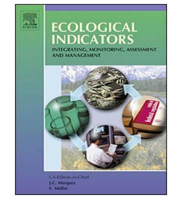
Ecological Indicators 114 (2020) 106336

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind



Extending water resources performance metrics to river ecosystems

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ARTICLE INFO

Keywords:
Water resources
Reliability
Sustainability
River ecosystem

ABSTRACT

A persistent challenge in integrated water management is the ability to accurately evaluate human and ecological tradeoffs. Two-dimensional (2D) hydraulic models are frequently used to evaluate water management alternatives concerning aquatic species physical habitat needs or preferences. Recent studies have assessed the timing or duration of suitable habitat conditions, but no standardized approach exists to integrate and interpret ecohydraulic model outputs within a water management framework. Such an approach is needed to maximize the information obtained from model outputs and to facilitate communication between river scientists and water managers. This study presents a general framework to aggregate and summarize 2D hydraulic model outputs by adapting the traditional water resources metrics of reliability, resilience, vulnerability, and sustainability. Just as these metrics are typically used to quantify distinct aspects of water resources performance, applying them to ecohydraulic conditions facilitates interpretation of ecological performance and human-ecosystem water management tradeoffs. This paper examines the utility and limitations of the proposed framework and metrics in a simple application to fall-run Chinook salmon in a typical Mediterranean-montane stream.

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1. Introduction

Performance of a water resources system is often well-defined in the operation of a dam or diversion. A specific volume and timing of water is generally desired to maximize clear objectives (e.g., irrigation demand, electricity production), with a unit of water providing a unit increase in performance up to the demanded volume. Performance can be described by the percentage of time objectives are met (reliability in time), the percentage volume that is supplied (reliability in magnitude), the ability to recover from a deficit (resilience), and the deficit magnitude (vulnerability) (Hashimoto, Stedinger, and Loucks, 1982; Loucks, 1997). For river ecosystems, a unit of water does not always provide the same ecological benefits depending on whether physical or biological thresholds are exceeded at a specific time of year (Rosenfeld, 2017). A persistent challenge is the ability to accurately evaluate ecological performance across water management scenarios to improve allocation of freshwater resources across objectives (Horne et al., 2016).

Ecological performance is often quantified based on *deviations from the natural flow regime* (e.g., Richter et al., 1996; Gippel et al., 2009) given the prevalence of hydrologic data (Eng et al., 2017) and the established ecological significance of the natural flow regime (Poff et al., 1997). For example, Pauls et al. (2016) evaluated ecological performance based on changes in streamflow magnitude, frequency, and duration under alternative management scenarios. Vogel et al. (2007) and Gao et al. (2009) proposed the eco-deficit and -surplus metrics to concisely quantify deviations from the unimpaired flow - duration curve. However, flow-based metrics cannot capture the complex, often non-linear physical habitat responses to flow because they assume a direct relationship between streamflow and ecological response (Rosenfeld, 2017).

Numerous hydraulic habitat conditions (e.g., water depth and velocity) and thresholds (e.g., sediment entrainment, floodplain inundation) have been identified as critical controls on river ecosystems. Aquatic species are adapted to how physical habitat conditions change through time and when, how often, and by how much physical thresholds are exceeded (Rosenfeld, 2017). Because aquatic species needs and life-history strategies are more directly and mechanistically linked to these hydraulic patterns and processes than to streamflow, performance metrics that assess deviations from natural physical habitat suitability patterns may be more ecologically significant than metrics that only consider deviations from natural hydrology.

Several recent studies have used two-dimensional (2D) hydraulic models to evaluate ecological performance of water management scenarios. 2D hydraulic models simulate the spatial distribution of hydraulic conditions (e.g., water depth, flow velocity) and, when

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https://doi.org/10.1016/j.ecolind.2020.106336
Received 9 December 2019; Received in revised form 6 March 2020; Accepted 20 March 2020
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combined with species- or process-specific hydraulic suitability curves, can explicitly capture non-linear relationships resulting from flow interactions with channel morphology (Lane et al., 2018; Vanzo et al., 2016; Crowder and Diplas, 2006; Harrison et al., 2011; Bruno et al., 2013; Carolli et al., 2017; Cioffi and Gallerano, 2012; Szemis et al., 2013). 2D hydraulic models have been shown to be sufficient for most ecohydraulics applications (Grant and Kramer, 1990; Leclerc et al., 1995), and limit computation and parametric requirements compared to 3D models (Pasternack and Senter, 2011). Carolli et al. (2017) assessed monthly and annual changes in the proportion of time suitable hydraulic habitat conditions were provided for marble trout under alternative water management scenarios. Escobar-Arias and Pasternack (2010) evaluated the number of days in each year that suitable habitat conditions were provided for fall-run Chinook salmon life-stages under alternative water management scenarios and channel types. These and similar studies aggregate complex ecohydraulic suitability information, but only assess the *timing* of suitable habitat conditions.

Additional performance metrics that can be extracted from 2D hydraulic model outputs such as reliability in magnitude, resilience, and vulnerability provide distinct and complementary information about ecological performance. Just as multiple metrics are commonly used to assess traditional water resources performance, there is a need to evaluate multiple dimensions of ecological performance o improve understanding of human – ecological tradeoffs. Here, we propose a general framework to apply the well-established water resources concepts of reliability, resilience, vulnerability, and sustainability (RRVS) to hydraulic model outputs to meet this need. Specifically, this study will:

- Outline a general framework for aggregating 2D hydraulic model outputs in space and time to summarize complex, non-linear hydraulic responses to flow with respect to specific ecological objectives.
- Propose a set of eco-Reliability, -Resilience, -Vulnerability, and -Sustainability (eco-RRVS) metrics to quantify ecological performance of water management alternatives.
- Evaluate the utility and limitations of this framework and eco-RRVS metrics in an application to fall-run Chinook salmon in a typical Mediterranean-montane stream.

Lane et al. (2018) proposed a framework to evaluate ecosystem functions related to hydraulic conditions under alternative water management scenarios. The current study goes one step forward and contributes to developing a general framework to estimate the ecological performance of alternative water management strategies by applying well-established water resources performance criteria (reliability, resilience, vulnerability, and sustainability) to hydraulic model outputs.

2. Methods

2.1. General framework

Application of water resources performance metrics to ecological objectives at any location requires five key steps (Fig. 1): (1) Develop a sampling frame. The spatial extent of the reach, the spatial resolution at which ecological objectives will be evaluated, and the time step of analysis must be defined upfront. A set of discrete discharges that encompass the streamflow variability over which performance metrics will be evaluated must also be defined. (2) Define the desired ecological objectives. Ecological objectives refer to specific physical processes or hydraulic habitat conditions, usually defined in terms of depth and velocity ranges, that relate to individual species, life-stages, or communities of interest in the stream reach under study. Suitable hydraulic conditions must be clearly defined in terms of the magnitude (hydraulic thresholds) that a given objective must exceed and the time period (henceforth bioperiod) and spatial boundary in which these conditions are ecologically relevant. (3) Aggregate 2D hydraulic conditions *in space* to concisely quantify performance of an ecological objective for a single discharge. The result is a single dimensionless value that aggregates the spatial distribution of depth and velocity conditions over the study reach. For example, a discharge may generate a distribution of modeled depths and velocities that results in 50% of the study area providing suitable conditions for salmon spawning. (4) Define the reference condition bounds differentiating satisfactory from unsatisfactory performance of an objective in each time step over the bioperiod. The reference conditions against which performance is measured must be clearly articulated and quantified. (5) Finally, define how to aggregate dimensionless ecological performance *in time* to generate long-term summary performance metrics. That is, develop the rules to reduce a complex ecological objective down to a set of simple dimensionless metrics for a given river channel and flow regime.

There are spatial and temporal distinctions between the standard and eco- RRVS frameworks worth noting. Spatially, standard RRVS metrics are aggregated over time at discrete locations in space, such as the diversion point of an irrigation service area. For eco-RRVS metrics, there is an extra step needed to associate a performance value with a discrete location, which is to aggregate the spatial distribution of hydraulic conditions (e.g., depth or velocity) occurring over a given stream reach into a single dimensionless value (Fig. 1, *Evaluate suitability in space*). Temporally, standard RRVS metrics are often calculated relative to established volumetric delivery targets for a particular date or time period, whereas eco-RRVS metrics seek to quantify performance relative to uncertain targets that are highly variable through time, usually depending on the date, season, and climate conditions (Fig. 1, *Evaluate suitability in time*).

