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Research article

Dam operations may improve aquatic habitat and offset negative effects of climate change

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ABSTRACT

Dam operation impacts on stream hydraulics and ecological processes are well documented, but their effect depends on geographical regions and varies spatially and temporally. Many studies have quantified their effects on aquatic ecosystem based mostly on flow hydraulics overlooking stream water temperature and climatic conditions. Here, we used an integrated modeling framework, an ecohydraulics virtual watershed, that links catchment hydrology, hydraulics, stream water temperature and aquatic habitat models to test the hypothesis that reservoir management may help to mitigate some impacts caused by climate change on downstream flows and temperature. To address this hypothesis we applied the model to analyze the impact of reservoir operation (regulated flows) on Bull Trout, a cold water obligate salmonid, habitat, against unregulated flows for dry, average, and wet climatic conditions in the South Fork Boise River (SFBR), Idaho, USA.

Our result showed that regulated and unregulated flows had similar aquatic habitat quality regardless of climatic conditions except for the summer period, when habitat quality was higher in the regulated than unregulated flow scenario due to lower stream temperature in the former than latter case, underpinning the importance of thermal regimes. Current dam operation provides a suitable habitat for Bull Trout year-round but blocks the migration corridor to a portion of the headwater tributaries. Conversely, unregulated flows had an unsuitable thermal regime during the warm summer period but fish were able to migrate to cooler headwater streams. Dam management maintained high quality habitat during a series of drought climatic years, thus we suggest dam management may be used to offset or mitigate impacts of future climatic variability and climate change on aquatic habitat.

1. Introduction

Dams are beneficial to fulfill food and energy demand as well as for recreation, flood control and environmental water management. However, their management affects hydrological processes, alters stream flow, sediment transport, water temperature, and potentially habitat loss and reduction of aquatic biodiversity (Bunn and Arthington, 2002; Poff et al., 1997; Ward and Tockner, 2001, Benjankar and Yager, 2012). Typically, regulated flow decreases magnitude of peak flows and increases minimum base flows. Dam management impacts stream thermal regimes spatially and temporally beside hydrological alterations (Angilletta et al., 2008; Preece and Jones, 2002; Steel and Lange, 2007). However, the magnitude of its effects depends on many factors such as size and purpose of the dam, magnitude of flow release from the dam and local hydraulics (Lessard and Hayes, 2003).

Not only human influences, but also gradually changing climate may increase precipitation variability and extreme events, e.g., droughts and floods (IPCC, 2013) and decreased snowpack, thereby

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altering stream hydrology and thermal regime (Dettinger and Anderson, 2015; Isaak et al., 2010; Sohrabi et al, 2013). Extreme climatic events are expected more frequently with global climate change (Diez et al., 2012). Furthermore, changing climate will impact the thermal regime of river systems as well as shift the availability of certain aquatic habitats selected by different species (see, Battin et al., 2007; Perry et al., 2005). However, reservoir management may mitigate or prevent some detrimental effects of climate change on the downstream aquatic habitats.

Following previous studies, which showed that reservoir management could provide an opportunity to manipulate water temperatures via flow release, to accommodate aquatic species requirements (Null et al., 2013; Yates et al., 2008), we test the hypothesis that dam management could help mitigate some of the impacts caused by climate change on stream flows and temperature downstream. We use a process-based integrated model, which couples catchment hydrology, hydraulics, water temperature and fish habitat models to quantify the impacts of dam operation on aquatic habitat quality for different climatic conditions and compare the habitat quality between regulated and unregulated (natural flow and thermal regime) flows.

To address our goal, we used the South Fork Boise River (SFBR) (Idaho, USA) as a study site, whose hydrology is regulated by Anderson Ranch Dam and reservoir operation. The reach is a critical rearing habitat for Bull Trout, which is classified as a threatened species and whose habitat is federally protected through the Endangered Species Act (ESA). We hypothesized that dam management changed fish habitat downstream in turn altering the behavior of Bull Trout and their use of the area. We evaluated reservoir-operation impacts on aquatic habitat under extreme climatic conditions such as droughts, which may persist for several years and floods.

2. Methods:

2.1. Study area

The South Fork Boise River (SFBR), located between Anderson Ranch and Arrowrock Reservoir is ~45 km long and, has average width of 41 m and slope of 0.0043 (Fig. 1). The basin hydrology (drainage area of 3382 km^2) is snowmelt dominated, with snowmelt runoff occurring from late March to May. The runoff periods are followed by warm, dry summers, which result in decreased stream flows. Stream flows are regulated by Anderson Ranch Dam for irrigation, flood control and power production. The regulated maximum flows occur in May during normal water years when the reservoir fills. The river can be divided into two segments a 23 km long (upper) south open canyon reach, which is site for this work, and a 22 km long (lower) north narrow canyon reach. The study reach has pools, riffles and runs with several braided sections and side channels. Most of the side channels are ephemeral, connected wilth the main channel during high flows, while some side channel are connected throughout the year.

