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Editorial

The National Sedimentation Laboratory: 50 years of soil and water research in a changing agricultural environment

ABSTRACT

The papers in this issue are based on selected presentations made at a symposium convened to celebrate the 50th anniversary of the founding of the National Sedimentation Laboratory (NSL) of the US Department of Agriculture (USDA), Agricultural Research Service (ARS), located in Oxford, Mississippi. The mission of the NSL is to find solutions to problems associated with soil erosion and sediment delivery from upland areas, erosion and sedimentation in stream channels, the impact of sediment and other agricultural contaminants on the biological well-being of receiving surface water bodies, and the loss of nutrients and agricultural chemicals from agricultural activities on the landscape. The papers in this issue present a broad overview of current research activities by NSL scientists and their colleagues. Copyright © 2009 John Wiley & Sons, Ltd.

KEY WORDS soil erosion; sediment transport; water quality; ecohydrology; ecology; watershed; conservation; computer model

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INTRODUCTION

Although indigenous peoples modified landscapes in many ways, much of North America was relatively pristine prior to the advent of European settlement and the attendant deforestation and cultivation. In North-Central Mississippi, for example, displacement of Native Americans *ca*. 1835 was followed by exploitative, non-sustainable agriculture that triggered large-scale loss of topsoil, gully erosion (Figure 1), and nearly complete filling of stream channels forcing up to 1·5 m of valley sedimentation (Figure 2). These developments were eloquently described as early as 1860 by Eugene W. Hilgard (Hilgard, 1860), widely regarded as the Father of soil science. The history of this region since Hilgard has been dominated by efforts to cope with soil productivity loss and later on also with environmental degradation. Legend holds that one such coping effort was created from a chance encounter between two political leaders, US Senator James O. Eastland and US Representative Jamie L. Whitten, who were touring the eroding farmlands of constituents in the 1950s. In the ensuing conversation, these congressmen resolved to use their influence to obtain federal legislation to establish a sedimentation laboratory near the University of Mississippi in Oxford, which became reality in 1958.

The laboratory was christened 'The National Sedimentation Laboratory' (NSL) in recognition of the wide relevance of its mission. Readers of this issue, however, will note that the problems studied during five decades of NSL research are definitely not unique to the US. Besides the NSL, the town of Oxford, Mississippi is also the onetime-home of Nobel-prize winning novelist William Faulkner, who received global recognition for his saga of the lives of ordinary folk populating a fictional Yoknapatawpha County that closely parallels the real community of Oxford. In reflecting on his career, Faulkner stated, that he became successful only after, 'I discovered that my own little postage stamp of native soil was worth writing about, and that I would never live long enough to exhaust it'. Somehow Faulkner was able to use lives and experiences from a very small place to generate stories of universal appeal and relevance. In the same way, the past and present scientists of the NSL hope that their feeble efforts have somehow contributed to stewardship of all of earth's resources for the benefit of future generations. This volume is a sample of that heritage. This volume contains papers presented at a symposium held to mark the 50th anniversary of the establishment of the US Department of Agriculture (USDA), Agricultural Research Service (ARS) and NSL. Additional selected papers will appear in a subsequent issue of this journal.

50 YEARS OF NSL RESEARCH

The mission of the NSL is to find solutions to problems associated with soil erosion and sediment delivery from upland areas, erosion and sedimentation in stream channels, the impact of sediment and other agricultural contaminants on the biological well-being of surface waters and the loss of nutrients and agricultural chemicals from agricultural activities on the landscape. The emphasis of NSL research has evolved during its 50-year

Figure 1. Gully erosion in northern Mississippi in the 1920s. Silt and sand depositing in gully floor. Gully is about 100 m wide and 2 km long (Lentz *et al.*, 1929).

existence, reflecting changing problems and national priorities. Clearly, the nature of this work and its impact extend far beyond problems associated with the movement of sediments, agricultural production or flood control. The NSL was directed to focus on long term, high-risk research that would complement efforts by others. The research activities can be summarized by recognizing three periods: from 1958 to 1972, from 1972 to 1994 and from 1994 to present.

