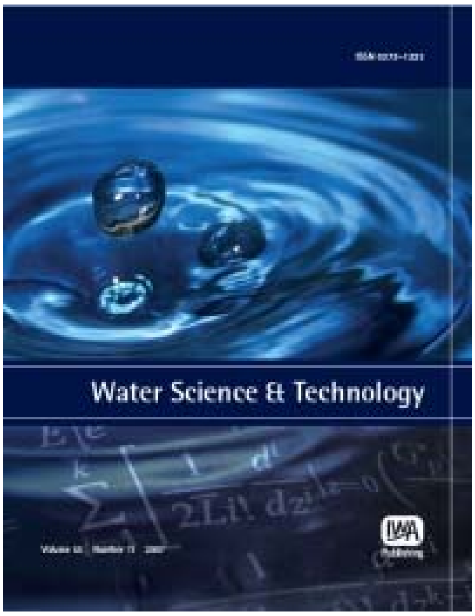
Water Science & Technology

The challenge of documenting water quality benefits of conservation practices: a review of USDA-ARS's conservation effects assessment project watershed studies

M. D. Tomer and M. A. Locke

ABSTRACT

The Conservation Effects Assessment Project was established to quantify water quality benefits of conservation practices supported by the U.S. Department of Agriculture (USDA). In 2004, watershed assessment studies were begun in fourteen agricultural watersheds with varying cropping systems, landscapes, climate, and water quality concerns. This paper reviews USDA Agricultural Research Service 'Benchmark' watershed studies and the challenge of identifying water quality benefits in watersheds. Study goals included modeling and field research to assess practices, and evaluation of practice placement in watersheds. Not all goals were met within five years but important lessons were learned. While practices improved water quality, problems persisted in larger watersheds. This dissociation between practice-focused and watershed-scale assessments occurred because: (1) Conservation practices were not targeted at critical sources/pathways of contaminants; (2) Sediment in streams originated more from channel and bank erosion than from soil erosion; (3) Timing lags, historical legacies, and shifting climate combined to mask effects of practice implementation; and (4) Water quality management strategies addressed single contaminants with little regard for trade-offs among contaminants. These lessons could help improve conservation strategies and set water quality goals with realistic timelines. Continued research on agricultural water quality could better integrate modeling and monitoring capabilities, and address ecosystem services.

Key words | agricultural watersheds, conservation practice assessment, water quality, watershed modeling

M. D. Tomer (corresponding author)
USDA-ARS,
National Laboratory for Agriculture and the Environment,
2110 University Boulevard,
Ames, Iowa 50010,
USA
E-mail: *mark.tomer@ars.usda.gov*

M. A. Locke
USDA-ARS,
National Sedimentation Laboratory,
598 McElroy Drive,
Oxford, Mississippi 38655,
USA

INTRODUCTION

Agricultural conservation practices in the U.S. are implemented by landowners on a voluntary basis, with financial incentives provided by the U.S. Department of Agriculture (USDA). The incentives include cost sharing for establishing each practice and annual rental payments where lands are contracted to be under perennial conservation cover. These incentive payments were authorized by the U.S. Congress at U.S. $3.5 billion annually (Becker 2002), a level at which cost-benefit analysis is legally required to ensure this taxpayer investment in conservation is being fairly returned in terms of environmental benefits. However, benefits of conservation practices had not been adequately quantified to allow this analysis to take place. The Conservation Effects Assessment Project (CEAP) was initiated by USDA to remedy this knowledge gap and provide information that could be used to improve the cost-benefit balance of USDA conservation programs (Mausbach & Dedrick 2004). The CEAP project was comprised of national resource assessments (for cropland, grazing land, wetlands, and wildlife), watershed assessment studies, and bibliographies (Duriancik *et al.* 2008). Our focus here is on the cropland component, specifically Benchmark watershed assessments undertaken by the Agricultural Research Service (ARS; see Richardson *et al.* 2008). The National Cropland Assessment is being conducted using survey data gathered from farm producers and simulation modeling using the APEX and SWAT models; results are being published in a series of regional reports; the first one on the

doi: 10.2166/wst.2011.555

Upper Mississippi River Basin was recently released (USDA 2010). The CEAP watershed assessment studies included ARS Benchmark watershed studies discussed here, NRCS Special Emphasis watershed studies, and NIFA watershed studies (Duriancik *et al.* 2008; Richardson *et al.* 2008; Osmond 2010). Results from individual watershed studies are being published in a wide variety of journals and several special issues.