2.2. Case study application

A simple application to a typical Mediterranean-montane stream is used to demonstrate the proposed framework. Mediterranean-montane river systems are highly seasonal and have been heavily manipulated for water management objectives including hydropower, water supply, flood regulation, and sediment control (Moir and Pasternack, 2008). In the California Sierra Nevada, USA, many of these rivers support federally- and state-protected native aquatic species including fall- and spring-run Chinook salmon and Central Valley steelhead. These native species are adapted to specific physical habitat conditions associated with predictable seasonal changes in the flow regime (Gasith and Resh, 1999; Yarnell et al., 2015). This study focuses on fall-run Chinook salmon (*Oncorhynchus tshawytscha*) as an important species in Sierra Nevada streams that has well-established hydraulic habitat preferences, but the framework could be applied to other species for which hydraulic preferences have been established. The following section describes an application of the five general steps above to this case study.

2.2.1. Develop a sampling frame (Step 1)

The spatial scale of hydraulic analysis has a strong influence on relationships with ecological response (e.g., measures of species abundance, dispersal and other population dynamics) (Zavadil and Stewardson, 2013; Frissell et al., 1986) and should be selected based on the ecological objectives of interest. This study considered a one-meter grid resolution hydraulic model and resulting depth and velocity rasters because this spatial resolution captures the sub-reach scale hydraulic variability that has been consistently linked to aquatic species response (Frissell et al., 1986; Kammel et al., 2016). Applying this spatial resolution requires one-meter digital terrain data as input. A daily time-step is used here because daily variability in physical habitat conditions is commonly linked to aquatic species response (Olden and Poff, 2003). Applying this time-step requires daily streamflow as input. While coarser time-steps could be used within this framework, the daily time-step is a typical scale that aquatic habitat and water management are

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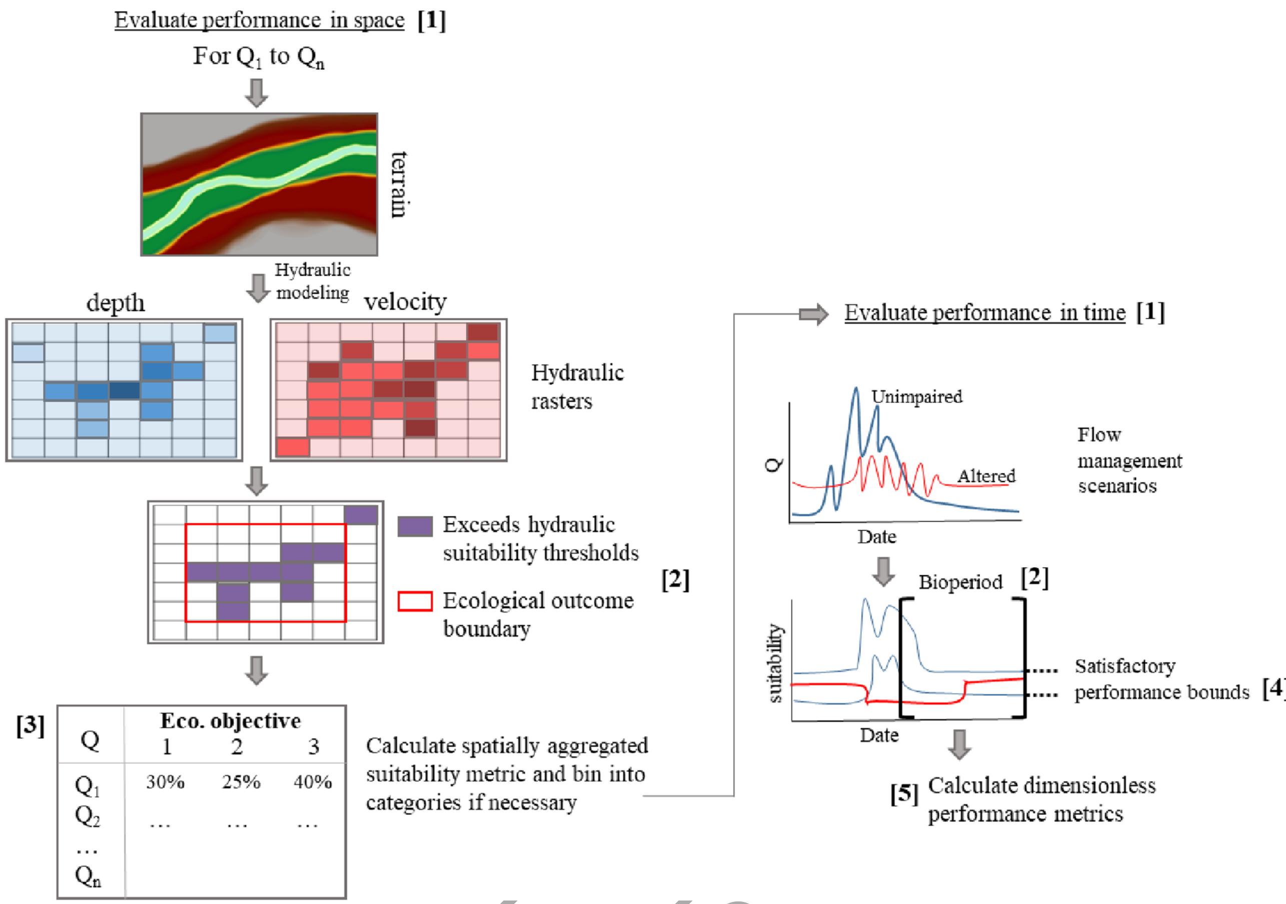

Fig. 1. General framework to summarize 2D hydraulic model outputs and assess ecological performance. Key steps include to: (1) develop a sampling frame, (2) define ecological objectives, (3) aggregate in space, (4) define satisfactory performance bounds, and (5) aggregate in time.

considered over so other time-steps should be well justified.

2.2.2. Define ecological objectives (Step 2) and how to aggregate performance in space (Step 3)

Three ecological objectives for fall-run Chinook salmon were selected for assessment based on available hydraulic preferences (Escobar-Arias and Pasternack, 2010; Lane et al., 2018; Gostner et al., 2013): river bed spawning (1) preparation and (2) occupation and (3) hydraulic habitat diversity. These ecological objectives are described below, including suitable hydraulic conditions, relevant bioperiod, and how ecological performance is aggregated in space.

2.2.2.1. River bed spawning preparation and occupation. To spawn, these fish require (1) *bed preparation,* high shear stress capable of mobilizing the active layer ($\tau_0^* > 0.03$), to rejuvenate sediment while salmon are migrating (bioperiod: Apr 1–Sep 30), and (2) *bed occupation*, low shear stress ($\tau_0^* < 0.01$), to maintain a stable bed when salmon are present (i.e., spawning, incubation and emergence stages) (bioperiod: Oct 1–Mar 31) (Escobar-Arias and Pasternack, 2010; Konrad et al., 2002). Bed mobility transport stages delimited per grid cell by nondimensional boundary shear stress or shields stress (τ_0^*) thresholds (Jackson et al., 2015) were used to quantify these conditions according to Eq. (1), where τ_b is bed shear stress, g is gravity, D_{50} is median grain size, and ρ_s and ρ are the density of sediment and water, respectively (Pasternack, 2011).

$$\tau_0^* = \frac{\tau_b}{g(\rho_s - \rho)D_{50}} \tag{1}$$

Bed shear stress τ_b is calculated as the product of water density and shear velocity ($u^* = U\sqrt{C_d}$), where U is depth-averaged velocity for an individual grid cell, and C_d is the depth-based drag coefficient. τ_0^* therefore varies spatially and with discharge as a function of depth and velocity. Ecological performance for each discharge input was calculated as the areal proportion of the bankfull channel (the region where spawning could occur) (*ecological objective boundary* in Fig. 1) that falls within defined sediment mobility ranges based on shields stress.

2.2.2.2. Hydraulic habitat diversity. HMID values were then binned into three categories to correspond with previous literature: low (< 5), mid (5–9), and high (> 9) hydraulic diversity (Gostner et al., 2013).

$$HMID_{reach} = (1 + CV_v)^2 \bullet (1 + CV_d)^2 \tag{2}$$

Once all ecological objectives were defined in terms of suitable depth and velocity conditions or condition categories, a set of representative discharges defined in Step 1 was evaluated to generate a set of dimensionless, spatially aggregated performance metric values for each ecological objective (Fig. 1, step 3).