2.2. Integrated model

We used an integrated modeling framework (Benjankar et al., In Preparation) that couples catchment hydrology and water temperature (Sohrabi, 2016; Sohrabi et al, 2017), hydraulics, water temperature and biological (fish habitat) models to analyze the impacts of dam operation on aquatic habitats. For hydrologic model to estimate the relationship between rainfall and run-off, we used Penn State Integrated Hydrology Model (PIHM), is a fully coupled and semi-distributed hydrologic model (Kumar et al., 2013). The model simulates hydrological processes, including evapotranspiration, surface and subsurface flow and stream flows from soil moisture of unsaturated zone and groundwater table. The hydrologic model was calibrated for water year 2010 at Featherville gage station and validated the model for 2006, 2007 and 2013 water years at Featherville and for 2006, 2007, 2010 and 2013 water years at Anderson Ranch Dam (Fig. 1). Percent BIAS (PBIAS) were less than 4% at both gage stations and for all years, except 2006 water year. Errors were 21% and 23% at Featherville and Anderson Ranch Dam gage stations, respectively for the year 2006 (Sohrabi, 2016).

We developed a one-dimensional (1D) and two-dimensional (2D) hydrodynamic model using DHI software MIKE 11 (1D) (DHI, 2011a) and MIKE 21 (2D) (DHI, 2011b) to simulate water temperature and hydraulics (flow depth and velocity). Hydraulic models are constrained with upstream (discharges) and downstream (water surface elevations) boundary conditions and 2 m by 2 m resolution digital elevation model (DEM) of both terrestrial and submerged topographies surveyed with the aquatic-terrestrial Experimental Advanced Airborne Research LiDAR (EAARL) (McKean et al., 2009). The 1D model was supported by high-resolution cross-sections extracted every 30 m from the DEM. Hydrograph and thermographs were recorded at the reservoir outlet and were used as boundary conditions for hydraulic and temperature models for the regulated case. For the unregulated case, we used the thermograph of the SFBR upstream of the reservoir.

The 1D hydraulic and temperature model extends the 45 km reach from Anderson Ranch Gage Station to the Neal Bridge Gage Station (Fig. 1). The model was calibrated by comparing simulated and measured water surface elevation (WSE) for discharges 8.5 and 45.6 m^3/s. Root mean square error (RMSE) for 8.5 and 45.6 m^3/s were 0.12 m at random locations. For model validation, we compared simulated and observed WSEs and water wave-travel at three locations: Cow Creek Bridge, Private Bridge and Canyon section (Fig. 1). The model predictions matched the patterns of water surface elevations at all three stations and RMSEs were 0.02–0.15 m. Comparisons between simulated and measured temperatures at Cow Creek Bridge, Danskin Bridge, Private Bridge and Canyon section showed RMSE of 0.70–1.43 °C, which are comparable with other studies (Hébert et al., 2015; Loinaz et al., 2013; Wang et al., 2010).

We developed a 2D hydraulic model for the entire study site (23 km) with a 2 m grid size DEMs (Fig. 1). The 2D model was calibrated by comparing observed and predicted WSEs (at several locations along the reach) and flow velocities (at 2 cross sections) measured at 8.5 m^3/s discharge. The model was validated with WSEs at discharges of 17 and 46 m^3/s, and with velocities measured along the reach at the discharge of 17 m^3/s because of safety concerns at higher flows. RMSEs for WSE were between 0.18 and 0.2 m, whereas velocity RMSEs ($R^2 = 0.77$) were between 0.07 and 0.25 m/s. The simulated flow wave matched the observed pattern fairly well, which strengthens our confidence in the developed model. The performances of both WSE and velocity for calibration and validation flows were comparable to those reported by other studies (e.g., Boavida et al., 2013; Guay et al., 2000; Pasternack et al., 2004; Tarbet and Hardy, 1996).

We developed a fish habitat model in ArcGIS using simulated hydraulic variables of water depth and velocity, water temperature and univariate rearing habitat preference criteria for Bull Trout (Fig. 2a). Water depths and velocities for rearing habitat preference curves were adopted from previous studies (Lewis River workshops, 2000; WDFD, 2004). Observed water depths and velocities at Bull Trout observed locations in the SFBR system fitted fairly well with the adopted univariate curves. Geometric product of the individual suitability indices, *SI*, of physical parameters of water depth and velocities were used to determine the habitat