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# Memorandum

***To:*** Matt Jaeger, Montana Fish, Wildlife & Parks

***From:*** Kyle Flynn, KF2 Consulting, PLCC

***Copy:*** Kyle Cutting and Jeff Warren, U.S. Fish & Wildlife Service

***Date:*** September 23, 2020

***Subject:*** Literature review on the efficacy of routing surface water in pipelines to improve winter oxygen habitat condition

This memo has been prepared to document available literature on the efficacy and consequences of rerouting surface water inflows into frozen or otherwise oxygen deficient lakes using pipelines for the purpose of improving fish habitat or lake dissolved oxygen (DO) concentration. It also describes the application of a simplistic water quality model to evaluate how such an effort may influence Arctic grayling habitat in Upper Red Rock Lake (URRL). Finally, it discusses some rudimentary considerations for the proposed pipeline based on the September 10 and 11, 2020 field survey. Work has been completed as part of Amendment # 2 to Montana Fish, Wildlife & Parks (FWP) contract # 33815A.

## Literature Review

The literature review comprised of multiple keyword searches in Google Scholar including those listed in Table 1, review of relevant cited literature in those studies, and direct inquires to several prominent researchers in the field of lake restoration and artificial aeration. Additionally, a questionnaire was developed that will be distributed to state and federal agencies and nongovernmental organizations (NGOs) seeking opinions and experience from others around the country. The purpose of the survey was to identify case studies, unpublished results, or other information that may support the use of piping surface water to improve DO conditions in targeted habitat areas for the purpose of fish overwintering. FWP is distributing the survey (Attachment A) through their survey monkey account.

Based on the literature review, it was found that extraordinarily little information exists on the direct application of tributary pipelines for oxygenating fish habitat during ice-covered conditions. Conversely, a notable amount of literature exists on hypolimnetic oxygenation with pipelines. Klapper (2003) provide a review of technologies for lake restoration including the use of pipelines to mix, destratify, or oxygenate the hypolimnion of eutrophic or hypereutrophic lake. Gravity pipelines are used in areas with significant topographic relief providing an economic advantage over other methods. For example, where reservoirs or lakes exist in series, and where an oxygen-saturated lake is followed by a lake that is stratified with anoxic conditions, water from the oxygenated lake is supplied to hypolimnion of the lower lake via pipeline (Figure 1). Oxygen is therefore transferred from a location of high DO concentration to a place in the waterbody at risk of oxygen deficit.

**Table 1. Summary of Google Scholar keyword searches included in the literature review and potentially relevant results.**

| ID | Keywords | Potentially Relevant Results [a,b,c] |
|---|---|---|
| 1 | pipeline AND winterkill | Ellis and Stefan (1990), Ellis and Stefan (1991), Cott et al. (2008a), Cott et al. (2008b), Nürnberg (2007) |
| 2 | pipeline AND winterkill AND fish | Cott (2007) |
| 3 | pipeline AND winter AND lake | Riddick et al. (1950), Dunlaska (2002; 2003), Łopata, G Wiśniewski (2013) |
| 4 | pipeline AND winter AND oxygen | Neto et al. (2007) |
| 5 | pipeline AND aeration AND ice cover AND lake | Fast (1994), Lorenzen and Fast (1977), Mohensi et al. (2001) |
| 6 | pipeline AND ice covered AND oxygen | Flick (1968) |
| 7 | pipeline AND ice covered AND lake | Carlson (1981) |
| 8 | pipeline AND aeration | Sehsah and Elsbaay (2012) |
| 9 | gravity AND pipeline AND winter AND aeration | Fast (1968), Ashley (1985) |
| 10 | gravity pipeline AND winter AND oxygen | None |
| 11 | gravity pipeline AND winter AND oxygen AND lake | Wirth et al. (1975), Macdonald and Lawrence (2004), Gibbons and Wagner (1986) |
| 12 | surface flow AND pipeline AND winter AND lake | None |
| 13 | piping AND oxygen AND water AND fish | Boyd (1998), Horne et al. (2019), Mobley et al. (2012), Boyd and Tucker (1979), Gerling et al. (2014) |
| 14 | piping AND oxygen AND water AND fish AND winter | Fast (1975), Gafsi et al. (2009), Wirth et al. (1970) |
| 15 | pipeline AND winter AND fish AND habitat AND oxygen | None |
| 16 | water addition AND ice covered AND lakes | None |
| 17 | pipeline AND oxygenate AND ice cover AND lake | Growchowska (2020); Łopata (2020); Harris and Judd (2011) |
| 18 | piping AND water AND winter AND fish habitat AND lake | None |
| 19 | piping AND spring water AND winter AND fish habitat AND lake | None |
| 20 | oxygen AND addition AND pipeline AND lake | Kozac et al. (2020), (Gołdyn et al., 2014) |

[a] Findings include search results from the top ten pages of each Google Scholar keyword search
[b] Duplicative results of subsequent Search ID are not included
[c] Most of the search results do not directly address piping surface water for oxygen enhancement