2.2.3. Define reference conditions (Step 4)

Based on the well-established premise that departures from the natural flow regime are expected to result in ecological degradation (Richter et al., 1996), satisfactory performance of an ecological objective refers here to limited departure from reference conditions, where reference conditions are defined as the ecohydraulic conditions that would occur under an unimpaired flow regime at that location at that time (Fig. 1, step 4). Satisfactory performance is assessed in each time-step as either: (i) falling within 10% of reference conditions or (ii) matching the binned condition category occurring under reference conditions, depending on whether the ecological objective is based on suitable area (e.g., river bed preparation and occupation) or categorical (e.g., hydraulic habitat diversity). Unsatisfactory performance is analogous to the water resources concept of a water demand deficit, indicating that the system is not meeting the desired conditions.

2.2.4. Define how to aggregate ecological performance in time (Step 5)

Discharge-specific hydraulic conditions were integrated through daily streamflow time series (a daily time-step was defined in Step 1) using piecewise linear interpolation between model runs to generate daily performance time series for each ecological objective (Fig. 1, Step 4). Alternatively, model runs of each possible discharge could have been performed, but it was computationally intensive. Satisfactory performance in each time-step was then evaluated relative to reference conditions (defined in Step 4). Together, this information was used to quantify the magnitude (i.e. reliability in volume and vulnerability) and frequency (i.e. reliability in time and resilience) of satisfactory performance (i.e. no deficit) over the bioperiod as described in the following section. The result of Step 5 was a set of dimensionless eco-RRVS metrics for each ecological objective under each flow management scenario.

2.3. Calculating eco-RRVS metrics

This section describes the proposed approach for adapting traditional water resources performance metrics as proposed by Hashimoto et al. (1982) and Sandoval-Solis et al. (2011) to ecological objectives. Performance metrics include time-based and volumetric reliability, resilience, vulnerability, and sustainability. Table 1 compares the definitions of performance metrics for traditional water resources objectives and ecological objectives.

2.3.1. Eco-reliability

Water system reliability is the probability of meeting a water demand over a period of interest in volume or time (Hashimoto et al., 1982). Similarly, the authors define eco-reliability as the probability of achieving satisfactory performance as defined in Step 4 for a specific ecological objective over the bioperiod, either in magnitude or time. Eco-reliability in magnitude is the cumulative suitable area of an ecological objective supplied under a flow management scenario ($SA_{alt_t}{}^{i}$) divided by the cumulative daily suitable area supplied under reference conditions ($SA_{ref_t}{}^{i}$) over the bioperiod (n) (Eq. (3)). Note that, unlike traditional reliability, eco-reliability in magnitude can be over 100% if the cumulative suitable area is greater under the flow management scenario than the reference scenario.

$$Rel^{i}_{mag} = \frac{\sum_{t=1}^{n} SA_{alt_t}{}^{i}}{\sum_{t=1}^{n} SA_{ref_t}{}^{i}} \tag{3}$$

Eco-reliability in time is the probability of achieving satisfactory performance over the bioperiod (Eq. (4)), or number of time-steps with satisfactory performance (n_s) over the total number of time-steps in the bioperiod (n_b).

$$Rel^{i}_{time} = \frac{n_s}{n_b} \tag{4}$$

2.3.2. Eco-resilience

Water system resilience is a measure of a system's ability to recover from deficit (Hashimoto et al., 1982), or the probability that satisfactory performance occurs after a period of unsatisfactory performance. Resilience is also well-established in the ecological literature (Bisson et al., 2009; Gunderson, 2000), and we define eco-resilience as the probability of returning to satisfactory ecological performance following an unsatisfactory period. Eco-resilience is calculated as the number of times the system moved from unsatisfactory to satisfactory performance (n_{UtoS}) divided by the total number of unsatisfactory time-steps in the bioperiod (n_U) (Eq. (5)).

$$Res^{i} = \frac{n_{UtoS}}{n_U} \tag{5}$$

2.3.3. Eco-vulnerability

Not all unsatisfactory conditions have the same impact on a water system, so vulnerability is often evaluated based on average severity, or the sum of monthly or yearly deficit volumes divided by the duration that the system was in deficit (Sandoval-Solis et al., 2011). Vulnerability is also prevalent in ecological theory (Füssel, 2007; Glick et al., 2011; De Lange et al., 2010), and is generally considered as a function of exposure to a stressor and recovery potential. Eco-vulnerability is defined here as the average departure from suitable habitat conditions (e.g. 50% less channel area is suitable for spawning on average compared to reference conditions) or from surpassing some physical threshold. It is calculated as the sum of the daily difference between supplied and demanded suitable area divided by the number of time-steps experiencing unsatisfactory performance and then standardized based on the average daily suitable area under reference conditions (McMahon et al., 2006) (Eq. (6)).

$$Vul^{i} = \frac{\sum_{t=1}^{n} |SA_{ref_t}{}^{i} - SA_{alt_t}{}^{i}|/n_u}{\sum_{t=1}^{n} SA_{ref_t}{}^{i}/n_b} \tag{6}$$

2.3.4. Eco-sustainability

Loucks and Van Beek (1997) proposed the sustainability index to facilitate comparison of water management alternatives across multiple complementary performance metrics. Sandoval-Solis et al. (2011) proposed a variation of this index as the geometric mean of M performance metrics (C^{i}_{M}) for the i^{th} water user (Equation (7)). Sustainability can be directly applied to ecological objectives (i) using any combination of the dimensionless metrics (M) described above.

$$Sus^{i} = \left[\prod_{m=1}^{M} C^{i}_{M}\right]^{1/M} \tag{7}$$

Prior to calculating the sustainability metric, eco-reliability in magnitude was re-scaled to range from 0 to 100%. Based on the assumption that positive and negative departures from reference conditions are equally undesirable. The rationale behind the assumption is that negative departures from reference conditions for an specific ecological objective are insufficient, and positive departures may be

Table 1
Performance metric definitions for traditional water resources objectives and ecological objectives.

Performance metrics		Water resources objectives	Ecological objectives
Reliability	in time	Probability of meeting a water volume target in time (no deficit) over the period of interest (Hashimoto et al., 1982)	Probability of falling with satisfactory performance bounds in time (no deficit) over the bioperiod
	in volume/ magnitude	Total water volume supplied divided by total volume demanded over period of interest (always ≤ 100%) (McMahon et al., 2006)	Cumulative suitable area supplied relative to reference conditions over bioperiod (can be > 100%)
Resilience		Probability that a period of success (no deficit) occurs after a period of failure (deficit) (Hashimoto et al., 1982)	Probability that satisfactory performance (no deficit) occurs after a period of unsatisfactory performance (deficit)
Vulnerability		Average monthly volumetric deficit divided by average monthly demand (Sandoval-Solis et al., 2011)	Average daily suitable area deficit divided by average daily suitable area supplied under reference conditions
Sustainability		Geometric mean of above performance metrics (Sandoval-Solis et al., 2011)	

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detrimental for other ecological objectives. Any surplus in eco-reliability (i.e. $SA_{alt_t}^{\ i} > SA_{ref_t}^{\ i}$) was instead subtracted from 100% such that values equal to or greater than 200% were re-scaled to 0%. Eco-vulnerability was subtracted from 100% to generate a comparable 'lack of vulnerability' measure for comparison with other performance metrics.

2.4. Performance assessment

In addition to the five eco-RRVS metrics described above, several plots were generated to visualize performance relative to reference conditions across climate conditions and ecological objectives: daily suitability, cumulative suitability, and suitability non-exceedance. These plots are also frequently used to illustrate flow-based ecological response such as in Vogel et al. (2007) and Gao et al. (2009). Together, these three plots provide information about the timing, magnitude, and return frequency of satisfactory performance over the bioperiod that can be used to help interpret metric results. Ecological performance was also assessed at a monthly time-step to identify seasons in critical condition and limiting performance metrics.

2.5. Study application

2.5.1. Problem formulation

Given concerns over the impacts of hydropower on native salmonids in Mediterranean-montane streams, this case study assessed the ecological performance of a mid-sized hydropower project for fall-run Chinook salmon. An existing hydraulic model of a typical semi-confined pool-riffle stream reach was applied to evaluate performance of three ecological objectives related to fall-run Chinook salmon under a hydropower-altered flow management scenario in three climate conditions (Wet, Moderate, Dry). Two gauge stations were chosen to represent typical unimpaired (North Yuba River below Goodyears Bar) and hydropower-altered (New Colgate Powerhouse) Mediterranean-montane flow regimes. These gauge stations lie within similar physio-climatic and geologic settings and contain daily streamflow data spanning wet (Water Year, WY, 2011), moderate (WY 2012), and dry (WY 2014) conditions (Fig. 2). Climate conditions were determined as follows: WYs with annual streamflow volume above the 75th percentile over the period of record were considered wet, years below the 25th percentile were dry, and years in the interquartile range were considered moderate.