Research activities from 1958–1972

Initial work was limited to physical aspects of sedimentation, with three main areas of emphasis: erosion and sediment transport, reservoir sedimentation surveys and nuclear applications technology. Plot-scale erosion studies were performed at the Mississippi Agricultural and Forestry Experiment Station in Holly Springs, Mississippi. Sediment sampling in the 300 km^2 Pigeon Roost Creek watershed in Marshall County, Mississippi, was conducted from 1957–1979 to determine the impact of land use changes and conservation practices on run-off and sediment production. Additionally, NSL workers at Pigeon Roost attempted to improve techniques of sediment gauging and sediment transport computations. Studies of basic flow and transport processes were carried out in two large flumes at the NSL. Notable results from this period included a series of laboratory experiments in which the forces on bed sediment grains were measured, generalized and compared to previous models.

Beginning in 1965 sedimentation surveys in more than 1200 reservoirs across the US were conducted as part of a large national interagency effort to gain data and information regarding reservoir life expectancy and management options. In addition, reservoir sedimentation data allowed more precise measures of long-term, large-watershed sediment yield than other types of monitoring. These surveys are part of the Reservoir Sedimentation Survey Database sponsored by the US federal interagency Advisory Committee on Water Information's Subcommittee on Sedimentation (http://ida.water.usgs.gov/ressed).

A third major research program was supported by the former US Atomic Energy Commission to study the fate and movement of radioactive fallout from aboveground-nuclear tests in agricultural watersheds across the US. This program led to two significant findings. First, the depth distribution of Cesium-137 in sediment profiles within reservoirs and ponds could be used to determine when layers in a sediment profile were deposited with two significant dates (1954 and 1964). Knowing these layers, one could calculate deposition rates of the sediment profile. The second discovery was that Cesium-137 and soil moved together across the landscape. By determining the Cesium concentration at a point on the landscape, the upland soil erosion/deposition rates and soil redistribution patterns across the landscape could be calculated.

Research activities from 1972–1994

In the early 1970s, the NSL was expanded to include an upland soil erosion mechanics component. Research focused on a better understanding of the underlying erosion/run-off/sedimentation processes, and the properties of the eroded sediment. Specialized research equipment and facilities were developed to conduct this work, including portable rainfall simulators that provided the capacity of applying a wide range of rainfall intensities, and laser equipment that could measure changes in the soil surface elevations and roughness following a rainfall event.

The research program further broadened with addition of environmental studies. The application of satellite remote sensing data for measuring surface water quality found that satellite reflectance data from Landsat-1 imagery could be used to monitor suspended sediment concentrations in surface water. Pesticide- volatilization/disappearance studies from crop canopy were found related to sediment yield, and that application drift and volatilization were major pathways of loss from field sites.

The NSL also had a significant role in the Demonstration Erosion Control (DEC) Project to evaluate the

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(a)

(b)

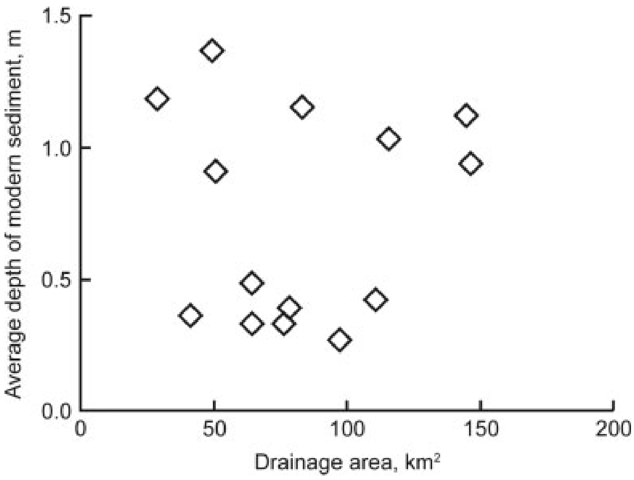

Figure 2. Valley sedimentation, northern Mississippi. (a) Typical deposition of sand on culitivated lands by flooding adjacent to occluded stream channel. (b) Average depths of modern sediments based on borings along valley cross sections (Happ, 1968).

