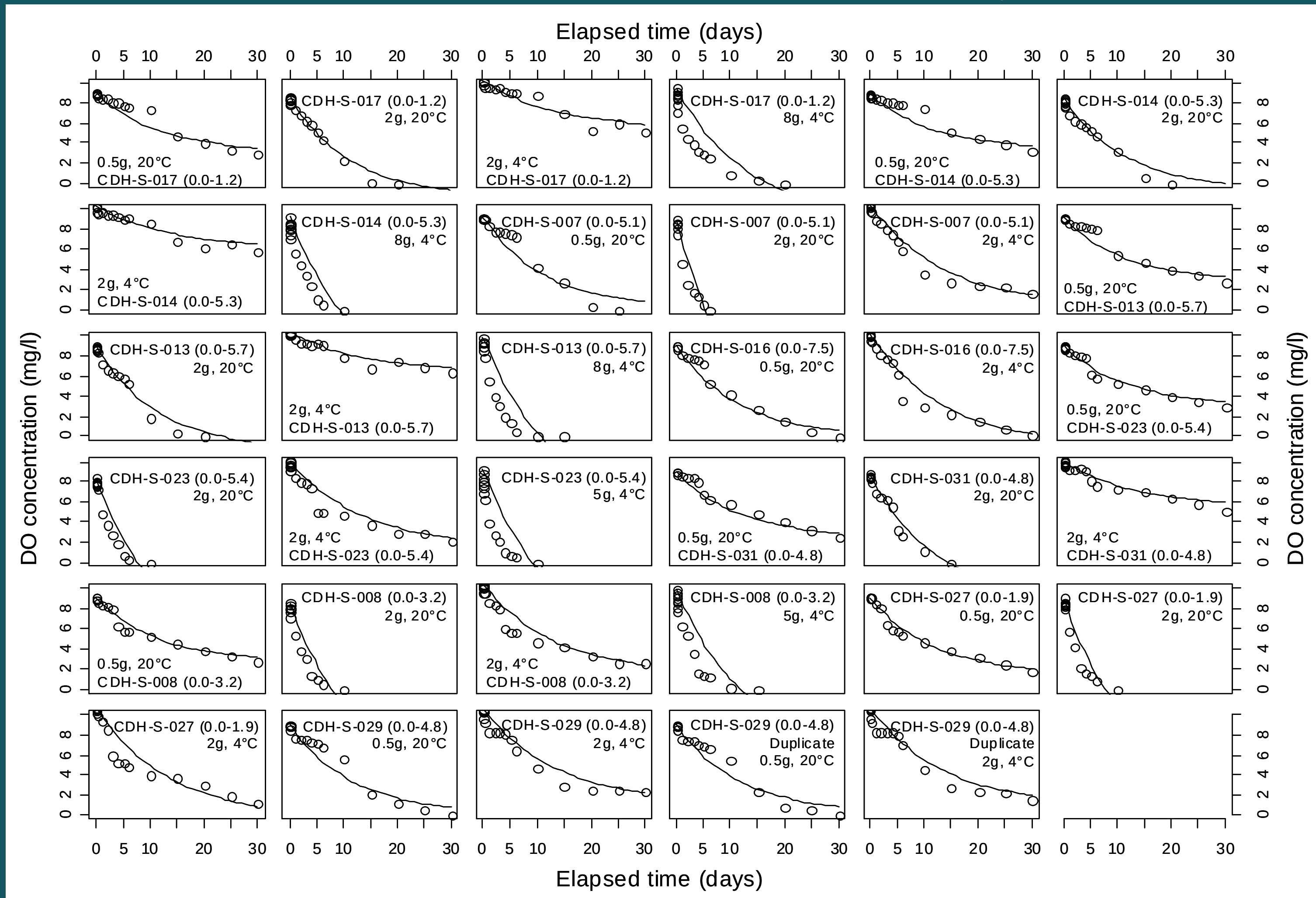
$$OD = OD_{t=\infty}\left(1 - e^{-k(t-t_0)}\right)$$