2.5.2. Hydraulic model development

The present study builds upon terrain generation, hydraulic modeling and parameterization for case of study parameters extensively discussed, documented and validated in Brown and Pasternack (2019) ib and Lane et al. (2018). Terrain data for a typical semi-confined pool-riffle reach was synthesized using River Builder (Brown et al., 2014; Brown and Pasternack, 2019) as detailed in Lane et al. (2018). The goal of the design process was to capture the essential organized features of each channel type so that their functionalities can be evaluated in a reductionist approach without the random details and noise of real river corridors that cause highly localized effects. The model first generates a reach-averaged river corridor that is scaled by reach-averaged bankfull width and depth, with user-defined sediment size, slope, sinuosity, floodplain width and lateral slope as user-defined input variables. 140 longitudinal nodes were spaced at 1 m (~1/10 bankfull channel widths). Next, this approach incorporates subreach-scale (< 10 channel widths frequency) topographic variability using a sinusoidal function to represent depth and width variability about the median values. The sinusoidal function parameters were adjusted iteratively to achieve field-derived values for bankfull depth, width-to-depth ratio, sinuosity, and the coefficient of variation of width and depth. Floodplain confinement, the bankfull to floodplain width ratio, was used to set valley width and overbank topography (Lane et al., 2018).

The surface-water modelling system (Aquaveo, LLC, Provo, UT) user interface and Sedimentation and River Hydraulics – Two-Dimension (SRH-2D) algorithm (Lai, 2008) were used to produce an exploratory hydrodynamic model for an archetypal Mediterranean-montane stream. SRH-2D is a finite-volume numerical model that solves the Saint-Venant equations for the spatial distribution of water surface elevation, water depth, velocity, and bed shear stress at each computational node. It can handle wetting/drying and supercritical flows among other features and has been widely applied in river restoration and ecohydraulics studies (Erwin et al., 2017; Stone et al., 2017; Lane et al., 2018). Results from any other well established 2-D hydraulic model platforms can be used for this purpose. The parametric eddy viscosity equation was used for turbulence closure. A coefficient value of 0.1 suitable for shallow rivers with coarse bed sediment was used in that equation. A computational mesh with internodal mesh spacing of 1 m (relative to a channel width of 10 m) was generated for the synthetic terrains described above. Because this study was purely exploratory using a numerical model of a theoretical river archetype, no calibration of bed roughness or eddy viscosity was possible. Similarly, no validation of model results was possible (Lane et al., 2018). This is typical of exploratory or archetype-based hydraulic modeling studies (Brown et al., 2014; Brown et al., 2015; Vanzo et al., 2016).

Eight steady hydraulic model runs were performed, with upstream and downstream model boundary conditions established as follows. A series of eight discharge values ranging from 0.2 to 2 times bankfull flow stage were set as upstream boundary conditions for the model to evaluate the range of discharges expected to occur within a typical reach. Based on the simple synthesized terrain, hydraulic conditions are expected to scale linearly between the eight modeled discharges,

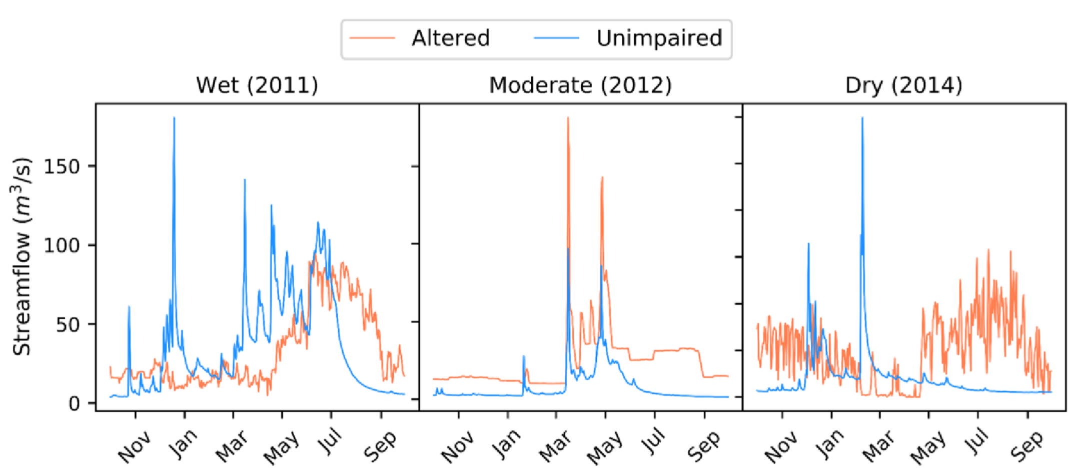

Fig. 2. Daily unimpaired and hydropower-altered hydrographs in wet, moderate, and dry years.

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enabling use of linear interpolation to assess conditions at intermediate discharges. Bankfull flow stage refers to the water surface elevation at which flows spill onto the floodplain. The downstream boundary conditions for each model run were determined using Manning's equation, with Manning's roughness value assigned as 0.04 based on typical unvegetated gravel/cobble surface roughness for these streams (Abu-Aly et al., 2014). Velocity was calculated using SRH-2D's Conveyancing approach in which flow direction is considered to be normal to the inlet boundary (Lai, 2008), a standard practice for hydraulic modeling. See Lane et al. (2018) for more details on hydraulic model development. Each model run produced a set of depth, velocity, and shear stress rasters at a 1-meter grid scale for the modelled river reach that were used as input to the proposed framework to calculate ecological performance metrics (see Fig. 1).

3. Results and discussion

Here, we evaluate the ability and limitations of the eco-RRVS metrics and associated performance plots to provide distinct, physically meaningful measures of ecological performance at daily, seasonal, and annual time-steps. Results are evaluated with respect to three ecological objectives under wet, moderate, and dry conditions below a hydropower project (Table 2).

3.1. Interpreting eco-RRVS metrics

3.1.1. Eco-reliability in magnitude

For many ecological objectives (e.g., bed preparation and occupation), eco-reliability in magnitude is a measure of cumulative suitable area relative to reference conditions over the bioperiod. It provides a cumulative assessment through time of the area of the channel providing suitable conditions and can easily indicate if an objective over- or under-performs relative to defined reference conditions. Daily cumulative eco-reliability plots indicate when and by how much suitable habitat area differs from reference conditions over the bioperiod. For instance, Fig. 3b illustrates that, under reference conditions, a reduced rate of increase in suitable bed preparation area occurs progressively earlier in the year from wet to moderate to dry conditions as indicated by the earlier reduction in the slope of the cumulative suitable area plots. By contrast, the hydropower scenario exhibits a nearly linear increase in suitable bed preparation area over the entire bioperiod across all three climate conditions, resulting in earlier and larger surpluses in suitable area under progressively drier conditions. This corresponds with annual eco-reliability values of 141%, 212%, and 367% in wet, moderate, and dry conditions, respectively. Physically, a bed preparation areal surplus translates to more of the river corridor exhibiting sufficient shear stress for sediment mobility compared to reference conditions. Together the daily and cumulative suitable area plots (Fig. 3a and b) indicate that, while the portion of the channel mobilizing sediment diminishes by early spring (dry) to mid-summer (wet) under reference conditions, under the hydropower scenario significant sediment mobility continues over the water year. Bed occupation exhibits different patterns of reliability, with altered cumulative suitable area curves generally tracking reference curves in wet and dry conditions but increasing at a constant lower rate in normal conditions, resulting in magnitude-based reliabilities of 120%, 50%, and 86% in wet, normal, and dry conditions, respectively (Fig. 4b).

For ecological objectives based on spatially aggregated hydraulic indices rather than cell-wise hydraulic conditions (e.g., HMID), eco-reliability in magnitude and the associated performance plots (Fig. 5) summarize spatial performance over the bioperiod. In the case study, eco-reliability in magnitude of HMID is a measure of the cumulative hydraulic diversity relative to reference conditions, so a high reliability (90%) under wet conditions (Table 2) indicates that a similar total amount of spatial variability in depth and velocity conditions is exhibited over the year. The exceedance curves illustrate the relative exceedance of different HMID values (Fig. 5c). For instance, low HMID is exceeded 25% of the time in a moderate year under the reference scenario but is never exceeded under the hydropower scenario.

