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A CASCADE OF MODELS TO GUIDE RESERVOIR OPERATIONS: APPLICATION ON THE DEADWOOD RIVER SYSTEM

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ABSTRACT

Adaptive management strategies are increasingly being used by resource managers to optimize complex water delivery systems at the scale of entire watersheds. A variety of models have been proposed to evaluate systems in a piecemeal approach that often times operate at different spatial and temporal scales and prove difficult to integrate with associated field data. In the Deadwood River system of Central Idaho, a series of cascading models was utilized to examine potential impacts of reservoir operations on endangered resident bull trout. Results from integrating limnologic, temperature, nutrient, hyporheic, and hydraulic models show that reservoir operations must remain dynamic depending upon the hydrologic conditions (wet vs. dry) present during any given year. Assimilating models that operate at various levels within a watershed will become increasingly important as climate change affects the regional hydrology and water resources operations must adjust to meet current and future demands.

INTRODUCTION

Growing populations and global climate change are challenging resource managers' current operations policies via increasing demand and greater uncertainty of hydrologic inputs [Kingsford, 2011]. Future policies will be forced to have greater flexibility and operate with real-time information in order to maximize beneficial use within their delivery systems [European Commission, 2012]. These complex systems will require modeling parameters at varying spatial and temporal scales in order to advise managers on certain parameters of interest. This proves difficult at the watershed level as inputs and outputs must be assimilated into a global transport model. The current state of models prevents a global solution and independent model results must be fed into lower level nested models as is currently done in downscaling global climate models for regional use.

A cascading model approach was tested in the small, mountainous Deadwood River Basin in Central Idaho in order to optimize U.S. Bureau of Reclamation dam operations for beneficial uses. Beneficial uses included contractual irrigation water deliveries, minimum instream flows during winter months, and enhancement of endangered bull trout habitat above and below the reservoir. Calculating the physical components of bull trout habitat required a limnologic model within the reservoir that provided inputs to the river system below the dam. The limnologic model included hydrology, temperature, nutrients and biological activity, which was simulated for dry, average and wet years. Simulations were then input into nested hydraulic models for the river system below the dam. These hydraulic models utilized a MIKE11 1D model for overall transport and load calculations and results were further fed into sub-models for temperature, nutrients, hyporheic exchange, and MIKE21 2D hydraulics for specific areas [DHI, 2009]. These models required accurate and distributed data in addition to high-resolution topography of both submerged and emergent land- and river-scapes. Here we show that new field tools such as the Experimental Advanced Airborne Lidar (EAARL) sensor and multi-sensor data collection equipment with radio connection can provide the support information and ancillary data for running a set of cascading models that represent the complex behavior of a reservoir-stream system [McKean et al., 2009; Tonina et al., 2011].

STUDY SITE

The Deadwood River is located in the granitic Central Idaho batholith and drains the mountainous area around Deadwood Summit. Historically, the river ran from its peak elevations (2625 m) in the basin, for approximately 64 km to its confluence with the South Fork Payette River (Figure 1). Since 1931, the river has been separated into two distinct reaches by the Deadwood Dam and Reservoir complex. The reservoir is operated for irrigation storage and flood control. The dam does not generate hydropower except for a small system to power remote communications for dam operation and data transmission. The dam has deep intakes within the reservoir hypolimnion and does not have the capability for selective withdrawal (the ability to release water from various depths in the reservoir). Deadwood Dam and Reservoir are at an elevation of 1625.8 m (normal, non-spill reservoir capacity) and has a capacity of 189,956,205 m^3 when full. The Deadwood River above Deadwood Dam (Upper Deadwood River) flows unimpeded approximately 26 km from Deadwood Summit (2091 m) to the Reservoir. Air temperatures range annually from -20 °C to 30 °C, with a normal diel range of 15 °C. Precipitation is snow dominated, with an average of 72.2 cm near the reservoir and 140 cm at Deadwood Summit. In the spring, snowmelt throughout the basin contributes large and significant amounts of flow to the river, which is held over for irrigation deliveries during the summer months.

Below Deadwood Dam, the Lower Deadwood River flows from an elevation of 1584 m approximately 38 km to the confluence with the South Fork Payette River, at an elevation of 1128 m. The lower river lies in a mountainous canyon that is mostly confined, with limited floodplain features. Since dam closure, no bankfull flows have occurred in the lower river system and channel substrate consists of large cobbles and boulders. The total watershed area (both above and below the dam) is approximately 614 km^2.

