FEATURE

Integrating Ecosystem Models with Long-Term Monitoring to Support Salmon Recovery

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Okanogan summer-run Chinook Salmon *Oncorhynchus tshawytscha* holding in the Similkameen River near Oroville, Washington. Photo credit: Brian Miller, Confederated Tribes of the Colville Reservation.

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The Ecosystem Diagnosis and Treatment model (EDT) is a deterministic, life cycle-based habitat model developed to support the conservation and recovery of declining Pacific salmon *Oncorhynchus* spp. and steelhead *Oncorhynchus mykiss* in the Pacific Northwest. Originally conceived in the 1990s, the current generation of EDT is proving its value as a data synthesis and analysis platform, capable of transforming complex environmental data into useful quantitative metrics to guide decision making. Here we describe the integration of EDT with long-term research, monitoring, and evaluation in the Okanogan River in the state of Washington to support the ongoing conservation and recovery of steelhead listed under the Endangered Species Act. The lessons learned in this important Columbia River subbasin demonstrate the value of EDT as an adaptive management tool that is both effective and transferable. Modeling tools like EDT are one of many technological advances that will help resource managers identify priority habitats for conservation and restoration.

INTRODUCTION

The conservation and recovery of Pacific salmon *Oncorhynchus* spp. and steelhead *Oncorhynchus mykiss* is an enormous technical and social challenge. While many factors have contributed to species decline, freshwater habitat degradation is particularly complex because these habitats intersect with and are negatively impacted by many aspects of economic development (Lackey et al. 2006; Lackey 2017). Species recovery will depend in part on our collective ability to protect and restore functional habitats (GSRO 2020), a challenge that only becomes more difficult in a rapidly changing climate (GSRO 2020; Crozier et al. 2021). This will necessarily require continued investments in watershed restoration, instream flow protection, management of novel threats like invasive species, and improved harvest and hatchery management, as well as changes in hydropower operations to address multispecies needs in a changing environment (Ruckelshaus et al. 2002; Beechie et al. 2012a, 2012b, 2012c).

Salmon and steelhead conservation in the 21st century will require the effective application of sound scientific guidance with the will to make politically difficult decisions (Lackey et al. 2006; Lackey 2017). While obstacles remain, investments in science and advances in technology can help us meet the moment (Knudsen and Doyle 2006). For example, the identification and protection of thermal refugia and restoration of functional temperature regimes is a critical conservation need in a rapidly changing climate. Fortunately, the widespread availability of inexpensive temperature loggers, coupled with advances in remote sensing and rapid increases in computing power, is facilitating the development of temperature models and monitoring networks needed to meet this challenge (Isaak et al. 2017, 2018; Isaak and Young 2019). Better information about the distribution of thermal refugia will in turn help guide the policy changes necessary to ensure their long-term protection.

While undoubtedly important, these advances are incomplete unless they can be linked to the habitat requirements of salmon and steelhead at useful spatial scales for management. This role is filled by habitat models that connect the salmonid life cycle and knowledge about fish–habitat relationships to quantitative information about habitat conditions (Pess and Jordan 2019; Zabel and Jordan 2020). Habitat models are indispensable tools in that they provide platforms for synthesizing data, organizing knowledge, and testing assumptions about species–habitat relationships (Zabel et al. 2020). While they cannot fully capture the complexity of natural systems and their quantitative predictions rarely conform to reality, models can nonetheless be accurate enough to guide pressing management decisions (Lee 1993; Mangel and Hilborn 1997; Blair et al. 2009; Scheuerell and Hilborn 2009; Zabel et al. 2020).

Salmon recovery efforts have spawned a diversity of habitat models over the past 3 decades. Examples include the Ecosystem Diagnosis and Treatment model (EDT; Blair et al. 2009), the Shiraz model (Scheuerell and Hilborn 2009), the Unit Characteristic Method (Cramer and Ackerman 2009), and various life cycle models developed by the National Oceanic and Atmospheric Administration for salmon populations listed under the Endangered Species Act (ESA) in the Pacific Northwest (Beechie et al. 2020; Zabel and Jordan 2020). First developed in the mid-1990s, EDT is finding new value as a data synthesis and decision support platform supporting the conservation and recovery of ESA-listed species in the Columbia River basin.

This article describes one such application of EDT in the Okanogan River subbasin in the state of Washington and British Columbia. The Confederated Tribes of the Colville Reservation (CTCR) have integrated Okanogan EDT with long-term research, monitoring, and evaluation (RME), using the model to translate complex physical and biological data into useful habitat performance metrics. The CTCR uses these metrics to report on habitat status and trends and to support ongoing habitat restoration efforts. Okanogan EDT has evolved over time to become a centralized information clearinghouse and analysis platform that is informing adaptive resource management in this important subbasin.