Figure 3. Adjustment of a floating instrument platform in Goodwin Creek used for data collection and development of acoustic technology for field measurement of sediment transport.

performance of stream channel erosion control structures constructed by the US Army Corps of Engineers and the Natural Resources Conservation Service in the highly unstable streams, draining the Bluff Line watersheds in the Loess Hill region of Mississippi. A precursor of this program led to the establishment of the Goodwin Creek Experimental watershed near Batesville, Mississippi, in 1979 (Figure 3). This 21 km^2 watershed was partitioned into 14 nested subwatersheds with supercritical flumes at each outlet to monitor run-off of water and sediments. Design of the research facilities and program benefited greatly from prior experience with the Pigeon Roost watershed. Studies were conducted on rainfall/runoff relationships, bank stability, bed forms and sediment transport, and the effect of land use on run-off and sediment loadings. DEC research advanced the state-of-the-art regarding control of erosion and sedimentation in watersheds plagued by channel incision. Improvements in the prediction of suspended-sediment transport were developed from data from Goodwin Creek and laboratory flumes. Suspended sediment in alluvial flows was shown from a series of laboratory experiments to not have a significant effect on the von Kármán constant. Initiation of motion and transport of sediment composed of mixtures of sand and gravel were studied from data collected on the channels of Goodwin Creek, as well as from experiments conducted in flumes of the hydraulic laboratories. These studies provided data that documented the complexities and discrepancies from the Shields curve of the initiation of motion of individual grain sizes in a sediment composed of sand and gravel.

Research activities from 1994 to present

Computer modelling of soil erosion, sediment transport and water quality has become an important component of the NSL research. The NSL is custodian of three ARS benchmark computer models (NSL, 2008). The Revised Universal Soil Loss Equation (RUSLE) model evaluates the effects of conservation practices on soil erosion caused by rainfall and overland run-off at the field scale. The Agricultural Non-Point Source (AGNPS) pollutant loading model is used to evaluate the benefits of agricultural conservation practices on water quality and sediment yield at the watershed scale. The Conservational Channel Evolution and Pollutant Transport System (CONCEPTS)

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model assesses the impacts of in-stream and riparian conservation measures on stream morphology and sediment loads. A key NSL collaborator, the National Center for Computational Hydroscience and Engineering (NCCHE) at the University of Mississippi has developed a series of state-of-the-art one-, two- and three-dimensional computer models of free surface flow, sediment transport and water quality, GIS tools and decision support systems. The NCCHE models are used to perform detailed evaluations of in-stream structural conservation measures, levee breach analysis and flood-risk assessment.

The DEC project offered the opportunity to conduct prototype scale ecological engineering experiments in agricultural and mixed-cover watersheds (Wang *et al.*, 1997). Effects of water and sediment control techniques, such as low-head drop structures, vegetated ditches, stiff grass hedges, slotted board risers, slotted inlet pipes, impoundments, riparian zone revegetation with willow cuttings and constructed wetlands on the movement of soil, nutrients and agrichemicals into streams and lakes were evaluated. Furthermore, effects of some measures on aquatic macroinvertebrates, fish, birds, reptiles and amphibians were also examined.

The use of acoustic and seismic technologies was advanced to evaluate, measure and improve understanding of the physical principles of soil erosion, sedimentation processes, sediment accumulation in impoundments and reservoirs, and the structural integrity of impoundment/reservoir dams. Most of this technology was developed by another key NSL collaborator, the National Center for Physical Acoustics at the University of Mississippi.