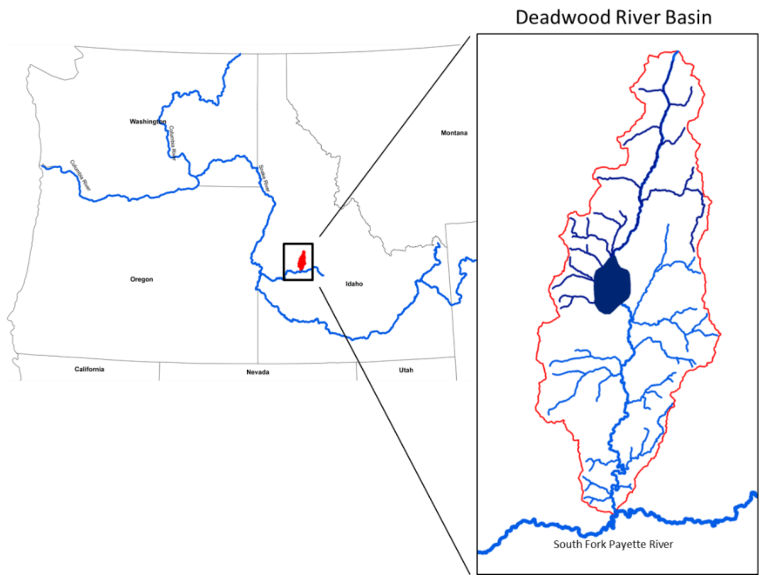

Figure 1. The Deadwood River Basin in relation to the larger Snake and Columbia River Basins

METHODS

Lake monitoring occurred from 2007-2011 on the Deadwood Reservoir using a combination of manual sampling and deployed limnologic sensors. The stationary sensors were located in 3 representative regions in the reservoir and continuously monitored the environmental parameters listed in Table 1. Manual sampling of constituents (Table 1) occurred weekly or biweekly depending upon the location and measured parameter. The buoyed sensors were removed during the winter to avoid damage from ice cover; however manual sampling was periodically performed during ice cover through bore holes.

Table 1. Monitored and modeled parameters in the Deadwood Reservoir

Continuous water column profiles	**Manual sampling variables**
Water temperature	Nitrite + nitrate, dissolved
Dissolved-oxygen concentration	Ammonia, dissolved
pH	Orthophosphate, dissolved
Conductivity	Total phosphorous
Chlorophyll-a fluorescence	Total Kjeldahl nitrogen
Barometric pressure	Organic carbon, dissolved
Secchi depth	Total organic carbon
	Turbidity
	Chlorophyll-a/ Pheophytin-a
	Silica, dissolved

The limnologic model utilized a coupled hydrodynamic-ecological model called ELCOM-CAEDYM [Hodges et al., 2000; Gal et al., 2009] to capture the physical and ecological characteristics of the reservoir for certain management scenarios. The reservoir was modeled at

100 m by 100 m grid spacing for a 14 month duration beginning November 1. Simulations were run for dry, average, and wet hydrologic years with varying degrees of winter discharge released through the dam to examine how winter flows affected reservoir processes. Time series data of pertinent parameters at the dam outlet were output directly to the downstream river models as upstream boundary conditions.

Watershed topography was surveyed with the EAARL sensor in 2007, which provided a continuous high-resolution 3 m by 3 m digital elevation model of the stream bathymetry and surrounding terrestrial topography. The bathymetry was used to support a 1-dimensional hydraulic model (DHI MIKE11) with closely spaced cross-sections extracted every mean channel width (30 m) from the bathymetry. This allowed unprecedented resolution of the flow processes.

The 1D hydraulic model was coupled with a temperature module to simulate a 14 month-long hydraulic and temperature regime for variable hydrologic conditions, dry, average and wet [Benjankar et al., 2013]. Tributary inputs were monitored over the full domain of the model and accounted for as instantaneously mixed inputs. Water surface elevations and fluxes were output to a series of nested sub-models at various locations of interest along the model domain to further investigate physical bull trout habitat parameters. Floodplain connectivity was evaluated for potential spring flood discharges at sub-bankfull to overbank conditions [Tranmer et al., 2013]. Hyporheic exchange was evaluated via pore water fluxes to check for proper surface-subsurface water exchange for macroinvertebrates and bull trout spawning requirements [Marzadri et al., 2012]. A 2-dimensionsal MIKE21 hydraulic model was used to examine potential refugia at varying dam discharges to determine if critical depths and velocities are reached that would prohibit upstream bull trout migration. River hydraulics were also input to the FLUX multiple regression nutrient model [Walker, 1996] in order to monitor nutrient loads in the lower river.