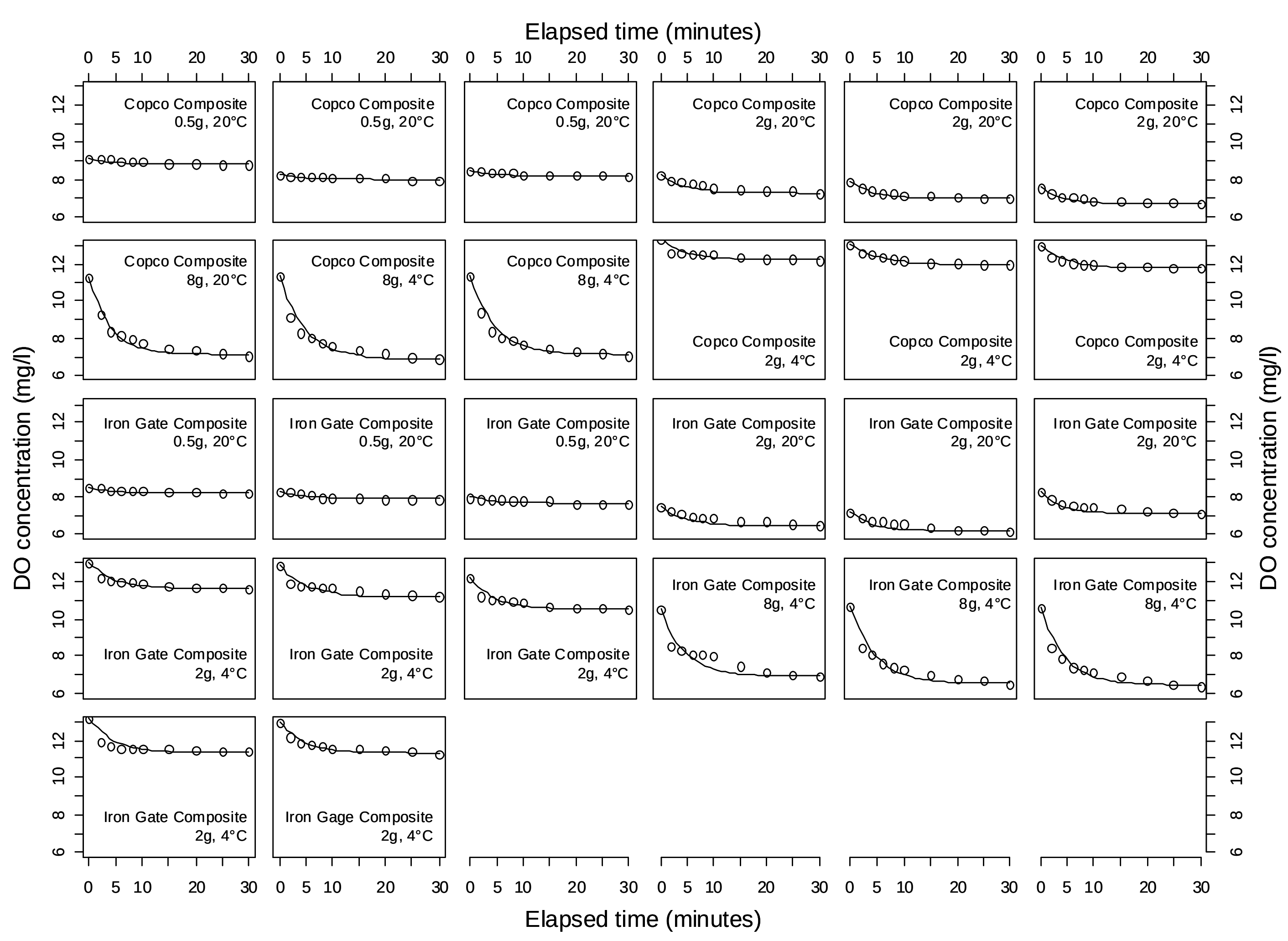
ANALYSIS

2009 Biochemical oxygen demand (BOD) rate (k_d) and ODu/SSC



ANALYSIS

2010 Initial oxygen demand (IOD) rate (k_i) and ODu/SSC

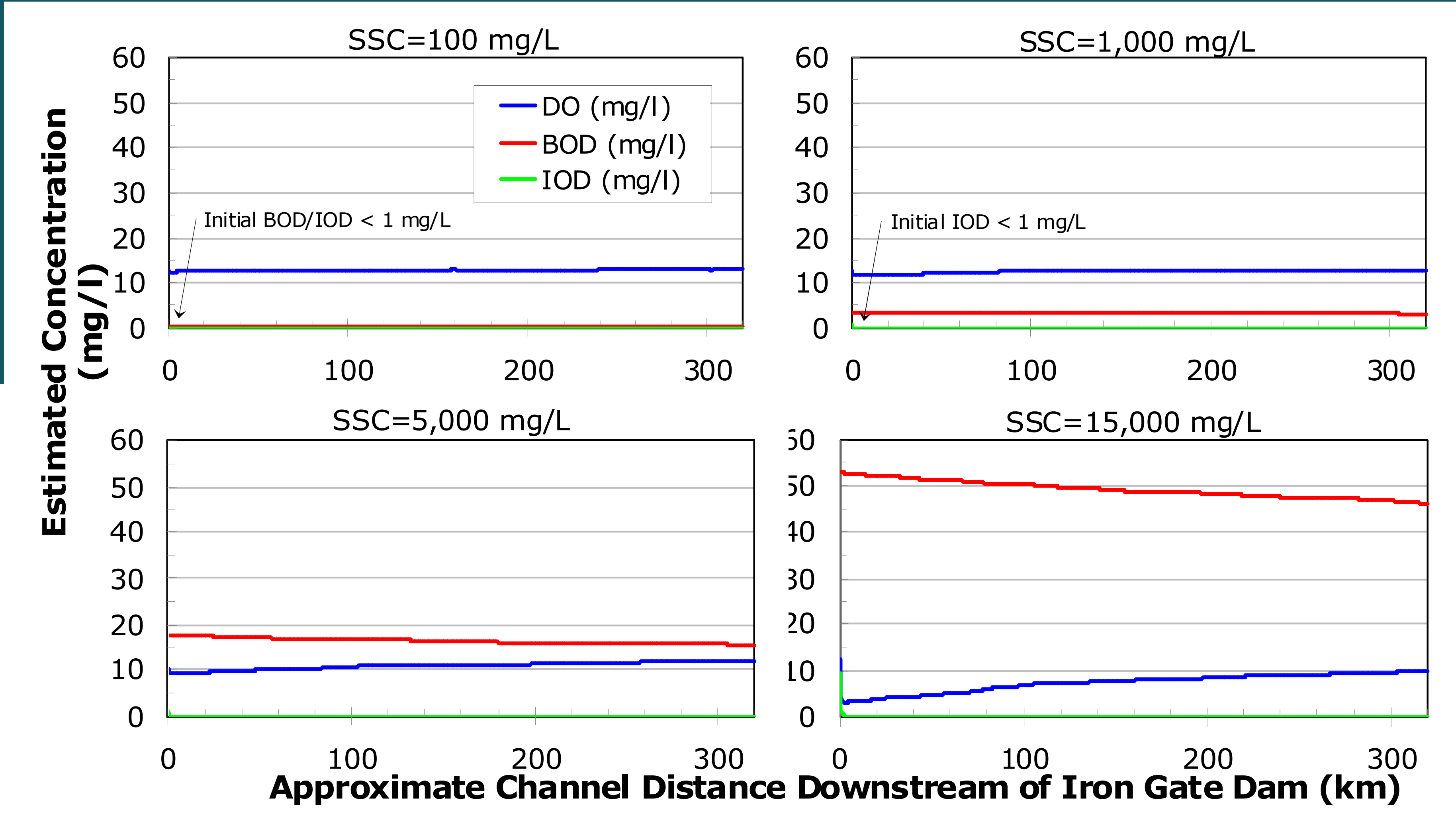


RESULTS

Oxygen Demand Component	Reservoir	Year	Fitted 1st Order Rate Constant (k_i, k_d) at 20°C		Fitted Temperature Coefficient θ	Average Oxygen Demand ODu/SSC	
			d^{-1} (95% CI)		exp(1/°C)	mg-O/mg-dry-wt (95% CI)	
IOD	Iron Gate	2010	353	(339–367)	1.01	6.27×10^{-4}	(6.06×10^{-4}–6.48×10^{-4})
	Copco 1	2010	384	(368–399)	1.01	6.35×10^{-4}	(6.28×10^{-4}–6.43×10^{-4})
	Combined	2010	368	(361–375)	1.01	6.31×10^{-4}	6.23×10^{-4}–6.38×10^{-4})
BOD	Iron Gate	2009	0.097	(0.090–0.104)	1.01	3.62×10^{-3}	(2.81×10^{-4}–4.44×10^{-4})
	Copco 1	2009	0.080	(0.073–0.086)	1.01	3.47×10^{-3}	(3.06×10^{-4}–3.87×10^{-4})
	Combined	2009	0.088	(0.086–0.091)	1.01	3.52×10^{-3}	(3.32×10^{-3}–3.72×10^{-3})

