Received: 8 July 2016 | Revised: 6 April 2017 | Accepted: 8 April 2017
DOI: 10.1002/aqc.2785

WILEY

RESEARCH ARTICLE

Developing a landscape-scale, multi-species, and cost-efficient conservation strategy for imperilled aquatic species in the Upper Tennessee River Basin, USA

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Abstract

1. Strategic conservation of imperilled species faces several major challenges including uncertainty in species response to management actions, budgetary constraints that limit options, and the need to scale expected conservation benefits from local to landscape levels and from single to multiple species.
2. A structured decision-making process was applied to address these challenges and identify a cost-effective conservation strategy for the Federally listed endangered and threatened aquatic species in the Upper Tennessee River Basin (UTRB). The UTRB, which encompasses a landscape of ~58 000 km^2, primarily in western North Carolina, eastern Tennessee, and south-western Virginia, harbours one of the most globally diverse assemblages of freshwater fishes and mussels at temperate latitudes. To develop a strategy for conservation of 12 fish species and 24 mussel species over a 20-year period, a management strategy that would best recover these species was identified given costs and uncertainty in management effectiveness.
3. The main insights came from a trade-off analysis that compared alternative allocations of effort among management actions. A strategy emphasizing population management, which included propagation and translocation, performed best across a wide range of objective weightings and was robust to uncertainty in management effectiveness. Species prioritization was based on the expected conservation benefit from the best performing strategy, degree of imperilment, and species-specific management costs. Sub-basin prioritization was based on expected conservation benefit from the best performing strategy and feasibility of habitat management and threat abatement.
4. Although the strategy was developed for imperilled aquatic species in the UTRB, the structured process is applicable for developing cost-efficient strategies to conserve multiple species across a landscape under uncertain management effectiveness. The process can assist a manager with limited resources to understand which species to work on, where to conduct that work, and what work would be most beneficial for those species in those catchments.

KEYWORDS
conservation evaluation, endangered species, erosion, fish, impoundment, invertebrates, mining, river, stream

1 | INTRODUCTION

Development of a conservation strategy for imperilled species should account for expected benefits to the species, costs of management, and uncertainty in species response to management actions at multiple scales (Joseph, Maloney, & Possingham, 2009; Naidoo et al., 2006; Regan et al., 2005; Tulloch et al., 2015). The task is made even more challenging by the incompleteness of data available to evaluate potential consequences of management actions (Drescher et al., 2013). Policy makers and managers naturally seek strategies that minimize the risk of failing to achieve conservation objectives and are robust to uncertainties in conservation outcomes (Tulloch et al., 2015). Projecting consequences of management actions while accounting for uncertainties helps managers compare alternatives and assess risks. Although the individual management actions that comprise a strategy are typically implemented at the local scale, the consequences of those actions should be evaluated ultimately using their landscape-scale effects (Roux, Nel, Fisher, & Barendse, 2016). For example, connectivity in river networks can be critical for all life-history stages to facilitate colonizing restored habitats (Galbraith & Vaughn, 2011). Lengyel et al. (2014) stressed the importance of a multi-scale approach for effective conservation planning.

Implementation of a conservation strategy results in an allocation of substantial but limited organizational resources (Bottrill et al., 2008). Thus, an effective strategy should allocate those resources efficiently among management actions for the purpose of best achieving conservation objectives given costs (Collier, 2011; Joseph et al., 2009; Linke, Turak, & Nel, 2011). Structured decision making (SDM), which originates from decision analysis, offers an explicit and transparent process to find the allocation that is most likely to achieve conservation objectives (Conroy & Peterson, 2013; Gregory et al., 2012; Howard, 1988). The application of SDM to natural resource management and conservation is increasing, as its usefulness for decision making in the face of competing objectives and uncertainty has become apparent (Gregory, Arvai, & Gerber, 2013; Gregory & Long, 2009; Martin et al., 2011; Reichert, Langhans, Lienert, & Schuwirth, 2015; Robinson, McGowan, & Apodaca, 2016; Smith et al., 2015). SDM strives to identify the best strategy to achieve what decision makers and stakeholders value by deconstructing a decision problem into its universally recognizable components for deliberation by stakeholders, resource experts, and analysts (Goodwin & Wright, 2004; Gregory et al., 2012; Keeney, 1992). Once the decision problem is defined and framed, the next step is to identify the fundamental objectives followed by the development of alternative strategies to meet those objectives. By comparing projected consequences of alternative strategies, the preferred strategy is selected that has the best chance of meeting those objectives. Explicit evaluation of trade-offs and sensitivity of the decision to uncertainty contribute to finding a robust solution (Gregory & Long, 2009; Runge, Converse, & Lyons, 2011). Transparency and explicitness, which are quality indicators of good governance, are hallmarks of SDM.

Decision analysis is compatible with, and a natural extension of, the evolving efforts in conservation planning for aquatic resources (Collier, 2011; Linke et al., 2011). As with decision analysis in general, initial steps begin with specifying particular values or outcomes that define the conservation objectives (Boon, Holmes, Maitland, & Fozzard, 2002; Dunn, 2004; Linke et al., 2011). Conservation objectives have been based on integrative principles (e.g. the CARE principles), species distributions, or vulnerability to threats while considering costs and public acceptance (Boon et al., 2002; Hermoso, Januchowski-Hartley, Linke, & Possingham, 2011; Linke et al., 2011; McDermid, Browne, Chetkiewicz, & Chu, 2015). Sets or portfolios comprising areas or species to prioritize for conservation become the strategic alternatives to evaluate desired outcomes. Game, Kareiva, and Possingham (2013) cautioned, however, that finding the best conservation actions should precede prioritizing species or locations to ensure clarity on what actions to take, for which species, and where. The approach presented in this paper was to use SDM to find the allocation of effort among management actions that best achieves the conservation objectives, and then prioritize species and catchments based on the expected conservation benefits.

The SDM process with a multi-scale approach was applied to identify a cost-effective conservation strategy for the imperilled aquatic species in the Upper Tennessee River Basin (UTRB; Figure 1), which face a variety of threats. This paper describes and presents the results from that SDM process (US Fish and Wildlife Service [USFWS], 2014). The extraordinary biodiversity in the UTRB is one of the primary factors that led the United Nations Educational, Scientific, and Cultural Organization (UNESCO) to designate the Southern Appalachians as a Man and the Biosphere Reserve in 1988 (http://www.samab.org/) and The Nature Conservancy (2009) to identify the UTRB as one of the most significant biodiversity hotspots in the United States. For this paper, imperilled species are those species listed as endangered or threatened under the Federal Endangered Species Act. Because nearly all imperilled aquatic species in the UTRB are fishes or mussels, the strategy focuses only on these two faunal groups. The overarching goal of the strategy is to maximize the recovery of imperilled aquatic species and the UTRB habitat upon which they depend. Under that strategic goal, the two fundamental objectives that encompassed all other objectives are to: (1) maximize imperilled species viability and (2) maximize operational efficiency. In developing the strategy, the intent was to identify which management actions to emphasize in order to best achieve those fundamental objectives over a 20-year period consistent with multiple generations for many of the species and within organizational planning horizons.