The NSL has also been involved with two other large multi-agency efforts. In the Mississippi Delta Management Systems Evaluation Area project from 1995 to 2005, the NSL was assigned the responsibility to assess the environmental impact of agrichemical applications, especially in cotton production, on the water quality and ecology of oxbow lakes and streams in the Mississippi Delta and to develop alternative practices that would minimize these effects (Nett *et al.*, 2004). The Conservation Effects Assessment Project began in 2003 and was designed to quantify the watershed-scale environmental benefits of conservation programs used by private landowners that participate in selected USDA conservation programs. The NSL played a lead role in developing regional watershed models that quantify environmental outcomes of conservation practices in major agricultural regions. Furthermore, this project included selection of a total of twelve 'benchmark' watersheds from locations across the US for detailed research. The NSL manages and performs research in three of these twelve national benchmark watersheds (Kuhnle *et al.*, 2008; Locke *et al.*, 2008; Wilson *et al.*, 2008).

PAPERS IN THE SPECIAL ISSUE

The symposium celebrating the 50th anniversary of the NSL was organized along four broad themes: erosion and sediment research, water quality and ecology, watershed management and conservation, and modelling. The papers in this special issue are arranged following these themes.

Erosion and sediment research

The four papers in this group present research on establishing linkages between upstream instability and downstream impairment in unstable stream systems (Bennett and Rhoton, 2009), better understanding of sediment transport processes in shallow flows (Prasad *et al.*, 2009) and improved acoustic remote sensing technologies to characterize soil properties (Howard and Hickey, 2009; Leary *et al.*, 2009).

Unstable fluvial systems are characterized by actively migrating knickpoints, incising channel beds, failing banks and recruitment of large woody debris, and it would appear that river corridors downstream of these processes would be adversely affected or impaired because of higher fluxes of sediment and other riverine products. The paper by Bennett and Rhoton (2009) explores the geomorphic linkage between upstream instability and downstream degradation for the Yalobusha River in North-Central Mississippi. They found that excessive sedimentation and large woody debris recruitment have had a marked effect on stream corridor function in the area where a large debris plug had developed. However, the high sediment loads associated with the unstable portions of the Yalobusha River and their associated products were not communicated farther downstream to a large, flood control reservoir, Grenada Lake.

In shallow overland flows saltation is the most common transport mode of sediment particles. A better understanding of the saltation mechanism offers greater insight in the dynamics of sediment transport processes in shallow flows and might indicate how transported sediment affects the ecological functions of lotic benthic habitats. Prasad *et al.* (2009) present a new two-phase continuum mathematical model of water and sediment flow. The model accounts for inter-grain and grain-bed interactions. Laboratory flume experiments are used to both evaluate the validity of the model and improve the model. The model correctly predicts trends in particle velocities and saltation heights, and yields a velocity-concentration relationship that is consistent with experimental observations.

Leary *et al.* (2009) and Howard and Hickey (2009) show the potential of acoustic technology in erosion and sediment research. The impact of raindrops on a soil surface during a rainstorm may cause soil-surface sealing and soil crusting upon drying. The formation of soil-surface seals and crusts may have a profound influence on the erodibility of soils, with the consensus being that the reduced hydraulic conductivity due to sealing is a highly significant contributing factor. Leary *et al.* (2009) discuss two acoustic techniques, one with sensitivity to changes in hydraulic properties (sealing) and the other to changes in mechanical stiffness (crusting). Measurements were made on two soils having different erodibility

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characteristics. Half of each soil sample was subjected to a simulated rainstorm, while the other half was simply wetted. The rained-on samples for both soils showed a lower acoustic-to-seismic admittance than the samples that were only wetted, indicating that the raindrop impact produces a stiffer soil surface. The rained-on side of both soils also had larger acoustic pressures than the wetted side indicating that the impact of raindrops also increases the flow resistivity (decreased hydraulic conductivity) of the surface.