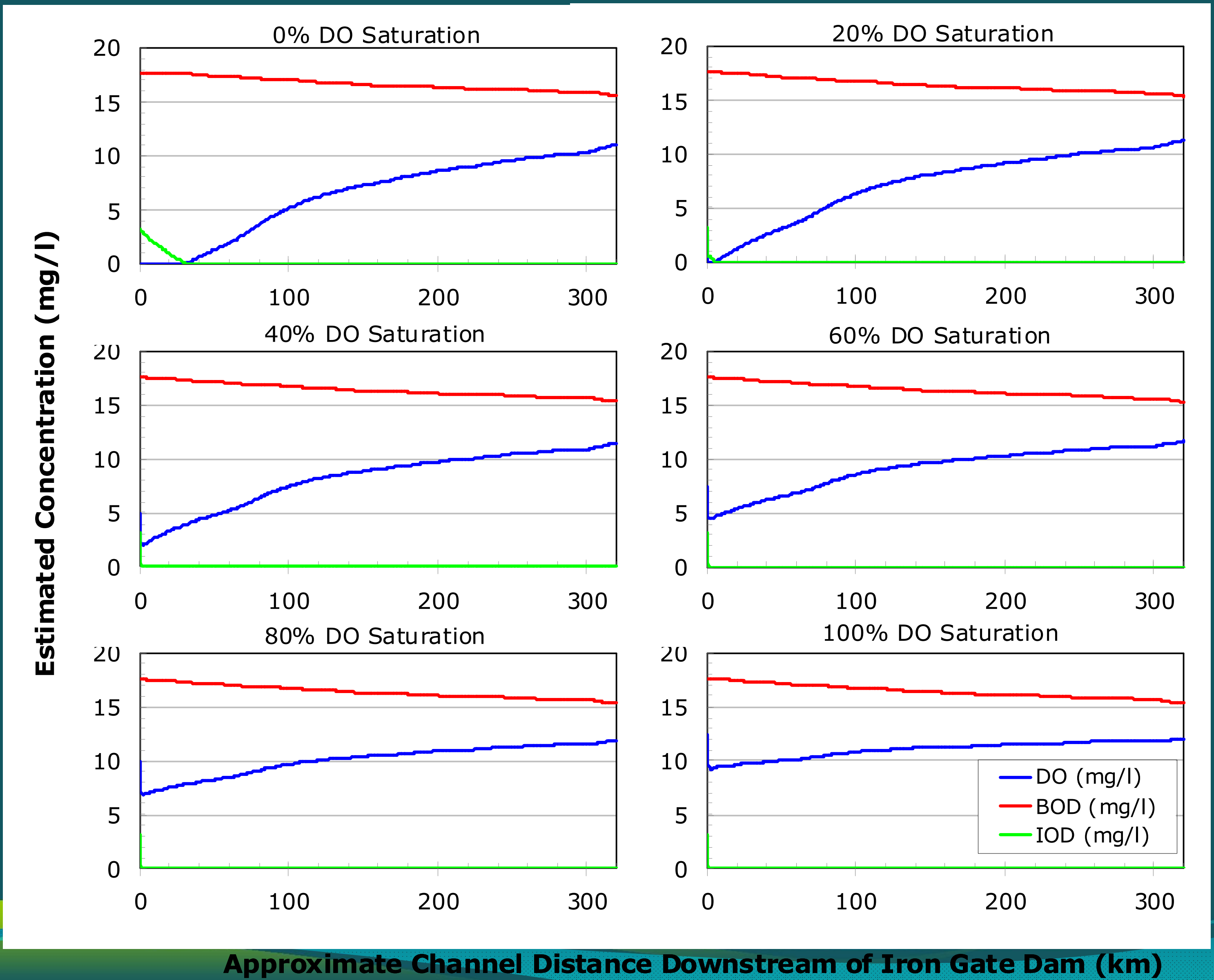
RESULTS – MODEL SENSITIVITY RUNS

Vary SSC while other parameters remain the same.