2 | METHODS

2.1 | Study area

The UTRB, which encompasses a landscape of ~58 000 km^2 primarily in western North Carolina, eastern Tennessee, and southwestern Virginia (Figure 1), harbours one of the most globally diverse assemblages of freshwater fishes and mussels occurring at temperate latitudes (Etnier & Starnes, 1993; Jelks et al., 2008; Parmalee & Bogan, 1998). Within North America, the UTRB is unsurpassed for its number of imperilled fishes and mussels;

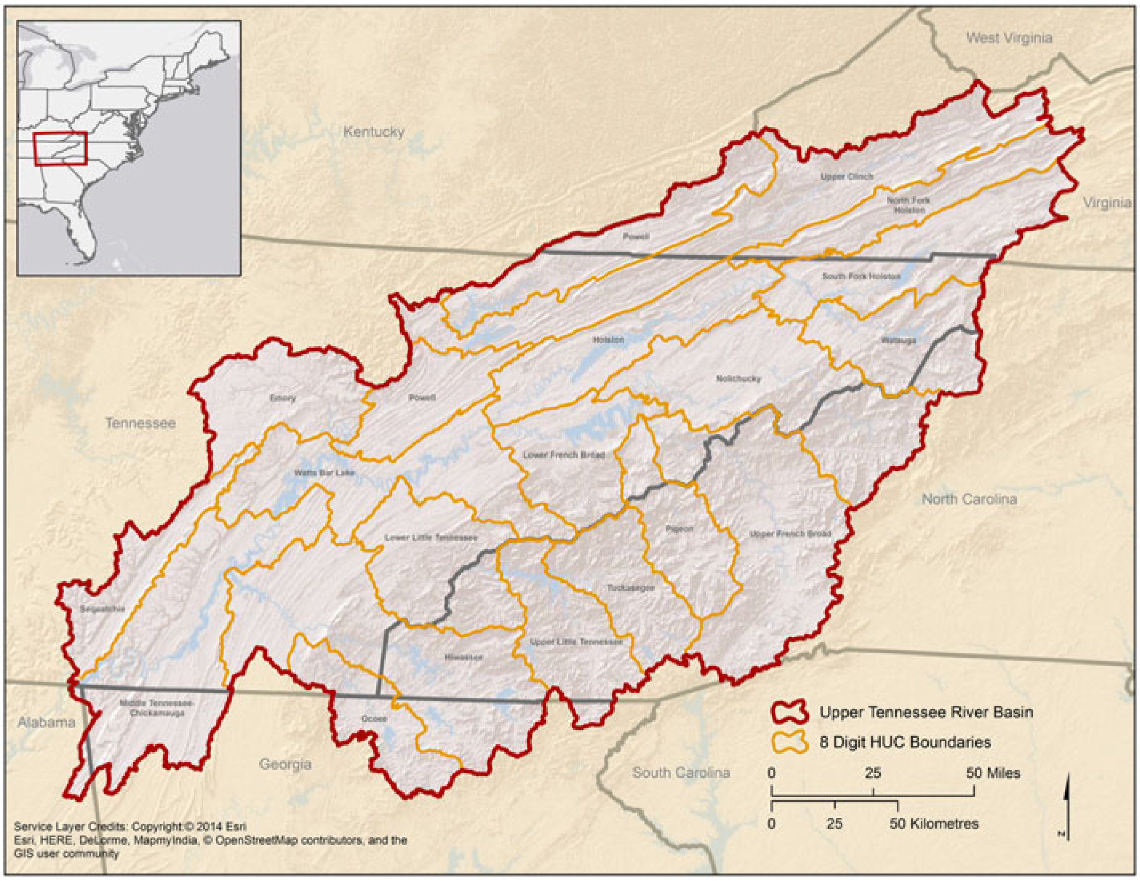

FIGURE 1 The UTRB encompasses 57 912 km^2 and includes the entire Tennessee River basin upstream of the confluence with and including the Sequatchie River. For this paper, small portions of the UTRB in Alabama and Georgia are omitted from consideration

12 fish species and 24 mussel species are covered in the strategy (Table S1, Supporting information). Many of these species are critically endangered globally (Jenkins & Burkhead, 1994; Williams, Bogan, & Garner, 2008). Moreover, many are endemic to the UTRB or are currently restricted to it, which heightens the importance for effective conservation of this unique aquatic fauna (USFWS, 2014). The sources and stressors that could contribute to imperilment within the UTRB include increased predation, presence of invasive species, degraded physical habitat, low abundance of mussel host fishes, altered flows, degraded water quality, lack of dispersal caused by habitat fragmentation (e.g. from dams), disease outbreak, and reduced reproduction due to low population size (Allee effect). The extent that these factors were limiting imperilled-species status was considered in strategy development.

In this paper, the term 'basin' refers to the entire UTRB (Figure 1). The term 'sub-basin' refers to partitions of the UTRB defined by the 8-digit Hydrologic Unit Code (Seaber, Kapanos, & Knapp, 1987). The term 'sub-catchment' refers to partitions of the sub-basins defined by the 12-digit Hydrologic Unit Code (Seaber et al., 1987).

2.2 | Strategy development

The development of a strategy to conserve the imperilled aquatic species of the UTRB followed these steps:

1) Identify the management strategy that will maximize species viability for the imperilled aquatic species of the UTRB while considering operational efficiency of management by:
   a) Identifying conservation objectives and specifying performance measures for each objective. In an SDM process, performance measures are used to compare how well alternative actions and strategies are likely to perform on stated objectives. Keeney (1992) and Gregory et al. (2012) describe desirable properties for performance measures including that they are unambiguous, comprehensive, direct, operational, and understandable.
   b) Inventorying a comprehensive set of management actions (Table S2) and formulating them into broad alternative strategies that address threats and other factors limiting species viability while considering operational efficiency.
   c) Projecting the consequences of alternative strategies on each imperilled species and its habitat and estimating the costs of implementing management strategies within the designated management units of the UTRB.
   d) Conducting a trade-off analysis to determine the management strategy that best achieves the conservation objectives of maximizing conservation benefits while minimizing operational costs.
   e) Evaluating the sensitivity of the trade-off analysis to uncertainty in management effectiveness and variation in relative

importance (weighting) of the objectives and corresponding performance measures.

2) Prioritize species for focused management based on the expected conservation benefit per species (as predicted from the best performing strategy identified in step 1), level of imperilment, and species-specific management costs.
3) Prioritize sub-basins for habitat management based on expected conservation benefit within a sub-basin (as predicted from the best performing strategy identified in step 1) and feasibility of habitat improvement and threat abatement (a proxy for costs) within each sub-basin.

Expert elicitation can provide important information for decision making when data from research or monitoring is incomplete or unavailable (Burgman, 2015; Drescher et al., 2013; Feio et al., 2016; US Environmental Protection Agency, 2011). Team members (USFWS, 2014) provided their judgement on likely outcomes for conservation benefits and costs along with uncertainty in those judgements if alternatives were implemented (Drescher et al., 2013; Gregory et al., 2012). The modified Delphi process was followed to elicit the judgements (Burgman, 2015; Drescher et al., 2013). Costs (staffing level and operational cost) for individual management actions were assessed under status quo management, and then the effort relative to status quo was used to estimate cost under each management strategy. Status quo management involves an unstructured and opportunistic mix of species-specific population restoration and habitat restoration efforts spread across the UTRB.