SETTING

The Okanogan River is a tributary to the Columbia River, originating in British Columbia and flowing south to its confluence between Wells and Chief Joseph dams at river kilometer 858 (Figure 1). The Okanogan is the third largest of the Columbia's 20 major subbasins and the most upstream major tributary that remains accessible to anadromous species. This system currently supports threatened summer steelhead and stable populations of summer/fall Chinook Salmon *O. tshawytscha* and Sockeye Salmon *O. nerka*.

Aquatic habitat conditions in the Okanogan have been negatively impacted by a long history of resource development, beginning with intensive fur trapping and mineral prospecting in the early 1800s (UCRTT 2017). The subsequent discovery of gold spurred rapid population growth and the expansion of agricultural and livestock industries throughout the mid to late 1800s (UCRTT 2017). By the early to mid-1900s, many tributaries had become over-appropriated and were commonly drawn nearly or completely dry. Spring Chinook Salmon were extirpated from the subbasin by the 1930s (UCRTT 2017). Agricultural, industrial, and residential development continued throughout the 20th century, introducing passage barriers, pollution, and additional habitat degradation (UCRTT 2017). The majority of the mainstem and many tributaries have been developed for flood control, irrigation, and other purposes (UCRTT 2017). This development history continues to negatively affect resident and anadromous fish and other aquatic life (UCRTT 2017; Carlson et al. 2020).

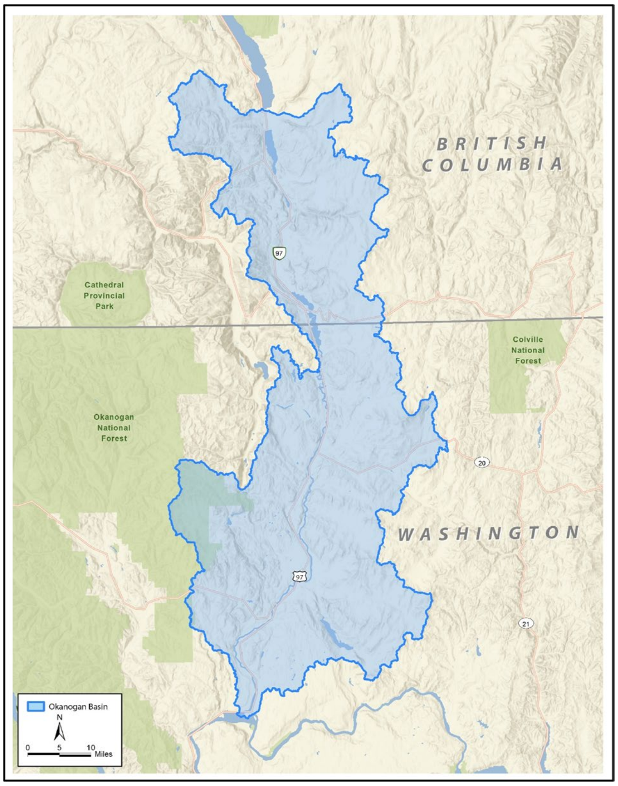

Figure 1. Okanogan subbasin.

A considerable amount of habitat and biological data has been collected in the Okanogan subbasin as part of ongoing habitat status and trend monitoring conducted by the CTCR Fish and Wildlife Department (OBMEP 2020; USGS 2021). The CTCR monitors and reports on hydrologic, geomorphic, and biological habitat conditions at established locations throughout the subbasin on a 4-year cycle. Three reporting cycles, 2005–2009, 2010–2013, and 2014–2017, have been completed and a fourth (2018–2021) is underway. The CTCR also monitors steelhead and Chinook Salmon population status using a combination of redd counts, weirs, mark–recapture, snorkel surveys, and PIT tag arrays. Population status and trends are reported annually (OBMEP 2020).

The CTCR uses the Okanogan EDT model as a tool for integrating monitoring data into a set of habitat metrics used to meet reporting requirements under the Columbia Basin Fish Accords. The Accords require signatories to systematically report on habitat status and trends in Columbia River tributaries supporting ESA-listed salmonids, per the terms and conditions of the 2008 Federal Columbia River Power System Biological Opinion (NMFS 2008). Okanogan EDT results are also used by the CTCR habitat implementation program, the Upper Columbia Salmon Recovery Board, and other subbasin partners to inform habitat protection and restoration planning in pursuit of ESA recovery objectives.

EDT BACKGROUND

The EDT model is a lifecycle-based habitat model designed around the recursive properties of the Beverton–Holt stock recruitment function (Beverton and Holt 1957) as described by Moussalli and Hilborn (1986). It was conceived in the mid-1990s by a team of fisheries biologists and mathematicians in response to multiple ESA listings of Pacific salmon and steelhead across the region (Lichatowich et al. 1995; Mobrand et al. 1997; Blair et al. 2009). The first-generation proof of concept (EDT1) was successfully implemented on the Grand Ronde River (Lichatowich et al. 1995; Lestelle et al. 1996).

The second-generation version of EDT (EDT2) was developed to support subbasin planning, a regionwide watershed planning effort in the Columbia River basin in the early 2000s (Bisson et al. 2001; Marcott et al. 2002; NPCC 2021). The EDT2 platform was publicly available and enjoyed wide use, with applications in over 140 subbasins across the Pacific Northwest and California (e.g., Knight and Bouwes 2005; Blair et al. 2009; NPCC 2021). However, EDT2 has been criticized for its complexity, inflexible rule structure, and lack of transparency (Steel et al. 2009), and certain applications of the model have been criticized for overreliance on professional judgment to fill data gaps (McElhany et al. 2010). While EDT2 has been subjected to sensitivity analyses (Steel et al. 2009; McElhany et al. 2010) and validated in specific watersheds (Rawding 2004; Thompson et al. 2009), systematic validation of EDT has to date been limited (Roni et al. 2018).

The Okanogan EDT model and all other current EDT applications are implemented on the third-generation EDT platform (EDT3). While the underlying computational architecture remains the same, the EDT3 user interface and database structure have been redesigned to address specific criticisms of EDT2. The EDT3 platform provides more transparent access to the species–habitat rules and model population structure and greater flexibility to modify these parameters if desired. Improved population modeling capabilities allow EDT3 to emulate life history complexity more effectively than its predecessors. Metadata management has also been improved to support generation of data quality metrics, allowing the end user to evaluate habitat performance metrics based on the strength of the data used to generate those results. Software modules and the model source code for EDT3 are publicly available (https://bit.ly/3mYbiGt).

EDT COMPONENTS

Conceptually, EDT consists of four components: a model habitat environment, a model population, quantitative species–habitat rules, and a report module that integrates this information into habitat performance outputs.

Model Habitat Environment

The EDT model habitat environment is composed of a reach and diagnostic unit network representing the full extent of anadromous habitat within the target watershed, migratory corridors, and estuary and ocean habitats. Environmental conditions in each reach are described using over 40 familiar habitat attributes (Table 1) and parameterized following established rating guidance (Lestelle 2005; Doyle and Lestelle 2021). Obstruction reaches, which represent natural and anthropogenic impediments to migration, are parameterized using percent passage by life stage and month. Diagnostic units are user-defined groups of reaches useful for analysis purposes, such as hydrologic units, habitat strata, or management watersheds. A habitat scenario is composed of a full set of reach-level attribute ratings representing a specific period or management condition. For example, a scenario representing

Table 1. Environmental attributes used to describe salmonid habitat in ecosystem diagnosis and treatment (EDT).

Attribute category	Environmental attribute	Rating schedule	Okanogan EDT data source[‡]
Channel morphometry	Channel length	Reach	1, 2
	Channel width	Reach and month	1, 2
	Gradient	Reach	1, 2
Confinement	Confinement – natural	Reach	1, 2
	Confinement – anthropogenic	Reach	1, 2
Habitat composition	Primary channel – 8 habitat types	Reach	1, 3
	Peripheral/transitional – 4 habitat types	Reach and month	1, 2
Riparian and channel integrity	Bed scour	Reach and month	2
	Icing	Reach and month	1, 4
	Riparian/stream interface	Reach	2
	Woody debris	Reach	1, 2
Substrate conditions	Embeddedness	Reach	1, 3
	Fine sediment	Reach	1, 3
Hydrology	Flow: diel variation	Reach and month	1, 3
	Flow: inter-annual high flow variation	Reach and month	1, 3
	Flow: inter-annual low flow variation	Reach and month	1, 3
	Flow: intra-annual variation	Reach and month	1, 3
Water temperature	Temperature: daily maximum	Reach and month	1, 3
	Temperature: daily minimum	Reach and month	1, 3
	Temperature: food effect	Reach and month	1, 3
	Temperature: spatial variation	Reach and month	1, 3
Water quality	Dissolved oxygen	Reach and month	1
	Metals in sediments	Reach	n/a
	Metals in surface water	Reach	n/a
	Miscellaneous toxins	Reach	n/a
Biological community	Benthic richness	Reach	1, 3
	Fish community richness	Reach	1, 3
	Fish species introductions	Reach	1, 3
	Fish pathogens	Reach	4
	Hatchery fish outplants	Reach	1
	Predation risk	Reach	4
	Salmon Carcasses	Reach	1
Obstructions and withdrawals	Obstructions	Reach, month, and life stage	1, 4
	Unscreened withdrawals	Reach and month	

[‡]1 = The Confederated Tribes of the Colville Reservation quantitative habitat survey; 2 = LiDAR, aerial imagery, or quantitative modeling; 3 = extrapolation from representative reaches; 4 = professional knowledge/opinion.

current conditions could be based on the average of observed habitat and water quality conditions over a 10-year period, coupled with a 20-year hydrologic record.

Three types of habitat scenarios are analyzed in EDT: template, patient, and degraded. Template scenarios are commonly based on the pre-development baseline but may reflect a combination of pre-development conditions and anthropogenic constraints where appropriate (Blair et al. 2009). Patient scenarios typically represent current conditions but can be flexibly defined to meet different analysis needs. For example, a series of patient scenarios could be defined to represent different monitoring cycles or projected conditions under different management alternatives (Blair et al. 2009). Degradation scenarios represent undesirable future conditions that can be defined hypothetically or using outputs from other predictive models (Blair et al. 2009), such as modeled climate change effects on watershed processes (Flitcroft et al. 2016), water temperature (Isaak et al. 2017), and hydrologic conditions (Wenger et al. 2010).

Population Model

Populations in EDT are based on the multistage Beverton–Holt production model (Beverton and Holt 1957; Moussalli and Hilborn 1986; Mobrand et al. 1997) and are constructed using life history trajectories. A trajectory is a unique spatio-temporal pathway representing one possible path a specific life history form (e.g., age-2/2 transient rearing summer steelhead) could travel through the model habitat environment during its life cycle. Each step on this pathway is randomly generated from a set of user-defined life stage constraints. Each EDT population is composed of thousands of trajectories, referred to collectively as a trajectory set, that together represent the potential range of age–classes, spawn timing, behavioral types, and migratory patterns for the target population. A properly designed trajectory set will emulate both the extant diversity and best available knowledge of truncated and extirpated life histories of the target population.

Species–Habitat Rules

The species–habitat rules are a set of species and life stage-specific sensitivity curves that degrade life stage survival from benchmark levels based on exposure to modeled environmental attributes. The benchmarks are deterministic parameters representing the maximum density, survival rate, and optimum duration of each life stage under ideal habitat conditions in nature (Lestelle and Doyle 2021). Each rule set is a synopsis of scientific understanding of the habitat requirements of the target species, synthesized from the available literature through deliberation with experts and iterative testing (Lestelle et al. 2004; Blair et al. 2009). The species–habitat rules for Chinook Salmon and steelhead have recently been updated to reflect improved scientific understanding of species–habitat relationships (Doyle and Lestelle 2021; Lestelle and Doyle 2021).

EDT includes species–habitat benchmarks for migratory corridor (i.e., the Columbia River) and marine environments, but does not modify these benchmarks using environmental attributes and species–habitat rules. Marine and migratory corridor survival are simple user-modifiable multipliers that reduce survival from benchmark. This allows the user to calibrate out-of-basin survival based on observed smolt-to-adult recruitment and maintain the same out-of-basin conditions across analysis scenarios. While out-of-basin conditions can be individualized for the template, patient, and degraded scenarios, the typical EDT analysis applies the same conditions to each to avoid confounding model analysis of in-basin habitat conditions.

Integration

The EDT3 Report Generator integrates the model habitat environment, a selected trajectory set, and the species–habitat rules and benchmarks and generates a range of outputs selected by the user. A standard EDT analysis consists of performance reports and one or more diagnostic splice reports. Performance reports provide the basis for the EDT patient–template analysis (Blair et al. 2009), referred to in EDT3 as a diagnostic splice report. A diagnostic splice compares a selected focal (patient) scenario to one or more reference (template, other patient, or degraded) scenarios by systematically replacing focal scenario input attributes and result parameters with the equivalent parameters from each reference scenario and evaluates the effect of each substitution on the Beverton–Holt parameters for each trajectory. Then, EDT3 mathematically integrates those effects across all trajectories (Lestelle and Doyle 2021).

The performance report exposes a selected trajectory set (population) to a selected habitat scenario, calculates Beverton–Holt parameters for each trajectory based on its unique exposure to the environmental attributes in that scenario using the species–habitat rules, and integrates these parameters across all trajectories using user-selected weighting functions. Performance report results are expressed in terms of juvenile and adult habitat capacity, density-independent intrinsic productivity, and life history diversity (i.e., the proportion of trajectories with spawner–recruit productivity >1), analogs to the viable salmonid population metrics defined by McElhany et al. (2000).

Different splice report configurations are used to identify changes in population and habitat performance over space and time. Patient–template and patient–degraded diagnostic splices are designed to identify the locations and limiting factors that would generate the greatest improvement and greatest losses in viable salmonid population parameter performance if patient conditions were restored to template or were allowed to decline, respectively. Patient–patient scenario splices can be used creatively to meet different analysis needs. For example, if the patient–template splice identifies poor fry-to-parr survival as a dominant factor affecting population performance, the user could design a suite of patient–patient splices comparing current conditions to hypothetical habitat improvements provided by different combinations of restoration actions to develop a conceptual restoration strategy. This ability to systematically evaluate habitat performance across a range of known and projected future conditions is an inherent strength of the EDT platform.

Limitations

All ecosystem models have two inherent forms of uncertainty—structural and parameter—that must be acknowledged when using model predictions to guide management decisions (Knudsen and Michael 2009). The use of trajectories to model salmonid populations is a primary source of structural uncertainty in EDT. As predefined entities, trajectory distributions within the model habitat environment do not change in response to modeled habitat conditions—i.e., they are not agent-based. This limitation is countered by EDT by generating thousands of spatially and temporally unique trajectories and exposing all to modeled conditions to determine which succeed (Blair et al. 2009). While this approach is sophisticated and unique among salmon habitat models, trajectories are nonetheless an imperfect representation of biological complexity. For example, plasticity between resident and anadromous forms in response to environmental conditions is an important component of *O. mykiss* life history (Kendall et al. 2015). The EDT platform lacks the ability to model anadromous and resident trajectories as a single population and cannot emulate this aspect of diversity.

Another important structural limitation of EDT is that it is steady state. The EDT model assumes that the fixed set of environmental input conditions used in each habitat scenario remain static until the model population reaches an equilibrium state. As such, the model cannot emulate how a population composed of sequential cohorts will respond to variable environmental conditions across generations. This is important to recognize when comparing EDT results to observed abundance, which varies year to year in response to environmental variability and other factors.

There are two major sources of parameter uncertainty in EDT that are common to all models that predict species-specific responses to environmental conditions (Knudsen and Michael 2009). The first concerns the validity of the species-specific life stage benchmarks and the rules quantifying their relationship to environmental conditions. The benchmarks and rules are a synthesis of best available science about species–habitat relationships (Lestelle et al. 2005; Lestelle and Doyle 2021). While the benchmarks and rules reflect current scientific understanding, both incorporate assumptions that are an unavoidable source of uncertainty. For example, the benchmarks assume optimal fitness under ideal conditions in natural environments (Lestelle and Doyle 2021), which may not be valid for populations with significant hatchery influence (e.g., Araki et al. 2009; Anderson et al. 2020). Steel et al. (2009) conducted a comprehensive review of EDT2 and concluded that the combined parameter uncertainty inherent to the benchmarks and rules is likely significant. While they cautioned against relying on EDT abundance predictions, they determined that habitat prioritization results were robust (Steel et al. 2009).

The second source of parameter uncertainty in EDT relates to the environmental attribute inputs. The EDT model was developed during a period when many watersheds were data poor and the designers recognized that many data gaps would necessarily be filled using professional knowledge. McElhany et al. (2010) determined that parameter uncertainty overreliance on professional knowledge was a critical limitation affecting the reliability of many early EDT analyses. This form of parameter uncertainty is decreasing in significance as long-term data sets and other sources of reproduceable quantitative information have become more prevalent.

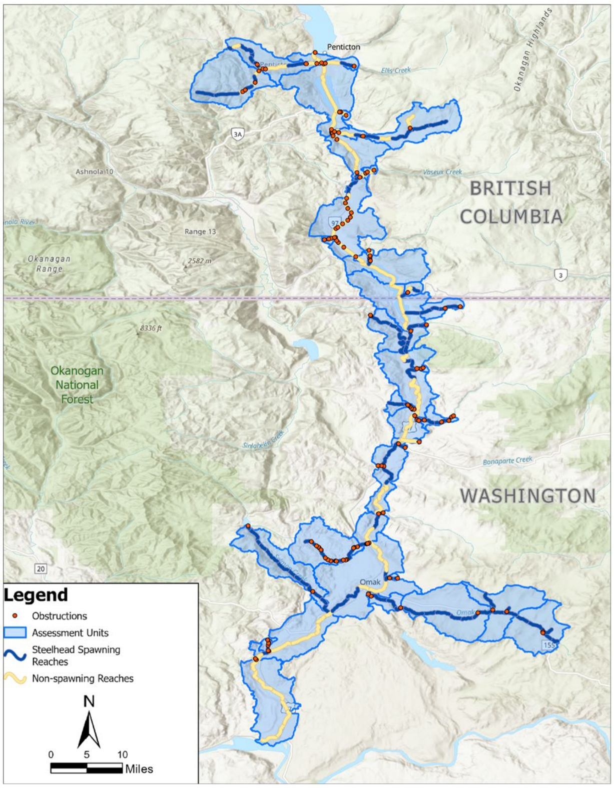

Figure 2. Okanogan Ecosystem Diagnosis and Treatment reach and assessment unit network displaying steelhead spawning habitat.

THE OKANOGAN EDT MODEL

The Okanogan EDT model is composed of 206 habitat and 152 obstruction reaches, representing 453 km of currently accessible anadromous habitat in the United States and Canada. Habitat reaches are defined around geomorphic discontinuities (i.e., changes in gradient and/or confinement) and range from 1 to 4 km in length. Okanogan model reaches are grouped into 41 diagnostic units, referred to as assessment units (AUs), that are roughly equivalent to U.S. Geological Survey Hydologic Unit Code 12 subwatersheds (Figure 2). Two species are currently modeled in Okanogan EDT, summer steelhead and summer/fall Chinook Salmon, each as two separate populations spawning in the United States and in Canada. Their respective trajectory sets are designed to emulate the range of life history expression observed in the extant population and inferred from historical data (Doyle 2013; Doyle and Blair 2013; Bourret et al. 2016).

Quantitative habitat and biological monitoring data collected by CTCR and partners are the primary source of information used in Okanogan EDT (USGS 2021). These data and other relevant sources of information, including remote sensing data and outputs from other quantitative models, are used to parameterize a new habitat scenario for each 4-year monitoring cycle. Each scenario represents the average of observed environmental attribute conditions over the respective 4-year period. Table 1 identifies the information sources used to parameterize each Okanogan EDT environmental attribute. Table 2 summarizes the information sources used in the 2017 patient scenario by attribute category as a proportion of total reach length.

The CTCR adapted the template and degraded scenarios from the EDT2 Subbasin Planning model (NPCC 2004) with substantial updates. Template flow variability attributes were revised using historical hydrologic modeling (Wenger et al. 2010) and habitat composition, substrate, and riparian conditions ratings were updated using representative data from suitable reference reaches. The CTCR developed a new "2040" habitat scenario using downscaled ensemble climate model predictions for the Okanogan subbasin (Mote et al. 2016; Rupp et al. 2017) and a subbasin-specific spatial model built on the STARS/SSN platform (Peterson and Ver Hoef 2014; Ver Hoef et al. 2014).

The CTCR generates performance and diagnostic splice reports for each new patient scenario and uses model results for status and trends reporting. The CTCR assess habitat status by comparing population and habitat performance results for each monitoring cycle to template conditions. Trends are assessed by comparing changes in patient scenario status relative to template between monitoring cycles. Status and trend analyses for the 2005–2009, 2010–2013, and 2014–2017 cycles, and the hypothetical 2040 scenario are posted to the Habitat Status and Trends Report Card (HSTR), a customized Web-based reporting tool (https://bit.ly/3EW26si). The HSTR summarizes status and trend and habitat prioritization results for each monitoring cycle at subbasin, AU, and reach scales, and the environmental input attributes used in each scenario with supporting metadata. The HSTR implementation tab, developed in collaboration with regional habitat practitioners, links priority habitat attributes in user-selected priority reaches and AUs to potentially suitable management actions to support restoration planning.

Okanogan EDT has demonstrated the ability to capture the effects of specific restoration actions and environmental variability on habitat performance at reach and AU scales.

Table 2. Summary of data and information sources used to parameterize environmental attributes in the Okanogan Ecosystem Diagnosis and Treatment (EDT) model.

	Okanogan EDT Habitat Attribute Data Source by Percent of Modeled Reach Length			
Attribute category	**Quantitative Monitoring Data**	**Remote Sensing or Modeling**	**Extrapolation from Similar Reaches**	**Professional Knowledge**
Channel morphometry	25%	75%	25%	–
Confinement	23%	76%	1%	–
Habitat composition	66%	26%	5%	2%
Riparian and channel integrity	9%	63%	16%	12%
Substrate conditions	32%	0%	50%	17%
Hydrology	27%	19%	44%	–
Water temperature	49%	12%	36%	–
Water quality	10%	80%	10%	–
Biological community	63%	15%	9%	12%
Obstructions and withdrawals	75%*	–	–	25%

*Obstructions include natural and anthropogenic barriers identified by survey, effects on passage by life stage are modeled. Unscreened withdrawals cannot be reliably detected by survey, attribute ratings are based on professional judgement.

	Sediment Conditions	Flow Variability	Cover and Complexity	Channel Stability
% of Template	76%	88%	89%	94%
Factor Trend	▼	▼	▼	▼
Factor Weight	2.5	0.8	0.6	0.4
Level of Proof	1.9	1.7	1.7	1.7

Figure 3. Okanogan ecosystem diagnosis and treatment habitat status and trends report card results for Loup Loup Creek, demonstrating modeled changes in steelhead abundance and priority limiting factor conditions between 2009 and 2013 in response to barrier removal, streamflow restoration, and negative impacts from headwater fires.

For example, HSTR results for Loup Loup Creek AU show that EDT accurately predicted the observed increase in steelhead abundance following barrier removal and streamflow restoration actions implemented between 2009 and 2013, and subsequent negative trends in substrate conditions caused by a series of damaging fires in the headwaters of the watershed (Figure 3; Table 3).

As stated previously, caution must be used when comparing EDT abundance results to observed abundance estimates. Abundance estimates generated through EDT are intended

Table 3. Ecosystem diagnosis and treatment (EDT) equilibrium abundance estimates for the template and 2017 habitat scenarios, EDT abundance trend estimates between 2013 and 2017 scenarios, and observed abundance of summer steelhead in the U.S. portion of the Okanogan subbasin from 2014 to 2017. DS = downstream boundary of assessment unit defined by a partial or complete barrier to anadromous fish passage.

	EDT Equilibrium Abundance Estimate			Observed Abundance 4-year geomean ± 90% CI (range), trend/year	
Population or Assessment Unit	**Template**	**2017**	**2013–2017 Trend**	**Natural Origin**	**Natural and Hatchery Origin**
U.S. steelhead population	1,162	334	74	292 ± 18 (109–497), −46/year	1,274 ± 80 (1,027–1,411), −937/year
Okanogan – Talant Creek	<1	0	0	0 ± 0 (0–2), +0/year	6 ± 0 (5–8), −9/year
Okanogan – Swipkin Canyon	37	0	0	3 ± 0 (1–6), −3/year	29 ± 2 (2–36), −37/year
Okanogan – Alkali Lake	7	0	0	2 ± 0 (1–4), +0/year	17 ± 1 (12–21), −7/year
Okanogan – Whitestone Coulee	26	0	0	4 ± 0 (2–8), −4/year	36 ± 2 (27–45), −46/year
Okanogan – Mosquito Creek	36	0	0	1 ± 0 (1–2), −1/year	9 ± 1 (6–11), −12/year
Okanogan – Haynes Creek South	25	0	0	24 ± 2 (10–47), −41/year	211 ± 13 (157–262), −434/year
Similkameen River	94	28	24	15 ± 1 (7–28), −25/year	126 ± 8 (94–156), −276/year
Loup Loup Creek-Lower DS	28	10	−5	11 ± 1 (3–33), +3/year	35 ± 2 (12–154), −17/year
Salmon Creek-Lower	318	128	41	44 ± 3 (29–79), +15/year	160 ± 10 (98–223), −41/year
Omak Creek-Lower DS	72	12	−19	69 ± 6 (8–207), −6/year	229 ± 14 (44–492), −11/year
Wanacut Creek DS	6	0	0	1 ± 0 (0–1), +0/year	0 ± 0 (0–8), +0/year
Johnson Creek	56	0	0	6 ± 0 (1–19), +5/year	37 ± 2 (20–57), +0/year
Tunk Creek-Lower DS	2	0	0	7 ± 0 (3–12), −1/year	39 ± 2 (23–49), −14/year
Bonaparte Creek-Lower DS	6	1	0	30 ± 2 (5–71), +5/year	97 ± 6 (43–138), +31/year
Antoine Creek-Lower	46	5	0	3 ± 1 (0–19), +2/year	14 ± 1 (0–72), +14/year
Tonasket Creek DS	5	4	1	5 ± 1 (0–27), −2/year	18 ± 1 (2–49), −35/year
Ninemile Creek DS	24	14	3	3 ± 0 (0–9), −6/year	7 ± 0 (1–25), −25/year

to be used as indicators of habitat performance useful for comparing conditions between spatial units and identifying priority habitats and limiting factors, rather than accurate measures of abundance. When considered in this context, Okanogan EDT results comport with the 4-year geomean of observed steelhead and Chinook Salmon abundance at the subbasin level. Table 3 presents EDT abundance estimates for the U.S. steelhead population under the template and 2017 habitat scenarios, abundance trends since 2013, and the 4-year geomean of observed natural origin and total spawner escapement in the U.S. portion of the subbasin. Results predicted by EDT fall within or near the 90% confidence interval for natural origin abundance at the subbasin level and selected AUs. More importantly, the pattern of abundance predictions is consistent with the distribution of natural-origin spawners throughout the subbasin.

POWER OF EDT

The CTCR has successfully integrated EDT modeling with long-term RME in the Okanogan subbasin. This tool has allowed us to meet habitat status and trend reporting requirements under the Columbia Basin Fish Accords. As the application has matured, we have realized additional benefits that demonstrate the value of EDT as a monitoring and adaptive management tool.

The use of EDT has helped us improve RME program effectiveness and efficiency by imposing a disciplined structure for how our data are used and managed. Incorporating data into EDT has exposed important spatial and structural data gaps, forcing us to develop creative solutions that have improved our monitoring program. For example, we determined that our riparian monitoring protocol was not providing useful data for parameterizing reach-level conditions in EDT. In response, we developed a new approach that combines field verification with high-resolution National Agricultural Imagery Program orthophotos and LiDAR to characterize floodplain vegetation condition and stream channel connectivity at the EDT reach level. This approach provides us with better information for less effort and has provided efficiency gains we are using to meet other needs.

Integration of EDT has created useful adaptive management feedback loops between habitat monitoring and restoration planning (Figure 4). The CTCR habitat implementation program and their subbasin partners use EDT results to identify habitat protection and restoration priorities and screens potential priority limiting factors using level-of-proof metadata. Restoration priorities with large parameter uncertainty are referred back to the CTCR monitoring program as data gaps so monitoring effort can be targeted strategically to support restoration planning. Feedback from the CTCR's habitat implementation program and their subbasin partners has inspired improvements to the HSTR to make EDT results more useful to the restoration community.

Integration of RME has also improved EDT by reducing parameter uncertainty and informing model improvements. Focused collection of habitat and biological monitoring data by the CTCR has reduced the need to rely on professional judgment to parameterize environmental attributes, reducing a key source of parameter uncertainty (McElhany et al. 2010). Reduced uncertainty and the ability to challenge model predictions against observed abundance over long time periods

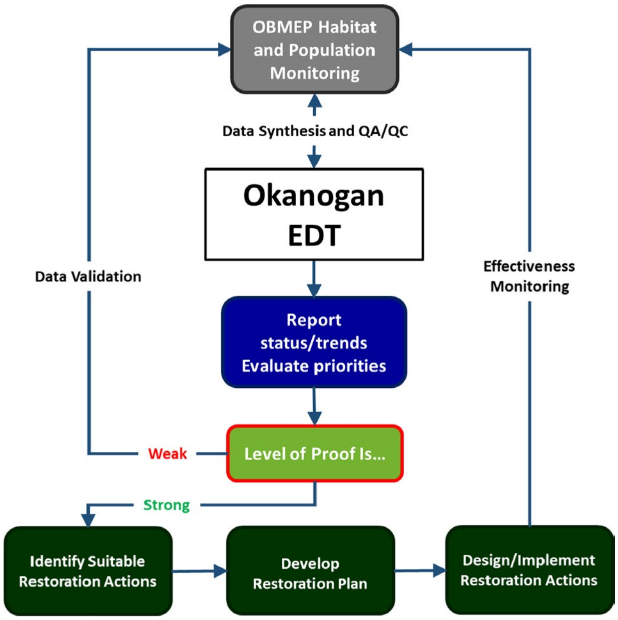

Figure 4. Adaptive management feedback loop between habitat monitoring, status and trends reporting, and restoration planning in the Okanogan subbasin. OBMEP = Okanogan Basin Monitoring and Evaluation Program; EDT = Ecosystem Diagnosis and Treatment; QA/QC = data review for quality assurance and quality control.

has exposed weaknesses in certain habitat rules. This, in turn, led to an update of the EDT rules for Chinook Salmon and steelhead to incorporate new scientific knowledge (Doyle and Lestelle 2021; Lestelle and Doyle 2021).

As Okanogan EDT has matured, its value has extended into other areas of resource management. The model played a central role in the development of the Water Resource Inventory Area (WRIA) 49 watershed plan update, a requirement of the 2018 Streamflow Restoration Act (Revised Code of Washington 90.94). Our team used EDT to analyze the projected effects of development-related water demand and offsetting streamflow and habitat restoration actions on aquatic habitats over a 20-year planning horizon. The EDT results demonstrated that proposed streamflow and habitat restoration measures would offset the effects of future water demand and achieve a net ecological benefit (Carlson et al. 2020).

CONCLUSIONS

The Okanogan EDT model has proven its value as an adaptive management tool supporting the conservation and recovery of Columbia River basin salmon and steelhead. The CTCR's early commitment to EDT has provided a consistent structure for organizing, synthesizing, and interpreting complex habitat data. The ability of EDT to normalize disparate information resources into a consistent set of reporting metrics that are comparable across watersheds, an original strength, is becoming more valuable in an increasingly data-rich world. The combination of RME with EDT and other model-based approaches provides upper Columbia River basin resource managers with a powerful toolkit for salmon and steelhead recovery. Building on their success in the Okanogan, the CTCR is developing an EDT model and habitat monitoring program for the adjacent Methow River subbasin, a critical stronghold for endangered upper Columbia River spring Chinook Salmon.

The challenges of salmon and steelhead recovery in the Pacific Northwest remain daunting, and much must be done to ensure these iconic species remain with us at the end of the 21st century. Resource managers will need to leverage every available resource to meet the moment. Decades of investment in habitat monitoring combined with advances in technology are rapidly filling data gaps while simultaneously threatening to overwhelm us with information. This speaks to the need for synthesis tools capable of integrating complex information into useful knowledge for adaptive management. The Okanogan EDT model is effectively serving this role in this important upper Columbia River subbasin.

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