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Memorandum

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Copy: Kyle Cutting and Jeff Warren, Ph.D. | U.S. Fish & Wildlife Service

Date: March 04, 2022

Subject: EFDC+ dissolved oxygen modeling of Upper Red Rock Lake

Previous spreadsheet modeling efforts of Upper Reck Rock Lake (URRL) recommended that more robust modeling tools be developed to consider hydrodynamic and water-quality effects of various restorative strategies for improving wintertime dissolved oxygen (DO) concentrations in URRL (Flynn, et al., 2019; Flynn, 2020). This work follows up on the above recommendation by developing an Environmental Fluid Dynamics Code (EFDC) model of URRL.

The purpose of modeling is to evaluate two engineering alternatives considered for implementation within URRL: (1) construction of a pipeline from Shambow Pond to transfer oxygenated water nearer the center of URRL where grayling habitat is more prevalent and (2) a storage release scenario where stored water in Widgeon Pond is released to provide an oxygenated flushing flow into URRL from Elk Springs Creek. Work has been completed under subcontract to Water & Environment Technologies (WET) as part of FWP Project No. 33815A.

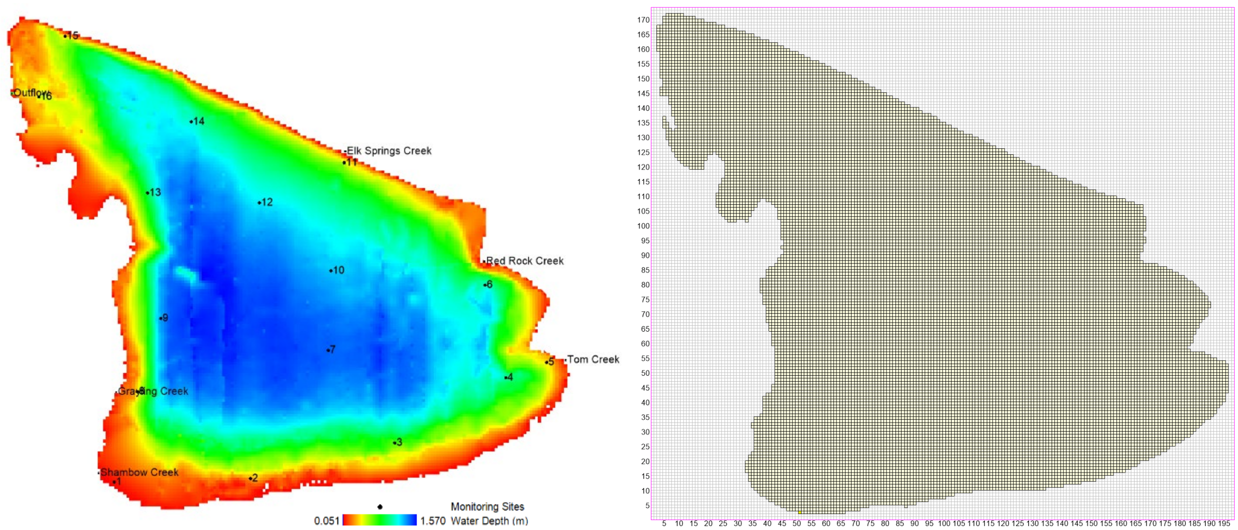
Model Description

EFDC is a state-of-the-art hydrodynamic model that can be used to simulate aquatic systems in one, two, and three dimensions, including both hydrodynamic, sediment, and eutrophication components. The model has evolved over the last two decades to become one of the most widely used and technically defensible hydrodynamic models in the world. It has been applied to over 100 water bodies including lakes, wetlands, estuaries, and coastal ocean regions in support environmental assessment and regulatory management (DSI, LLC, 2020).

The EE Modeling System (EEMS) provides an interface to EFDC, including both EFDC_Explorer (EE) and EFDC+. EE is a proprietary Graphical User Interface (GUI) that provides pre-processing and post-processing tools to assist in developing, calibrating, and analyzing EFDC models. EFDC+ is the state-of-the-art, open-source, multifunctional surface water modeling engine included in the EEMS software package. All simulations described as part of the work on URRL were executed in version 10.3.8 of EFDC_Explorer.

Model Setup and Development

The model grid was constructed by developing a 25 m uniform mesh over the URRL extent using the USFWS bathymetry (Andrews, 2017). A 25 m grid was found necessary to compute appropriate spatial gradients in water quality within the waterbody, noting both a 10 m and 100 m mesh were initially tested, but the 25 m grid balanced computational times and numerical stability. Due to shallow depths, a single layer model was used (2-dimensional), although a multi-layer model (3-dimensional) also was tested. The site bathymetry (depth) and the associated model grid used in the EFDC+ model setup are presented in **Figure 1**. Bed elevations corresponding to the depths shown in the figure originated from North American Vertical Datum (NAVD) 88 and ranged from 2012.92 to 2014.496 meters. It is important to note that the maximum depth in the grid is 1.57 m and the X and Y components correspond to cells referenced in the I and J directions in EFDC.



(a) (b)

Figure 1. EFDC+ grid used in URRL DO modeling. (a) Bathymetry (depth) and (b) cell computational map.

Initial conditions and boundary conditions in URRL are limited. Because of this, the modeling approach was to simulate “typical” critical wintertime conditions in EFDC+ using best available data. This data included historical monitoring of 16 unique sites over the 2016 though 2021 period (shown as 1 through 16 in **Figure 1**), winter 2019-2020 sonde and miniDOT monitoring during the solar aerator pilot testing (Flynn, et al., 2022), and data collected during the Widgeon Pond storage test release during the winter of 2021 (K. Cutting, personal communication 8/20/2021). Although in-lake data were collected over these periods, inflows and outflows (i.e., boundary conditions) were not measured and therefore require estimation. Because of this, the model represents no specific point in time, but rather is an amalgamation of observations over the monitoring record typifying what may happen in URRL during a critical DO year.

Mean monthly inflows used in the EFDC+ model are found in **Figure 2**. Estimation methods are found in **Table 1**. Outflow was assumed to be the sum of all inflows with no lag in time or storage accommodation. Given the variability of a single season of measurements made on Shambow Pond

(Flynn, 2020) and Elk Springs Creek (K. Cutting, personal communication 8/20/2021), and uncertainty of those points in characterizing representative inflow to URRL (e.g., Shambow Measurements were made at the outlet of the pond and thus were not directly measured at the inlet to the lake, while Elk Springs Creek very closely approximated atmospheric saturation), temperature and DO of the influent tributaries had to be estimated. All boundary conditions were assumed to be at 2°C and atmospheric saturation with respect to DO concentration (10.5 mg/L). This is a coarse assumption and should be verified if the model is to be used in the future.