2.2.1 | Simple multi-attribute rating technique (SMART) trade-off analysis and sensitivity analysis

The SMART trade-off analysis was used to evaluate unavoidable trade-offs between achieving conservation benefits and minimizing management costs (Goodwin & Wright, 2004; Gregory et al., 2012). The first step was to normalize the projected consequences within each objective, and then take a weighted average of each alternative (Goodwin & Wright, 2004). The weights used in the weighted average reflect the relative importance of each fundamental objective. The weighted average becomes the basis for comparing alternatives. The alternative with the highest final score is considered the optimal management strategy.

Uncertainty can be an impediment to finding the best management strategy (Maxwell et al., 2015; Regan et al., 2005; Runge et al., 2011), and management effectiveness is a pervasive source of uncertainty. A sensitivity analysis was conducted to identify alternatives that are robust to uncertainty in management effectiveness by repeating the SMART trade-off analysis across effectiveness. Management effectiveness was treated as a percentage of full performance that ranged from 0% (completely ineffective) to 100% (fully effective). Weights assigned to the fundamental objectives reflect the relative importance placed on the objectives; the relative importance can (and often does) vary among stakeholders (Davies, Bryce, & Redpath, 2013). A second sensitivity analysis was conducted to identify alternatives that are robust to variation in the weights assigned to the species viability objective versus the cost objective.

2.2.2 | Species and sub-basin prioritization

Conservation benefits are not expected to be achieved equally or at similar costs among all species and sub-basins even under the optimal management strategy. Thus, priorities were based on a consideration between expected conservation benefit and management costs. Management costs were categorical summaries based on cost for management actions (Table S3) and the team's experience with species-specific management. Relative degree of imperilment was taken into account when prioritizing species. Catchments were prioritized at the sub-basin level based on predicted frequency of occupied habitat and species occurrence and feasibility of implementing habitat management within each sub-basin.

As a measure of the degree of imperilment, the team members provided their judgment on the likelihood of extinction over the next 20 years within three categories: (1) low = ≤10%, (2) medium = >10–50%, and (3) high = >50% (Table S1). Expected conservation benefit — the maximum increase in abundance and distribution from the current condition — was measured as the difference between current status and what would be expected to result from applying the optimal management strategy. For distribution, the difference was standardized by dividing by current distribution. For prioritization, the measure of conservation benefits for a species was categorized as equal to 3 if gains were expected in both abundance and distribution, 2 if gains expected were either in abundance or distribution but not both, and 1 if no gains were expected in abundance and distribution. Population management costs were categorized (3 = low, 2 = medium, 1 = high) based on Table S2. Feasibility of implementing habitat management actions was characterized using three categories as judged by team experts (USFWS, 2014):

a) 1 = infeasible/low feasibility. There is little or no opportunity for habitat restoration/protection and threat abatement. Even with significant investments in habitat restoration/protection, threats are likely to continue or increase over time.
b) 2 = moderately feasible. There is limited opportunity for habitat restoration/protection and threat abatement. Significant investments in habitat restoration/protection might reduce threats over time.
c) 3 = high degree of feasibility. There is substantial opportunity for habitat restoration/protection and threat abatement. Significant investments in habitat restoration/protection are likely to reduce threats over time.

Measures for conservation benefit, cost, and imperilment were standardized as the value divided by the maximum. Standardized measures were multiplied and ranked to arrive at the final priority for species or sub-basins.

2.2.3 | Strategy goals and objectives

The overarching goal of the strategy was to maximize conservation and recovery of species and their habitat (Figure 2). Under that goal, the fundamentally important objectives were to: (1) maximize imperilled species viability and (2) maximize operational efficiency. The species viability objective was considered separately for fishes and

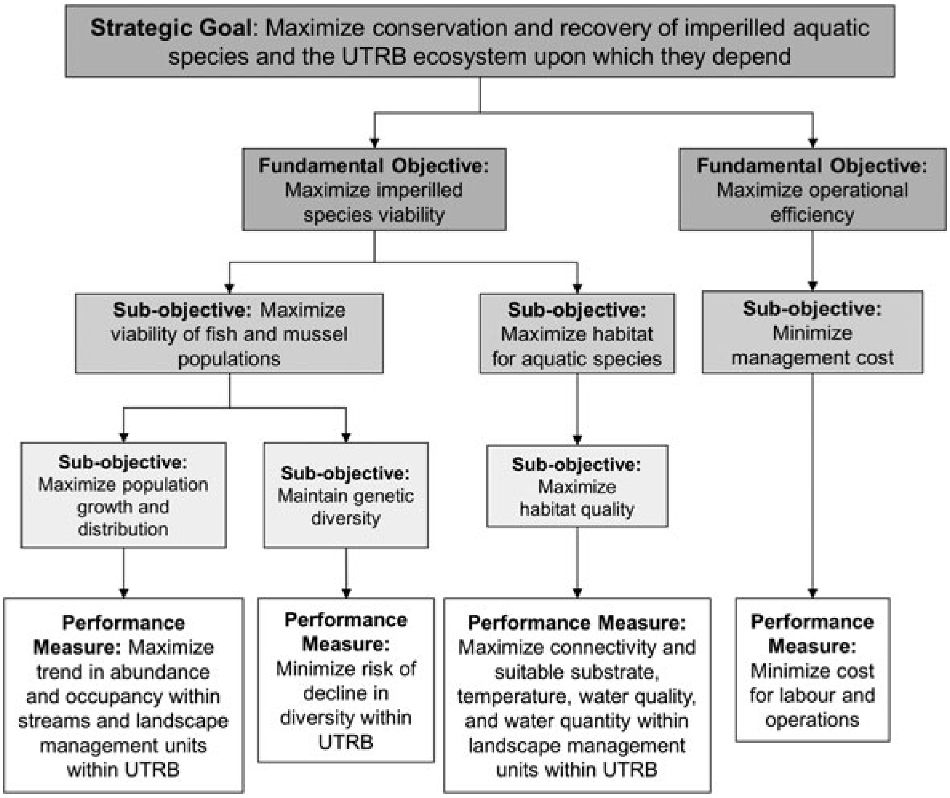

FIGURE 2 Hierarchy organizing the general goals and fundamental objectives for strategic decisions for conservation of imperilled aquatic species in the UTRB

mussels to allow for faunal group-specific differences when comparing conservation actions. Maximizing habitat quality, defined generally for all species, and maintaining genetic diversity were treated as sub-objectives to species viability. The operational efficiency objective was defined as minimizing management costs.

The performance measures for the species viability objective were trend in abundance, number of habitat units occupied as a proxy for distribution, and risk of decline in genetic diversity. Habitat units were at the sub-catchment level for fishes and important stream reaches for mussels. The performance measure for the habitat quality objective was based on the presence of the following habitat elements: (1) connectivity, (2) suitable substrate, (3) water temperature, (4) water quality, and (5) water quantity. The performance measures for operational efficiency were based on management cost as measured by staffing levels and operational costs.

The performance measure for trend in abundance over a 20-year period was categorical (−1 = decline, 0 = stability, +1 = increase). The trend in abundance was projected for current conditions, and what would be expected as a consequence of implementing population management emphasis (primary focus is population restoration and conservation/protection), habitat management emphasis (primary focus is habitat restoration and conservation/protection), and status quo management. The performance measure for habitat quality was based on the presence of suitable habitat elements at the end of a 20-year period. One point was awarded for each characteristic present within a sub-basin, to a maximum of 5 points. Habitat quality was projected at the sub-basin level, and the average across habitat units was used for comparisons. The performance measure for risk of decline in genetic diversity over a 20-year period was related to removal of threats and expanding populations: −1 = no removal of threats and no additional populations, 0 = addressing threats to existing populations, 1 = moving individuals through active translocation using best management practices (BMPs), 2 = both addressing threats and individuals using BMPs. Risk of decline in genetic diversity for all species combined was projected for what would be expected as a consequence of implementing population management emphasis, habitat management emphasis, and status quo management.