RESULTS

Dam operations must be adjusted for wet and dry hydrologic years in order to optimize physical indicators of sustainability concerning bull trout in the basin. Results from the reservoir modeling indicate that substantially different processes occur in the reservoir during years of different hydrologic inputs with potential benefits originating from both cases. Dry years have lower pool volumes that thermally stratify early in the spring and turnover earlier in the irrigation season, providing moderately productive and very warm river temperatures that extend through the late summer and into the fall. In contrast, wet years maintain greater pool volume that stratifies later in the spring and remains stratified longer into the fall. Figure 2 is an annual time series of temperature throughout the water column near the dam outlet that depicts the thermocline during reservoir drawdown. This period of extended stratification during a wet year leads to anoxic conditions in the hypolimnion that recycles nutrients within the sediments. When the fall turnover does occur late in the season, elevated nutrient concentrations are convected into the water column prompting a phytoplankton algal bloom within the reservoir that is further exported to river. This late season flux of nutrients and biotic material through the dam provides a substantial growth opportunity for bull trout prior to reduced wintertime metabolic rates.

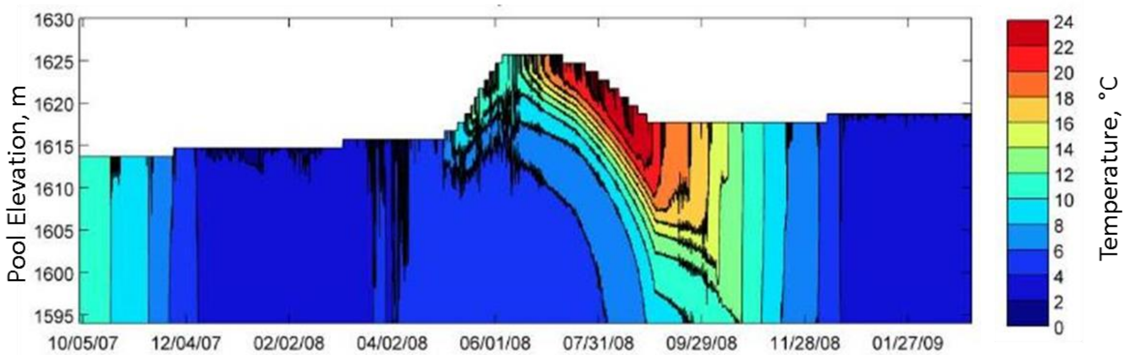

Figure 2. Example time series of reservoir pool temperature profile drawdown near the dam outlet for a moderately wet hydrologic year.

As river performance depends upon the upstream reservoir conditions, the temperature regime changes with the hydrologic year and the time of season. During dry years, spring releases from the reservoir are abbreviated and river temperature depends heavily on tributary inputs below the dam. This leads to a mostly natural temperature signal in the spring that increases in the middle of the summer to above average temperatures when the warm pool is drawn down to the dam intake and tributary inputs are reduced (Figure 3). These warmer water temperatures persist later in to the season and can be extended by releasing water after irrigation demand ends. In contrast, wet years provide more consistent temperatures that increase to only a fraction of the normal temperature regime (Figure 3) due to the increased pool volume. The greater volume of water maintains a stable thermocline late into the season, providing instream temperatures near 5 °C throughout the spring and summer irrigation period.

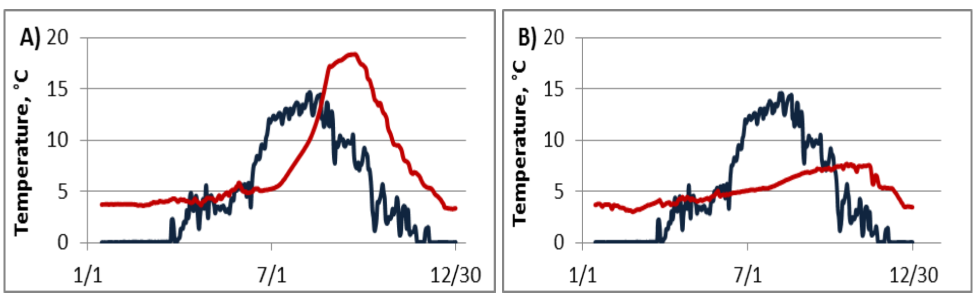

Figure 3. Natural (blue) vs. dammed (red) water temperature regime for A) dry years and B) wet years

Nutrient concentrations in the reservoir are products of temperature related mixing phenomena and primary productivity, which fluctuate seasonally from tributary inputs during snowmelt runoff and nutrient recycling during the rest of the year. High nutrient concentrations occurred in the spring from increased nutrient loading during snowmelt, as particulate constituents were mobilized from the hillslopes to tributaries, and internal lake mixing that brings nutrient rich water and sediment from the hypolimnion. Water quality parameters improve once the thermocline is stabilized in the reservoir and phytoplankton utilizes available nutrients for primary productivity. During dry years, lower pool volumes permit higher water temperatures and early fall mixing that reaerates the hypolimnion and produces a mild phytoplankton bloom lasting until early October. Wet years allow the thermocline to persist longer into the season and collect higher nutrient concentrations in the hypolimnion; therefore when turnover does take place substantial phytoplankton blooms can last until November.