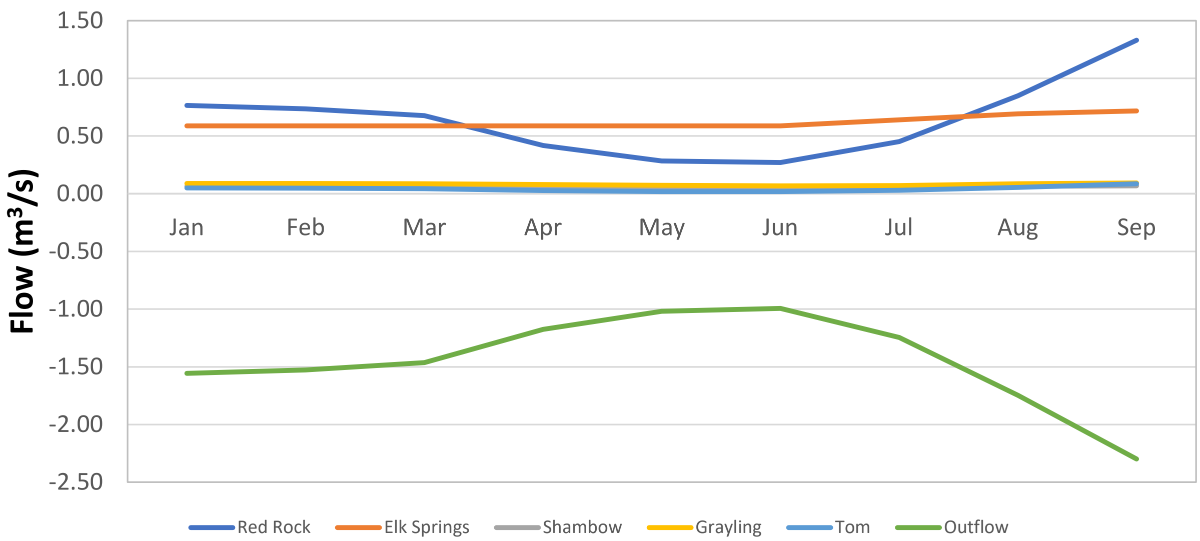


Figure 2. Summary of monthly tributary boundary conditions (i.e., inflows and outflows) used in the URRL EFDC+ model. All data are estimated.

Table 1. Boundary conditions for the URRL EFDC+ model and associated estimation methods.

Tributary [a]	Available Flow Data	Missing Flow Estimation Method
Red Rock Creek	Apr–Oct (1997 through current) monthly statistics	Fill monthly wintertime data from USGS 06010500 using monthly ratio to mean monthly Apr–Oct flow
Elk Springs Creek	FWP measurements 2016-2018; FWS measurement 2021 Widgeon release	Average between available measurements (assume spring fed)
Tom Creek	FWP measurements Apr–Oct (2016 through 2017)	Use scaling factor from Red Rock Creek for winter flows (assuming similar pattern)
Shambow Creek	FWP measurements Oct–Apr 2019	Mean monthly flows with scaling factor from Elk Springs Creek
Grayling Creek	FWP measurements Oct–Apr 2019	Mean monthly flows with scaling factor from Elk Springs Creek
Outflow	None	Assumed to be the sum of the inflows

[a] Tributaries were assumed to be 2°C, and at atmospheric saturation with respect to DO concentration (10.5 mg/L).

Initial conditions within URRL also had to be estimated. During a typical critical winter, it is believed water column temperatures will be near freezing before ice-on due to the shallow depth of the lake (assumed to be 0.1°C) and dissolved oxygen concentrations will be at atmospheric saturation as the lake is fully mixed. Following becoming ice-covered, underlying water temperatures warm and become supersaturated with DO due to macrophyte photosynthesis (Flynn, et al., 2022). DO eventually then declines precipitously following snow cover until reaching hypoxic or anoxic conditions in late winter, and then rebounds 2-4 weeks prior to ice off as snow cover declines to 0 cm (March 27 in 2014 and February 16 in 2015, respectively; Davis 2016 and Davis et al. 2019). An initial condition of 12.5 mg/L DO was assumed for the entire URRL volume in EFDC+ (supersaturated), which increases slightly in the model until the ice-covered period begins due to an incorrect computational formulation in EFDC+[1].

A heat coupled ice model was initially used to simulate ice cover using atmospheric data from a nearby climatic station (Red Rock RRDM8, https://mesowest.utah.edu/). However, given difficulties with this method and budgetary constraints, the approach was abandoned. Instead, a specified on/off ice cover was used. In this approach, an ice cover was placed over the lake on day 51 of the simulation (November 21) and was removed on Day 181 (March 31), representing a 130-day ice-cover duration. The specified duration is comparable to that of the literature (Davis, et al., 2019), although some studies have suggested longer times (Flynn, et al., 2022).

Gas exchange does not occur between the water and atmosphere in EFDC+ during ice cover; however the on/off formulation the model does not correctly reduce lake volume by the specified ice-thickness for either hydrodynamic or water quality computations. Therefore, two runs were completed to evaluate model outcomes: (1) with the water depth and outlet location as reflected in the original FWS bathymetry (Andrews, 2017) and (2) with an initial condition reflecting 0.5 m of ice depth and the outlet location adjusted to reflect the 0.5 m of ice cover. EFDC+ simulations were then run from day 45 (November 15) to day 196 (April 15) using a dynamic time-step (minimum 0.4 seconds) and using the Smagorinsky with water column diffusion formulation, where only a background/constant horizontal eddy viscosity coefficient was applied.

Lastly, oxygen losses were represented using a constant sediment oxygen demand (SOD), which reflects the combined effect of oxidation of organic material in sediments as well as senescent decay of macrophytes once the lake becomes snow covered. SOD was specified at –0.7 g/m^2/d at 20°C, which corresponds to an SOD of –0.26 g/m^2/d at an in-situ wintertime temperature of 4°C, noting SOD is temperature adjusted (temperature coefficient of 1.065). SOD was calibrated up slightly within the EFDC+ model from past efforts noting that 0.21 g/m^2/d was previously determined from whole lake DO depletion data (Flynn, et al., 2022). Models were then evaluated for the following conditions to evaluate in-lake changes in DO due to proposed management actions on the lake:

- **Existing Condition –** representing baseline critical winter conditions where much of the lake is deoxygenated and oxygen is only present around the tributary mouths. No management activities are present in the existing conditions model run. Other runs are subsequently compared to this run to assess management effectiveness.