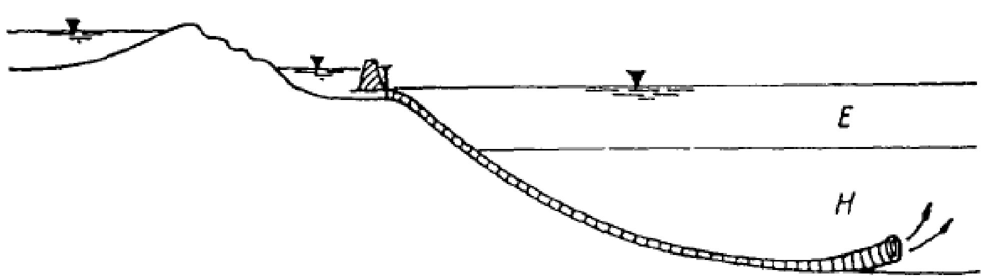
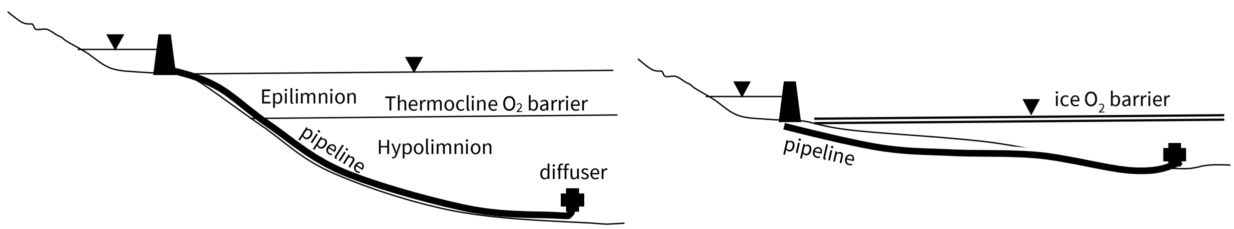



**Figure 1. Modification of surface water inputs to improve oxygen deficiency in a hypolimnion of a stratified lake. Taken from Klapper (2003) and drawn originally in Paul and Klapper (1985).**

The practice in Figure 1 shares many similarities with what is envisioned at URRL. The thermocline during stratification act as a barrier to oxygen exchange between the epilimnion and hypolimnion therefore behaving akin to ice-cover and separating the water from the atmosphere. Surface water inflow pipeline technologies therefore only differ in when and where water is placed. In the case of a deep lake during summer stratification, oxygenated water is moved vertically from the surface inflow or epilimnion to the hypolimnion via pipeline (Figure 2a). In URRL, water would be moved laterally from shallow nearshore areas with insufficient depth and high sediment area to volume ratios to deeper waters during winter (Figure 2b). The two approaches are strikingly similar to one another.




**(a) Deep lake summer stratification** **(b) Shallow ice-covered lake**

**Figure 2. Possible surface water pipeline configurations for enhancing oxygen conditions in lakes. (a). Entry of surface flow in a stratified deep lake for hypolimnetic oxygenation. (b) Entry of surface water in a shallow ice-covered system for oxygenating deeper depths.**

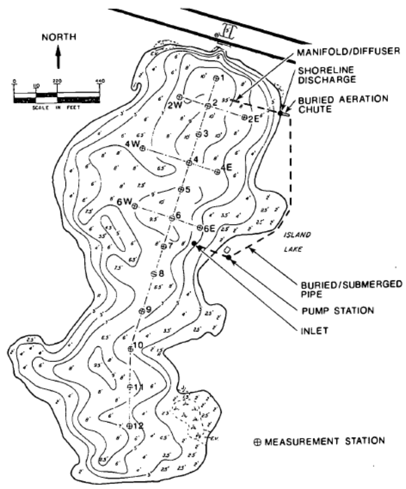
Several investigators have used gravity pipelines for oxygenation of hypolimnetic waters experiencing anoxia or hypoxia. Łopata & Wiśniewski (2013) describe the use a surface water inflow and gravity pipeline to redirect oxygen-rich warm waters from a water reservoir located at a higher elevation to a lower lake with a stratified with anoxic hypolimnion improve oxygen conditions in hypereutrophic Lake Łajskie in Poland. Gołdyn et al. (2014) and Kozak (2020) describe piping water from two tributary springs to the hypolimnion of Uzarzewskie Lake (Poland) for lake restoration. Analogous approaches were applied in lake Jabeler See in Germany (Paul & Klapper, 1985) and in Miłkowskie Lake Poland (Grochowsksa, 2020).

Accordingly, the ecotechnology of gravity piping surface water inflows, which combines oxygen import and mixing as described above, is considered a novel or innovative technology (Dunalska & Wiśniewski, 2016; Dunalska, 2020). Pipelines in these cases were placed directly on the bottom of the lake, diverting upstream oxygenated inflows to the deepest portion of the downgradient lake therefore improving oxygen concentration of hypolimnion and causing increases in redox potential.

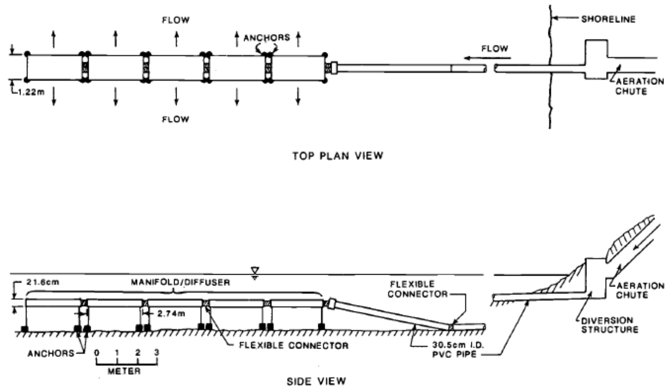
Other more complex variations of this approach include pumping oxygen-oversaturated water from the surface down to the highest deficit near the sediment. Gerling et al. (2014) and Gafsi et al. (2009) provide a review of side stream pumping or supersaturation efforts, which involves withdrawing hypolimnetic water from the lake, injecting concentrated oxygen gas at high pressure, and returning the oxygenated water to the hypolimnion. This is done in shallow ecosystems to prevent disruption of thermal stratification and is believed to hold promise for successful oxygenation of shallow ecosystems[1].

[1] A technology like this would be difficult to implement at URRL without connection to the electrical grid.