Nutrients and biological activity in the river are dominated by reservoir processes and materials exported from the hypolimnion. Nutrients exported from the reservoir diminish as they progress downstream due to dilution from tributary inputs and uptake from primary production. Primary producers within the lower river system changed over the course of the river from phytoplankton at the dam outlet to a periphyton dominated community susceptible to seasonal senescence and sloughing near the river's end. Chlorphyll-a concentrations in the water column were below the analytical detection limit for most of the year, with the exception of the fall spike from reservoir turnover.

Hyporheic investigations in the lower river found that discharge had negligible effects on hyporheic processes at low winter flows (less than few m^3/s). High discharge dam releases have some effect on hyporheic residence time (the time downwelled stream water spends within the streambed sediment before re-emerging into the stream) but negligible effect on fluxes. Macroinvertebrate populations were examined in relation to hydraulics and hyporheic fluxes to look for disruption of the ecosystem food base. Population distress in species richness and diversity were apparent directly below the dam, but disappeared after few kilometers downstream.

DISCUSSION

This study was designed to guide reservoir operations in the Deadwood River system in order to support the physical habitat indicators required for endangered species. These types of multidisciplinary investigations will become increasingly common in the future in order to manage water resources sustainably at the watershed scale. The availability of real-time data acquisition in instrumented basins will provide managers with the ability to make on-the-fly decisions and optimize beneficial uses with regards to water resources. For the Deadwood River Basin, a scientific team that included biology, limnology, hydrology, and hydraulics was required to design, model and interpret the data collection and results. As sophistication builds across areas of expertise, models will integrate separate modules that will facilitate understanding of complex natural systems.

The Deadwood River system responds to annual hydrologic conditions in a complex manner that must include hydrologic variables in addition to terrestrial pressures of forest fires, avalanches, landslides, and debris flows. Calibrated models, along with on-line data transmitting field instrumentation, have provided the ability to manage this system with respect to real-time data and make decisions for the specific water year subject to contractual water deliveries. Potential benefits to managing bull trout habitat within the Deadwood River system exist for both ends of the hydrologic spectrum and can be optimized by actively adapting dam operations.

Dry hydrologic years have lower reservoir pool volume and drawdown occurring earlier in the year, providing warm water to the dam outlets and the lower river section. It is advised that spring releases are limited so as to retain as much water as possible in the reservoir during the irrigation season to facilitate habitat for migratory bull trout in the upper basin and maintain downstream river temperatures near optimal for endangered species. Below the dam, bull trout habitat can be enhanced by releasing warm water to the lower river later in the season to extend growth period prior to winter conditions.

Wet hydrologic years have greater flexibility to meet natural hydraulic conditions, however are limited by temperature regime. Greater reservoir pool volume will facilitate conditions for migratory species that reside in the reservoir and spawn in the upper basin tributaries. Greater hydrologic inputs allows for simulated spring floods to modify in-stream habitat conditions when extra water is available during wet and normal hydrologic years. High pool volumes maintain cold, anoxic conditions in the hypolimnion that facilitate recycling of nutrients within the bed sediments. When reservoir turnover occurs in the fall, those elevated nutrient concentrations are then exported to the river at the end of the season. While cold instream temperatures are maintained throughout the irrigation season during a wet year, enhanced productivity in the fall can provide bull trout with increased feeding opportunities.

CONCLUSIONS

New tools and instruments are becoming available to scientists and managers to provide inputs for numerical models. Cascading models will become more common for understanding complex systems such as the interaction between reservoir, stream and their dependent ecosystems. Here we present a series of cascading models employed in the Deadwood River Basin in Central Idaho, USA in order to guide reservoir operations to enhance endangered bull trout habitat and optimize beneficial uses within the watershed.

Results show that reservoir and river processes differ depending upon the hydrologic year (wet vs. dry) and flexible operations are required to maximize benefits. Further monitoring of bull trout populations is required to ensure active reservoir operations are not detrimental; however, extension of late season flows provides an opportunity to enhance habitat for species of interest.

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