[1] The EFDC+ model (v10.3.8) incorrectly computes atmospheric saturation at elevations above sea level (note: this has subsequently been revised due to this project but was not integrated into the version of the model that was available at the time). The error above results in DO concentrations that are higher than would occur at elevation, and hence are supersaturated with respect to elevation prior to ice-cover. Inadvertently this represents the photosynthetic effect of macrophytes causing DO supersaturation in URRL at the onset of the simulation.

- **Shambow Pipeline –** representing a flow of 0.057 m^3/s (2 ft^3/s) diverted from Shambow Pond, aerated (if necessary), and discharged northeast of the Grayling Creek inlet during the winter ice-covered period. This represents the WET preliminary pipeline design (Siddoway, et al., 2021).
- **Widgeon Pond Release –** representing a 15-day release of 180,265 m^3 (146.1 acre-feet) of stored water from Widgeon Pond beginning on 2/20, that ultimately discharges at the mouth of Elk Springs Creek and enters the lake on 2/21 and contributes a peak of 1.4 m^3/s declining to baseflow of 0.589 m^3/s over the release period (K. Cutting, personal communication 8/20/2021).

Results from the model scenarios above are compared in the next section to frame management recommendations for URRL based on estimated changes in Arctic grayling habitat under different modeling scenarios. Suitable habitat was defined as water depth > 1 m and DO > 4 mg/L.

Results and Discussion

Observed and predicted values for each of the 16 monitoring locations over the 2015 through 2021 period in URRL are shown in **Figure 3** for the existing condition hydrodynamic and water-quality run. Time series with respect to data collected during 2019-2020 and in 2021 are shown in **Figure 4** and **Figure 5**. Overall, the model generally reproduces higher DO concentrations in areas where higher DO was measured and conversely low DO in areas where low DO was measured, thereby fitting the general character of URRL. However, there is clearly significant scatter in the data about the 1:1 line and calibration attempts provided little improvement to model outcomes. Model parameter adjustments shifted points up or down but did not reduce the variance around the 1:1 line. As such, little can likely be done to improve the model calibration.

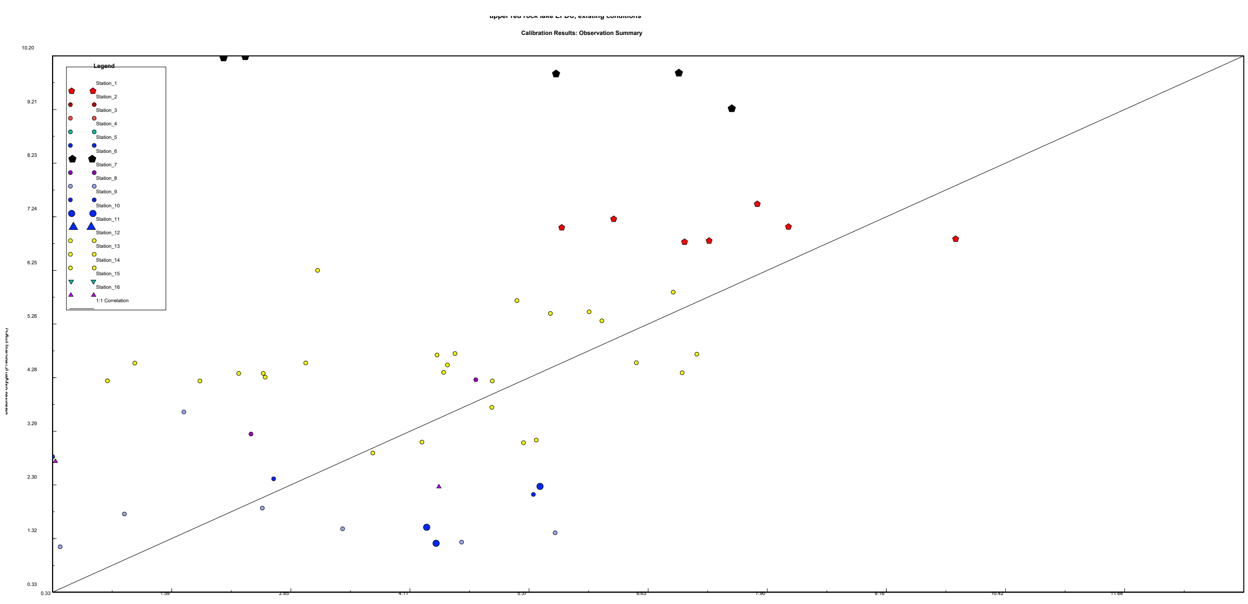


Figure 3. Observed vs. predicted DO values for the URRL EFDC+ model under the existing condition (baseline) scenario. Calibration stations 1 through 16 correspond to the monitoring locations (stations) shown in Figure 1a.

Adjustment of the SOD rate and modification of the background/constant horizontal eddy viscosity/diffusivity (estimated to be 0.001 m^2/s) generally improved the fit against the time-series data, although this did not provide great fits at all locations or times, especially in proximity to tributary boundary conditions. Lower horizontal dispersion coefficients were required to match observed data than used in past URRL calculations, which creates a more concentrated oxygenated plume near the tributary inlet and less DO dispersion outward into the lake. This is evident at 250-m from the Elk Springs tributary inflow which diminishes the influence of the Widgeon pulse at that location. Time series generally pattern historic observations, albeit not perfectly as noted in the figures below and the oxygen rebound noted from the Widgeon release is nearly immediate in EFDC+.