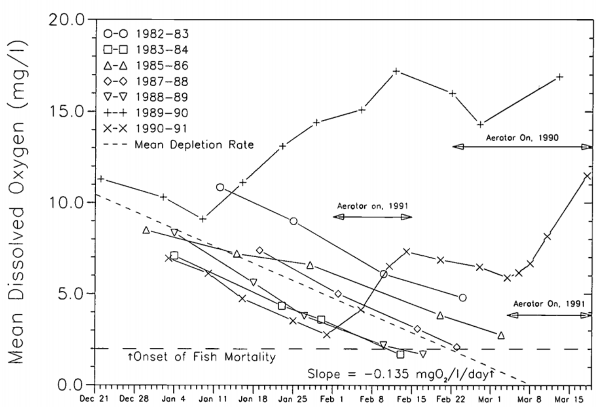
Several literature studies have documented using surface water inflow pipelines to remedy DO deficiency in ice-covered lakes. Ellis and Steffan (1991) discuss piping aerated water to Island Lake, MN (Figure 3) to prevent open water safety hazards from polynya formation during aeration. In this application, water was withdrawn from the lake at approximately 1 m below the ice using a pump, conveyed to the shoreline via pipeline, aerated using a pump and baffle/cascading aerator, and then reinjected near mid depth so that water temperature stratification would be disturbed as little as possible. The approach showed appreciable improvement in mean DO concentration in the lake (Figure 3c) and was 75% efficient in aeration of lake water (Figure 3d), thus demonstrating that the addition of oxygenated water can improve in-lake conditions[2].



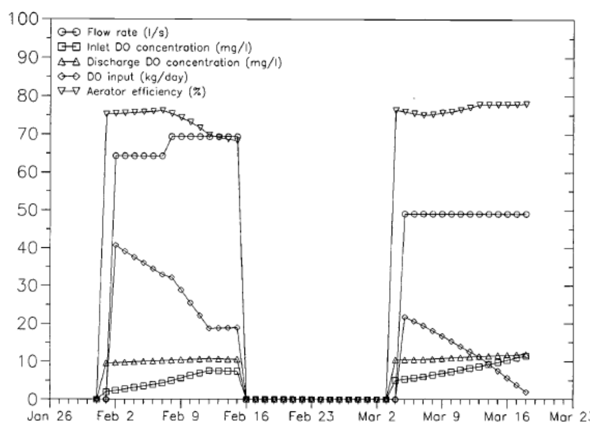

**(a)**




**(b)**




**(c)**




**(d)**

**Figure 3. Pipeline aeration project in Island Lake, MN, a small (17.1 ha) shallow winterkill prone lake with mean depth of 1.45 m and maximum depth of 2.8 m (Ellis and Stefan, 1991). (a) Island Lake Bathymetry. (b) Schematic arrangement of aerator and discharge diffusers. (c) Mean lake DO concentrations resulting from project. (d) Aerator efficiency in 1991.**

[2] In one of the years investigated (e.g., 1989-1990), dissolved oxygen concentrations exceeded saturation levels under the ice from macrophyte photosynthesis. During that time, pipeline operation was diluting under-ice DO concentrations.

Harris and Judd (2011) discuss the use of a gravity flow pipeline for protection of trout during winter months in Navajo Lake, Utah. The lake is shallow and becomes depleted of DO by macrophyte decay during winter ice cover. Management of the fishery includes piping spring water into the lake to increase dissolved oxygen levels and create a refuge for trout to over-winter. Measurements of dissolved oxygen near the spring outfall range between 4 to 6 mg/L, but drop rapidly within a 50 foot radius of the spring to below 1 mg/L, noting trout survival is highest during years when spring inflow is high and more oxygen rich water enters the lake.

Based on these outcomes, the concept of oxygenating targeted fish habitat is not new. Mobley (2012), Wirth et al. (1970), and Mohensi et al. (2001) discuss the concept of targeted oxygenation of usable fish habitat, albeit during summer months in cool deep anoxic waters. Extensive literature also exists on other aeration technologies to avert large-scale fish winterkill (Barica & Mathias, 1979; Barica, et al., 1983; Ellis & Stefan, 1989; Fast, 1994; Schwalme, 1995). A similar approach would be applied to URRL during the winter months, in the spirit of efforts discussed previously.

## Model Analysis

The URRL 2-D DO diffusion model described in Flynn et al. (2019) was used to estimate changes in Arctic grayling habitat for the Shambow Pond pipeline alternative. Suitable habitat was defined as water depth > 1 m and DO > 4 mg/L and the model was updated with flow and DO measurements made during the winter of 2019 and 2020. This included flow measurements in Grayling Creek, Shambow Creek, and Tom Creek, DO measurements in Shambow Pond, and an updated sediment oxygen demand (SOD) rate based on observations during 2020.

Mean daily flow exiting Shambow Pond averaged 2.0 $ft^3/s$, with wintertime flows ranging from 1.5 to 2.5 $ft^3/s$ (Figure 4; personal communication A. Brummond). Water temperature was approximately 2°C and DO was highly variable ranging from 0.0 to 11.2 $mgO_2/L$, averaging 4.5 mg $O_2/L$ over the deployment period (Figure 5). Several weeks during March and April exhibited anoxic conditions[3]. Consequently, a Shambow pipeline could potentially provide oxygen refugia during portions of the winter but may not always be of benefit. Aeration would be required if using water from this pond.