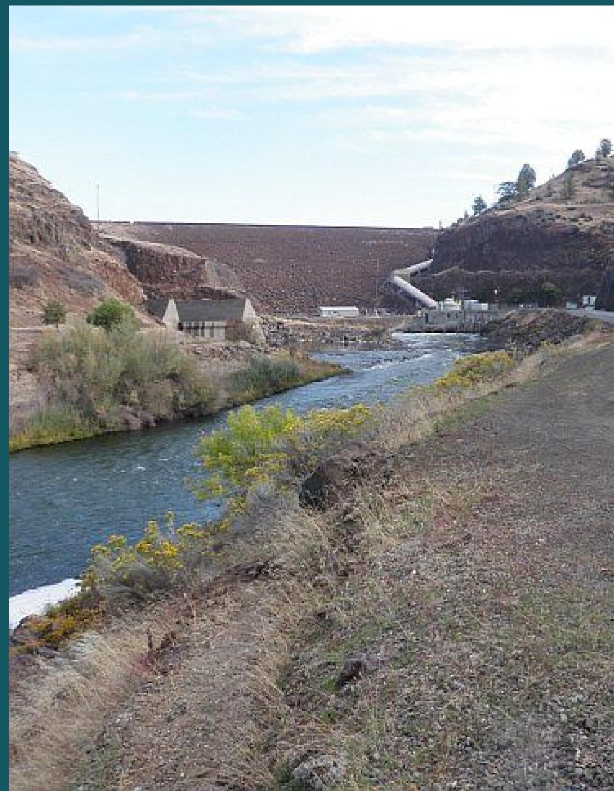
RESULTS – MODEL SENSITIVITY RUNS

Vary initial DO while other parameters remain the same.



DRAWDOWN SCENARIOS

- Multiple drawdown scenarios considered as alternatives were developed for EIS/EIR analyses.
  - Impacts to water quality and aquatic species
  - Feasibility and foregone power

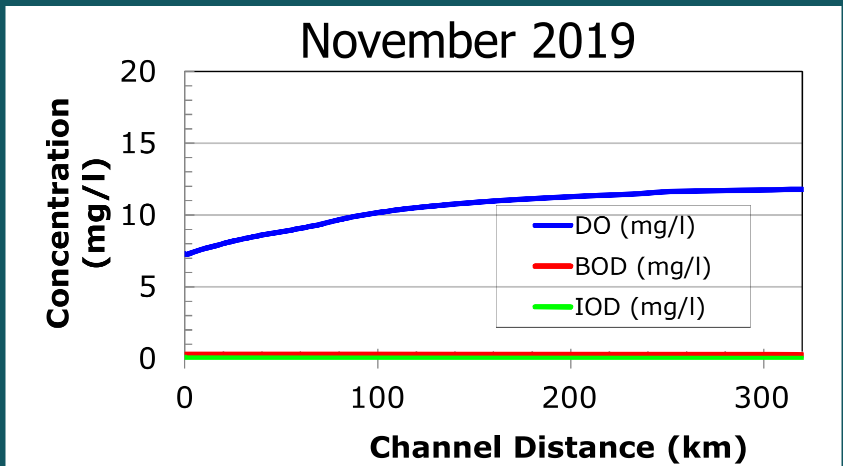


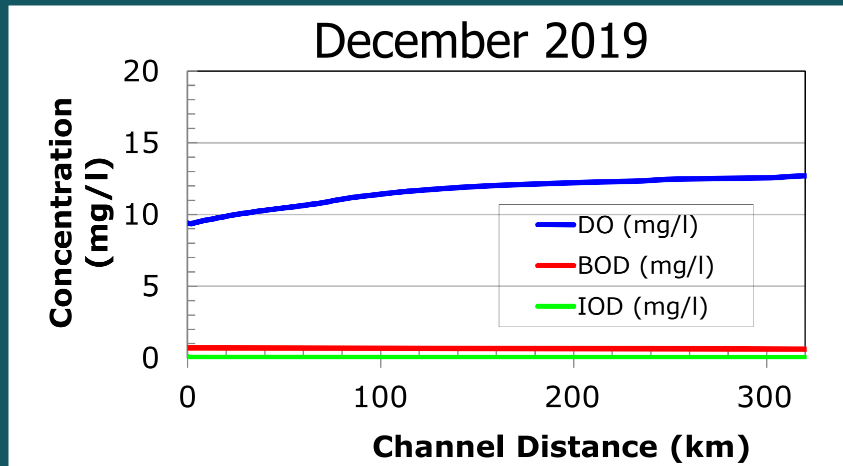
- Scenario 8: 2-phase drawdown for Copco 1 beginning November 2019, single-phase drawdown for J.C. Boyle and Iron Gate reservoirs beginning January 2020.

DRAWDOWN SCENARIOS

- Scenario 8 background DO = 80% saturation (PacifiCorp 2009)
- IOD = 0–8.6 mg/L and BOD = 0.3–43.8 mg/L for all water year types and six months following drawdown.