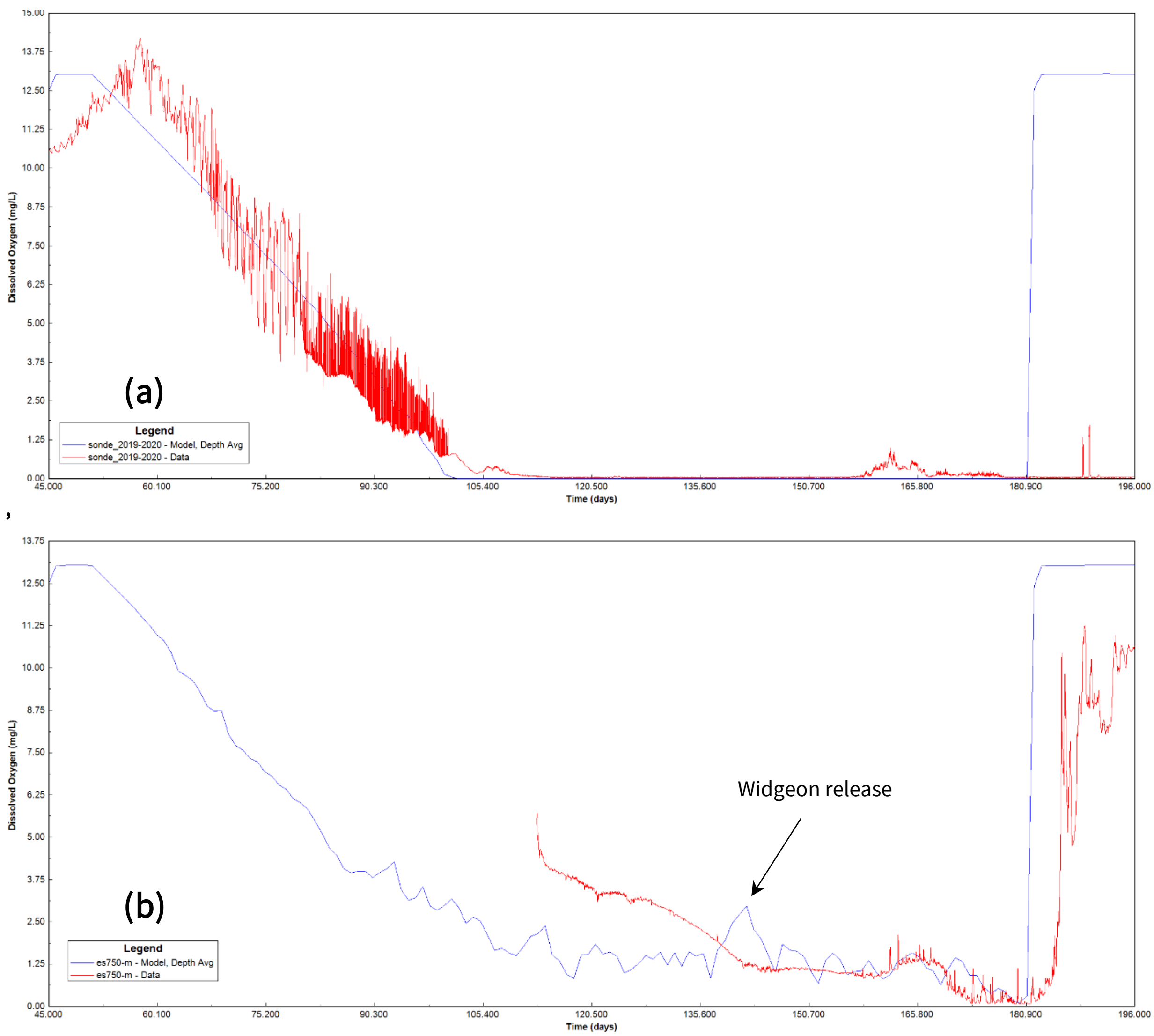


Figure 4. Observed vs. predicted DO time-series for the URRL EFDC+ model under the existing condition scenario. (a) DO data from mid-lake reported in Flynn et al. (2022). (b) Data at 750-m from the Elk Springs Creek inlet during the 2021 Widgeon Pond release (K. Cutting, personal communication 8/20/2021) [2].

[2] It is important to recognize that management actions were undertaken in the lake when these data were collected and results are therefore the results are for comparative purposes only (e.g., solar aerator implementation in 2019-2020 and the Widgeon Pond release in 2021).

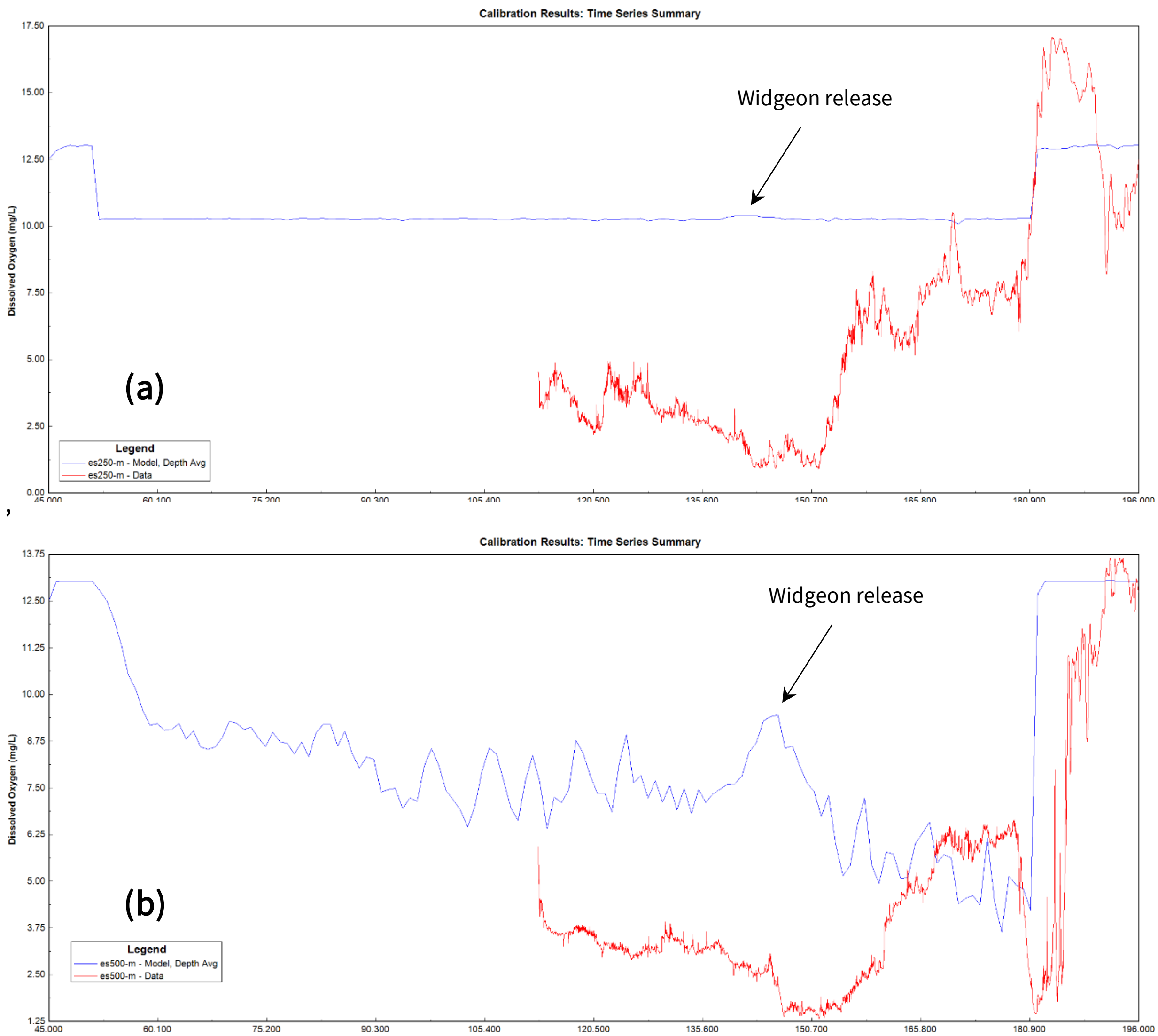


Figure 5. Observed vs. predicted DO time-series for the URRL EFDC+ model under the existing condition scenario. (a) Data at 250-m and (b) 500-m from the Elk Springs Creek inlet during the 2021 Widgeon Pond release (K. Cutting, personal communication 8/20/2021). The Widgeon release is believed to have entered URRL on day 143 of the simulation (February 21) [3].