Howard and Hickey (2009) investigate acoustic-to-seismic (A/S) coupling techniques for measuring the depth to the fragipan. Fragipans, which are dense subsurface soil layers of low permeability, influence the hydrology and ecohydrology of the soil on a field scale. A suite of traditional geophysical measurements was taken to characterize the soils at two sites with different depths to the fragipan horizon. Data at these two field sites indicate that this A/S technique is sensitive to the spatial variability of the depth to the fragipan. At present, inversion of the A/S data for the fragipan depth requires use of data from a separate geophysical measurement or soil cores to provide a field calibration.

Water quality and ecology

The five papers in this group present research on the spatial distribution of excess nutrients (Shields *et al*., 2009), and on environmentally-friendly conservation practices to reduce soil, nutrient and pesticide run-off to improve water quality (Lizotte *et al*., 2009; Pierce *et al*., 2009) and ecology (Smiley *et al*., 2009a, b).

Shields *et al*. (2009) highlight the problem of misplaced plant nutrients. They performed an assessment of nutrient sources, sinks and inputs to streams within the Delta and Hills ecoregions of the Yazoo River Basin of northern Mississippi. The mean total *N* concentration for the Delta was about three times as large as that for the Hills, and both were about two to four times higher than US Environmental Protection Agency (EPA) criteria for each of these ecoregions. The Delta mean *P* concentration was about four times greater than that for the Hills and is about four to five times the levels set as criterion by the EPA. Delta mean *N* and *P* concentrations were inversely proportional to contributing drainage area, whereas those of Hill sites were not. Delta *N* and *P* concentrations peak strongly in spring when agricultural fertilizers are applied and stream flows are highest. Concentrations of *N* in Hill streams do not exhibit seasonal patterns, but mean monthly *P* levels are correlated with mean monthly discharge.

Pierce *et al*. (2009) and Lizotte *et al*. (2009) present research on best management practices (constructed wetlands and vegetated agricultural ditches) to reduce nutrient and pesticide concentrations in surface waters. Pierce *et al*. (2009) compare nutrient allocation in two wetland plant species, *Bacopa monnieri* (water hyssop) and *Leersia oryzoides* (rice cutgrass), that are subjected to a range of water regimes ranging from drained to continuously flooded. Results indicated that species-specific flood responses in plant nutrient status are due to differing interactions of *B. monnieri* and *L. oryzoides* with the soil environment. *L. oryzoides* demonstrated greater *P* uptake than *B. monnieri* across treatments, resulting in decreased concentrations of $PO_4{}^{-3}$ in effluent. Although *N* was also affected by flooding and species, generalizations on *N* allocation within the system are difficult to describe due to the changes in species of *N* in response to oxidation–reduction gradients and biotic assimilation.

Cultivated floodplains often contain water bodies such as backwater wetlands that receive significant inflows of water and associated pollutants from fields. These backwater wetlands, with modification, could be managed to provide ecological services such as reducing pesticide loads from non-point sources. Lizotte *et al*. (2009) examined the pesticide trapping efficiency of a modified backwater wetland amended with a mixture of three pesticides (atrazine, *S*- metolachlor and fipronil) using a simulated small run-off event. Pesticides were rapidly removed from water, and no target pesticides were detected after day 56. Results indicate that modified backwater wetlands can efficiently trap pesticides in run-off from agricultural fields during small to moderate rainfall events, mitigating impacts to receiving waters in the main river channel.

Smiley *et al*. (2009a,b) describe the ecological benefits of various agricultural conservation measures. Smiley *et al*. (2009a) evaluated relationships between water chemistry and fish communities within channelized headwater streams of Cedar Creek, Indiana and Upper Big Walnut Creek, Ohio. Their results suggest that if water chemistry is the focus of a conservation plan, then the most effective conservation practices may be those that have a combined influence on nutrients, herbicides and physicochemical variables. Most importantly, greatest benefits for fish require approaches that address physical habitat as well as water chemistry degradation in channelized headwater streams.