2.2.4 | Alternative management strategies

Formulation of alternative management strategies was guided by identifying primary threats and ecological factors that currently limit imperilled fish and mussel population growth, distribution, and viability. The limiting factors considered were predation, invasive species, physical habitat, abundance of mussel host fishes, flows and water quantity, water quality (e.g. dissolved oxygen, temperature, contaminants), lack of dispersal due to habitat fragmentation (e.g. from dams), disease, and reduced reproduction due to low population size (Allee effect). Experts ranked the top three limiting factors for imperilled fishes and mussels, collectively. A rank of 1, 2, and 3 received 30, 20, and 10 points, respectively, and then the points were summed for each factor separately for fishes and mussels. The summed scores were standardized between 0 and 100 for least to most important (Table 1). Reduced reproduction due to low population size, contaminants, and lack of

TABLE 1 Ranking of factors that could limit the viability of imperilled fishes and mussels in the UTRB. Potential limiting factors with a score of zero included: Predation, invasive species, dissolved oxygen, water temperature, and disease and are not included in this table

Potential limiting factors	Standardized score Fishes	Mussels
Reduced reproduction due to low population size (Allee effect)	88	100
Water quality/contaminants	100	89
Lack of dispersal/habitat fragmentation	88	78
Physical habitat	50	33
Host fish	0	22
Flows	13	11

dispersal were among the top three limiting factors for both fishes and mussels.

Two broad management strategies were considered to address the limiting factors: (1) population management emphasis (i.e. places greater emphasis on population management actions but also includes habitat management actions) and (2) habitat management emphasis (i.e. places greater emphasis on habitat management actions but also includes population management actions). Population management emphasizes actions that address reduced reproduction due to low population size and lack of dispersal/fragmentation by increasing populations (augmentations) and establishing additional populations (reintroductions) through propagation and release of cultured individuals and translocated adults into suitable habitat (George et al., 2009; Neves, 2004; Strayer et al., 2004). Habitat management emphasizes actions that address water quality, physical habitat, and flows by protecting or restoring occupied and unoccupied habitat within the historical UTRB range of imperilled species (Haag & Williams, 2014; Strayer & Dudgeon, 2010; Strayer et al., 2004). It is important to note that within these broad strategies, population and habitat management are not mutually exclusive. Rather, each represents a strategic allocation of effort that includes both population and habitat management but in different measures. These two strategies — population management emphasis and habitat management emphasis — were compared with a status quo management, which is now being implemented by the USFWS.

An inventory of management actions (Table S2) was taken together with associated costs (Table S3). Management strategies were defined by the level of effort or agency resources committed to implementing management actions (Table 2). The level of effort under the status quo strategy reflects what is currently being done, and the other strategies were designed as alternatives to the status quo. For example, under the status quo strategy about half of potential new populations would be established, whereas under the habitat and population management strategies 20% and 90% of potential new populations would be established, respectively. In addition, under the status quo strategy about 20% of potential sites are acquired or placed into conservation easements, whereas under the habitat and population management strategies 30% and 10% would be acquired or placed into easements, respectively.

3 | RESULTS

3.1 | Strategy analyses

3.1.1 | Comparing alternative management strategies

Projected species level consequences for trends in abundance and occupancy of habitat units (Tables 3 and 4), habitat quality (Table 5) and operational costs (Table 6) were summarized at the UTRB level and combined with operating costs into a consequence table (Table 7). Risk to loss of genetic diversity was assessed at the UTRB level and other conservation benefits were scaled up from the local effect to the UTRB (Table 7). The performance measures for each objective were projected over a 20-year period, standardized, and combined to result in a final score for each strategy. To account for different levels of importance among objectives, each performance measure was weighted when combined into a final score. Importance among objectives will vary among stakeholders, thus the sensitivity of the trade-off analysis to variation in objective weightings was investigated.

On average, the population emphasis strategy was expected to do best for abundance and distribution metrics for both fish and mussel species (Tables 3 and 4). Abundance or distribution metrics were expected to improve by emphasizing population management compared with other strategies in six out of 12 fish species and 20 out of 24 mussel species. Population management emphasis was the only strategy that was expected to improve genetic diversity (Table 7). Habitat management emphasis was expected to improve habitat quality compared with the other strategies in 10 of the 12 sub-basins (Table 5). Annual costs were expected to be highest for a habitat emphasis and lowest for a population emphasis (Table 6).

3.1.2 | Trade-off and sensitivity analyses

The projected conservation benefits and management costs for each management strategy (Table 7).were used in a SMART trade-off analysis to compare alternatives. The population management strategy was best at meeting all objectives except for the habitat quality and staff costs objectives. The habitat management strategy best met only the habitat quality objective, and the status quo strategy best met only the staff cost objective. Importantly, the emphasis on population management was found to be optimal across a wide range of objective weightings and, by extension, to variation in stakeholder values (Table S4). Only when minimizing labour and management costs was highly important (i.e. weight on cost was ≥60% of total weight) did the status quo strategy become optimal.

The management effectiveness ranged from 0.1 to 1.0 (e.g. from achieving 10% to 100% of the expected conservation benefit). Because the emphasis on population management was found to be broadly optimal under full effectiveness, the sensitivity analysis was focused on when population management was less than fully effective. As the likelihood declined from fully effective (i.e. 1.0), the strategy emphasizing population management remained optimal, and its final weighted score converged with that of status quo management only after management was deemed highly ineffective (i.e. likelihood <0.2) (Figure 3). Unless the likelihood of population management

TABLE 2 Relative level of effort to implement management actions under alternative management strategies. Level of effort ranges from no implementation (0) to maximum implementation (1). The level of effort under the status quo strategy reflects what is currently being done, and the other strategies were designed as alternatives to the status quo. Details of the various management tasks and derivation of status quo level of effort are given in Table S2

Management actions			Alternative management strategies		
Type	Task	Basis for level of implementation	Status quo	Habitat emphasis	Population emphasis
Population emphasis	Implement ESA Section 7 and 10 regulations/influence agencies	Level and consistency of enforcement	0.7	0.7	0.8
	Use available means to protect or establish populations	Number of species and populations	0.5	0.5	0.9
	Conduct status assessment/list candidate species	Number of species	0.3	0.3	0.3
	Increase populations	Number of species and populations	0.7	0.6	0.9
	Establish new populations	Number of species and populations	0.5	0.2	0.9
	Manage captive populations	Number of species	0.0	0.0	0.5
Habitat emphasis	Develop BMPs for managing stream and riparian habitat	Number of sites	0.6	0.8	0.7
	Land acquisition and easements	Number of sites	0.2	0.3	0.1
	Restoration of instream and riparian habitat	Number of sites	0.3	0.4	0.1
Monitoring/Research	Life history	Number of species	0.4	0.6	0.6
	Population and habitat monitoring	Number of populations and sites	0.5	0.5	0.5
	Evaluate and monitor threats	Number of species	0.6	0.7	0.7
	Genetics monitoring and research	Number of species	0.3	0.2	0.5
	Population viability analyses	Number of species	0.2	0.0	0.7
	Evaluate habitat for reintroductions	Number of species	0.1	0.1	0.8
	Propagation and captive management research	Number of species	0.1	0.1	0.4
	Evaluate ecosystem services	Categorical effort	0.1	0.3	0.2
Communication and partnerships	Outreach	Categorical level of effort	0.3	0.8	0.5
	Work with partners and industry	Potential partnerships established	0.5	0.9	0.7
Agency Operations	Intra-agency	Categorical level of effort	0.5	0.5	0.5