The CEAP watershed assessments faced the problem of determining how conservation practices impact water quality in relatively large watersheds, beyond the field scale at which practices are implemented. This was part of the project goal of identifying public benefits of conservation practices, because water is a public resource of vital concern, especially in larger streams and rivers that provide important drinking water, fishery, and recreational resources. At a fundamental level, the scientific challenge of identifying cumulative watershed-scale effects derived from a set of field-scale conservation practices is one of scientific control. Large watersheds are not replicable and it is generally not feasible to consistently implement (or withhold) experimental treatments across large areas of private agricultural land. These issues diminish as the scientific approach and objectives are narrowed down to the field scale. Large agricultural watersheds include a mix of practices and it is difficult to isolate the effect of individual practices. Yet, as the CEAP watershed projects progressed, it became clear that more is involved in the question of watershed-scale effects than experimental control and spatial scaling.

This paper provides a review of results from the watershed assessments undertaken in USDA's Agricultural Research Service (ARS) Benchmark watersheds (Figure 1, and Richardson *et al.* 2008), and examines the challenge of identifying water quality impacts in large watersheds. First, we will summarize conservation practice assessments conducted at field and watershed scales, through both modeling and field studies. We then summarize progress made in modeling of agricultural watersheds in these watersheds. Finally, we discuss reasons that conservation practice effects that may be readily identified at the field scale are more difficult to identify at the watershed scale.

PRACTICE ASSESSMENTS

Assessments of conservation practices can be undertaken through several approaches, including modeling studies, field experiments, edge-of-field monitoring, and watershed scale studies. Watershed scale studies can be conducted either through analysis of an observed time series following practice implementation, or a paired watershed study.

Figure 1 | General map of the United States showing Benchmark Watersheds of the USDA-ARS Conservation Effects Assessment Project.

Although the paired watershed approach is more powerful statistically (Loftis *et al.* 2001; King *et al.* 2008) the single time series approach is simpler to implement and is more common. In this section, we summarize conservation practice assessments that were conducted in the CEAP Benchmark watersheds. These practices are listed in Table 1 where CEAP research on each practice is summarized, and a review article is suggested for further reading on each type of practice.

Conservation reserve program (CRP)

The CRP was initiated as part of the Conservation Title of the 1985 US Farm Bill passed by Congress and implemented by the USDA. Begun during a time of concern about the economic impact of crop surpluses on agriculture's profitability, this program was designed to take highly erodible land out of production and to establish perennial cover for ten years under rental contract. The program was later expanded to encourage establishment of riparian buffers under CRP. The CRP has largely been deemed successful (Hansen 2007), with quantifiable economic benefits estimated to be about 80% of the program costs (recognizing that not all benefits were quantifiable). Several CEAP Benchmark watersheds, in Mississippi and Iowa, documented CRP set aside lands as a key conservation practices on the landscape (Locke *et al.* 2008; Tomer *et al.* 2008b; Wilson *et al.* 2008b), Direct environmental benefit of this practice have been separately estimated in two Mississippi CEAP watersheds. Kuhnle *et al.* (2008) found about 20% of the Goodwin Creek watershed was converted from cropland to permanent cover between 1982 and 2005; this conversion was largely attributed to CRP and resulted in more than a 60% reduction in sediment. Establishing CRP within a Mississippi Delta lake watershed reduced total sediments by 85% and nutrients by greater than 28% when compared with adjacent areas under row crop practices (Cullum *et al.* 2010).

Table 1 | Summary results of conservation practices assessment studies undertaken within the CEAP watersheds