Smiley *et al*. (2009b) consider the effects of ‘drop pipe’ structures that are used to control edge-of-field gully erosion on amphibian and reptile communities (Figure 4). Amphibians and reptiles were sampled from four actively eroding gullies and four sites of each of three types of drop pipe-created habitats from 1994 to 1996. Increased pool size, habitat area and hydroperiods resulted in greater amphibian and reptile species richness and abundance. The results suggest that the drop pipes may be used to control gully erosion as well as creating riparian wetlands that support amphibian and reptile communities.

Watershed management and conservation

The two papers in this group explore the benefits of agricultural conservation measures in a large watershed (Garbrecht and Starks, 2009) and the benefits of riparian buffers on the watershed scale (Yuan *et al*., 2009).

While soil and water conservation research and demonstration projects in agricultural watersheds have shown to be very effective at reducing overland soil erosion

Figure 4. Drop pipe structure (foreground) creates complex wetland habitat at field edge. Inset shows reptile captured in drop pipe-associated habitat.

and sediment delivery to channels at field and small catchment scales ($\sim$1 to 100 ha), this cannot be readily observed at the outlet of large watersheds ($>$10, 000 ha). Garbrecht and Starks (2009) developed pre- (1940s) and post-conservation (2000s) suspended sediment rating curves for the 787 km^2 Ft. Cobb Reservoir watershed in West-Central Oklahoma. They found that average annual suspended-sediment yield was seven times greater for the pre-conservation period than that for the post-conservation period. The substantial reduction in suspended-sediment yield was related to land use and management changes, and the wide range of conservation practices implemented in the second half of the 20th century.

In recent years, there has been growing recognition of the importance of riparian buffers between agricultural fields and water bodies. Riparian buffers play an important role in mitigating the impacts of land use activities on water quality and aquatic ecosystems. However, evaluating the effectiveness of riparian buffer systems on a watershed scale is complex, and watershed models have limited capabilities for simulating riparian buffer processes. Yuan *et al*. (2009) provide a thorough literature review on the performance of vegetative buffers to reduce sediment loadings to streams by trapping sediment in upland run-off moving to streams. They report that although sediment trapping capacities are site- and vegetation-specific, and many factors influence the sediment trapping efficiency, the width of a buffer is important in filtering agricultural run-off and wider buffers tended to trap more sediment. In general, sediment trapping efficiency did not vary by vegetation type, and grass buffers and forest buffers had roughly the same sediment trapping efficiency.

Modelling

The four papers in this group present four different model applications of physical processes, water quality and stream ecology: improved watershed-scale run-off generation (Dahlke *et al*., 2009); sediment-associated water quality in lakes (Chao *et al*., 2009); impact of riparian buffers on stream morphology (Langendoen *et al*., 2009) and the effects of large wood structures (LWS) on stream morphology and habitat suitability (He *et al*., 2009).

Two widely used watershed models, AGNPS and SWAT, use the Soil Conservation Service Curve Number (CN) method to predict run-off, which assumes that the initial abstraction of rainfall that is retained by the watershed prior to the beginning of run-off is a constant fraction of the maximum retention. This method is not valid for the Northeast US where saturation excess is the most dominant run-off process, and locations of run-off source areas, typically called variable source areas (VSAs), are determined by the available soil water storage and the landscape topographic position. The correct prediction of run-off generation and pollutant source areas in the landscape is important when siting conservation measures and estimating their impact on water quality. Dahlke *et al*. (2009) applied a VSA interpretation of the CN run-off equation that allows the initial abstraction to vary with antecedent moisture conditions, and coupled this modified CN approach with a semi-distributed water balance model to predict run-off for the Town Brook watershed in the Catskill Mountains of New York State. The modified CN equation captured VSA dynamics more accurately than the original equation. However, during events with high antecedent rainfall, VSA dynamics were still underpredicted suggesting that VSA run-off is not captured solely by knowledge of the soil water deficit.