TABLE 3 Conservation benefits for imperilled fishes projected over a 20-year period to compare alternative management strategies. Conservation benefits were measured by trend in abundance on a categorical scale (declining, stable, or increasing) and number of sub-basins (12-digit Hydrologic Unit Code (Seaber et al., 1987) occupied. The range for trend in abundance is −1 for high decline to +1 for high increase

	Trend in abundance within UTRB: declining = −1, stable = 0, and increasing = +1				Number of sub-basins occupied			
Common name	Current	Status quo	Habitat emphasis	Population emphasis	Current	Status quo	Habitat emphasis	Population emphasis
Chucky madtom (*Noturus crypticus*)	−1	−1	−1	-1	1	1	1	1
Citico darter (*Etheostoma sitikuense*)	0	1	0	1	2	3	3	3
Duskytail darter (*Etheostoma percnurum*)	0	−0.5	0	1	2	1	2	3
Laurel dace (*Chrosomus saylori*)	−1	−1	−0.5	0	4	2	3	4
Marbled darter (*Etheostoma marmorpinnum*)	−1	−0.5	0	0.5	4	4	4	5
Pygmy madtom (*Noturus stanauli*)	0	0	0	0.5	1	1	1	3
Sicklefin redhorse (*Moxostoma* sp.)	0	0.5	0.5	0.5	22	22	22	22
Slender chub (*Erimystax cahni*)	−1	−1	−1	−1	1	0	0	1
Smoky madtom (*Noturus baileyi*)	1	1	0	1	2	3	3	4
Snail darter (*Percina tanasi*)	1	1	1	1	21	21	21	21
Spotfin chub (*Erimonax monachus*)	0	0	0.5	1	26	26	26	29
Yellowfin madtom (*Noturus flavipinnis*)	1	1	0.5	1	10	10	10	11
Average	−0.08	0.04	0.00	0.46	8.00	7.83	8.00	8.92

TABLE 4 Conservation benefits for imperilled mussels projected over a 20-year period to compare alternative management strategies. Conservation benefits were measured by trend in abundance on a categorical scale (declining, stable, or increasing) and number of significant stream reaches occupied. The range for trend in abundance is −1 for high decline to +1 for high increase

	Trend in abundance within UTRB: declining = −1, stable = 0, and increasing = +1				Number of significant stream reaches occupied			
Common name	Current	Status quo	Habitat emphasis	Population emphasis	Current	Status quo	Habitat emphasis	Population emphasis
Alabama lampmussel (*Lampsilis virescens*)	0	−0.5	0	0.5	1	1	1	1
Appalachian elktoe (*Alasmidonta raveneliana*)	−1	−1	−1	−0.5	4	4	4	4
Appalachian monkeyface (*Quadrula sparsa*)	−1	−1	−1	−0.5	4	2	2	4
Birdwing pearlymussel (*Lemiox rimosus*)	0.5	0.5	0.5	1	7	7	6	10
Cracking pearlymussel (*Hemistena lata*)	0	0	0	0.5	3	3	3	10
Cumberland bean (*Villosa trabalis*)	0	0	0.5	1	1	1	1	1
Cumberland monkeyface (*Quadrula intermedia*)	−1	−1	−0.5	0.5	2	2	2	2
Cumberlandian combshell (*Epioblasma brevidens*)	0.5	0.5	0	1	6	6	6	10
Dromedary pearlymussel (*Dromus dromas*)	0	0	0	1	5	5	5	10
Fanshell (*Cyprogenia stegaria*)	0	0	0	1	3	3	3	9
Finerayed pigtoe (*Fusconaia cuneolus*)	0.5	0.5	1	1	7	4	4	10
Fluted kidneyshell (*Ptychobranchus subtentus*)	0.5	0.5	1	1	11	10	11	10
Golden riffleshell (*Epioblasma florentina aureola*)	−1	−1	−1	0	1	0	0	1
Littlewing pearlymussel (*Pegias fabula*)	−1	−1	−1	−0.5	2	0	0	6
Oyster mussel (*Epioblasma capsaeformis*)	0.5	0.5	0	1	7	7	7	10
Pink mucket (*Lampsilis abrupta*)	−1	0	−1	1	1	2	2	10
Purple bean (*Villosa perpurpurea*)	0	0	0.5	1	8	8	8	12
Rough pigtoe (*Pleurobema plenum*)	0.5	0.5	0.5	1	1	1	1	10
Rough rabbitsfoot (*Quadrula cylindrica strigillata*)	0	0	0.5	1	8	6	6	10
Sheepnose (*Plethobasus cyphyus*)	0.5	0.5	0.5	1	7	7	7	10
Shiny pigtoe (*Fusconaia cor*)	0.5	0.5	1	1	8	5	5	10
Slabside pearlymussel (*Pleuronaia dolabelloides*)	−1	−1	−0.5	0	11	5	5	10
Snuffbox (*Epioblasma triquetra*)	0	0	0	1	5	5	5	10
Spectaclecase (*Cumberlandia monodonta*)	−1	−1	−1	−1	4	4	4	4
Average	−0.17	−0.13	−0.04	0.58	4.91	4.09	4.09	7.83

TABLE 5 Predicted habitat quality performance measure for current conditions and alternative management strategies. Characteristics of quality aquatic habitat for imperilled species include free-flowing streams and suitable substrate, temperature, water quality, and water quantity. One point was awarded for each characteristic present within a sub-basin, for a maximum of 5 points. This measure represents general habitat suitability and might not reflect species-specific requirements. Sub-basins are at the 8-digit Hydrologic unit Code level (Seaber et al., 1987)

	Predicted habitat quality (maximum of 5 points)			
Sub-basin	Current condition	Status quo	Habitat emphasis	Population emphasis
Sequatchie	3.0	3.0	4.0	3.0
Hiwassee	2.0	2.0	3.0	2.0
Middle Tennessee-Chickamauga	1.0	0.5	2.0	0.5
Emory	3.0	3.0	3.8	3.0
Lower little Tennessee	4.0	4.0	4.5	4.0
Upper Clinch	4.0	4.0	4.5	4.0
North fork Holston	3.5	3.5	4.0	3.5
Powell	3.5	3.5	4.0	3.5
Holston	2.5	2.5	3.0	2.5
Nolichucky	2.5	2.5	3.0	2.5
Upper little Tennessee	4.0	4.0	4.0	4.0
Watts bar Lake	1.0	0.5	1.0	0.0
Average score	2.9	2.7	3.3	2.7

TABLE 6 Annual cost (in US $000 s) to implement actions under the status quo management (Table S3) and cost based on relative effort to implement alternative management strategies (Table 2)

