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Environmental Benefits Analysis of Fish Passage on the Truckee River, Nevada: A Case Study of Multi-Action-Dependent Benefits Quantification

by Jock Conyngham[1], S. Kyle McKay[2], Craig Fischenich[3], and Dan Artho[4]

OVERVIEW: As part of a combined flood risk management and ecosystem restoration General Investigation study currently underway, the Sacramento District (SPK) of the U.S. Army Corps of Engineers (USACE) seeks to restore system-wide fish passage along the mainstem Truckee River, which extends 121 miles from Lake Tahoe, California to the system's terminus at Pyramid Lake, Nevada. At the time of publication, this project had passed through Independent Technical Review and was being prepared for its Alternative Formulation Briefing. SPK engaged the Environmental Laboratory (EL) of the U.S. Army Engineer Research and Development Center (ERDC) to formulate alternatives for fish passage along the river and to assess the benefits of implementing various alternatives. SPK required a scientifically valid technique for comparing benefits of alternative actions at numerous structures that could be completed in a limited time window (approximately 6 months). No such means existed, so EL and SPK worked together to develop an approach. This project serves as case study for several notable issues, including: 1) the identification of relevant, meaningful metrics; 2) quantified utilization of expert elicitation; 3) the reduction of an unworkably large permutation of alternatives into a more coherent and logical array of sets; 4) the consideration and quantification of outcome uncertainty; and 5) rapid model development, application, and preparation for the USACE certification process. The study reports (Conyngham et al. 2007, 2009, *http://www.spk.usace.army.mil/projects/civil/truckeemeadows/index.html*) address each of these issues in greater detail. This Technical Note focuses on another issue important to the Truckee River study and common to many other ecosystem restoration efforts—assessing dependent benefits among multiple restoration actions in a connected system. Benefit dependencies arise when actions taken at one location affect the potential benefits from other actions or at other locations. Dependent benefits exist in most projects involving multiple actions and, although they are often neglected, can have a significant influence upon the preferred alternative array, cost effectiveness, and the project's actual level of goal attainment. The approach developed for the Truckee River Project is offered only as a conceptual example to those faced with addressing benefit dependencies for other large projects;

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[1] Research Ecologist, U.S. Army Engineer Research and Development Center (ERDC), Environmental Laboratory (EL), Missoula, Montana.
[2] Research Civil Engineer, ERDC-EL, Athens, Georgia.
[3] Research Civil Engineer, ERDC-EL, Vicksburg, Mississippi.
[4] Environmental Manager, U.S. Army Corps of Engineers (USACE), Sacramento District (CESPK).

documentation is currently being prepared for submission for USACE model certification. Further details on environmental benefits techniques can be found elsewhere (e.g., Conyngham et al. 2007, 2009) for the Truckee case and a series of publications in the Environmental Benefits Analysis area of ERDC EL's Ecosystem Management and Restoration Research Program (EMRRP) (http://cw-environment.usace.army.mil/eba/).

PROJECT DESCRIPTION: The general goal of the restoration effort for the Truckee River fish passage project is to *re-establish sufficient connectivity to sustain or recover viable populations of native fish species while accommodating social needs and uses of the resource*. The ERDC-EL team was tasked with identifying and assessing both upstream and downstream passage alternatives for all native fishes thought to be impacted by fragmentation. The establishment of criteria and goals to address recovery needs for warmwater fishes is an enterprise fraught with knowledge gaps and assumptions. Information is particularly lacking for many of the native species of the Truckee River. Therefore, the project objective was refined to *implementation of the most effective measures for fish passage improvement on the Truckee River*.

Though over 30 structures impede fish passage on the Truckee River, various agencies and owners are addressing many of them. In view of this ongoing work, SPK worked with EL to develop fish passage alternatives at 17 structures on the Truckee River. These structures range significantly in construction, purpose, size, and impact to upstream and downstream fish passage (Table 1; Conyngham et al. 2007). In light of these considerations, ERDC-EL examined each structure, assessed types and degrees of impact, and identified actions to improve fish passage. Site visits, meetings with dam owners and other counterparts, physical site constraints and opportunities, and upstream and downstream passage needs of relevant species all helped determine the selection of two to four alternatives per site.