The water quality of lakes in the Mississippi Delta is closely associated with excess concentrations of suspended sediment and the sediment quality of the lake bed. Most water quality models either do not account for these processes or account for them using oversimplified empirical relations. Chao *et al*. (2009) describe improved formulations of these processes and their implementation in a three-dimensional water quality model,

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CCHE3D_WQ, developed by the NCCHE. Application of the model to a shallow Mississippi Delta lake shows that simulated concentrations of phytoplankton (as chlorophyll) and nutrients were generally in good agreement with field observations. This application further shows that there are strong interactions between sediment-associated processes and water quality constituents.

Excess sediment is a major contributor to the impairment of streams in the US. The main sources of fine-grained sediments transported in streams are hill slopes and stream banks. Many of the stream systems in the mid-continent of the US are unstable with stream banks being the principal source of fine sediment, contributing up to 80% of the total suspended load. A goal of many stream restoration projects is to manage the riparian zone to reduce stream bank erosion. These projects could benefit from using proven models of stream and riparian processes to guide restoration design. Langendoen *et al.* (2009) present the integration of two computer models that simulate in-stream (CONCEPTS) and riparian (REMM) processes. The integrated CONCEPTS–REMM model was evaluated on its ability to simulate the hydrologic (soil water) and mechanical (plant roots) mechanisms that control stream bank erosion. The model was further used to study the effectiveness of woody and herbaceous riparian buffers in controlling stream bank erosion of an incised stream in northern Mississippi. The modelling exercise showed that a coarse rooting system, e.g. as provided by trees, significantly reduced long-term bank erosion rates for this deeply-incised stream.

In recent years, engineers have increasingly considered the use of LWS to stabilize sand-bed streams because it is low-cost and environment-friendly method of habitat rehabilitation and erosion control. Successful application of LWS can result in decelerated erosion and ecosystem recovery at lower cost than other practices. Simulation of the physical effects of LWS is desirable for developing design criteria, evaluating their impacts on channel morphology and aquatic habitat, and to remove uncertainty for rehabilitation projects. He *et al.* (2009) applied a depth-averaged two-dimensional model to simulate the effect of large wood structures on flow, sediment transport, bed change and fish habitat in a deeply-incised sharp bend in the Little Topashaw Creek, North-Central Mississippi. Habitat evaluations using kinetic energy and circulation metrics indicated that LWS only slightly increased the diversity of physical conditions. Weighted usable areas (WUA) for two fish species, blacktail shiner (*Cyprinella venusta*) and largemouth bass (*Micropterus salmoides*), were computed using hydrodynamic simulations of three discharges before and after the LWS construction and habitat preference curves for depth and velocity. The results show that the values of WUA for both fish species were increased after LWS installation at all three discharges.

CONCLUSIONS

Papers presented at the NSL 50th anniversary symposium, of which this issue is a sample, represent an impressive and broad array of scientific achievement. However, a frank assessment of these achievements in light of the overwhelming environmental problems now plaguing the planet reveals that much work is left to be done. Major challenges for the next 50 years by the NSL and like-minded workers worldwide include refinement of numerical models and wider use of 'numerical experiments' by researchers and resource managers. These models should be equipped to access ever larger data sets fed by networks of reliable sensors. Both fundamental and applied work are needed to create a new ethic in land management that is based on management of natural ecohydrological processes to purify water and rebalance the use of resources to produce crops and to sustain natural ecosystems. Future farmers should have far greater control of the movement of water, soil and nutrients that will prevent damages to downstream resources. Finally, someday science will advance to allow accurate, repeatable prediction of the total sediment load carried by a stream.

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