	Alternative management strategy (US $000)		
Management action type	Status quo	Habitat emphasis	Population emphasis
Population management	1973	1722	2578
Habitat management	1632	2176	563
Monitoring/research	1125	1312	1424
Communication and partnerships	71	157	108
Agency operations	56	56	56
Total	4856	5423	4729

TABLE 7 Consequence table with performance measures to compare alternative management strategies. Fish abundance trend at UTRB level: Declining, stable, improving (−1, 0, 1, respectively) averaged across species (Table 3). Fish distribution at the UTRB level: Number of sub-catchments (12-digit Hydrologic unit Code; Seaber et al., 1987) occupied per species averaged across species (Table 3). Mussel abundance trend at UTRB level: Declining, stable, improving (−1, 0, 1, respectively) averaged across species (Table 4). Mussel distribution at the UTRB level: Numbers of reaches occupied per species averaged across species (Table 4). Risk to loss of genetic diversity: −1 = no removal of threats and no added populations, 0 = addressing threats to existing populations, 1 = moving individuals using BMPs, 2 = both addressing threats and individuals using BMPs. Habitat quality at the UTRB level: Habitat score based on presence of suitable habitat components (i.e. free-flowing and suitable substrate, temperature, water quality, and water quantity) averaged across sub-basins (8-digit Hydrologic unit Code; Seaber et al., 1987; Table 5). Staffing level (full-time equivalent) within UTRB: Millions of US$ per year (Table 6)

			Alternative management strategy		
Objective	Sub-objective	Direction	Status quo	Habitat emphasis	Population emphasis
Species viability	Fish abundance trend	Maximize	0.04	0.00	0.46
	Fish distribution	Maximize	7.83	8.00	8.92
	Mussel abundance trend	Maximize	−0.13	−0.04	0.58
	Mussel distribution	Maximize	4.09	4.09	7.83
	Genetic diversity	Maximize	−0.17	−0.17	0.52
	Habitat quality	Maximize	2.73	3.34	2.68
Operating costs	Staff	Minimize	9.5	11.5	11.5
	Management costs	Minimize	4.8	5.4	4.7

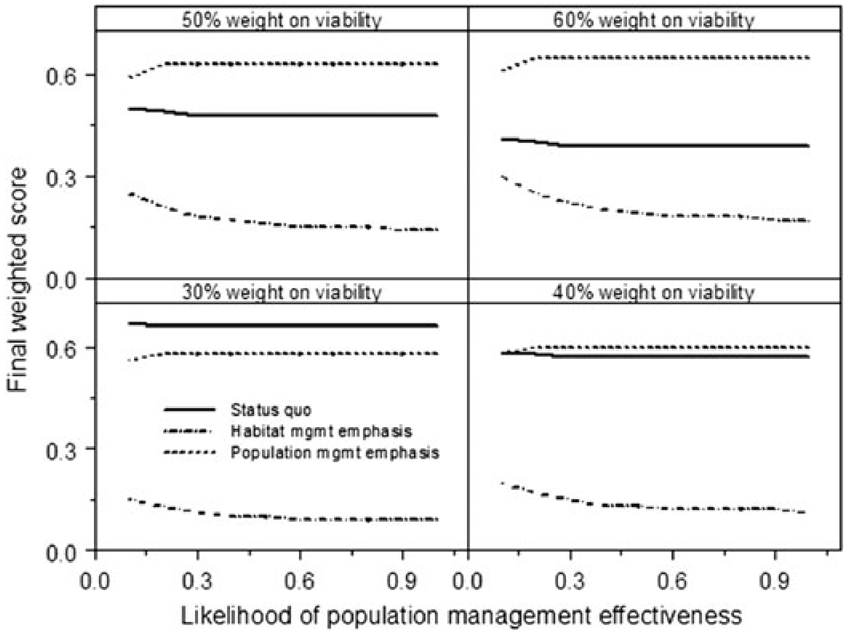

FIGURE 3 Sensitivity analysis to examine how uncertainty about management effectiveness might alter selection of optimal strategy. The final weighted score for each strategy is shown across a range in likelihood of population management effectiveness conditioned on the weight given to maximizing viability with the remaining weight given to minimizing cost. In no case did the optimal strategy, which is indicated by the highest line, switch as a function of management effectiveness

effectiveness dropped below 0.1, the emphasis on population management remained optimal.

The strategy that emphasized population management was found to be optimal as long as the weight on maximizing viability was at least 40% of total objective weighting relative to minimizing cost. The particular scenario shown in Figure 3 represents a boundary condition with 40% of total objective weight allocated to maximizing species viability and 60% allocated to minimizing cost and with the weight on viability split evenly among abundance, distribution, genetic diversity, and habitat quality. For all other scenarios where objective weight on maximizing species viability exceeded 0.4 and likelihood of management effectiveness exceeded 0.1, the final weighted score for population management emphasis exceeded that of the other strategies. Therefore, the selection of population management emphasis as the best management strategy was found to be robust to relative uncertainty in management effectiveness.

3.1.3 | Species and sub-basin prioritization

Degree of imperilment was classified as low, medium, or high for 25%, 8%, or 67% of fish species and 12%, 50%, or 38% of mussel species, respectively (Table S1). Expected conservation benefit was derived from the population management strategy because it was deemed to be optimal under a wide range of objective weightings and robust to uncertainty (Table S4, Figure 3). Highest priority was given to species with expected gains in abundance and distribution, medium to high imperilment, and low management costs (Tables 8 and 9). Lowest priority was given to species not expected to benefit from conservation regardless of cost (Tables 8 and 9). For example, the duskytail darter, which has a high degree of imperilment, is predicted to increase in abundance and occupy three sub-basins under the strategy emphasizing population management (Table 3). Its management costs are expected to be low to medium (Table 8). As a result its rank is third out of 12. In contrast, slender chub, which also has a high degree of imperilment, is predicted to continue to decline in abundance and its distribution is predicted to be restricted to one sub-basin regardless of conservation strategy. Its management costs are high. As a result its rank is tenth out of 12.

Based on distribution of conservation benefits and opportunity for habitat improvement and threat abatement, sub-basins were prioritized (Table 10). High priority catchments had high to moderate richness and high to moderate improvement/abatement feasibility. Low priority catchments had low or moderate richness and low improvement/abatement feasibility. The top five sub-basins are predicted to support 12 or more imperilled species at 20 or more sites each under the strategy emphasizing population management. Feasibility of reducing threats and improving habitat within these top sub-basins is predicted to be moderate or high. In contrast, the bottom five sub-basins are predicted to support no more than two imperilled species within no more than four sites each. Feasibility for these bottom sub-basins is predicted to be moderate or low.

4 | DISCUSSION

A structured decision-making process helped identify a cost-effective conservation strategy for the Federally listed endangered and threatened aquatic species in the UTRB. Emphasis on population management, including propagation and translocation, was found to be optimal across a wide range of objective weightings and was robust to uncertainty in management effectiveness. Species were ranked proportional to the expected conservation benefits based on the optimal strategy adjusted for management costs and the level of species imperilment. Sub-basins were ranked based on expected conservation benefits adjusted for the feasibility (a proxy for cost) of managing the habitat for imperilled species within it.