Scenario 8
Median Hydrology WY1976





DRAWDOWN SCENARIOS

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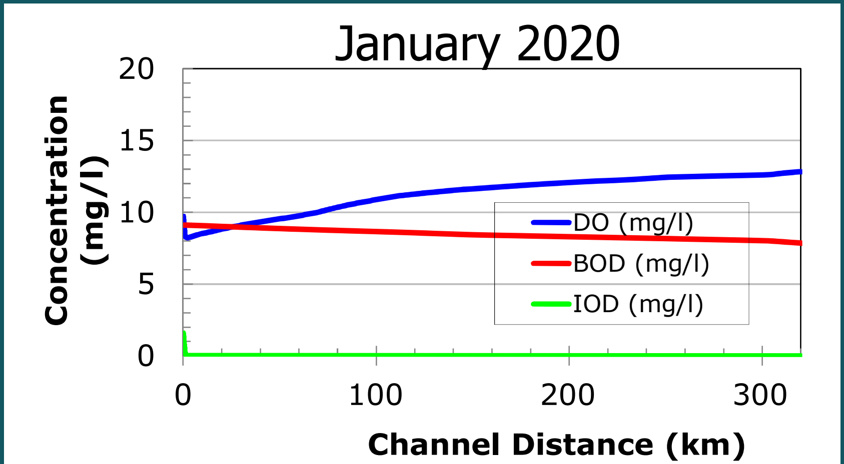