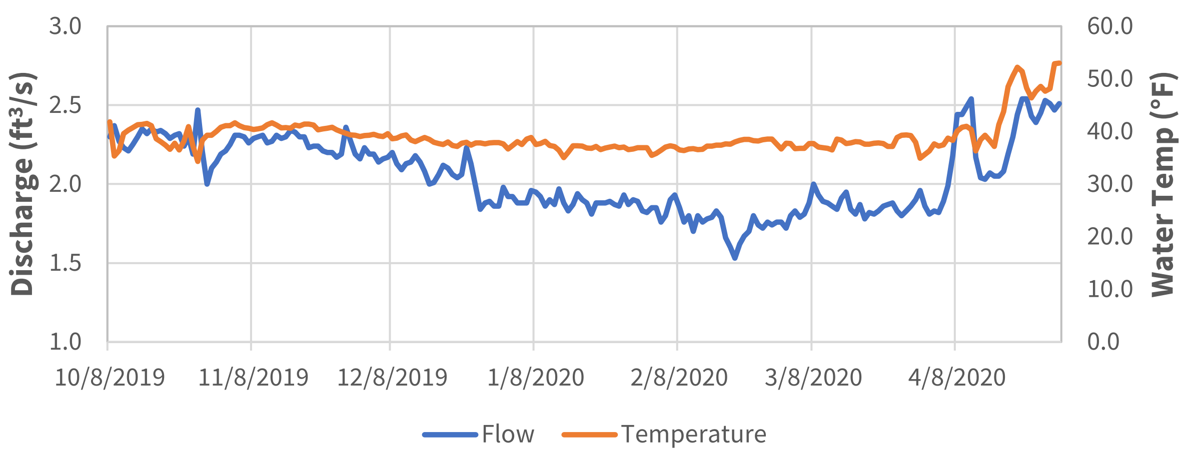



**Figure 4. Flow and water temperature at the outlet of Shambow Pond during the winter of 2019 and 2020.**

[3] Dataloggers should be deployed another winter to confirm these findings.

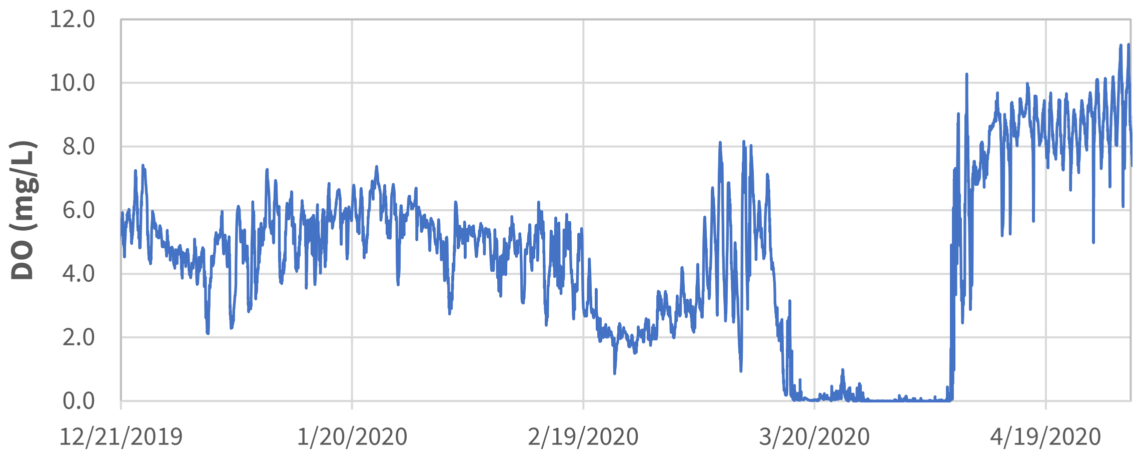



**Figure 5. Dissolved oxygen at the outlet of Shambow Pond during the winter of 2019 and 2020. Concentrations were hypoxic or anoxic from 3/16 to 4/7.**

The spatial 2-D oxygen model for URRL was updated with the information from above. Existing conditions are shown in Figure 6 and suggest no grayling habitat would be present during critical winter conditions under a high SOD/WODR scenario (as has been observed in prior years). Oxygenated areas only occur in the shallow waters near tributaries. Computations to estimate the daily oxygen concentration in the mixing zone surrounding the discharge port for a proposed pipeline scenario were made. Assuming the discharge enters in a single 100 m × 100 m grid, is discharged in a depth of 1 m (1.5 m total depth assuming 0.5 m of ice cover), and ignoring turbulent diffusion because advection in the immediate mixing zone would be dominant (discharge waters would be renewed continually), a steady state mass balance can be written as follows

$$0 = Q_{in} o_{in} - Q_{in} o - SOD \times A \quad (1)$$

where $Q_{in}$ is the pipe inflow into the model grid element ($m^3/d$), $o_{in}$ is the DO concentration of the pipeline water ($g/m^3$), $o$ is the DO concentration of the model grid element ($m^3/d$), SOD is the sediment oxygen demand ($gO^2/m_2$) in the mixing zone, and $A$ is the grid element area ($m^2$).

Assuming available flow is split between two discharge ports, Equation 1 can be rearranged as follows

$$o = \frac{Q_{in} o_{in} - 2SOD \times A}{Q_{in}} \quad (2)$$

With pipeline flow estimated be 2 $ft^3/s$ (0.057 $m^3/s$; half that value in each discharge port), $o_{in}$ at 4.5 $mgO_2/L$ representative of average conditions in Shambow Pond (assumes no deoxygenation in the pipeline), and SOD approximated to be 0.21 $gO^2/m_2$ based on the winter oxygen depletion rate in 2020, the mixing zone for each grid cell with discharge water would result in a steady state concentration of 3.6 $mgO_2/L$. Implementation of these assumptions in the 2-D DO model also does not provide any grayling habitat (Figure 7). Alternatively, a single port design could be used that would yield a mixing zone concentration of 4.1 $mgO_2/L$ and would comprise a single grid cell (1 ha) of habitat having depth > 1 m and DO > 4 $mgO_2/L$.

Based on the data and information presented previously, aeration will likely be necessary if a Shambow pipeline alternative were pursued. Shambow Pond waters are undersaturated with DO, but at temperatures observed during 2020 (2 °C), would approach 10.6 $mgO_2$/L if fully equilibrated with the atmosphere. Using the approach described in Equation 2, and assuming an aeration efficiency of 75% based on Ellis and Stefan (1991) (Figure 3d), water in the pipeline could be oxygenated to 8.0 $mgO_2$/L and would result in an estimated 7.1 $mgO_2$/L in the mixing zone in the 2-D spatial DO model (each outlet port). Implementation of this approximation in the 2-D DO model is shown in Figure 8. A total of 22 ha of grayling habitat could potentially be created in this scenario with DO concentrations diffusing out approximately 150 m radially from center from each outlet port. This suggests that the pipeline would potentially be successful (see subsequent caveats).