The main results and actionable insights come from the tradeoff analyses that relate to allocation of effort among management actions. The optimal allocation among actions comprises the basis for the overall strategic shift towards an emphasis on population

TABLE 8 Prioritization of imperilled fishes of the UTRB. Prioritization input variables included degree of imperilment, management cost, and expected conservation benefit from management actions accrued over the next 20 years. Degree of imperilment is based on a qualitative assessment of rangewide extinction risk over 20 years (Table S1). Expected conservation benefit is the maximum gain over 20 years relative to current status. Management costs are a categorical summary based on management action costs. Measures of imperilment, expected conservation benefit, and costs were standardized, multiplied, and ranked

		Expected conservation benefit		Management cost		Standardized measures			Prioritized rank	
Common name	Degree of imperilment	Gain in abundance trend	Gain in distribution	Cost of propagation	Cost of reintroduction	Imperilment	Conservation benefit	Costs	Product of standardized measures	Final rank
Marbled darter	High	1.5	0.3	Low	Low	1.00	1.00	1.00	1.00	1
Citico darter	High	1.0	0.5	Low	Low	1.00	1.00	1.00	1.00	1
Duskytail darter	High	1.0	0.5	Low	Medium	1.00	1.00	0.75	0.75	3
Laurel dace	High	1.0	0.0	Medium	Low	1.00	0.67	0.75	0.50	4
Pygmy madtom	High	0.5	2.0	Medium	Medium	1.00	1.00	0.50	0.50	4
Smoky madtom	High	0.0	1.0	Medium	Medium	1.00	0.67	0.50	0.33	6
Yellowfin madtom	Medium	0.0	0.1	Low	Medium	0.67	0.67	0.75	0.33	6
Spotfin chub	Low	1.0	0.1	Medium	High	0.33	1.00	0.50	0.17	8
Chucky madtom	High	0.0	0.0	High	Medium	1.00	0.33	0.50	0.17	8
Slender chub	High	0.0	0.0	High	High	1.00	0.33	0.25	0.08	10
Sicklefin redhorse	Low	0.5	0.0	High	High	0.33	0.67	0.25	0.06	11
Snail darter	Low	0.0	0.0	High	Medium to high	0.33	0.33	0.25	0.03	12

TABLE 9 Prioritization of imperilled mussels of the UTRB. Prioritization input variables included degree of imperilment, management cost, and expected conservation benefit from management actions accrued over the next 20 years. Degree of imperilment is based on a qualitative assessment of rangewide extinction risk over 20 years (Table S1). Expected conservation benefit is the maximum gain over 20 years relative to current status. Management costs are a categorical summary based on management action costs. Measures of imperilment, expected conservation benefit, and costs were standardized multiplied, and ranked

		Expected conservation benefit		Management cost	Standardized measures			Prioritized rank	
Common name	Degree of imperilment	Gain in abundance trend	Gain in distribution	Cost of propagation and reintroduction	Imperilment	Conservation benefit	Costs	Product of standardized measures	Final rank
Cumberlandian combshell	Medium	0.5	0.7	Low	0.67	1.00	1.00	0.67	1
Alabama lampmussel	High	0.5	0	Low	1.00	0.67	1.00	0.67	1
Oyster mussel	Medium	0.5	0.4	Low	0.67	1.00	1.00	0.67	1
Dromedary pearlymussel	High	1	1	Medium	1.00	1.00	0.67	0.67	1
Purple bean	High	1	0.5	Medium	1.00	1.00	0.67	0.67	1
Fanshell	Medium	1	2	Medium	0.67	1.00	0.67	0.44	6
Birdwing pearlymussel	Medium	0.5	0.4	Medium	0.67	1.00	0.67	0.44	6
Cumberland bean	High	1	0	Medium	1.00	0.67	0.67	0.44	6
Golden riffleshell	High	1	0	Medium	1.00	0.67	0.67	0.44	6
Snuffbox	Low	1	1	Low	0.33	1.00	1.00	0.33	10
Pink mucket	Low	2	9	Low	0.33	1.00	1.00	0.33	10
Cracking pearlymussel	High	0.5	2.3	High	1.00	1.00	0.33	0.33	10
Littlewing pearlymussel	High	0.5	2	High	1.00	1.00	0.33	0.33	10
Appalachian elktoe	Medium	0.5	0	Medium	0.67	0.67	0.67	0.30	14
Fluted kidneyshell	Medium	0.5	0	Medium	0.67	0.67	0.67	0.30	14
Shiny pigtoe	Medium	0.5	0.3	High	0.67	1.00	0.33	0.22	16
Finerayed pigtoe	Medium	0.5	0.4	High	0.67	1.00	0.33	0.22	16
Rough pigtoe	Medium	0.5	9	High	0.67	1.00	0.33	0.22	16
Rough rabbitsfoot	Medium	1	0.3	High	0.67	1.00	0.33	0.22	16
Cumberland monkeyface	High	1.5	0	High	1.00	0.67	0.33	0.22	16
Appalachian monkeyface	High	0.5	0	High	1.00	0.67	0.33	0.22	16
Slabside pearlymussel	Medium	1	−0.1	High	0.67	0.67	0.33	0.15	22
Sheepnose	Low	0.5	0.4	High	0.33	1.00	0.33	0.11	23
Spectaclecase	Medium	0	0	High	0.67	0.33	0.33	0.07	24

TABLE 10 Prioritization of sub-basins (8-digit Hydrologic unit Code; Seaber et al., 1987) for habitat management and threat abatement based on expected conservation benefits and management feasibility. Conservation benefits were in terms of the expected frequency of occupied sites and numbers of imperilled species in each sub-basin expected from implementing the best management strategy. Biodiversity was calculated (Shannon diversity) for each sub-basin. Measures of conservation benefit (in terms of biodiversity), and management cost (in terms of feasibility), were standardized, multiplied, and ranked

	Expected conservation benefit			Management cost	Standardized measures		Prioritized rank	
Subbasin	Number of occupied sites	Number of imperilled species	Biodiversity	Feasibility	Biodiversity	Feasibility	Product of standardized measures	Final rank
Nolichucky	33	18	2.9	2.7	0.95	0.89	0.85	1
Upper Clinch	52	23	3.1	2.5	1.00	0.83	0.83	2
Powell	40	19	2.9	2.3	0.95	0.78	0.74	3
Upper little Tennessee	34	16	2.2	3.0	0.71	1.00	0.71	4
Lower little Tennessee	20	12	2.3	2.3	0.76	0.78	0.59	5
Tuckasegee	6	5	1.7	3.0	0.57	1.00	0.57	6
Watts bar Lake	40	18	2.7	1.4	0.89	0.47	0.42	7
Holston	11	10	2.3	1.7	0.74	0.56	0.41	8
Sequatchie	6	5	1.6	2.4	0.51	0.80	0.41	9
Upper French broad	3	2	1.0	2.5	0.34	0.83	0.28	10
Emory	9	3	0.7	2.6	0.22	0.87	0.19	11
Pigeon	3	3	0.7	2.5	0.23	0.83	0.19	12
Hiwassee	16	4	0.6	2.4	0.21	0.80	0.16	13
Lower French broad	2	2	0.7	2.0	0.23	0.67	0.15	14
Middle Tennessee-Chickamauga	9	2	0.6	1.3	0.21	0.42	0.09	15
North fork Holston	4	2	0.0	2.3	0.00	0.78	0.00	16
South fork Holston	1	1	0.0	2.0	0.00	0.67	0.00	16
Ocoee	1	1	0.0	1.8	0.00	0.60	0.00	16
Lower Clinch	0	0	0.0	1.2	0.00	0.39	0.00	16

management within UTRB. The species and sub-basin level prioritizations are in addition to the insights into how best to allocate among management actions. Taking this approach, it is clear what action to take for a priority species and in what sub-basins cost-effective actions can be taken to benefit the most species. Species diversity was valued when prioritizing sub-basins for conservation in the UTRB. Management actions would need to address threats to higher gradient streams within the priority sub-basins that are naturally less species-rich. Water quality and other factors within those less species-rich tributaries affect downstream reaches and rivers that support high species diversity.