3.1.2. Eco-reliability in time

Eco-reliability in time, the probability of achieving satisfactory performance (no hydraulic deficit) over the bioperiod, and the daily and cumulative suitable area plots provide critical information about the timing of suitable hydraulic conditions relative to reference conditions for a given climate scenario. For bed preparation, time-based reliability was highest in wet conditions (17%), with 31 of 183 days providing satisfactory performance (Fig. 3a), and extremely low in normal (2%) and dry (8%) conditions, indicating that the proportion of the bankfull channel providing necessary hydraulic conditions to mobilize sediment was rarely within 10% of the amount of sediment mobilization that occurred under reference conditions on any given day. Alternatively, time-based reliability of bed occupation was highest in dry conditions (36%) and very low in normal conditions (8%), with only 15 of 182 days falling within reference range (Fig. 4a). This is mirrored in the cumulative suitable area (Fig. 4b and 5b) and non-exceedance plots (Fig. 4c and 5c), which most closely match reference conditions in the wet year for bed preparation and in the dry year for bed occupation. When comparing the hydropower scenario with reference conditions, results indicate that the hydraulic conditions occurring below the hydropower plant are more suitable for bed preparation in a wet year and for bed occupation in a dry year. This raises a management challenge because both objectives are needed in a single year to promote effective salmon spawning.

Together, reliability in time and magnitude help to distinguish between situations where the total cumulative suitability is similar over the bioperiod (high reliability in magnitude) but the timing that suitable hydraulic conditions occur do not overlap with when they are most needed or expected by species. Reliability in time and magnitude may perform similarly in some settings, such as high performance for salmon bed preparation under wet conditions and low performance under dry conditions, indicating that suitable habitat conditions are either mimicking or different from reference conditions in both space and time, respectively. Alternatively, habitat conditions may mimic reference conditions only in space. For instance, hydraulic diversity exhibited high annual reliability in magnitude (90%) but low reliability

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Table 2
Performance of ecological objectives under wet (W), moderate (M), and dry (D) conditions based on the eco-RRVS metrics. All values are percentages and reflect calculations prior to re-scaling to calculate eco-Sustainability.

Eco-RRVS metrics	Bed preparation			Bed occupation			Hydraulic diversity		
	W	M	D	W	M	D	W	M	D
Eco-Reliability in magnitude	141	212	365	120	50	86	91	55	90
Eco-Reliability in time	17	2	8	20	8	36	52	26	22
Eco-Resilience	7	1	6	7	1	23	13	1	12
Eco-Vulnerability	89	100	100	60	52	48	48	47	99
Eco-Sustainability	20	0	0	25	16	36	32	21	21

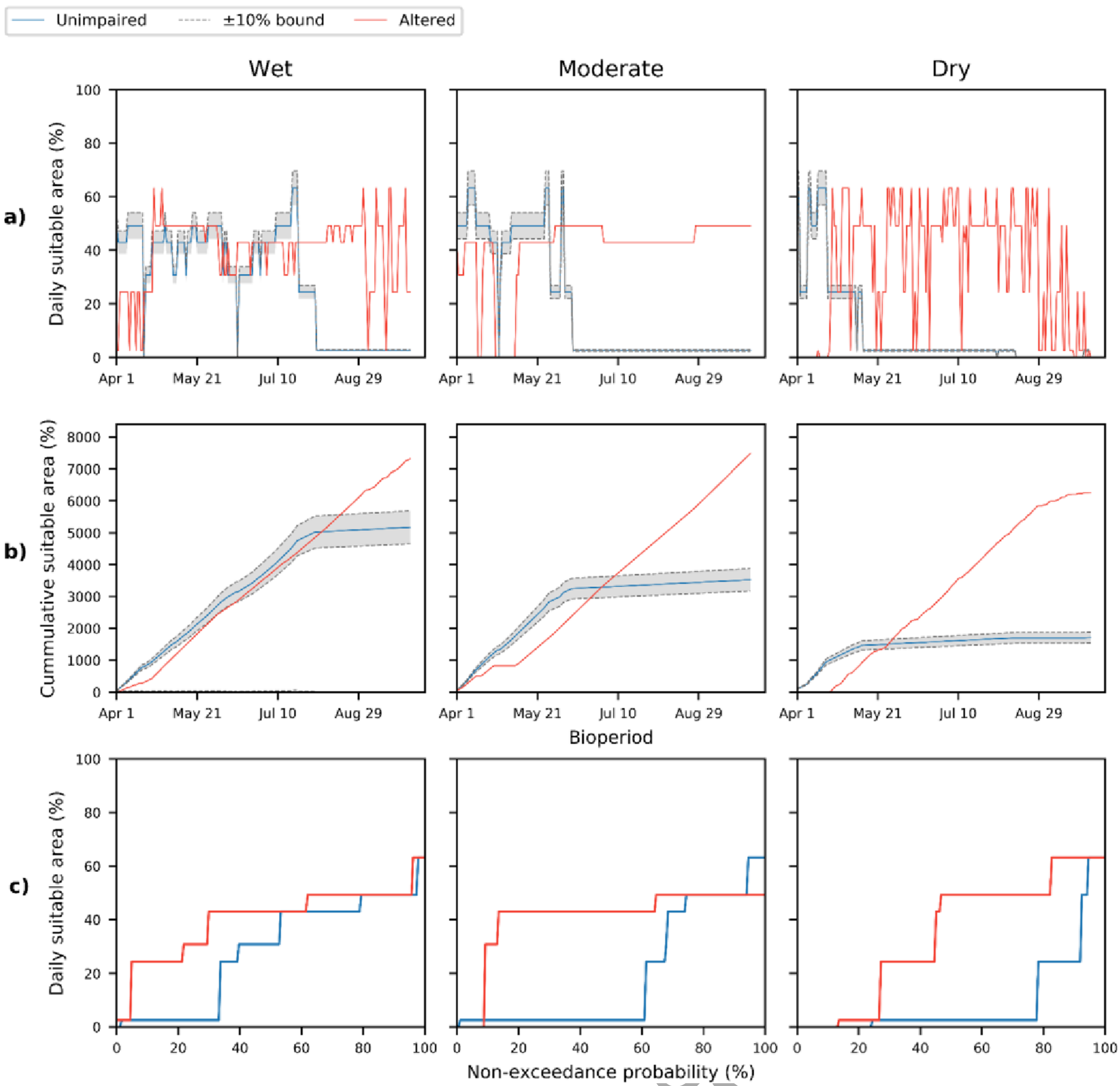

Fig. 3. (a) Daily and (b) cumulative performance and (c) daily non-exceedance plots for bed preparation under reference (blue) and hydropower (red) scenarios across climate conditions (columns). The satisfactory performance bounds of ± 10% reference conditions are represented by grey bands.

in time (22%) under dry conditions. Evaluation of the daily (Fig. 5a) and cumulative (Fig. 5b) performance plots indicates that there is a suitable area deficit through the first portion of the year (Oct – Feb) and a surplus through second portion (Mar – Aug), resulting in similar cumulative suitable area but very little overlap in the timing of different hydraulic diversity categories with reference conditions.

Additional information about aquatic species life-history strategies may increase the value of knowing hydraulic habitat conditions mimic reference conditions in terms of magnitude but not timing or vice versa. Some species may be able to shift the timing or location of certain behaviors (e.g. spawning, rearing) to some extent to take advantage of suitable conditions when and where they occur, while others may be less adaptable. Species and populations adapted to less predictable, rain storm driven hydrology are often more opportunistic and capable of utilizing suitable conditions whenever they occur, while species whose life-history strategies are closely linked to predictable snowmelt- or groundwater-dominated hydrology may require higher time-based reliability (Gasith and Resh, 1999).

3.1.3. Eco-resilience

Ecological resilience often refers to the return time of stable conditions following a disturbance (Gunderson, 2000). In the context of freshwater habitat, a useful definition of resilience varies with the physical or biological system of interest, the environmental context within which it operates, and the spatial and temporal scales under consideration (Bisson et al., 2009). Therefore, from a water management standpoint, a singular definition of resilience for each species may be less useful than understanding how natural processes and hydraulic habitat conditions have been fundamentally altered by changes to hydrology or channel form. As such, eco-resilience as defined here indicates the likelihood of return to reference-like hydraulic habitat conditions, not the associated likelihood of population recovery following a disturbance. However, this metric could be extended to estimate population response given additional information related to a species' ability to withstand or recover from unsuitable habitat conditions. Eco-resilience could also support ecological risk assessment efforts based on the likelihood of different ecological responses following a disturbance event.

In the case study, salmon bed preparation resilience - the likelihood

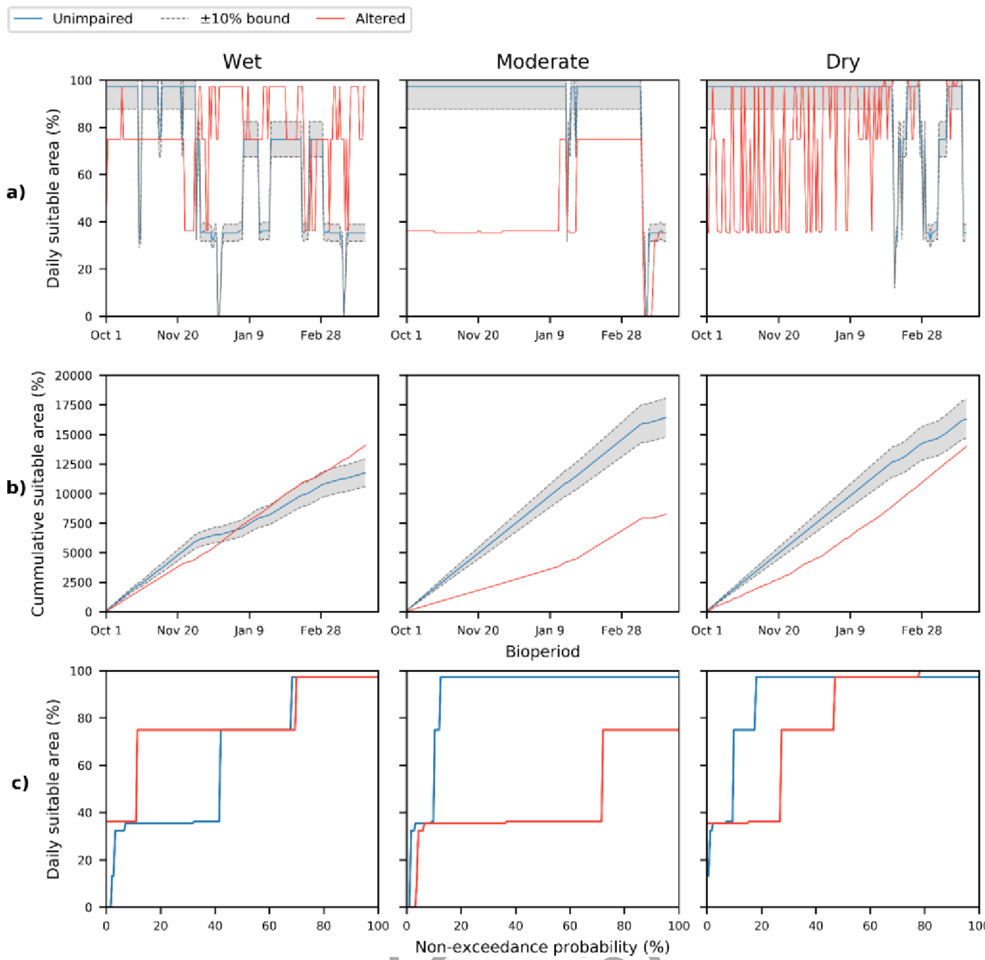

Fig. 4. (a) Daily and (b) cumulative performance and (c) daily non-exceedance plots for bed occupation under reference (blue) and hydropower (red) scenarios across climate conditions (columns). The satisfactory performance bounds of ± 10% reference conditions are represented by grey bands.

that a hydraulic deficit (i.e., > 10% more or less channel area mobilizing sediment than under reference conditions) is followed by no deficit – was extremely low across all climate conditions. This indicates that once the system is in hydraulic deficit it tends to stay in deficit. Eco-resilience of hydraulic diversity is the likelihood that hydraulic diversity returns to the reference condition category, regardless of whether that category is low or high diversity. Annual eco-resilience was extremely low across ecological objectives and climate conditions, ranging from 1 to 23% (Table 2). This low performance is due to eco-resilience being assessed on a daily time-step, while it may take several days to recover from a deficit period (Fig. 3a). In reality, whether reference-like hydraulic diversity returns on any given day is likely far less ecologically significant than if it returns within a certain month or season. Relaxing this time constraint may provide more meaningful information and is expected to improve performance. More information related to the critical timing and frequency of ecological objectives could be used to refine how resilience is calculated.

3.1.4. *Eco-vulnerability*

Eco-vulnerability quantifies the average severity of hydraulic deficits to complement information about the timing of deficits provided by other metrics (eco-reliability in time and eco-resilience). For example, eco-vulnerability of bed preparation was 89–100% across climate condition which indicates that, when shear stress conditions were different than reference conditions (i.e. when a deficit occurred), they were very different (i.e. the deficits were significant on average). By interpreting this metric in the context of the daily suitable area plots, it is evident that the low performance in normal and dry conditions corresponds to significantly more of the bankfull channel experiencing bed preparation conditions (45–65%) compared to the reference scenario (0–5%) over the summer. These results are further supported by non-exceedance curves indicating 50% exceedances of 2% and 45% channel area experiencing bed preparation under reference and hydropower scenarios, respectively (Fig. 3c).

While eco-vulnerability defined as the average hydraulic deficit quantifies average daily deviations from reference conditions over the bioperiod, for some ecological objectives it may be more relevant to know the maximum daily deviation from reference conditions. For example, if some minimum portion of the channel must retain suitable habitat conditions for fish passage, the maximum deviation from this state (i.e., the smallest suitable area of the bioperiod) could be more limiting and physically meaningful than average deviation. Eco-vulnerability could be evaluated using this alternative definition in future studies for relevant ecological objectives.

3.1.5. *Eco-sustainability*

The sustainability index (Sandoval-Solis et al., 2011) aggregates selected metrics into a single dimensionless performance metric for broader comparison across ecological objectives and scenarios. In this application, eco-sustainability enabled comparison across ecological objectives and climate conditions and identification of critical conditions. For instance, eco-sustainability of bed preparation was highest in wet conditions (20%) and 0% in the other conditions (Table 2), highlighting that bed preparation performs very poorly in terms of reliability, resilience, and vulnerability under hydropower alteration. Alternatively, eco-sustainability of bed occupation was highest in dry

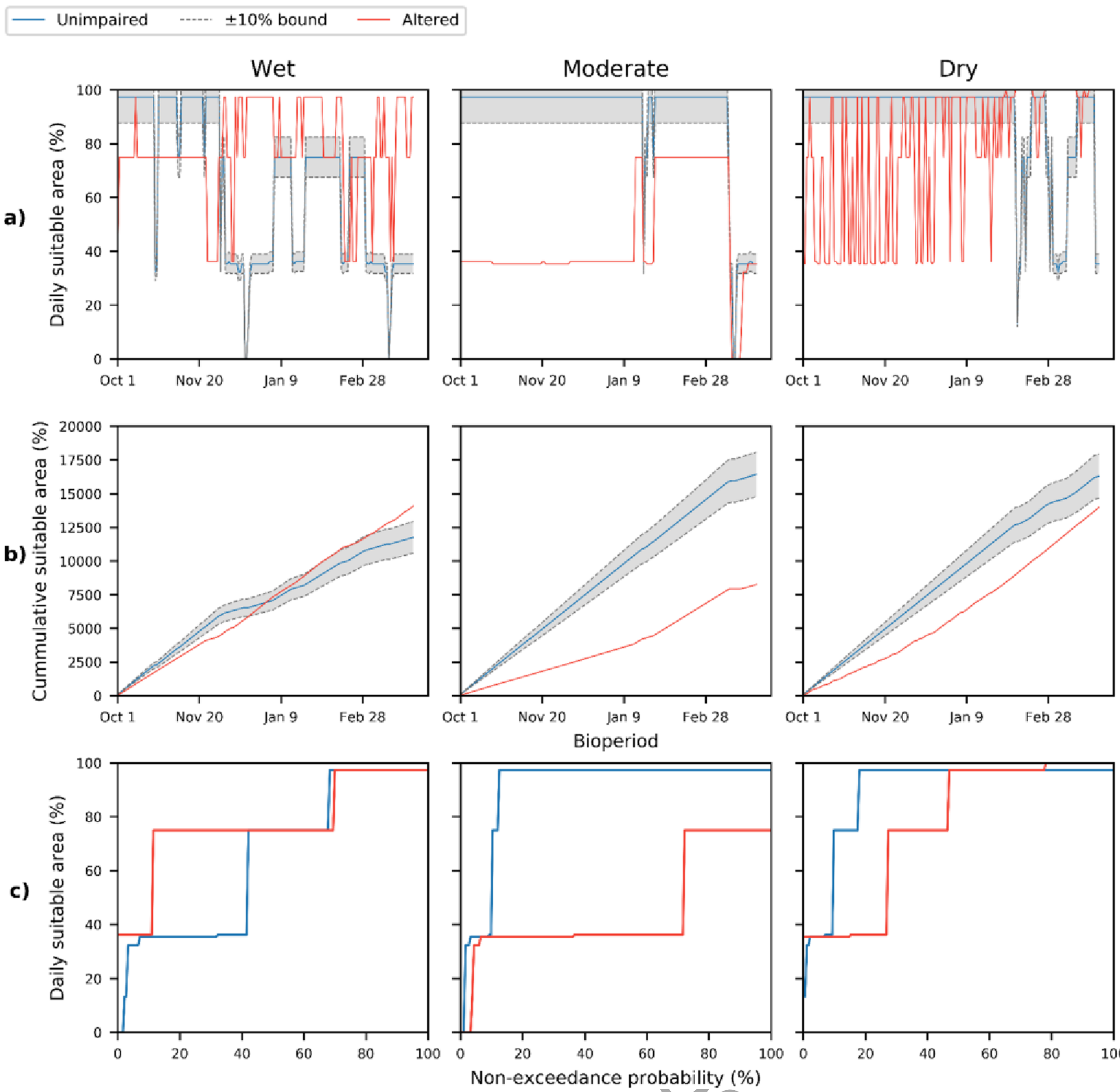

Fig. 5. (a) Daily and (b) cumulative performance and (c) daily non-exceedance plots for hydraulic diversity under reference (blue) and hydropower (red) scenarios across climate conditions (columns).

conditions (36%), followed by wet (25%) and moderate (16%). These findings indicate that, if suitable bed preparation is critical to maintaining a sustainable salmon population, flow management should focus on improving bed preparation performance.

3.2. Monthly performance assessment

Aggregating performance metrics at a monthly time-step highlighted months and seasons of markedly high or poor performance for different ecological objectives and climate conditions (Fig. 6). Seasonal performance trends varied substantially across all objectives and settings. In wet conditions, bed preparation performed best in May through July (eco-sustainability > 30%) and significantly worse earlier and later in the bioperiod eco-(sustainability = 0%), while in normal and dry conditions performance remained poor across all months. Bed occupation exhibited opposite trends in wet and dry conditions. In wet conditions, eco-sustainability was above 20% in all months except December and March when it dropped to 0%, indicating critical months for flow management improvement. Alternatively, in dry conditions, bed occupation performed best around December.

Monthly performance also varied with climate conditions for hydraulic diversity, with eco-sustainability peaking in January in dry conditions, March in normal conditions, and May in wet conditions. Under normal conditions, time-based reliability and resilience remained close to 0% and rose to 100% in March and April while volumetric reliability and vulnerability stayed above 50%, demonstrating that the improvement is driven by changes in the timing rather than the magnitude of suitable hydraulic conditions. This trend is inverted in dry conditions, which provide very low eco-sustainability in February to April driven by a sharp decrease in reliability in magnitude and vulnerability.

This decrease in reliability and vulnerability can be explained by a rapid increase and decrease in daily HMID under the hydropower and reference scenarios, respectively, over the same date range. Fig. 5a (dry) indicates a series of rapid increases in daily HMID under the hydropower scenario that appear from the hydrograph in Fig. 2 to be driven by low flow events, while a series of natural storms occurring upstream of the hydropower plant (Fig. 2) decrease HMID in the reference scenario(Fig. 5a).

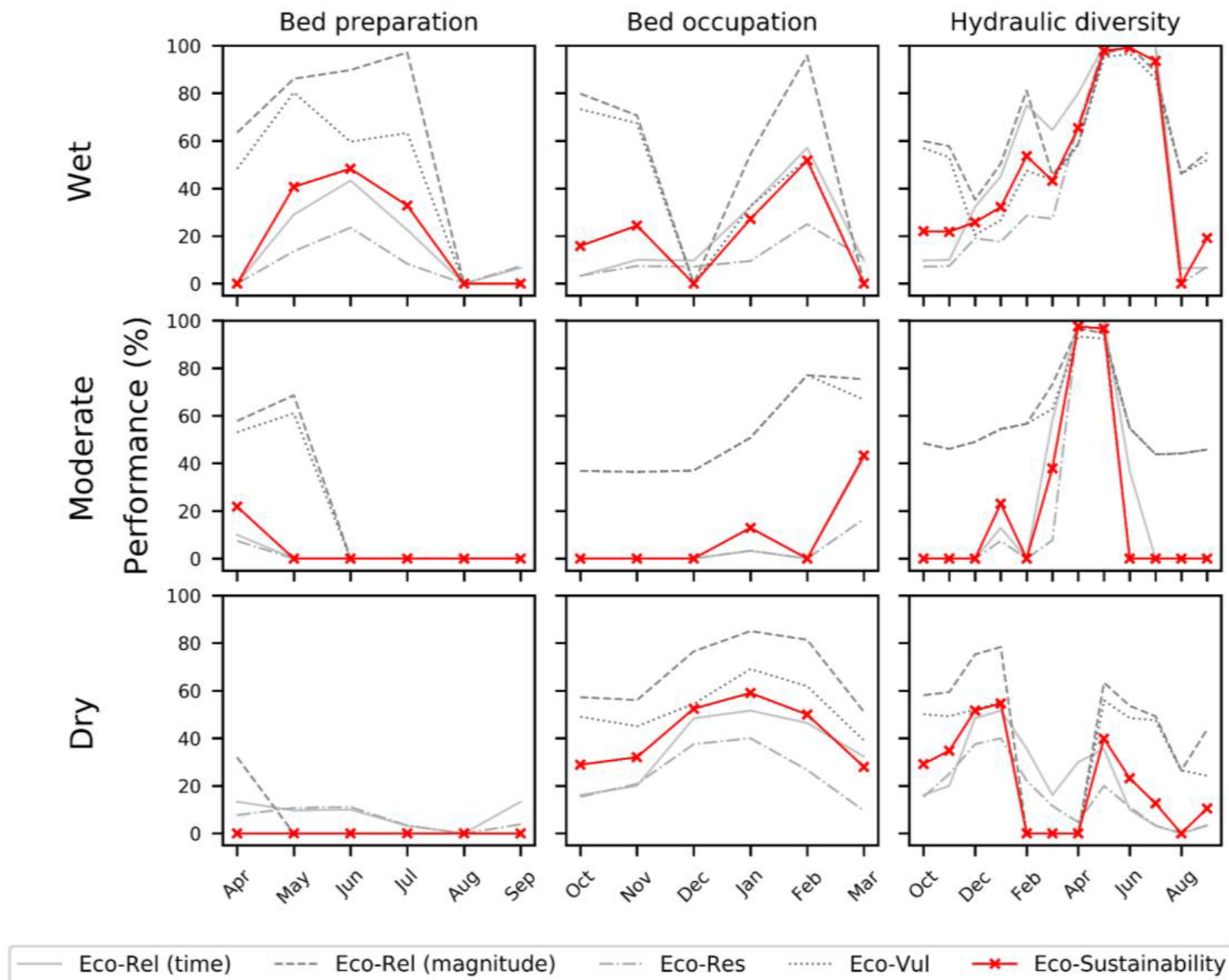

Fig. 6. Monthly performance metrics over the relevant bioperiods for bed preparation, bed occupation, and hydraulic diversity across climate conditions. Relevant metrics were re-scaled prior to plotting (see Eco-sustainability section for details).

3.3. Utility of eco-RRVS metrics

The notion that there is a particular suite of constant habitat conditions that is most beneficial for aquatic species, or that such an ideal steady-state could even persist in dynamic or human-influenced environments, is highly flawed. Attempting to optimize flow releases to conform to idealized steady conditions could result in the loss of complexity and variability necessary to support various freshwater life-history stages and strategies. However, from a water management standpoint, simple ecological metrics that can be evaluated alongside traditional water management objectives are needed to support the integration of ecosystems into water planning models. By evaluating performance based on a system's ability to mimic (i.e., minimize deviations from) naturally variable hydraulic patterns in space and time rather than its ability to maintain a desired set of hydraulic conditions, the eco-RRVS metrics are hypothesized to promote natural processes and variability. This is similar to existing methods that evaluate ecological performance based on deviations from the natural flow regime, except that the proposed metrics are derived from hydraulic rather than streamflow conditions. The proposed metrics and plots therefore facilitate representation of nonlinear and threshold-based relationships between flow and ecosystem response.

Case study results demonstrate that applying well-established performance metrics can facilitate interpretation of complex water management tradeoffs. For example, performance of salmon bed preparation in a wet year can be summarized as 141% reliability in time, 17% reliability in time, 89% vulnerability and 7% resilience (7%) (Table 2). If this ecological outcome was an irrigation water delivery, the agricultural user would receive 41% more water over the year than demanded, but only 17% of that water would be delivered when it was needed. When a deficit occurred, it would be an average of 89% of the user's water demand and their water supply would only recover from deficit 7% of the time. This analogue provides a clear and concise way of framing tradeoffs. For bed preparation, such a surplus in weighted useable area at the wrong time may translate to excessive bed scour and actually reduce spawning habitat quality over the bioperiod.

Just as multiple performance metrics are applied to capture distinct aspects of water system performance (Hashimoto et al., 1982), we found the eco-RRVS metrics to provide distinct and complementary measures of ecological performance. Differences in areal performance under hydropower alteration (magnitude-based reliability) did not always correspond with differences in the timing (time-based reliability), severity (vulnerability), or ability to recover from (resilience) hydraulic deficits. These metrics can also be combined using the eco-sustainability metric and summarized at daily, seasonal, or long-term (annual or multi-year) scales as needed. Daily suitability plots (Fig. 3a, 4a, 5a) illustrate high-resolution performance sequences, while monthly plots (Fig. 6) highlight seasonal trends and months experiencing critical conditions. This study considered three years to demonstrate application of the framework to compare performance under three distinct climate conditions. Future studies could extend the assessment period to evaluate long-term ecological performance alongside traditional water management objectives, but this is outside the current study scope.

Together these multi-scale performance metrics provide intuitive information that can help decision-makers identify opportunities to reallocate available water across months and days to improve ecological objectives. For example, hydraulic diversity performed better in magnitude (66%) than time (17%) over the dry year, but from February through April magnitude-based reliability dropped to zero (Fig. 6). Closer inspection of daily performance plots (Fig. 5) reveals rapid spikes in hydraulic diversity during this period driven by extremely low flow conditions, indicating that increasing flow earlier in the spring would significantly improve hydraulic diversity below the hydropower plant.

3.4. Limitations of eco-RRVS metrics

The choice of reference conditions should be made mindfully and with the aim of meeting specific physical or biological targets, particularly in the context of shifting baselines (Butler, 2011) and reconciliation ecology. Some ecological objectives actually demonstrate higher performance under managed than unimpaired flow regimes. Unlike traditional water management objectives, for which more water is generally better, this 'over-performance' may have negative ecological consequences. For instance, increasing sediment mobility beyond what occurs under the natural sediment regime in sediment-scarce systems (such as below most reservoirs) may drive erosion and affect habitat conditions for some biota (Rowe et al., 2009). As the ecological standard underpinning this assessment typology was the natural functioning of unimpaired rivers, any over-performance of objectives was considered to reduce performance to the same extent as equivalent under-performance. Additionally, performance results will be sensitive to the thresholds used to define suitable hydraulic conditions, so care should be taken to select appropriate suitability curves or describe hydraulic thresholds such as the bed mobility equation used here.

Considering that the natural flow regime provides suitable habitat conditions for native ecosystems, a reasonable assumption of the eco-RRVS metrics is that desirable or necessary hydraulic conditions are those that would occur in a given stream reach in the absence of impairments. More information about the habitat needs of species or life-stages may indicate more accurate hydraulic suitability requirements or more realistic time periods over which an ecological objective is suitable. An alternative reference condition, particularly for objectives considered detrimental to aquatic biota, could be minimizing areal occurrence rather than minimizing deviations from a dynamic target based on reference conditions. Particularly for species experiencing other stressors that did not occur under 'natural' conditions, managing for a constant minimum or maximum threshold may be a more appropriate decision. This adjustment could be easily made within the proposed framework in the definition of satisfactory performance and reference conditions. Alternatively, reference conditions could be based on the full range of performance experienced across all years in a given climate condition rather than a single year. This would allow for a broader range of satisfactory performance and promote inter-annual variability in flow management decisions. However, neither of these alternatives accounts for shifts in climate conditions that may require the establishment of new reference conditions to reflect changes in desirable or attainable objectives.

Since the eco-RRVS metrics are derived from 2D hydraulic model outputs, performance can only be evaluated for any stream reach for which a 2D hydraulic model has been or can be developed. Additionally, while reach-scale performance is useful for some ecological objectives and management contexts, the ability to assess performance across reaches (e.g., at the segment- or watershed-scale) would improve understanding of the larger spatial patterns of ecological performance, particularly in geomorphically heterogeneous basins. Rapid advances in data acquisition technology (e.g. lidar)), widespread availability of numerical models, and access to computational resources make the proposed methods increasingly applicable over larger scales with limited time and financial requirements.

Relevance of the proposed performance metrics depends on the ecological objectives of interest. Aquatic habitat based objectives like salmon bed occupation that depend on daily and cumulative suitable area are well represented by the proposed reliability (time and volumetric), resilience, and vulnerability metrics. Alternatively, for event-based ecological objectives like floodplain inundation or redd dewatering events, the magnitude, duration, and frequency of individual disturbance events may be more ecologically significant than their exact timing or cumulative performance. Quantifying deviations in these hydraulic event patterns under flow alteration using the Uniform Continuous Under-Threshold approach (Parasiewicz et al., 2012; Gallo et al., 2014) is one established method for evaluating changes to event-based ecological objectives that could compliment the eco-RRVS metrics.

Finally, ecological objectives not well represented by hydraulic conditions will not be well captured by the proposed performance metrics. Stream temperature (Isaak and Rieman, 2013) or availability of sediment inputs (Wohl et al., 2015) are important considerations for assessing aquatic ecosystems and may be more constraining in some instances. For these objectives, hydraulic habitat is not expected to be the best predictor of ecological response to flow management decisions. Ecological performance metrics should be developed with respect to the specific limiting physical conditions and life-history strategies of the aquatic species of interest. There are many techniques available for evaluating these other factors, such as models to predict suspended sediment (Alizadeh et al., 2017) or stream temperature (Buahin et al., 2019) response to hydrologic inputs. However, the focus of the current study is on methods and metrics for integrating 2D hydraulic model outputs to improve representation of habitat-based ecological outcomes in water management decision making. Future research could summarize time series of other ecologically significant factors similarly to what is proposed for hydraulic habitat here by following framework steps 4 (define reference conditions) and 5 (aggregate ecological performance in time) to incorporate a broader suite of ecological considerations.

4. Conclusions

An emerging challenge for water managers is how to assess complex ecological objectives alongside well-defined human water management objectives. This study builds on ongoing efforts to evaluate ecological objectives in water planning models by evaluating hydraulic- rather than streamflow-based ecological objectives to account for non-linearity and support mechanistic interpretation of ecological responses. A general framework to evaluate ecological performance of water management alternatives based on 2D eco-hydraulic model outputs was introduced based on five main steps. In a simple application, the eco-RRVS metrics were shown to summarize space-time varying information to quantify distinct and complementary needs of fall-run Chinook salmon. By assessing the ability to mimic unimpaired ecohydraulic patterns in space and time, the proposed performance metrics are expected to more directly reflect natural processes and variability than flow-based performance metrics, although additional monitoring is needed to confirm this. Combined with daily and monthly ecohydraulic performance plots, the metrics facilitated identification of limiting habitat conditions in different hydrologic settings and time periods. Limitations include that ecological objectives not well represented by hydraulic habitat or for which clear physical thresholds have not been established will not be well-captured by the proposed metrics and should be evaluated using other techniques. The metrics are also sensitive to the definition of reference conditions; more detailed physical and ecological information should be used to refine these definitions

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5. Data availability

Data and programming scripts to calculate eco-RRVS metrics and generate plots are available from the corresponding author upon request.

CRediT authorship contribution statement

Belize Lane: Conceptualization, Methodology. **J. Pablo Ortiz-Partida:** Visualization, Software. **Samuel Sandoval-Solis:** Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors thank Dr. David Rosenberg and Dr. Greg Pasternack for their valuable comments that significantly improved the paper. This work was supported by the Utah Water Research Laboratory; the UC Davis Hydrologic Sciences Graduate Group; the California State Water Resources Control Board [Grant number 16-062-300]; and Mexico's National Science Foundation Ministry (Consejo Nacional de Ciencia y Tecnologia).

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