An independent estimate of the size of the mixing zone and habitat area can be made using a 1-D analytical turbulent diffusion model. Although mixing in ice-covered lakes occurs through several mechanisms including throughflow, sediment-heat generated currents, wind induced seiche (under ice-cover), groundwater upwelling, and convective mixing near the ice-water interface, for simplicity these processes can be lumped as turbulent diffusion. From a point initially concentrated at $x = 0$ under steady state conditions, with a first order SOD sink, the governing equation is

$$0 = D\frac{d^2c}{dx^2} - Kc \tag{3}$$

where $c$ is the volumetric concentration of DO in the water column ($g/m^3$), $D$ is the turbulent diffusion coefficient ($m^2/d$), $x$ is the spatial direction representing the principal axis of the lake, and $K$ is a first-order decay coefficient meant to approximate sediment oxygen demand (/d). An analogous equation can be written in the $y$ direction.

Equation 3 can be rearranged and solved either through direct integration or using a general solution that takes the form $c = \exp^{\lambda x}$ (Chapra, 2008), which is as follows

$$c = c_0 \exp^{\left(\sqrt{\frac{K}{D}}x\right)} \text{ for } x < 0 \tag{4}$$

$$c = c_0 \exp^{\left(-\sqrt{\frac{K}{D}}x\right)} \text{ for } x > 0 \tag{5}$$

where $c_0$ approximates the DO concentration of the discharge pipe due to the shallow depth.

For URRL with SOD approximating 0.07 /d (0.21 $gO_2/m^2/d$) and a diffusion coefficient of 7,500 $m^2/d$ as used in the 2-D modeling (see later caveat), an oxygenated plume > 4 mg/L around each outlet port would be approximately 200 m wide (Figure 9). This is slightly larger than estimated previously but suggests a comparable habitat for each outlet port in the 2-D model.

Although these computations are promising, it is important to note that the size of the mixing zone is a function of both advective and dispersive transport, and is heavily dependent on the turbulent diffusion coefficient, which is a sensitive model parameter (Figure 9). Moreover, Malm (1999) indicate horizontal dispersion coefficients in ice-covered lakes span several orders of magnitude and the estimate for URRL by Flynn et al. (2019) is believed to be anomalously high.

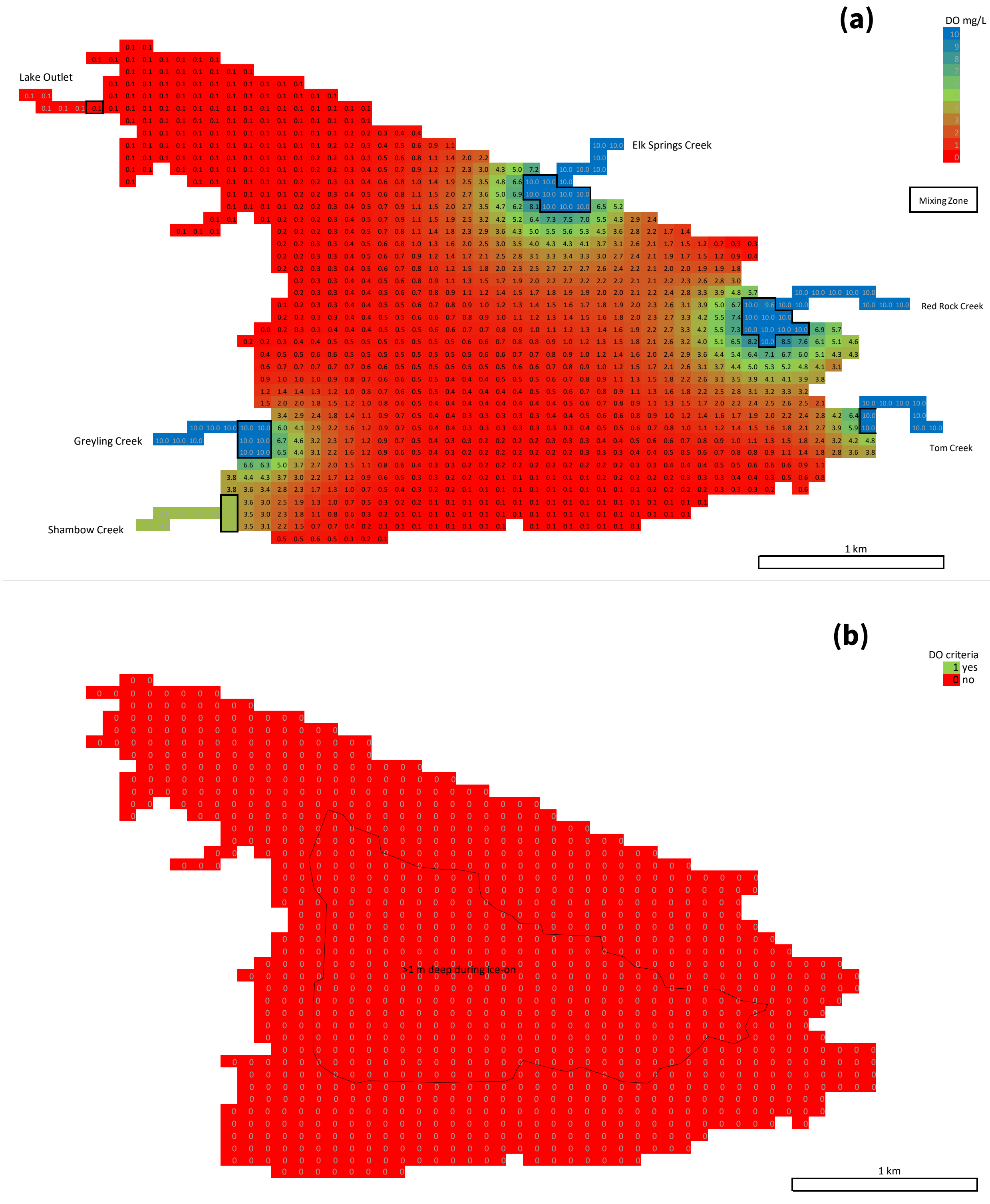



**Figure 6. 2-D Modeled Response of URRL under current conditions with updated data from the winter of 2019 through 2020. (a) Predicted oxygen concentrations. (b) Predicted winter habitat area (0 ha).**