DEPENDENT BENEFITS ALGORITHMS: Dependencies are direct or indirect relationships between system elements that affect mesoscale or system-wide patterns or processes. In linear systems such as rivers, a number of benefit dependencies are inherent due to the flow of material, organisms, and energy along the system. For example, the amount, type, and quality of the sediments passing a point on a river depend upon the upstream supply and controls.

Literature review and consultation with subject matter experts failed to reveal consensus regarding appropriate and specific metrics for bidirectional, multi-site fish passage projects in general, and demonstrated that no standard method for quantifying benefits from such projects presently exists. Asked to develop a methodology in short order that would be informative, accurate and defensible, the team modified an existing technique for upstream passage benefits for salmonids (Washington Department of Fish and Wildlife (WDFW) 2000) and developed an analogous approach for assessing downstream benefits.

"Passage efficiency" is a central performance metric in comparing alternatives in the present study, as it implicitly accounts for attraction and entry issues, fallback, predation, injury, delays, and a number of related factors. Efficiency is a measure or estimate of the passage technique's performance expressed as a percentage of the number of fish that successfully pass a structure and its immediate environment (WDFW 2000; Cote et al. 2009).

Table 1. Summary of Truckee River termini and assessed structures.

Structure	River mile (mi)	Relative Discharge of Diversion (%)*	Head loss at Obstruction (ft)	Function	Description
Pyramid Lake	0				Downstream terminus of the Truckee River System.
Marble Bluff	4	0.0	35	Grade Control	Channel-spanning concrete dam with existing fishway with ladders and fish lock.
Numana	12.5	3.1	12	Irrigation	Channel-spanning concrete weir with fish ladder. Bureau of Reclamation to address passage options, including removal.
S-S	21.75	0.6	NA	Irrigation	Washed out in 2005. Remnants of structure on left bank. Rebuild in planning phase.
Fellnagle	27	0.6	4	Irrigation	Channel-spanning rock weir with diversion structure on left bank.
Herman	31.5	1.9	2.4	Irrigation	Channel-spanning rock weir with diversion structure on left bank.
Derby	39.5	25.8	15	Irrigation	Bureau of Reclamation to take primary passage role.
Tracy PP	44	3.9	NA	Power Plant Cooling	Intake structure at river grade.
Cochran	66	0.8	NA	Municipal	Small, oblique diversion on right bank side channel. No upstream and only minor down-stream impedance.
Idlewild Ponds	66.5	0.3	NA	Recreational	Small diversion on right bank side channel. No upstream and only minor downstream impedance.
Chalk Bluff	69.8	10.7	3	Municipal	Channel-spanning weir with existing fish ladder and screen. Passage effectiveness monitoring recommended.
Orr	70	3.3	NA	Irrigation	No barrier or hydraulic control.
Lake	71.5	1.8	NA	Irrigation & Municipal	No barrier or hydraulic control due to channel bifurcation.
Last Chance	73	2.6	NA	Irrigation	Partial-spanning concrete wall, channel bifurcation.
Washoe-Highlands	76	34.9	8 - 10	Irrigation & Municipal	Channel-spanning concrete dam with large diversion right and existing non-functional fish ladder.
Verdi	80.5	40.6	13	Hydropower	Channel-spanning concrete and wood dam with stepped outflow and large withdrawal.
Steamboat	83.5	7.0	10	Irrigation & Municipal	Channel-spanning concrete weir.
Fleisch	86	44.0	14	Hydropower	Channel-spanning concrete dam with large diversion right and existing non-functional fish ladder.
Lake Tahoe	121.1				Upstream source of the Truckee River.

*Ratio of diversion rate to river discharge (all discharges were averaged either annually or during irrigation season depending upon structure operation).

Given the large ranges over which many fish species move, the cumulative effects of multiple structures are often critical in assessing the benefits of fish passage improvement. A population of 1000 fish encountering four structures with passage efficiencies of 50 percent will be reduced to approximately 62 individuals past the fourth structure. It is clear that the benefits of providing improved passage at a given location are a function of the number of fish that reach the site, whether from upstream or down (Cote et al. 2009). Passage efficiency, expressed as the passage rate at a given structure, must be multiplied by the cumulative passage rate of the adjacent structure in the channel system to identify actual benefits.

For upstream movement, this pattern can be shown mathematically as:

$$\%_{pass,t,i} = \%_{pass,i}\%_{pass,t,i-1}$$

where $\%_{pass,t,i}$ is the cumulative passage efficiency at structure *i,* $\%_{pass,i}$ is the efficiency of structure *i* in isolation, and $\%_{pass,t,i-1}$ is the cumulative passage efficiency at the next structure downstream. For instance, if 80 percent of the mobile population reach and pass structure *i-1* ($\%_{pass,t,i-1} = 0.8$) and passage at structure *i* is 75 percent ($\%_{pass,i} = 0.75$), then the cumulative upstream passage rate at *i* is 60 percent of the mobile population ($\%_{pass,t,i} = 0.8 * 0.75 = 0.6$) (See Figure 1).

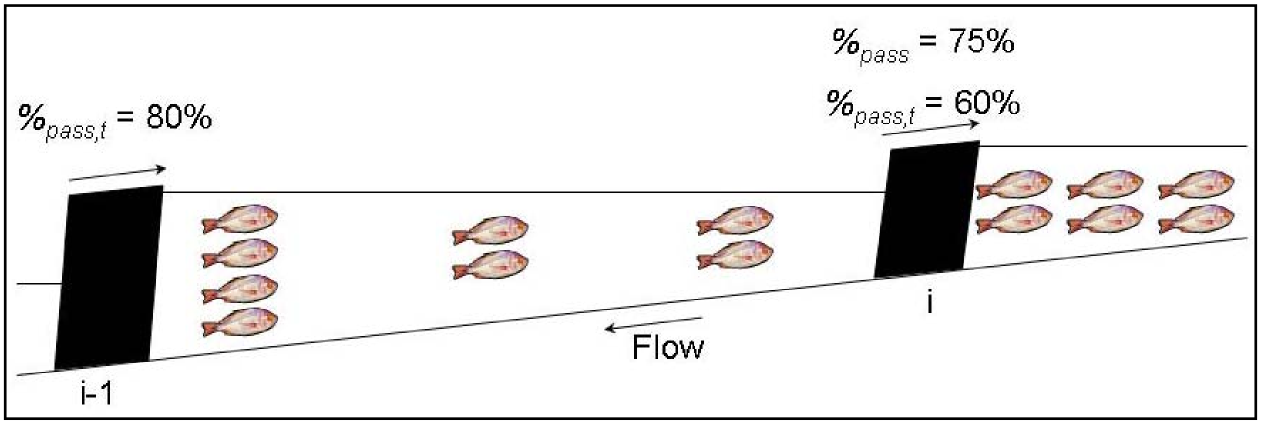


Figure 1. Example of cumulative upstream passage efficiency.

The above example shows that the cumulative passage efficiency at structure *i* depends on both its passage rate and the cumulative passage rate at the preceding structure. The efficiency (i.e. percentage of fish passing) can be compared among alternatives, along with cost and other factors related to habitat, to determine "*the most effective measures for fish passage improvement on the Truckee River*." This is one form of dependent benefits common to linear systems, although other types of dependencies can be important as well.

To demonstrate in greater depth the importance of dependencies and issues in scaling benefits, a hypothetical example of upstream fish passage on the "Fish River" is presented in Figure 2. This hypothetical river flows 20 miles from "Lake Up" to "Lake Down" and has three barriers to fish passage (Structures A, B, and C from downstream to upstream, respectively). While benefits in this case are scaled in miles, actual benefits are limited by passage rates and, in the case of the Truckee River assessment, include other non-spatial characteristics and processes—hence the use of conceptual "benefit-miles" as a summary metric (Conyngham et al. 2009).

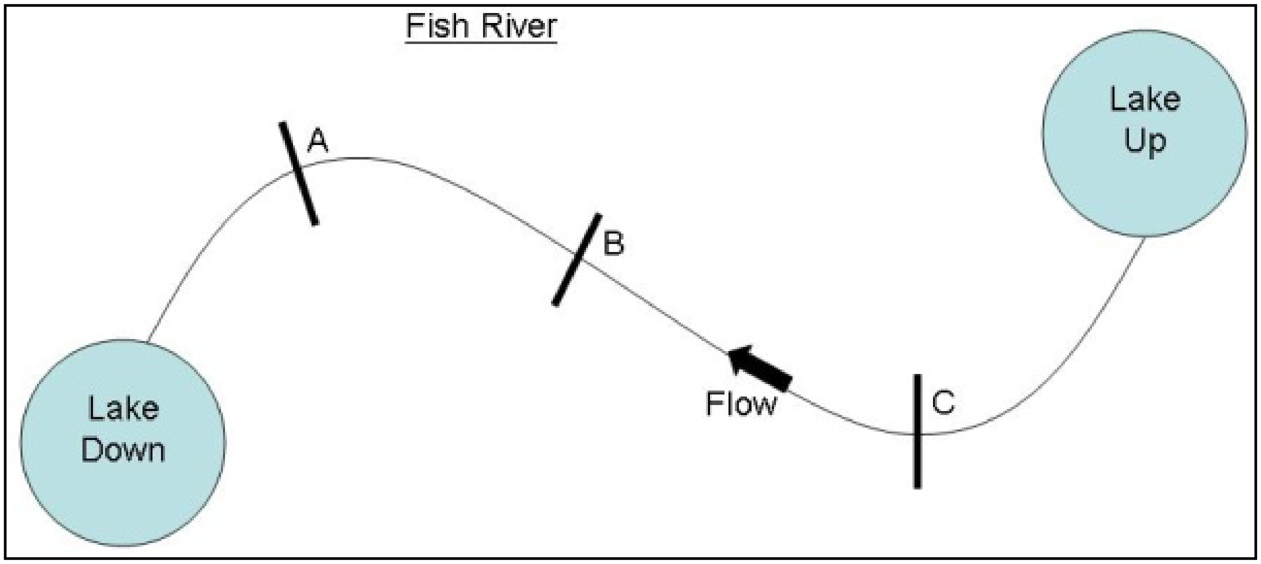


Figure 2. "Fish River" sample system.

To illustrate the importance of dependencies and changes in efficiency at a given structure, three scenarios are presented (Table 2):

1. Present condition of upstream fish passage in the system (Future Without Project, or FWOP).
2. Improvement of passage efficiency at Structure B from 50 to 80 percent.
3. Improvement of passage efficiency at Structure C from 50 to 80 percent.

Table 2. Fish River example of dependency in efficiency calculation.

River Mile	Structure	Structure Passage Efficiency	Cumulative Efficiency	Upstream Habitat (mi)	"Benefit-miles" of passage	Cumulative Benefit-miles
FWOP						
0	Lake Down	100	100	5	5	5
5	A	80	80	5	4	9
10	B	50	40	5	2	11
15	C	50	20	5	1	12
20	Lake Up		20	0	0	12
Alternative 1						
0	Lake Down	100	100	5	5	5
5	A	80	80	5	4	9
10	B	80	64	5	3.2	12.2
15	C	50	32	5	1.6	13.8
20	Lake Up		32	0	0	13.8
Alternative 2						
0	Lake Down	100	100	5	5	5
5	A	80	80	5	4	9
10	B	50	40	5	2	11
15	C	80	32	5	1.6	12.6
20	Lake Up		32	0	0	12.6

Several observations can be made with respect to dependencies and scaling in environmental benefits. If passage improvements at Structures B and C lead to equivalent improvement of fish passage efficiency at those structures (from 50 to 80 percent), then the cumulative efficiency of the system's passage is identical (32 percent). However, if benefits are evaluated by scaling efficiency based upon the quantity of habitat accessed (in river miles), then the cumulative benefits of passage are not equivalent (13.8 and 12.6 cumulative benefit-miles for Alternatives 1 and 2, respectively). The "lift" in this case relative to the Future WithOut Project (FWOP) alternative would be 1.8 and 0.6 habitat units for the alternatives, and would be compared using cost-effectiveness and incremental cost analyses.

Thus, although dependency in passage efficiency captures system-wide effects on a given population, measures of habitat quantity, species home range, and, if possible, habitat quality are usually required to define benefits accurately and distinguish between alternatives. By extension, knowledge about critical habitat needs and distribution (e.g., thermal refugia or spawning habitat that are not equally distributed in river reaches but might only exist in a given river section) can fundamentally redefine passage goals and require a simple restructuring of the benefits algorithm. This example also illustrates that a minor change in plan configuration can have a significant influence on total accessible habitat when dependencies are considered. Consideration of larger scale or system-wide characteristics and processes is needed to formulate the appropriate algorithms to quantitatively compare and prioritize restoration actions in mid-sized and large projects (Table 3).

TRUCKEE RIVER APPLICATION: The metrics and algorithm applied in the Truckee River case include other factors in addition to the passage efficiency of the individual alternatives. Among these, for example, are parameters addressing the fact that not all species use all areas on the river equally, that the biological imperative for movement is not uniform among species, and that some fish utilize intermediate reaches (that is, all individuals of a given species do not uniformly require or execute movements between two given points representing extreme ranges of movement). Adding to analytic complexity, the Truckee River project includes consideration for several alternatives at 17 sites for 8 species of fish and assesses both upstream and downstream passage benefits. The most sound way to combine these many factors into a method that allowed valid comparison among alternative plans was to utilize and assess estimates from a group of subject matter experts of passage rates through individual reach segments as the foundation for computation and combine these with other relevant factors (Table 2). Because the goal was to compare passage alternatives, relative benefit estimates rather than absolute estimates were satisfactory.

In the Truckee and most other river systems, obstructions and passage alternatives affect many fish species and age classes. Each structure impacts each species differently, however, due to physical, hydraulic, and operational characteristics of the structures, individual life history requirements, mobility, swimming physiology, and behavioral traits, as well as secondary factors such as habitat alteration and predation implications for a given alternative. For the Truckee basin, eight native species were selected to evaluate passage benefits. Two species that figure prominently in the analysis are the federally endangered cui-ui (*Chasmistes cujus*) and threatened Lahontan cutthroat trout (*Oncorhynchus clarki henshawi*). Six additional species were included

Table 3. Summary of parameters used in Truckee River fish passage benefit algorithms

Parameter	Description	Calculation
Habitat Quantity	Amount of available habitat in a given reach including significant tributary habitat.	River miles between structures including significant tributaries.
Reach Habitat Utilization Probability	This parameter measures the proportion of the habitat in a given reach that is likely to be utilized by a species assuming optimum passage or the probability of that species existing within that reach.	Scored on an arithmetic scale from 0 to 100% of the available habitat in the reach being utilized.
Population Condition	Relative importance of a given species based on its status in the Truckee Basin (e.g., federally listed as threatened).	Scored on an indexed scale between 0 (undesirable species), 1 (slightly impacted population), 2 (depressed population), and 3 (critical/on the verge of endangerment/extinction).
Species Mobility	The importance of migration in the life cycle of each species.	Scored on a qualitative scale between 0 (mobility has negative consequences), 1 (mobility is helpful but non-critical for species success), and 2 (mobility is critical for species success).
Upstream Passage Parameters		
Passage Efficiency for a Species, Structure, & Alternative	Accounts for the ability of a species to pass a given structure. This parameter is assessed for each alternative at each structure and includes operational efficiency, dependability, and presence or lack of temporal constraints.	Scored on an indexed scale for upstream passage efficiency between 0 (passage entirely impeded) and 4 (100% of fish pass).
Restoration Impact of Alternative	Measures the relative impact of the structure on other restoration objectives not associated with upstream fish passage (e.g., downstream passage of large woody debris, sediment, or organisms).	Scored on a constructed scale between 0 (sacrifices all other restoration objectives), 1 (neutral restoration impact), and 2 (significant positive effects due to alternative).
Downstream Passage Parameters		
Diversion Discharge Impact Factor	Calculates the relative potential for fish entrainment impacts at each diversion.	Ratio of diversion rate to river discharge (all discharges were averaged either annually or during irrigation season depending upon structure's period of operation).
Diversion Screening Efficiency	Accounts for the impact of a given diversion on fish passage including variables of screening efficiency, diversion withdrawal cross-sectional location, flow impingement characteristics, and likelihood of individual species and age class injury or mortality.	Indexed score between 0 (100% of diverted individuals are negatively impacted by the diversion and will not pass downstream) and 4 (no individuals are negatively impacted by the diversion).

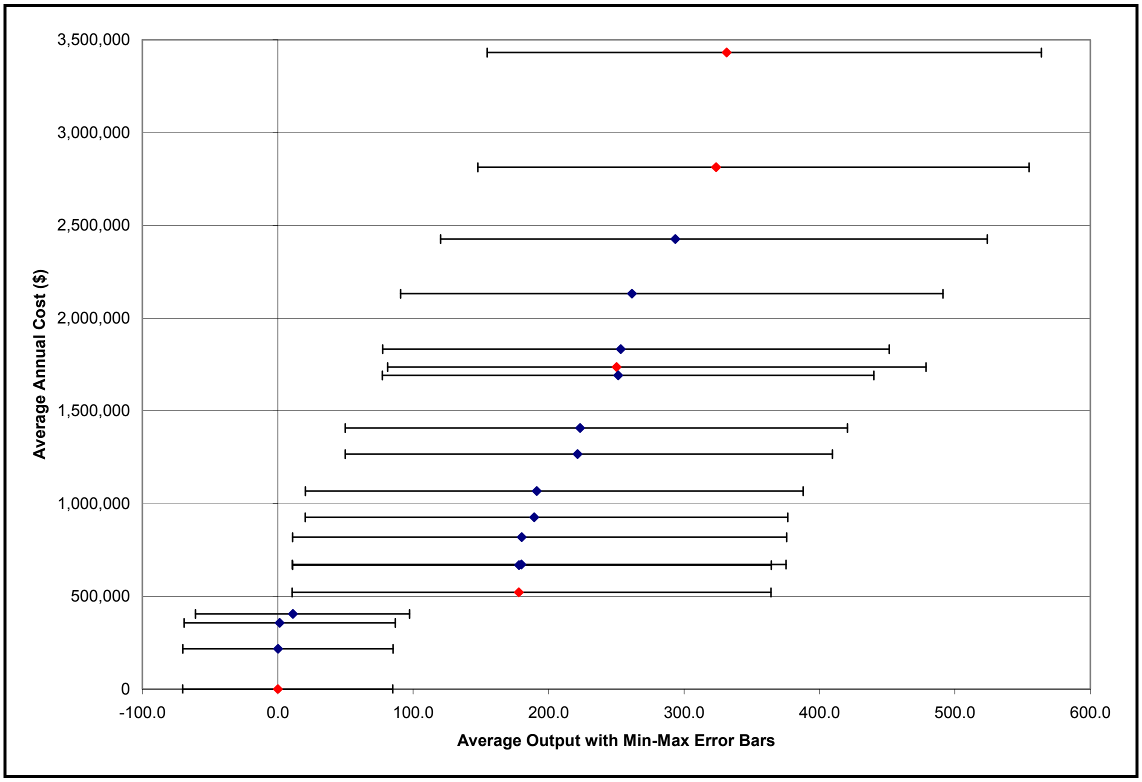
to help quantify project benefits for the broader native fish community thought to be impacted by fragmentation. Due to a long history of system alteration dating back to early mining settlements, little information exists on most of these species or their behavior in a natural, unfragmented channel system, considerably complicating the estimation of potential project benefits. A panel of subject matter experts was enlisted to score many of the parameters in Table 2 (though other parameters were either empirical facts such as river mileage or derived scores). The experts' scores reflected the best available knowledge of swimming physiology, behavior, ranges, and life history needs for the eight reference species in the Truckee basin and provided the basis for quantitatively assessing benefits. The invited panel included experts from the U.S. Fish and Wildlife Service, Pyramid Lake Paiute Tribe, ERDC EL, Nevada Department of Wildlife, U.S. Geological Survey, and Chinook Engineering (in technical support to the Truckee Meadows Water Authority).

For input data to support environmental benefits and cost-effectiveness/incremental cost (CE/ICA) analyses, the experts were asked to assign a range of scores (minimum, best estimate, and maximum) for passage and screening efficiency at each structure for each species in order to facilitate sensitivity testing and calculation of uncertainty in the current state of knowledge of the reference species. EL and counterparts then aggregated logical sets of nine downstream alternatives arrays and six upstream alternatives arrays into 54 distinct plans for cost-effectiveness and incremental cost comparison. Three distinct scenarios were developed using summed values for each plan: 1) best estimate, to reflect a most probable outcome; 2) minimum, which reflects the worst case and most pessimistic estimate of benefit; and 3) maximum, which reflects the best case and most optimistic estimate of benefit. Benefits summaries using the three categories of output were compared to determine if the alternative set selection differed significantly as a function of the assumed scenario. When analyzed with the IWR Planning Suite (*http://www.iwr.usace.army.mil/docs/projectfacts/IWRPlanningSuite.pdf*), three plans were consistently Best Buys and a fourth plan was a Best Buy under the maximum output scenario. A more detailed uncertainty analysis was pursued for Cost-Effective Plans using a Monte Carlo type analysis assuming a normally distributed set of outcomes with the expected outcome set to the mean and minimum and maximum outcomes to the third standard deviation. Five thousand random sets were generated and benefits were calculated for a given random set. From these analyses, statistical measures may be obtained to support the decisions of the project development team. Figure 3, for example, compares results for minimum, best expected, and maximum benefits as well as confidence intervals for a select number of plans.

CONCLUSIONS: This case study illustrates the development of a technique for benefit assessment that addresses dependent relationships between project elements, use of professional judgment to fill knowledge gaps, narrowing of a large population of alternatives, and uncertainty analyses. USACE personnel are often asked to address or undertake multi-element decisions or actions concerning complex systems with multiple gaps in fundamental knowledge of system or population dynamics. Working closely with counterparts, EL and SPK were able to formulate a benefits assessment for fish passage alternatives on the Truckee River that is technically defensible and, equally important, acceptable to a diverse group of stakeholders and partners. This model is currently being prepared for USACE certification.

Quantification of benefit dependency phenomena is critical to multi-node or multi-action passage projects. For the Truckee River, quantifying dependent benefits in passage required the project team to develop an appropriate technique for accurately comparing benefits from arrays of multiple actions at multiple sites. Although the complete benefits algorithms are complex, the fundamental mathematical engine is straightforward and can be readily modified for other projects or as knowledge increases about critical habitats, home ranges, the variables that underlie passage efficiency, and other factors that enable success in fish passage and population restoration efforts.

ADDITIONAL INFORMATION: Research presented in this technical note was developed under the Environmental Benefits Analysis (EBA) Research Program (*http://cw-environment.usace.army.mil/eba/*), a part of the Ecosystem Management and Restoration Research Program (EMRRP). The USACE proponent for the EBA Program is Rennie Sherman. The Technical Director is Dr. Al Cofrancesco. Technical reviews provided by Drs. Dave Smith and Rich Fischer (ERDC Environmental Laboratory) are gratefully acknowledged. For additional information, please contact the author, Jock Conyngham (406-541-4845, *Jock.N.Conyngham@usace.army.mil*), or the EMRRP Program Manager, Glenn Rhett, (601-634-3717, *Glenn.G.Rhett@erdc.usace.army.mil*). This technical note should be cited as follows:



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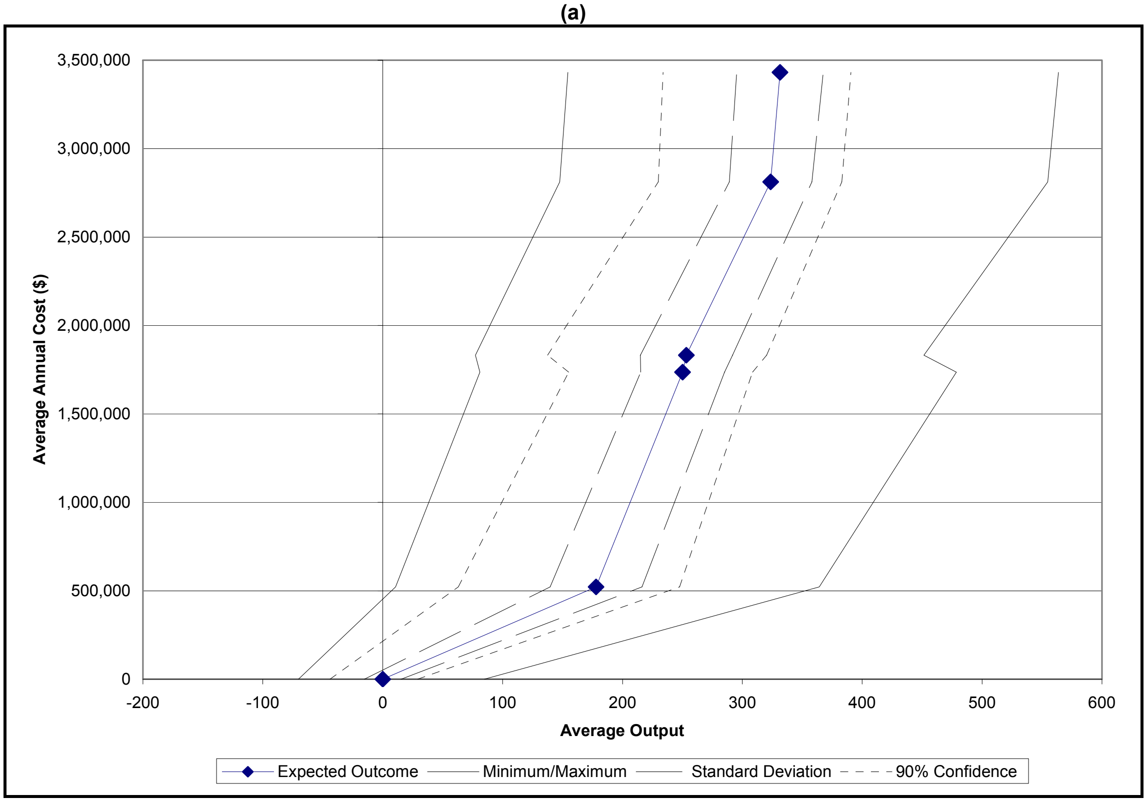

(b)

Figure 3. Uncertainty analyses applied in CE/ICA (x-axis = benefit, y-axis = cost). (a) Worst-expected-best scenarios for cost-effective plans. (b) Confidence intervals for select plans.

Conyngham, J. N., S. K. McKay, J. C. Fischenich, and D. F. Artho. 2011. *Environmental benefits analysis of fish passage on the Truckee River, Nevada: A case study emphasizing the treatment of dependencies*. EBA Technical Notes Collection. ERDC TN-EMRRP-EBA-6. Vicksburg, MS: U.S. Army Engineer Research and Development Center. http://cw-environment.usace.army.mil/eba/

REFERENCES

Conyngham, J., J. C. Fischenich, and M. Channell. 2007. *Alternatives assessment for improvement of fish passage on the Truckee River*. Report to USACE Sacramento District, U.S. Army Corps of Engineers.

Conyngham, J., S. K. McKay, J. C. Fischenich, and L. L. Skaggs. 2009. *Truckee River fish passage restoration: Environmental benefits, cost effectiveness, and incremental cost analysis*. Report to Sacramento District, U.S. Army Corps of Engineers.

Cote, D., D. G. Kehler, C. Bourne, and Y. F. Wiersma. 2009. A new measure of longitudinal connectivity for stream networks. *Landscape Ecology*. Springer 24: 101-113.

Washington Department of Fish and Wildlife (WDFW). 2000. *Fish passage barrier and surface water diversion screening assessment and prioritization manual.* Olympia, WA.