The outcomes of the decision analyses are conditional, in part, on the alternative strategies chosen to be evaluated. While not exhaustive, the three alternatives represented a realistic range in how organizational resources could be allocated among management actions in the UTRB for imperilled aquatic species conservation. The three alternatives did not dictate exclusive reliance either on habitat or population management actions; rather, the alternatives represented shifts in emphasis among the types of management actions (Table 2). The population management emphasis emerged as the best strategy for achieving conservation of imperilled aquatic species in the UTRB because its actions contribute directly to species recovery by establishing or augmenting the populations needed for delisting. Many species are restricted to three or fewer populations. A high level of effort, therefore, would be allocated to increasing distribution and abundance of imperilled species through propagation and adult translocation under the strategy that emphasizes population management. The population management strategy performed better because expected abundance and distribution was projected to increase more under that strategy than other strategies and at operational costs that are intermediate to the other alternatives.

Although the best-performing strategy shifts effort toward population management, effort will continue to be allocated to identify and ameliorate stressors through habitat restoration. Consistent with the recognition that both habitat restoration and protection are needed (Possingham, Bode, & Klein, 2015), conservation easements should continue to be established and habitat should continue to be restored, although some effort should shift to allow for increased population management. Land acquisition, while an important tool for terrestrial species conservation, is not as practical for riverine species, such as the majority of the 36 imperilled species in the UTRB. The linear nature of rivers and the size of their catchments disperse impacts and stressors over large areas, which can limit the effectiveness of localized land purchases for conservation (Allen, 2004; King et al., 2005). Even if entire catchments could be purchased (an extraordinarily expensive proposition), there is the potential that legacy stressors from upstream areas may have adverse impacts on imperilled species populations for decades after land acquisition (Allen, 2004). Population management actions, therefore, would still be necessary to restore and sustain populations in the catchment until legacy stressors have been ameliorated. An actionable insight from this decision analysis is that to some extent resources devoted toward establishing conservation easements would be more effective when protecting lands directly associated with known or newly established populations of imperilled species.

This strategy development process accommodates conservation of multiple species at the landscape scale, which is critically important considering that many other rare and highly endemic cryptic fishes and mussels continue to be identified and may be listed in the UTRB (Blanton & Jenkins, 2008; Jelks et al., 2008; Jones & Neves, 2010). The emphasis on population management aligns well with the goals of existing plans for conserving and recovering imperilled fishes and mussels in the UTRB and beyond (Cumberlandian Region Mollusk Restoration Committee, 2010; Virginia Department of Game and Inland Fisheries, 2010). The strategy also dovetails with the landscape approach to conservation embodied in the USFWS's network of Landscape Conservation Cooperatives (http://lccnetwork.org; USFWS, 2013). Information needed to support the strategy includes increased life history research, threat analyses, genetics monitoring and research, sensitivity to pollutants, population viability analyses, habitat evaluation for reintroduction, propagation and captive management research, and evaluation of ecosystem services, while maintaining existing population and habitat monitoring (Freshwater Mollusk Conservation Society, 2016). Communication and partnerships to support the strategy include increased advocacy, education, and outreach, and establishment of new partnerships, while maintaining intra-agency communications and promoting funding for the needs of imperilled species.

This strategic planning effort fits within the recent body of conservation planning work that has recognized the unavoidable trade-off necessary to achieve the highest conservation benefits in the face of limited budgets and uncertain outcomes (Bottrill et al., 2008; Game et al., 2013; Gregory & Long, 2009; Hermoso et al., 2011; Joseph et al., 2009; Naidoo et al., 2006; Reichert et al., 2015). Objectives and corresponding performance measures were explicitly defined, alternative management strategies accounting for costs and their projected consequences were identified, trade-offs between conservation benefits and costs were analysed to identify the best-performing strategy, and a sensitivity analysis was conducted particularly focused on uncertainty regarding management effectiveness. The decision analysis was followed with an *ad hoc* prioritization that considers both benefits and costs. We do not claim that the process or products are the most ideal or rigorous. In particular, we recognize that strategic planning is a mental commitment — not an actual allocation of resources — and that prioritization falls short of finding the optimal allocation resources to manage species or catchments (Game et al., 2013; Howard & Abbas, 2015). However, there are few examples that attempt to apply the theory of decision analysis to the complexities of conservation planning at the landscape scale for multiple imperilled species. In practice, the flexibility afforded by this conservation strategy fits the reality that conservation of multiple imperilled species at the landscape scale ultimately relies on resources from multiple agencies each with their own spending constraints.

Priorities for conservation of imperilled aquatic species should be based on the anticipated effectiveness and efficiency of management actions (Gangloff, Edgar, & Wilson, 2016; Wilson, Joseph, Moore, & Possingham, 2011). The decision-analytical approach presented in this paper is designed to achieve this goal. Management of environmental flows (Koehn et al., 2014; Runge et al., 2015), ecological river assessment (Reichert et al., 2015), waste water management (Schuwirth, Reichert, & Lienert, 2012), and conservation of endangered species in the face of climate change (Gregory et al., 2013) are all situations where a decision-analytical approach has been or could be helpful. The approach is scalable but often requires considerable time for collaboration, information gathering, and analysis. The approach is value-focused in contrast to being alternative-focused (Keeney, 1992), which happens when participants advocate a particular strategy or policy. Instead, a decision-analytical approach embraces an honest broker role to evaluate how well a creative set of alternatives meets the predetermined objectives (Pielke, 2007).

This strategy presented here for the UTRB can help guide planning and management at the landscape scale across a large and diverse suite of species. As such, it is essential that managers and conservation practitioners recognize the flexibilities the strategy affords and adapt its application at the local level to ensure that conservation efforts will be effective at any spatial scale. Thus, the next step is to advance from a coarse strategy to developing specific projects that focus on the implementation of population management emphasis for priority species and catchments.

ACKNOWLEDGEMENTS

We would like to thank the other members of the strategy team for their tireless efforts in bringing this project to fruition: Meredith Bartron, Rick Bennett, Jean Brennan, Stephanie Chance, Brian Evans, Shane Hanlon, Mary Jennings, Callie McMunigal, Martin Miller, Peggy Shute, and Kurt Snider. We thank Jessica Rhodes for help with map making. And we thank Nathan Allan, Greg Breese, and Martin Miller for reviews of early versions of the paper. The findings and conclusions in this article are those of the authors and do not necessarily represent the views of the U.S. Fish and Wildlife Service. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsements by the US Government.

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SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

How to cite this article: Smith DR, Butler RS, Jones JW, et al. Developing a landscape-scale, multi-species, and cost-efficient conservation strategy for imperilled aquatic species in the Upper Tennessee River Basin, USA. *Aquatic Conserv: Mar Freshw Ecosyst*. 2017;1–16. https://doi.org/10.1002/aqc.2785