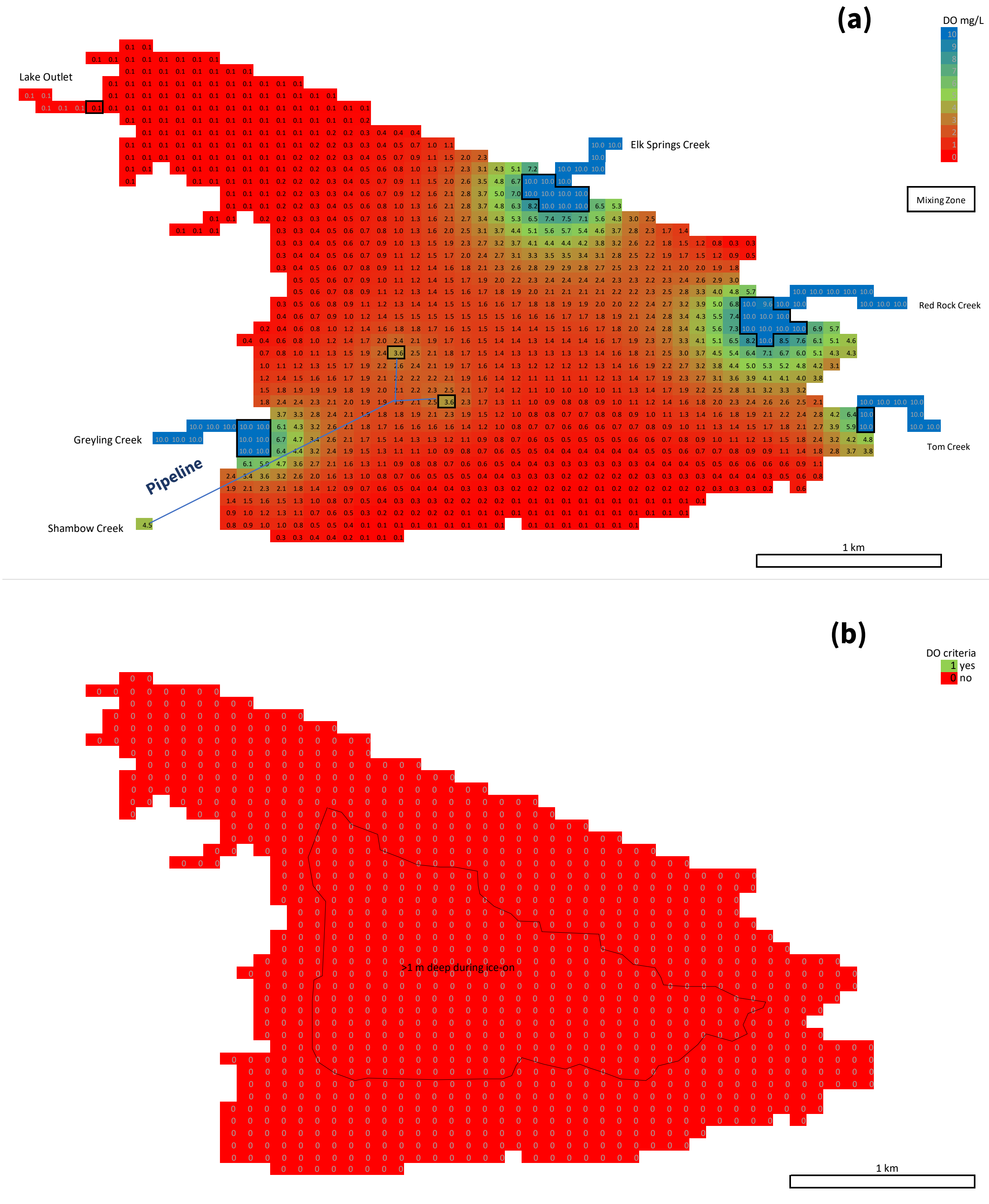



**Figure 7. 2-D Modeled Response of URRL to the Shambow Pond pipeline scenario under current conditions with an outlet port mixing zone concentration of 3.6 mg/L. (a) Predicted oxygen concentrations. (b) Predicted winter habitat area (0 ha).**