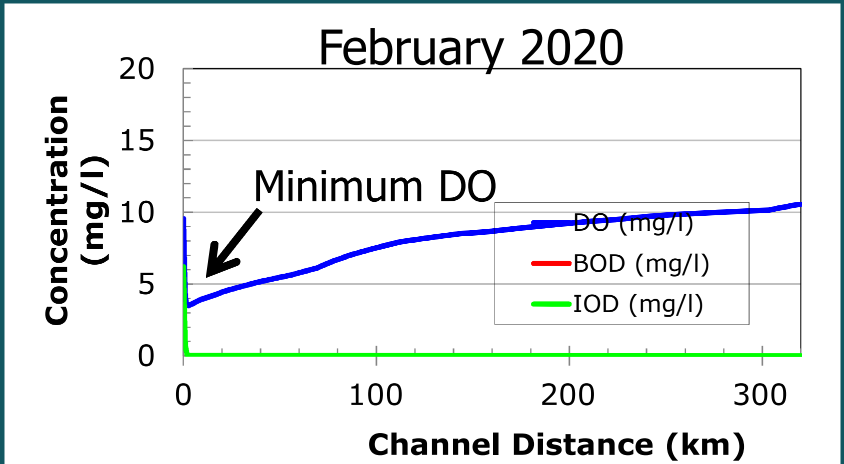

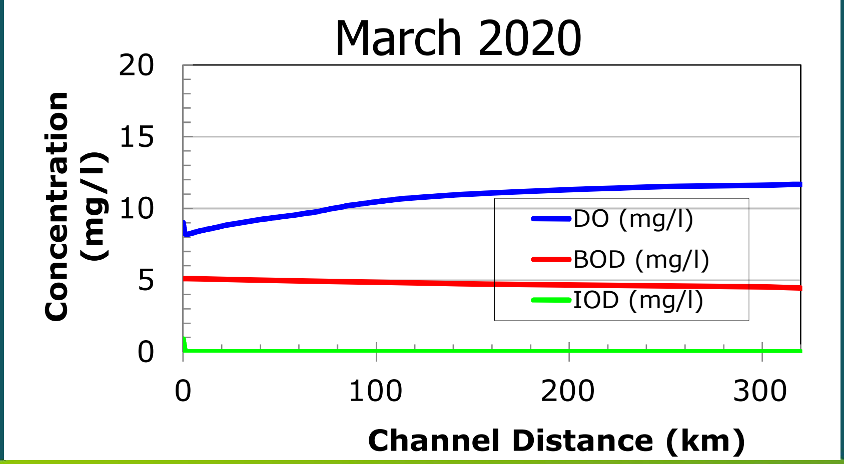

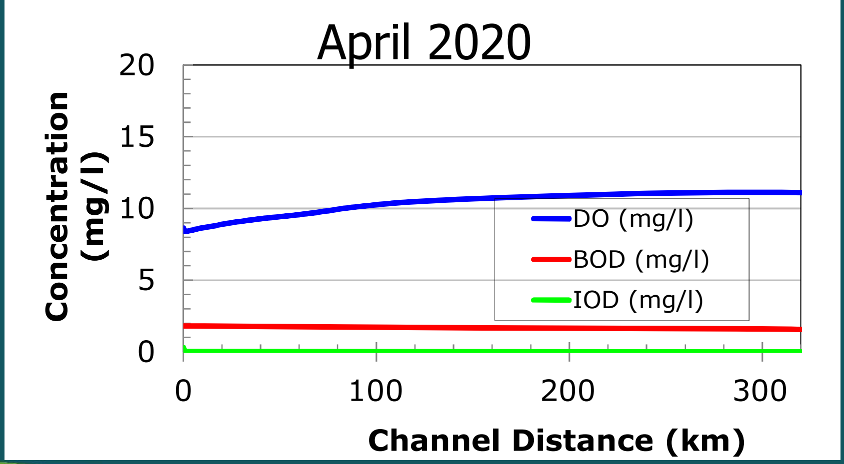

CONCLUSIONS

- Interpretation of results +/- 10 km.
- Hypoxia could occur several river miles downstream of the dams in the initial days and weeks following drawdown.
- Short-term DO levels most strongly affected by background DO, SSC, and water temperature.
- Tributary dilution and channel reaeration are primary mechanisms for increasing downstream DO.
- Short-term impacts to biota from low DO should be considered within the context of corresponding elevated SSC.
- Additional dam removal alternatives may yet be developed and additional studies would be undertaken if the Secretarial Determination is affirmative.

ACKNOWLEDGEMENTS

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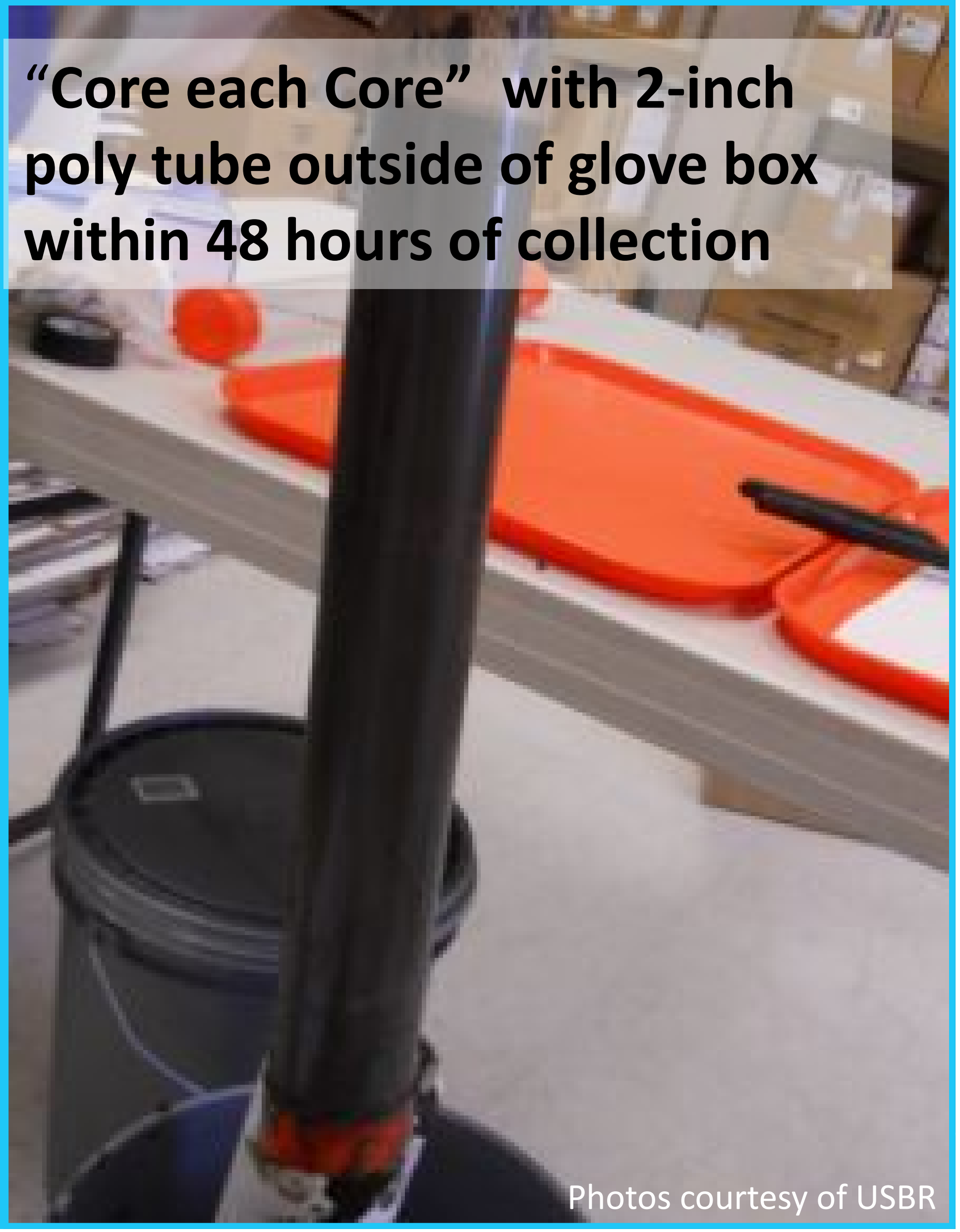
- Independent third party referee for peer review: Atkins North America Inc.
- Courtesy reviews: scientists at PacifiCorp, the Yurok Tribe, and the Center for Research in Water Resources Engineering at the University of Texas at Austin