Conservation practice	Pollutant/s (reduction)	Approach (scale[a])	References
Conservation reserve program (conservation cover)	Sediment concentration (63%)	Observed time series (W)	Kuhnle *et al.* (2008)
	Sediment (85%), nutrient (>28%) load	Runoff monitoring (F)	Cullum *et al.* (2010) Hansen (2007) (R)
Cover crops	Cover crop *N* uptake (varied)	Remote sensing calibration (W)	Hively *et al.* (2009)
	NO_3-N leaching load (61%)	Replicated field trial – 4 yrs (P)	Kaspar *et al.* (2007)
			Dabney *et al.* (2001) (R)
Livestock management: nutrient management	P loss – farm scale (43–60%)	Modeling study (B)	Ghebremichael *et al.* (2007)
Pasture rotation (fencing)	P load (estimated 32%)	Field study (W)	James *et al.* (2007)
			Russelle *et al.* (2007) (R)
No tillage	Sediment (64–77%)	Modeling study (W)	Yuan *et al.* (2008)
			Lal *et al.* (2007) (R)
Riparian buffers	Sediment, P loads (20%); total N (7%)	Modeling study (W)	Cho *et al.* (2010)
	Sediment load (72%)	Modeling study (W)	Moriasi *et al.* (2010)
			Lovell & Sullivan (2006) (R)
Split N application (w spring soil test)	NO_3-N concentration (30%)	Paired watershed (W)	Jaynes *et al.* (2004)
			Dinnes *et al.* (2002) (R)
Engineered hydraulic structures: flood retarding structures	Annual max. daily discharge (33%)	Modeling study (W)	Van Liew *et al.* (2003)
Sediment control structures	Sediment load (>15%)	Modeling study (W)	Kuhnle *et al.* (2008)
			Vanoni (2006) (R)

[a]P, plot scale, F, field scale; B, farm scale W, watershed scale; (R) Review of literature on this practice or set of practices.

Cover crops

Winter cover crops are a conservation practice that were implemented and are being evaluated in the CEAP watersheds in New York and Maryland (Bryant *et al.* 2008; McCarty *et al.* 2008; Hively *et al.* 2009). Cover crops can increase soil organic matter, and reduce runoff, erosion, and nutrient losses (Dabney *et al.* 2001). In tile drained areas of the Midwest, cover crops have been shown to decrease NO_3-N leaching by more than 60% with minimal impact on yield when the cover crop is killed 10–14 d prior to planting (Kaspar *et al.* 2007, and subsequent unpublished data). A remote sensing technique to estimate and map nutrient uptake by cover crops was developed in the Choptank watershed (Hively *et al.* 2009), providing a technique to help manage agricultural impacts on water quality in the Chesapeake Bay.

Livestock nutrient/pasture management

Livestock, pasture, and manure management were identified as important issues in watersheds in Iowa (Tomer *et al.* 2008b), New York (Bryant *et al.* 2008), and Texas (Harmel *et al.* 2008). In New York, reduced P losses were estimated for excluding of cattle from streams at the watershed scale (James *et al.* 2007) and precisely meeting feed diet P requirements at the farm scale (Ghebremichael *et al.* 2007). Manure management practices to minimize P in runoff were evaluated in Texas (Harmel *et al.* 2008). In Iowa River's South Fork (Tomer *et al.* 2008a) and in Texas' Leon River (Harmel *et al.* 2010), *E. coli* populations in stream water would lead to water use impairment in sub-basins with and without large densities of livestock, suggesting that managing bacterial loading in streams through manure and pasture management will remain a vexing issue.

Reduced and no tillage

No tillage practices or practices that provide year-round residue cover were identified as important practices in CEAP watersheds in Missouri (Lerch *et al.* 2008), Iowa (Tomer *et al.* 2008b), Oklahoma (Steiner *et al.* 2008), Mississippi (Locke *et al.* 2008), Indiana (Smith *et al.* 2008), and Maryland (McCarty *et al.* 2008). No-tillage is an important practice that will reduce amounts of runoff and erosion in most environments (Lal *et al.* 2007; Yuan *et al.* 2008). However under some soil conditions there are tradeoffs to consider; for example if surface crusting occurs then runoff can be increased under no tillage (Karlen *et al.* 2009). Also, in Missouri, no-tillage was associated with increased transport of herbicides in surface runoff, because herbicides are not incorporated into soil under no-tillage practices (Lerch *et al.* 2008).

Riparian practices

Riparian buffers are installed to encourage infiltration of runoff from cropland and thereby trap sediment, nutrients, and other contaminants to prevent their direct entry into surface waters. This practice was broadly implemented in CEAP watersheds in Indiana and Iowa (Smith *et al.* 2008; Tomer *et al.* 2008b). Natural forested buffers, often associated with riparian wetlands, were common in CEAP watersheds in Georgia, Mississippi, and Maryland (Feyereisen *et al.* 2008; