WATERSHED ASSESSMENT:
A MULTI-SCALE APPROACH USING ECOLOGICAL MODELING

Bruce A. Pruitt[1], K. Jack Killgore[2], W. Todd Slack[2], Leandro E. Miranda[3], and Carson A. Pruitt[4]

AUTHORS: [1]Professional Hydrologist, U.S Army Corps of Engineers, Engineer Research and Development Center, 960 College Station Rd., Athens, GA 30605; [2]Research Fishery Biologist, U.S. Army Corps of Engineers, Engineer Research and Development Center, 3909 Halls Ferry Rd., Vicksburg, MS 39180-6199; [3]Research Fishery Biologist, U.S. Geological Survey, Mississippi Cooperative Fish and Wildlife Research Unit, Mississippi State University, Mississippi State, MS 39762; [4]Graduate Student, School of Geography, University of Georgia, Athens, GA

REFERENCE: *Proceedings of the 2017 Georgia Water Resources Conference,* held April 19-20, 2017, at the University of Georgia

Abstract. Pursuant to Section 729 of the Water Resources Development Act of 1986 (as amended), a watershed study was conducted on the Duck River watershed located in the Interior Plateau, Tennessee. The objectives of the watershed study were to establish current (baseline) conditions and identify water resource problems, needs and opportunities.

A knowledge base was developed by compiling biological and geomorphological data across HUC12 watersheds from existing fish databases. Additional stream data were collected from low altitude, high resolution video resulting in a final subset of eleven of 18 stream geospatial test variables compiled on 213 stream segments and subjected to statistical analysis. An ecological model, stream condition index (SCI), was formulated based on the degree of statistical correlation (dependency) between the variables.

Stream segments were averaged within 63 HUC12 watersheds in the Duck Watershed. Based on the results of the model, the final HUC12 watersheds were scored followed by normalization on a scale from 0 to 1.0. Thirty-eight watersheds were considered major to severely disturbed, 18 watersheds were minimally disturbed, and seven watersheds were minor disturbed.

In addition to the analysis of geospatial data, fish Index of Biotic Integrity (IBI) scores were evaluated based on twelve metrics which addressed species richness and composition, trophic structure, fish abundance, and fish condition. Scores for the twelve metrics were summed to produce the IBI value for the site. By comparing the SCI to IBI scores, aquatic biota impairment was predominantly due to loss of streamside canopy, reduction of in-stream cover, and impacts to channel stability, all of which were considered to be limiting factors in regards to sustaining a healthy aquatic ecosystem in the Duck River watershed.

The findings of this study can be utilized to prioritize watersheds for restoration, enhancement and conservation, plan and conduct site-specific, intensive ecosystem studies, and assess ecosystem outcomes (i.e., ecological lift) applicable to future with and without restoration actions including alternative, feasibility, and cost/benefit analyses and adaptive management.

INTRODUCTION

Setting

Located south of Nashville, Tennessee, the study area was the Duck River watershed (hereinafter referred to as, "Duck Watershed") which is located in the Tennessee River Drainage Basin. The Duck Watershed extends through four Level IV Ecoregions within the Interior Plateau (71) ecoregion (Griffin et al. 1998): Western Highland Rim (71f), Eastern Highland Rim (71g), Outer Nashville Basin (71h), and Inner Nashville Basin (71i) (Figure 1). Encompassing 3,630 square miles (approximately 1,545 and 1,085 square miles in the Duck and Buffalo drainages, respectively), the Duck Watershed includes the Duck and Buffalo Rivers (Hydrologic Unit Codes 06040002, 06040003, and 06040004, respectively). The confluence of the Buffalo and Duck Rivers is approximately 12.7 miles upstream of the Tennessee River.

The Duck Watershed is home to one of the most diverse freshwater faunas in North America (Schilling and Williams 2002, Ahlstedt et al. 2004). The basin supports more species of fish than all European rivers combined, and higher species richness per kilometer than any other river in North America. Overall, the Duck Watershed supports a remarkable fish biodiversity, including approximately 150 species (Etnier and Starnes 1993). The Nature Conservancy states that the Duck Watershed is North America's richest river in variety of freshwater animal species, and in addition to fish, includes 60 freshwater mussel species and 22 species of aquatic snails (TNC web site).

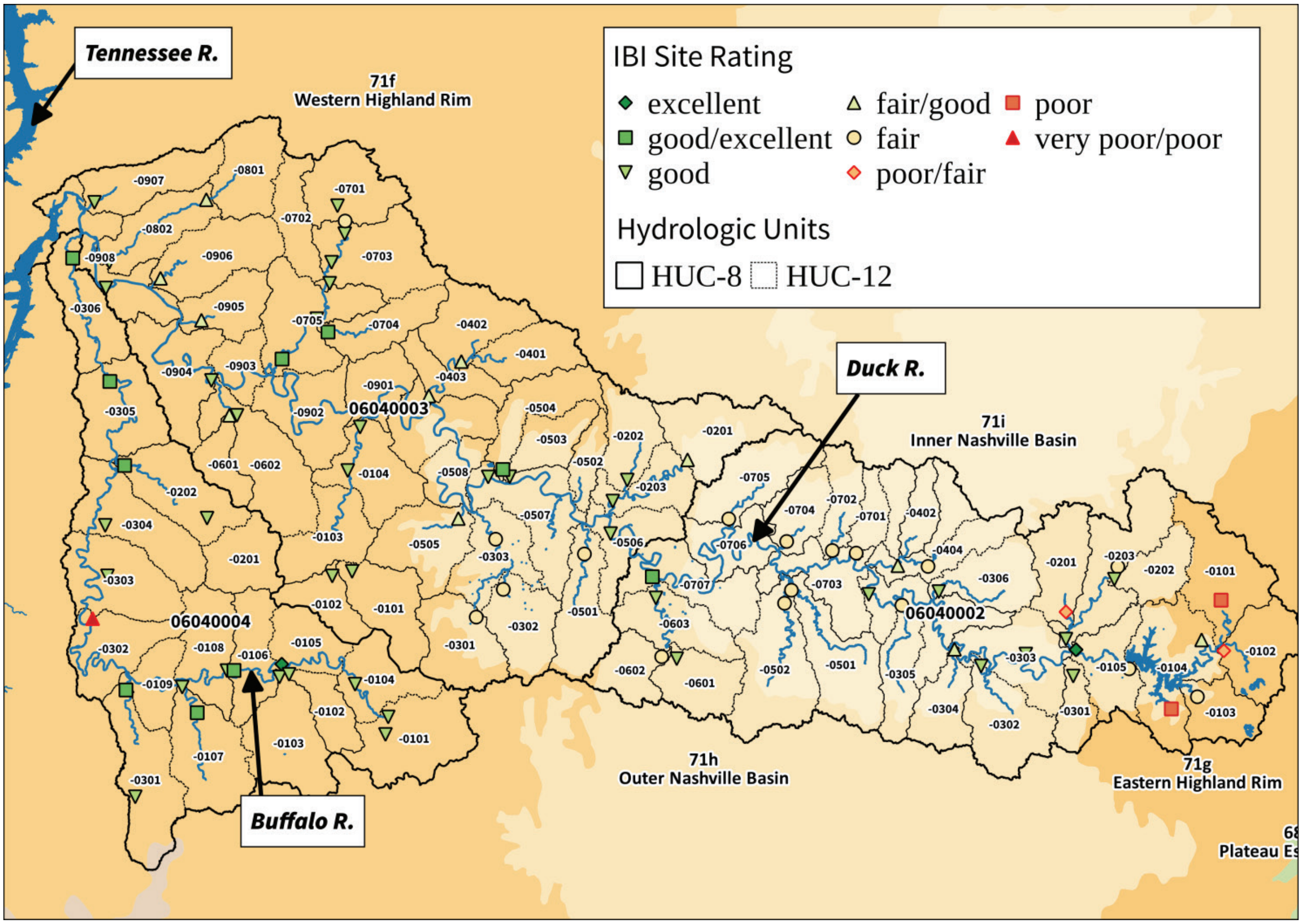

Figure 1. Level IV Ecoregions and HUC12 watersheds depicting fish IBI stations by ratings.

Project Goal and Objectives

The goal of the study was to establish current (baseline) conditions and identify water resource problems, needs and opportunities within the Duck Watershed. The following objectives were identified: 1) develop a knowledge base by compiling readily available databases that can be used to assess current and future land uses; 2) formulate an ecological model composed of key physical and biological parameters; 3) identify causes (disturbance regime) of aquatic biota decline; and 4) identify watersheds and stream corridors in need of more intensive studies.

METHODS

Several steps were undertaken pursuant to formulate and document a mathematical model (algorithm) supportive of achieving the project objectives: 1) Compile existing data and literature references (knowledge base); 2) Create a inventory of stream and watershed attributes; 3) Reduce and analyze data (preliminary analysis completed at the Level IV Ecoregion scale); 4) Develop reference standards and attainable conditions within each watershed or combination of watersheds; 5) Determine departure from reference conditions and rank watersheds accordingly (i.e., causes and sources of impairment); and 6) Develop correspondence between physical and biological conditions.

Literature Review & Knowledge Base

A knowledge base is a body of knowledge that formally organizes entities of interest and their relation to each other in a logical framework that allows inferences about a particular problem. Several databases were compiled, reviewed, and reduced into a knowledge base pertinent to the overall Duck Watershed: 1) TVA Fish IBI data (90 stations); 2) TDEC Benthic Macroinvertebrate data; 3) TVA and TDEC Aquatic Habitat datasets; 4) Low altitude video (213 video segments across 63 of 87 HUC12 watersheds); 5) Duck River mussel surveys.

Identify Attainable Reference Conditions

Establishment of attainable reference conditions (Stoddard et al., 2006) in the Duck Watershed based on aquatic diversity and habitat is fundamental to develop a gradient of impacts from which departure from reference conditions can be assessed (Figure 2). Types of reference conditions can be on-site or off-site analogs, historical, constructed or by creating a regional index. Reference sites provide a scale, in which, to compare the condition of other sites against. In addition to establishing achievable performance standards, monitoring analog reference sites in conjunction with restoration sites is paramount to address variation with respect to normal seasonal fluctuations, drought, climate change and catastrophic events (*force majeure*) which may not accurately reflect the cause of success or failure due to restoration actions.

In order to determine departure from reference conditions, reference watersheds and associated stream segments were identified within each HUC12 watershed, if present. If the natural variation associated with the attributes across reference watersheds were insignificant, the reference watersheds were aggregated for comparison against other watersheds that are considered impaired. Watersheds with similar types and degree of impairment were aggregated, as well. Primer™ computer software which includes ordination methods facilitated this process.

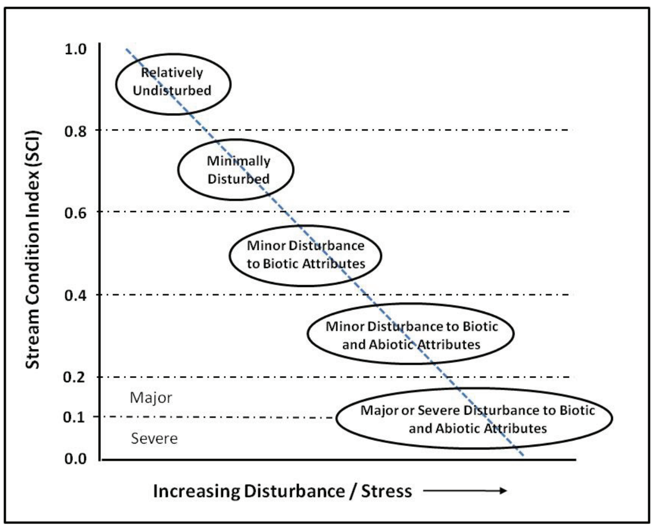

Figure 2. Stream condition index (SCI) scaled against environmental disturbance gradient (adapted from Pruitt et. al. 2012).

Establish Baseline Conditions

The low altitude flyover (Red Hen™ helicopter video at approximately 400 feet altitude), which was conducted during February 2014, provided the opportunity to assess physical geospatial data in regards to stream and riparian zone conditions including probable stressors. Eighteen physical features were identified and tested that represented stream and riparian zone conditions (Table 1).

Table 1. Initial screening variables tested on low altitude video.

Stream and valley classification	Vegetative riparian zone width
Accelerated bank failure	Head cutting
Sediment deposition and embeddedness	Active versus abandoned floodplain
Presence of coarse woody debris	Land use in valley flat (video view)
Presence of rills and gullies	Dredging operations
Channelization and de-snagging	Unrestricted cattle access
NPDES and discharges from MS4 areas	Impoundments and low flow dams
Dairies and concentrated animal feeding operations	Development in valley (video view)
Adjacent landfills	Silviculture

The physical features were tested based on competency to identification from aerial video, ability to discriminate between stream segments and watersheds, and capacity to determine departure from attainable reference conditions.

A subset of eleven model variables were selected for model formulation that were identifiable from the video and similarities between the final selection of model variables and the stream visual assessment protocol developed by the Natural Resource Conservation Service - NRCS (USDA 1998). Three variables used by USDA, insect/invertebrate habitat, salinity, and macroinvertebrates observed, were omitted due to the remote nature of the aerial video.

RESULTS

A total of 213 video segments across 63 of 87 HUC12 watersheds were evaluated using the eleven final variables. The values of each of the variables were subjected to Spearman's r correlation (Table 2). Significant correlations were determined based on regression analysis ($p < 0.01$). The effects of embeddedness and channel stability, which were observed to correspond to nine of the other eleven model variables, are noteworthy. Embeddedness increased directly with hydrologic alteration, and decreased indirectly with channel stability, riparian zone condition, and bank stability.

Channel stability corresponded directly and hydrologic alteration indirectly with riparian zone condition, bank stability, fish cover, pools, and canopy closure. Fish cover and pools responded favorably to improved channel stability, riparian zone condition, and bank stability. No correlation between structural dams and the other eleven variables was observed. Consequently, it was not used in the final stream condition index below.

Table 2. Correlation product matrix on stream condition index variables, significant correlations for positive and negative relationships highlighted green and magenta, respectively.

CS	HA	RZ	BS	WC	NE	DAMS	FC	P	CAN	CA	EMB	Symbol	Variable
1.00	-0.74	0.84	0.76	-0.46	-0.42	0.28	0.64	0.75	0.59	-0.03	-0.66	CS	Channel Stability
	1.00	-0.78	-0.50	0.17	0.25	-0.24	-0.55	-0.59	-0.55	0.30	0.48	HA	Hydrologic Alteration
		1.00	0.73	-0.34	-0.37	0.27	0.47	0.65	0.60	-0.13	-0.54	RZ	Riparian Zone
			1.00	-0.61	-0.56	0.11	0.50	0.63	0.43	-0.03	-0.61	BS	Bank Stability
				1.00	0.56	0.19	-0.38	-0.41	-0.25	-0.15	0.64	WC	Water Color
					1.00	0.08	-0.49	-0.51	-0.29	0.17	0.54	NE	Nutrient Enrichment
						1.00	0.08	0.21	0.17	0.09	-0.09	DAMS	Constructed Dams
							1.00	0.83	0.30	-0.27	-0.48	FC	Fish Cover
								1.00	0.44	-0.10	-0.51	P	Pools
									1.00	-0.05	-0.56	CAN	Canopy Closure
										1.00	-0.01	CA	Cattle Access
											1.00	EMB	Embeddedness

Model Formulation

The aforementioned statistical analysis was used to formulate the stream condition index (SCI):

$$\text{SCI} = \frac{\left(\sqrt[3]{\text{CS X FC X P}} + \sqrt[3]{\text{RZ X BS X CAN}}\right) / 2}{\left(\text{HA} + \sqrt[3]{\text{WC X NE X EMB}} + \text{CA}\right) / 3}$$

Where:

CS = Channel Stability	FC = Fish Cover
HA = Hydrologic Alteration	WC = Water Color
P = Pools	RZ = Riparian Zone
NE = Nutrient Enrichment	CA = Cattle Access
EMB = Embeddedness	BS = Bank Stability
CAN = Canopy Density	

As used herein, ecological models are algorithms which are empirical equations that express a relationship or correlation based solely on observation rather than theory. An empirical equation is simply a mathematical statement of one or more correlations in the form of an equation. In this case, the correlations were observed to be positive (direct) or negative (indirect) (Table 2). The variables were observed to be dependent or independent with respect to each other.

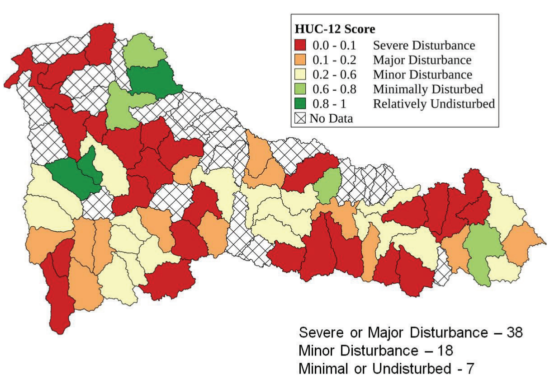

Figure 3. Stream condition index (SCI) scores per HUC12 watersheds, Duck River watershed, Tennessee.

For example, in the algorithm above, channel stability (CS) is highly correlated with fish cover (FC) and pools (P). Consequently, the three variables are considered dependent variables, and the geometric mean is derived. The observed interaction between variables occurs when the simultaneous influence of two measures on a model score is not additive. "Interaction" is analogous to dependence where a variable has a statistically significant influence on other variables.

Application of Stream Condition Index

A total of 213 video segments across 63 of 87 HUC12 watersheds were evaluated using the aforementioned eleven variables. SCI scores were calculated from average variable scores of video segments within each of the 63 watersheds and mapped in Figure 3. Thirty-eight of the 63 watersheds were considered to exhibit "major or severe disturbance to biotic and abiotic attributes". Eighteen of the 63 watersheds were considered to exhibit "minor disturbance to biotic and abiotic attributes", and seven of the 63 watersheds exhibited "minimally disturbed to relatively undisturbed".

The relationship between the SCI and a biological response was conducting using the Tennessee Valley Authority's Index of Biotic Integrity (IBI) database. The TVA has been collecting fish data in the Tennessee River system since 1986 and developed the IBI to monitor trends of the fish community. TVA established fixed and random monitoring stations to evaluate the watershed and levels of human disturbance such as point-source discharge and non-point source runoff. TVA developed the IBI as an environmental assessment tool following the procedure of (Karr 1981).

Twelve metrics addressed species richness and composition, trophic structure, fish abundance, and fish condition. Scores for the twelve metrics are summed to produce the IBI value for the site. The IBI database was provided by TVA along with descriptions of the protocols used in data collection. Ordination of fish species abundance among sites showed a pattern of IBI ratings with lower scores clearly separated from excellent scores (Figure 4).

Vector fitting indicated that sites with higher IBI ratings were associated with greater canopy and channel stability, while sites with lower IBI ratings occurred at sites with higher water color, nutrient enrichment, embeddedness, and hydrologic alteration.

Stream Condition and Aquatic Biota Correspondence

A bivariate plot of SCI (normalized to 0 to 1) and IBI scores showed a wedge shaped distribution (Figure 5), suggesting that anthropogenic change in habitat quality acts as a limiting factor. Wedge-shape bivariate relationships violate the assumptions of ordinary least squares regression and are better described by quantiles of the dependent variable (Dunham et al 2002).

An advantage of using quantile regression to model heterogeneous variation in response distributions is that no specification of how variance changes are linked to the mean is required, nor is there any restriction to the exponential family of distributions (Cade and Noon 2003).

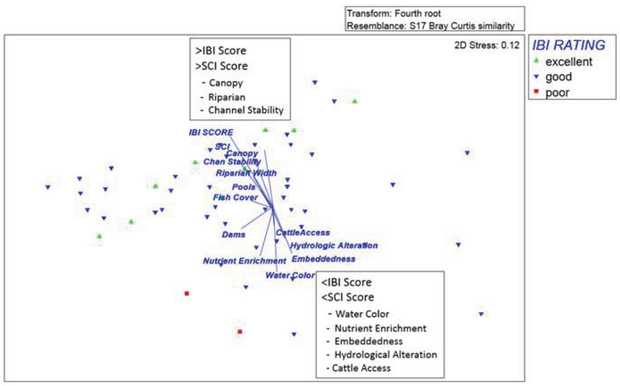

Figure 4. Nonmetric multidimensional scaling ordinations of fish species among sites. Index of Biotic Integrity (IBI) rating depicted by symbols. Vector identify the direction and strength of correlations; boxes summarize quadrant characteristics.

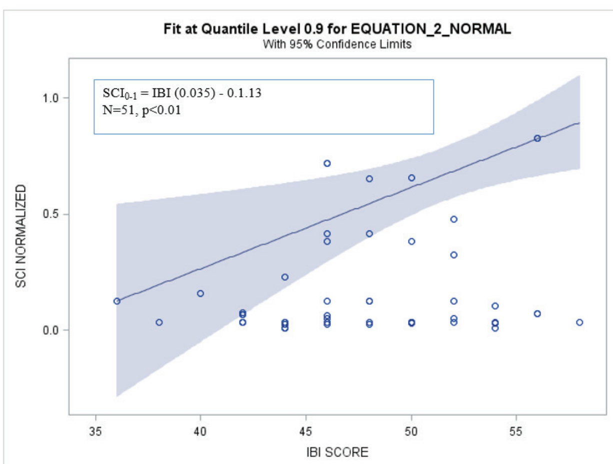

Figure 5. Estimate of 90th regression quantile equation for stream condition index (SCI), normalized to 0-1 as a function of the fish Index of Biotic Integrity (IBI).

An algorithm was developed that predicts SCI as a function of IBI score (Figure 4). This relationship indicates that either IBI score can predict SCI or vice-versa, which provides a tool to predict both stream conditions and status of the fish assemblage.

DISCUSSION

In general, the Duck Watershed experienced widespread aquatic impairment as evidenced by the 38 HUC12 watersheds that received low SCI scores (≤ 2) which indicates major to severe disturbance. Habitat loss was primarily due to embeddedness which was positively related to increases in hydrologic alteration, water color, and nutrient enrichment, and was negatively related to channel stability, riparian zone condition, bank stability, fish cover, pools, and canopy (Table 2).

The fish IBI scores complimented the SCI scores as evidenced by stream segments and HUC12 watersheds that exhibited both lower IBI and SCI scores. By examining the correlations between SCI and IBI metrics, six of the SCI metrics were significantly correlated with one or more IBI metrics including greater canopy and channel stability (higher scores) and higher water color, nutrient enrichment, embeddedness, and hydrologic alteration (lower scores).

Based on the direct relationship between SCI versus IBI scores, the biotic condition of the stream can be estimated from the SCI score, which is noteworthy because of the difficulty and expense of establishing biotic response variables. Consequently, by conducting a visual assessment of stream condition using the SCI, conclusions can be made in regards to fish diversity and distribution within a stream segment or a watershed.

Overall, the results of SCI-IBI scores observed in this watershed assessment can be utilized to: 1) Prioritize stream segments and watersheds for restoration, enhancement, preservation (conservation), and future risk of aquatic impacts; 2) Assess proposed project alternative analysis and cost/benefit analysis; 3) Develop performance standards and success criteria applicable to restoration actions; 4) Address impacts or improvements beyond the footprint of the project; 5) Establish monitoring plans including adaptive management; 6) Forecast future ecosystem outcomes; 7) Estimate the long-term effects of climate change on ecosystem processes and functions; 8) Assess stream conditions elsewhere and compare against reference conditions established during this watershed assessment; and 9) Justify proposed projects at the national significant priority scale.

CONCLUSIONS

The primary objective of the Duck Watershed study was to determine stream conditions at various scales. Ecological models, such as the Stream Condition Index (SCI) used herein, helped define the problem, lead to a better understanding of the correspondence between biotic and abiotic attributes of an aquatic ecosystem, provided analytical tools to enhance data interpretation, enabled comparisons between and across ecosystem types and physiography, and facilitated communication in regards to ecological processes and functions across scientific disciplines and to the public (project stakeholders).

The SCI provided an excellent method of rating watersheds based on their valley land use and cover, riparian zone condition, stream geomorphology, stream bedforms and habitat diversity, and water quality conditions. The SCI was formulated using statistical methods, consequently, reducing bias and subjectivity.

Based on the SCI scores calculated across 63 HUC12 watersheds, the following can be concluded: 1) Sediment in the form of embeddedness was the predominant cause of aquatic habitat loss. Embeddedness affected nine of the other ten variables. Embeddedness was indirectly correlated to channel and bank stability, riparian zone condition, and canopy closure, and directly related to hydrologic alteration, water color and nutrient enrichment; 2) Agricultural practices and cattle access contributed to bank failure and erosion leading to high sediment loadings as evidenced by the condition of the riparian zone and bank stability; 3) As evidenced by reduction in fish cover and pools, fish and aquatic benthic habitat were adversely affected by embeddedness, hydrologic alteration, and nutrient enrichment.

The use of low altitude, high definition video provides the following advantages: 1) At watershed and stream segment scales, it provides a rapid and reproducible method of covering more area expeditiously; 2) Acquiring private property access is generally not required; 3) Planform geometry (meander wave length, radius-of-curvature, and amplitude) is easily elucidated and measured using photogrammetry especially on large rivers; 4) Watershed-scale models (SCI) can be tested, refined and finalized by revisiting the video several times without additional field work; 5) Land use/cover and relative riparian zone condition is more obtainable; 6) Identification of sources of pollutants and sources of accelerated sediment is easily elucidated; 7) Identification of attainable reference conditions, by establishing the reference domain of all stream segments, is more easily achievable; 8) At the valley flat scale, video assessment facilitates the potential of recoupling adjacent wetlands to the frequent flood event; 9) The upstream and downstream effects of dams (fish barriers) can be visualized better; 10) With future flyovers, trend analysis can be conducted at watershed and stream segment scales including monitoring natural and anthropogenic changes, catastrophic events, and effects of climate change on stream hydrology and geomorphology; and 11) Video assessment provides a platform such that the general public can visualize stream corridor conditions.

Two disadvantages were identified: 1) Ecological assessments that require sampling of fish, benthic macroinvertebrates, mussels, etc. cannot be conducted. However, stream attributes that affect aquatic habitat can be assessed using low altitude video at the watershed-scale. Considering the scale of this effort and utility of readily available physical and biological data, aquatic biota databases were adequately addressed; and 2) The process of evaluating variables using video is extremely laborious and meticulous. Future computer software may reduce this level of effort.

The statistical treatise used in model development for the Duck Watershed can be utilized elsewhere in other physiographies and USACE Districts. The protocol used herein for establishing stream corridor conditions is applicable to the Tennessee River basin within Tennessee. However, the protocol can be transported to other river basins with additional beta testing and model refinement.

Over the past four decades, watershed assessments have evolved through three predominant scales, surface ("boots of the ground") to manned aircraft photography (various altitudes) to satellite imagery (over 400 miles altitude). However, with the advent of readily available, satellite imagery and computer software, high definition video and photography collected from aircraft has been underutilized until now with the advent of relatively inexpensive unmanned aircraft systems (UAS, "drones") equipped with nano-hyperspectral photography, thermal mapping and Laser Imaging, Detection and Ranging (LiDAR) capabilities.

Acknowledgements. Funding to support this research was provided by the USACE Nashville District (Ramuné Morales, Project Manager), and was supported by the following stakeholders: Tennessee Department of Environment and Conservation, The Nature Conservancy, Duck River Agency, and the Tennessee Valley Authority. The IBI database was provided by TVA (Evan Crews and Terry O'Quinn) along with descriptions of the protocols used in data collection.

LITERATURE CITED

Ahlstedt, S. A., P. D. Johnson, J. R. Powell, R. S. Butler, M. T. Fagg, D. W. Hubbs, S. F. Novak, and S. R. Palmer. 2004. Historical and current examination of freshwater mussels (Bivalvia: Margaritiferidae, Unionidae) in the Duck River basin Tennessee. Final Report: Tennessee Wildlife Resources Agency, Nashville, TN. Contract No.: FA-02-14725-00. 213p.

Cade, B. S. and B. R. Noon. 2003. A gentle introduction to quantile regression for ecologists. Front Ecol Environ 2003; 1(8): 412–420.

Dunham, Jason B., Brian S. Cade and James W. Terrell. 2002. Influences of Spatial and Temporal Variation on Fish-Habitat Relationships Defined by Regression Quantiles, Transactions of the American Fisheries Society, 131 (1): 86-98.

Etnier, D. A., and W. C. Starnes. The Fishes of Tennessee. University of Tennessee Press, Knoxville, Tennessee.

Griffith, G.E., J.M. Omernik, and S.H. Azevedo. 1998. Ecoregions of Tennessee. (2 sided color poster with map, descriptive text, summary tables, and photographs). U.S. Geological Survey, Reston, VA. Scale 1:940,000.

Karr, J. R. 1981. Assessment of biotic integrity using fish communities. Fisheries (Bethesda). 6(6):21-27.

Pruitt, B.A., S.J. Miller, C.H. Theiling, and J.C. Fischenich. 2012. The use of reference ecosystems as a basis for assessing restoration benefits. ERDC TN-EMRRP-EBA-11.

Schilling, E.M. and J.D. Williams. 2002. Freshwater mussels (bivalvia: Margaritiferidae and Uniondae) of the lower Duck River in middle Tennessee: A historic and recent review. Southeastern Naturalist 1(4): 403-414.

Stoddard, J., P. Larsen, C. P. Hawkins, R. Johnson, and R. Norris. 2006. Setting expectations for the ecological condition of running waters: The concept of reference conditions. Ecological Applications 16:1267-1276.

TNCWebSite. http://www.nature.org/ourinitiatives/regions/northamerica/unitedstates/tennessee/placesweprotect/duck-river.xml

USDA. 1998. Stream visual assessment protocol. United States Department of Agriculture, Natural Resources Conservation Service, National Water and Climate Center, Technical Note 99-1.