Results from the existing condition simulation of critical winter conditions DO is shown in **Figure 6** for both unmodified and ice-adjusted hydrodynamics as simulated on March 1st. It is apparent that grayling habitat in URRL is not present during late winter anywhere in URRL under the existing condition scenario using the currently defined management criteria of depth >1 m and DO >4 mg/L.

[3] The peak of the pulse was on day 143 (2/21) of the simulation and flow was linearly interpolated from the January mid-month estimate of 0.589 cms to 1.4 cms on 2/21 and then tapered back to baseflow over 15 days. If anything, the simulated volume entering URRL was overestimated. The observed data do not show any response until almost ten days after the pulse enters URRL.

The greatest areal extent of oxygenated water is near the mouths of the largest tributaries, although depths in proximity to the tributaries are exceptionally shallow and are not suitable for grayling habitat. An animation of the existing condition DO progression can be downloaded at the following hyperlinks: (a), (b), (c), and (d).

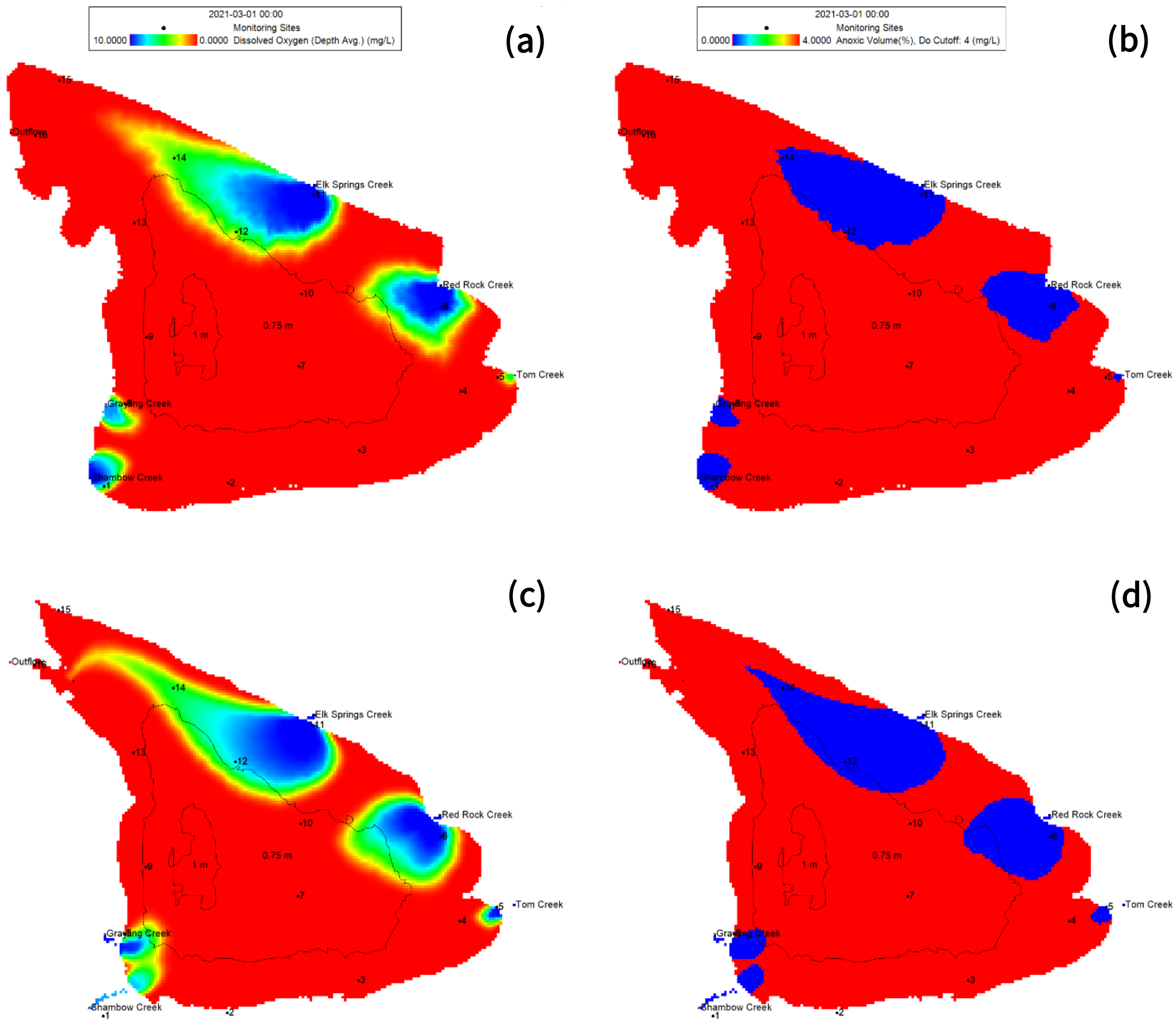


Figure 6. Simulated DO and grayling habitat in URRL using EFDC+ under the existing condition scenario. (a) Predicted oxygen concentrations under the full depth scenario. (b) Predicted permanent winter habitat area (0 ha) associated with the full depth scenario. (c) Predicted oxygen concentrations under the 0.5 m ice-covered condition. (d) Predicted permanent winter habitat area (0 ha) under 0.5 m ice-covered condition. Annual monitoring locations and boundary conditions shown for reference.

From review of the EFDC+ simulation (see hyperlinks), it is apparent that DO collapses sequentially from the exterior of the lake to the interior, due to enhanced influence of SOD on shallow water depths near the shoreline relative to deeper waters. Water column DO is then ultimately consumed near the center of the lake leaving the entire body of the lake anoxic. The modeled deoxygenation sequence could potentially serve as a stranding point for grayling in the center of the lake since it is the last location to deoxygenate, noting it is isolated by anoxic waters preventing migration back to shallower oxygenated waters near the tributary inlets.