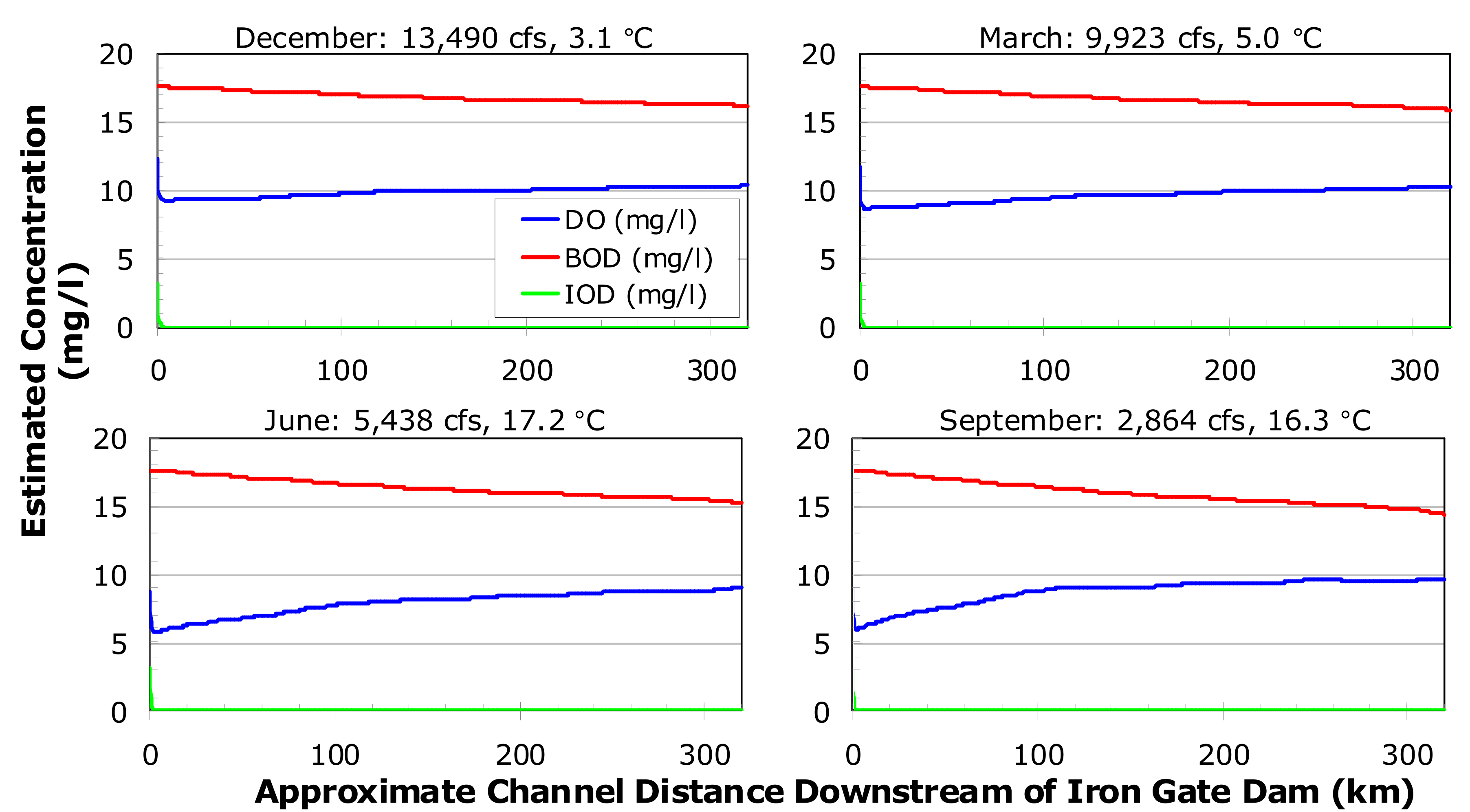
PHASE II - LABORATORY ANALYSES



Photos courtesy of USBR

RESULTS – BASE CASE

5,000 mg/L SSC for December, March, June, and September reservoir drawdown dates for Typical Wet Hydrology (WY 1984).



RESULTS – MODEL SENSITIVITY RUNS

Vary water temperature while other parameters remain the same.