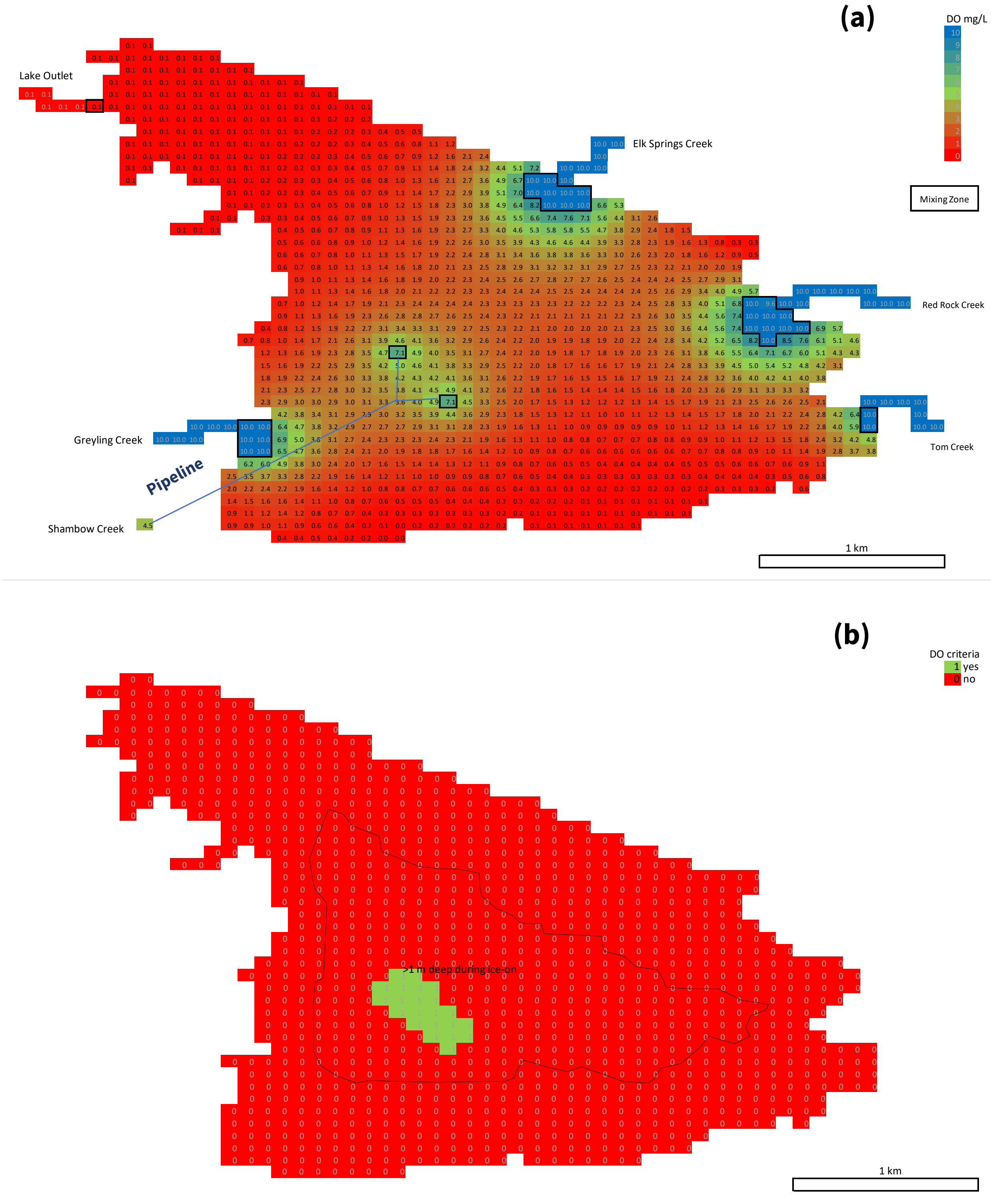



**Figure 8. 2-D Modeled Response of URRL to the Shambow Pond pipeline scenario with aeration of water and outlet port mixing zone concentration of 7.1 mg/L. (a) Predicted oxygen concentrations. (b) Predicted winter habitat area (22 ha).**

Given the discussion and results presented previously, a dye tracer study should be considered during ice-on to better constrain the turbulent diffusion coefficient for URRL and better approximate the anticipated area of grayling habitat that would be created by construction of a pipeline from Shambow Pond. As a matter of point, a significant reduction in grayling habitat area is noted when using a diffusion coefficient more characteristic of ice-covered lakes (Figure 9; e.g., *D*=75 or 750 $m^2$/d). Additionally, modeling has not considered comprehensive advection and dispersion transport equations simultaneously. Prior to pipeline construction, it is recommended that robust model be developed for URRL that considers hydrodynamics and/or computational fluid dynamics so the oxygen plume around the pipeline outlet ports (or diffusers) can be fully understood.

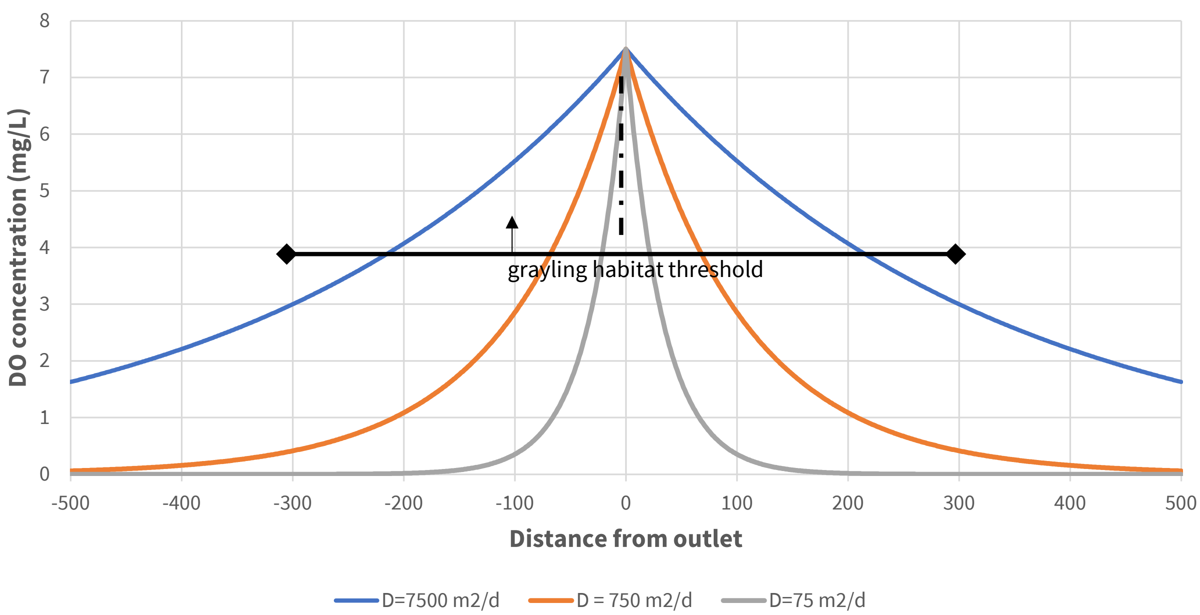



**Figure 9. DO concentration estimates at various lateral distances from an individual pipeline outlet port using a 1-D turbulent dispersion model. The sensitivity of applying differing turbulent diffusion coefficients is apparent.**

## Pipeline

A gravity pipeline has been proposed for URRL, which is recommended for grades >0.2 percent (USDA, 2010). Based on the field survey, the pipeline will be greater than 0.3 percent grade, but will depend on alignment and discharge point into URRL. Gravity pipelines are generally subdivided into two types: (1) low head and (2) high head gravity systems. A low head gravity system will occur at URRL as the surveyed water surface elevation difference between Shambow Pond and URRL on September 11, 2020 was 12.4 feet. Low head is defined as < 20 pound per square inch (psi) and the pressure under static head in this application would be quite low, 5.4 psi.

Based on available data, aeration will be required. Due to limited head drop between the point of entry and discharge point, novel aeration technologies are needed. Venturi aeration is the most likely candidate, but other technologies should be evaluated during design. The former is completed by acceleration of the fluid when passing through a constricted section (choke) in the pipe, which lowers internal pressure and draws in secondary flow of air through the air inlet pipe exposed to the atmosphere, which subsequently is used for aeration.

An important consideration is to safely convey flows during winter months. As such, the pipeline and air inlet pipe heat exchanger should be buried below the frost line. Frost depth depends upon several factors including: air temperature minima, number of freezing days in a year, soil type and cover, sun exposure, moisture content of overlying soil, the temperature of water source, and whether there is continuous flow in the pipeline. If water is moving, it will likely not freeze above 0°F (USDA, 2010), although in some cases, extreme frost penetration can still occur.

For situations where there is not continuous flow, and to provide a margin of safety in engineering design that will prevent pipe damage in the case of stoppage or water ponding, the extreme frost depth map should be consulted. Extreme frost depths at URRL are estimated to be approximately 50 inches below ground surface. All infrastructure (pipes, valves, etc.) should be constructed below this depth to protect them from freezing. For valves or other fittings requiring service, this should be done by installing them in a covered manhole or access hole below frost depth.

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Attachment A

# Attachment A

**Pipeline Questionnaire**

# QUESTIONNAIRE REGARDING THE USE OF PIPELINES FOR TARGETED OXYGENATION OF FISH HABITAT IN ICE-COVERED LAKES

**OVERVIEW:** Montana Fish, Wildlife & Parks, in cooperation with the U.S. Fish and Wildlife Service and the Red Rock Lakes National Wildlife Refuge, are attempting to improve overwinter habitat for an ESA candidate native Arctic Grayling population in a shallow (<1.5 meter during winter), high elevation lake in southwest Montana. Arctic Grayling in Upper Red Rock Lake require >4 mg $O_2$/L in water > 1m deep to avoid catastrophic overwinter population decline. Winter monitoring indicates that the under-ice habitat quality is often poor where depth is > 1 m, with < 2 mg$O_2$/L commonly observed.

We recently completed an engineering feasibility analysis to improve Arctic Grayling winter habitat. As part of this study, over 20 alternatives were identified and prioritized that enhance oxygen exchange, add oxygen, or modify bathymetry or circulation. Due to the remote location of Upper Red Rock Lake and its surrounding Wilderness setting, preference was given to construction of a pipeline to move oxygenated water from a tributary to parts of the lake > 1 m deep. The pipeline would transfer approximately 2 to 3 cubic feet per second of $O_2$ saturated water to a diffuser in the center of the lake to expand lake habitat and sustain grayling during ice-covered conditions.

Our initial literature review found few studies that pipe surface water to desirable habitat areas to improve dissolved oxygen conditions under ice-covered conditions.

**OBJECTIVE:** We are seeking opinions and experience from others around the country to identify case studies, unpublished results, or other information to support the possible use of this practice. Thank you for participating in this brief survey. Responses will be compiled and acknowledged in our final report.

# SURVEY QUESTIONS REGARDING THE USE OF PIPELINES FOR TARGETED OXYGENATION OF FISH HABITAT IN ICE-COVERED LAKES

1. Name of Respondent or Organization _____________________________ Date _______________

2. Do you or your Agency have knowledge of, or experience with, using a pipeline to transfer oxygenated water to improve under ice conditions for fish? _____ yes _____ no.

   If no, end survey.

   If yes, please provide the following:

   a. Project details
      i. Implementing Agency/Organization ______________________________________
      ii. Location _____________________________________________________________
      iii. Lake applied to ______________________________________________________
      iv. Lake area _________________($mi^2$) Lake Depth _____________(ft)
      v. Citation or reference __________________________________________________
      vi. Contact information (if any), email ________________ telephone ______________
      vii. Description of outcome(s) ______________________________________________
      _____________________________________________________________________
      _____________________________________________________________________
      _____________________________________________________________________

   b. Did the pipeline improve under ice conditions? _____ yes _____ no
      If yes, please describe what indicators were measured and how they improved __________
      _____________________________________________________________________________
      _____________________________________________________________________________

   c. Was there any evidence of winterkill observed at ice-out? _____ yes _____ no
      If yes, please describe ________________________________________________
      _____________________________________________________________________________
      _____________________________________________________________________________

   d. Were there any safety problems due to thin ice or open water? _____ yes _____ no
      If yes, please describe __________________________________________________________
      _____________________________________________________________________________
      _____________________________________________________________________________

   e. Would you recommend this approach over other techniques that improve under ice fish habitat for a remote location that does not have electrical power (note: solar aeration has already been piloted and was unsuccessful)? ______yes _____ no
      If no, please describe approaches that you feel are preferable to piping oxygenated water______________________________________________________________________
      _____________________________________________________________________________
      _____________________________________________________________________________

f. Are you aware of adverse impacts associated with the pipeline project including those related to construction, revegetation, operation, in-lake effects, species impacts, or any other factors? _____ yes _____ no
If yes, please describe ______________________________________________________________
______________________________________________________________________________
______________________________________________________________________________

3. Do you have any additional comments about the targeted pipeline oxygenation approach based on your experience?
______________________________________________________________________________
______________________________________________________________________________
______________________________________________________________________________
______________________________________________________________________________