During ice cover, especially with larger ice thicknesses, the lake becomes increasingly advective. Under ice depths ≥0.5 m, a preferential flow path develops from Elk Springs Creek to the URRL outlet, where oxygenated waters travel along the shallow northern lakeshore and short-circuit or bypass the deeper areas of the lake. This is believed to occur primarily due to the distance between the Elk Springs Creek inlet and the lake outlet, although Coriolis deflection could partly be a factor. Only a small polygon in the center of the lake contains depths >1 m at any time during maximal ice-cover (≥0.5 m; see contours of 0.75 and 1.0 m, respectively), such that the depth criterion for grayling habitat may have to be revisited by site managers in the future.

Predicted DO concentrations from the proposed Shambow Pond pipeline scenario are shown in **Figure 7**. In this case, spatial DO gradients in URRL are very similar to the existing condition scenario. The primary difference is the habitat created by the pipeline between the 0.75 m and 1.0 m depth contour[4] on the southwestern center of the lake and a concomitant reduction in the oxygenated area immediately around the Shambow Creek inlet. The amount of permanent habitat created depends on the amount of ice present. The pipeline is projected to create 0.3 ha of permanent grayling habitat immediately around the pipeline where hydrodynamics and water-quality computations are not influenced by the thickness of the ice. Assuming 0.5 m of ice cover, the pipeline will create 2.6 ha of permanent winter habitat and provide connectivity between deeper water areas of URRL and the Grayling Creek inlet.

Habitat estimates are larger than those computed by the simple 1-D analytical turbulent diffusion model presented in Flynn (2020), when applying the same eddy viscosity/diffusion coefficients. For example, an ice-covered lake having a eddy diffusivity of 100 m^2/d (0.001 m^2/s), which provides a reasonable fit with the limited observed data available and is similar to the range of 0.0001 to 0.01 m^2/s reported by Bengtsson (1996), would result in approximately 0.2 ha of habitat, which approaches that of the ice-uninfluenced existing condition EFDC+ scenario. Transport of oxygen from the pipeline increases as ice thickness grows and the amount of habitat is projected to increase up to 2.6 ha. An animation of the pipeline DO progression can be downloaded at the following hyperlinks: (a), (b), (c), and (d). It is important to note that DO and habitat estimates for the pipeline may be low as open water will persist longer in fall and exist earlier in spring due to a polynya at the site, although the exact duration is unknown and cannot be calculated.

[4] Depth contours are shown for an assumed thickness of 0.5 m of ice cover.

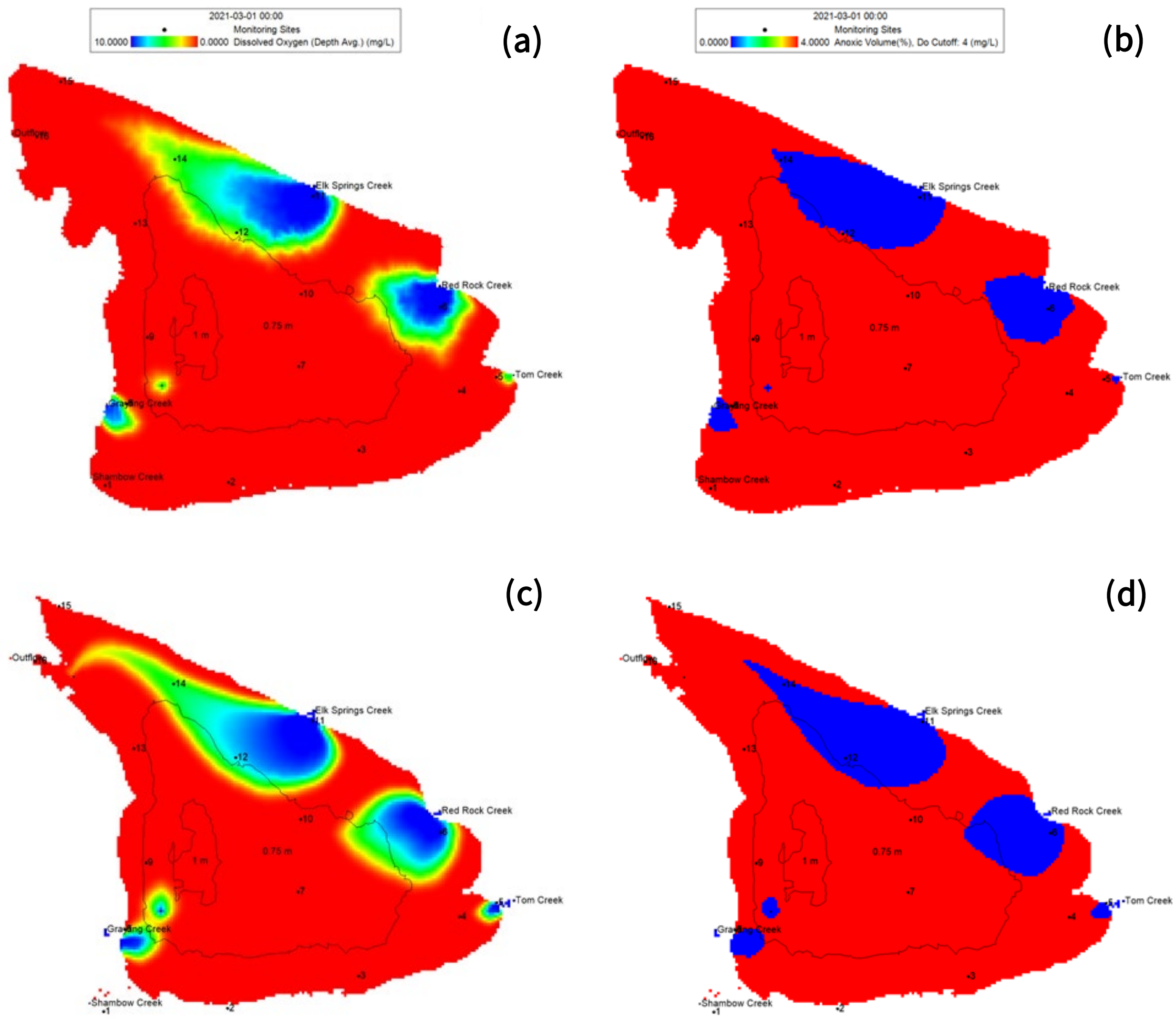


Figure 7. Simulated DO and grayling habitat in URRL using EFDC+ under the Shambow Pond pipeline scenario. (a) Predicted oxygen concentrations under the full depth scenario. (b) Predicted permanent winter habitat area of 0.3 ha associated with the full depth scenario. (c) Predicted oxygen concentrations under the 0.5 m ice-covered condition. (d) Predicted permanent winter habitat area of 2.6 ha under the 0.5 m ice-covered condition. Annual monitoring locations and boundary conditions shown for reference.

Simulation of the Widgeon Pond release is shown in **Figure 8**. Like the other two scenarios, spatial DO gradients in URRL are very similar to the existing condition scenario although the March 01 snapshot captures the near-maximum effect of the simulated February 20, 2021 release where a temporary increase in oxygenated waters is observed just beyond the 0.75 m ice-covered depth contour. Like the pipeline scenario, it does not create any habitat that meets the depth criterion, but it does create a temporary increase of between 1.6 to 13.6 ha of additional oxygenated area for approximately 1 month, although the effect is transient. An animation of the Widgeon Pond release DO progression is found at the following links: (a), (b), (c), and (d).

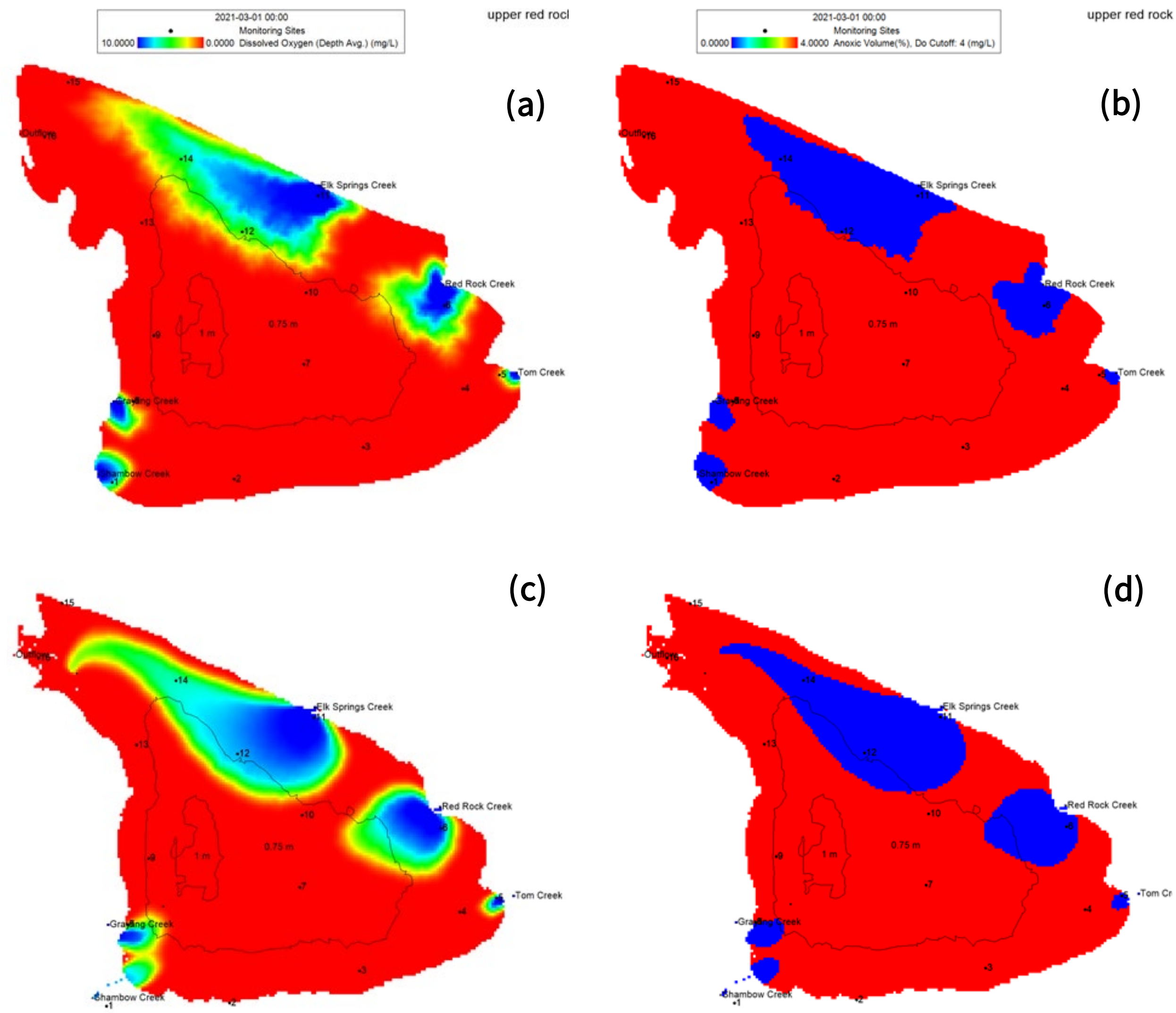


Figure 8. Simulated DO and grayling habitat in URRL using EFDC+ under the Widgeon Pond release scenario. (a) Predicted oxygen concentrations under the full depth scenario. (b) Predicted permanent winter habitat area of 0 ha associated with the full depth scenario. (c) Predicted oxygen concentrations under the 0.5 m ice-covered condition. (d) Predicted permanent winter habitat area of 0 ha under the 0.5 m ice-covered condition. Annual monitoring locations and boundary conditions shown for reference.

A summary of modeled results for each of the alternatives is shown in **Table 2** and conclusions regarding the modeling outcomes are found in the next section. Comparative overlays of the two engineering alternatives are shown in **Figure 9** whereby the difference between each scenario is identified by the light purple shaded areas. It is important to review the animations as this reflects a single point in time, and conclusions can be misleading if only looking at a single snapshot in time.

Table 2. Summary of EFDC+ model results for URRL under various management scenarios.

Scenario [a]	EFDC Model Name	Permanent Critical Condition (March 1) Habitat Created (ha)[b]
Existing condition	rrl_25m	---
Existing condition (ice)	rrl_25m_ice	---
Pipeline	rrl_25m_pipeline	0.3
Pipeline (ice)	rrl_25m_pipeline_ice	2.6
Widgeon Release (ice)	rrl_25m_widgeon	transient increase (0-1.6 ha)
Widgeon Release (ice)	rrl_25m_widgeon_ice	transient increase (0-13.6 ha)

[a] Hydrodynamics and water quality accounting for 0.5 m of ice cover (ice).

[b] >4 mg/L DO, >0.75 m (noting the depth criterion has been relaxed due to ice covered conditions). Otherwise, none of the alternatives provide grayling habitat.

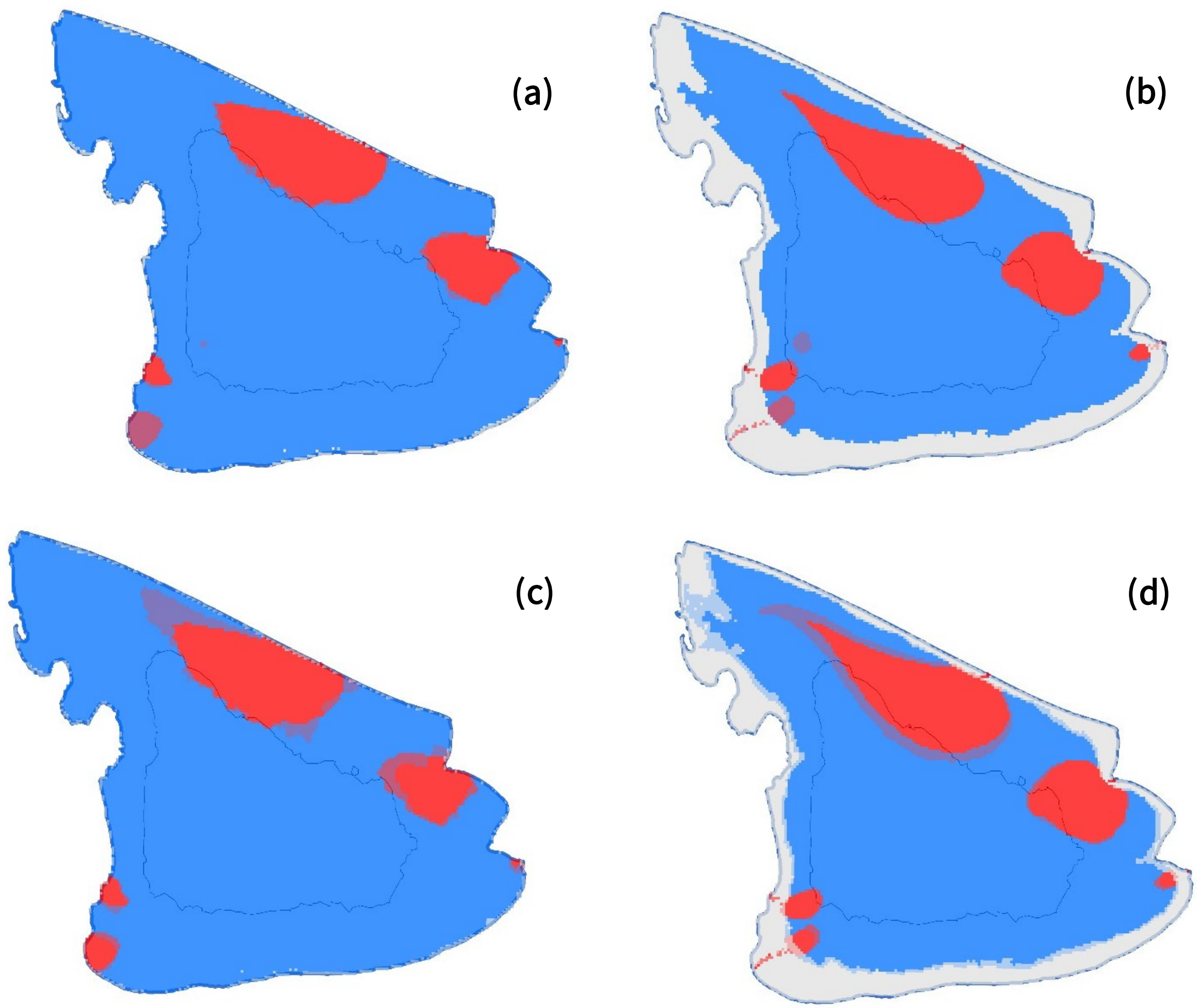


Figure 9. Overlay of simulated DO >4 mg/L for the existing condition and proposed scenarios. (a) Pipeline scenario. (b) Pipeline scenario with ice. (c) Widgeon release scenario. (d) Widgeon release scenario with ice. Grey areas are inactive cells while purplish areas indicate differences between computed values. The 0.75 m depth contour (under ice-covered conditions) is shown for reference.

Conclusions

Although the EFDC+ model provides an indication of wintertime lake dynamics in URRL, it is an approximation that simplifies complex lake DO processes. Data on boundary conditions and initial conditions within URRL are limited. Moreover, the ice simulation method employed is simplistic. Because of this, results are approximations only. Nonetheless, some engineering conclusions can be made about proposed management operations that will benefit grayling in URRL.

First, based on modeling outcomes, there does not appear to be any scenario where the permanent 25-ha habit target (>1 m depth and >4 mg/L DO) can be achieved during a critical wintertime condition. This is supported by EFDC+ modeling as well as an experimental release in 2021 that observationally did not provide any oxygenated habitat outside of 500 m from the Elk Springs Creek inlet and was limited due to shallow water depths. Both engineering solutions are imperfect, but each alternative should be considered to move oxygenated water to the deepest depths possible in URRL.

From a conservation perspective, a no-action scenario is unacceptable. Factors to assess the proposed effectiveness of the two engineering alternatives discussed in this document include the magnitude, duration, and frequency of overwinter habitat for grayling that would be created. The pipeline project will likely create a magnitude of 0.3 to 2.6 ha of oxygenated water between 0.75 and 1.0 m deep depending on critical condition assumptions over the entire winter. This will occur year after year provided the pipeline is operational and kept in a satisfactory condition. Conversely, the release of water from Widgeon Pond creates a larger initial magnitude of oxygenated water at the peak of the pulse release (1.6 to 13.6 ha depending on assumptions), but this is temporary and will last for less than a month based on both modeling and experimental data. No permanent habitat is created in the Widgeon Pond release scenario, which is confirmed by the empirical data from the 2021 release pilot project. Additionally, the bulk of oxygenated water created from the release was near the northwest corner of the lake which was the least-utilized area by over-wintering grayling during a previous radio telemetry study (Davis et al. 2019).

Because the loss of Arctic grayling in URRL would be regrettable, the most effective solution is to implement all possible activities that will improve oxygen levels in deeper areas of URRL. Currently proposed engineering activities are on opposite sides of the lake, are complimentary, and provide relatively independent outcomes. One project is nearly shovel ready (i.e., pipeline design complete, with permitting still required), and releases from Widgeon Pond can be continued in their current fashion to provide short-term increases in oxygenated habitat near the mouth of Elk Springs Creek. Further engineering feasibility evaluations, design, permitting, and construction activities to reinforce the dam and store additional water for release can also be evaluated, although it is unclear whether this will provide additional deep-water habitat continuously, or if water rights exist to sustain the volumes of water necessary to maintain flushing flows. A curtain or lateral dike may also be needed to redirect flows towards the deeper areas of the lake and prevent short circuiting to the lake outlet. Based on these considerations, it is believed neither alternative will achieve the desired habitat target fully. However, implementation of both will assure managers all things practicable have been done for grayling survival.

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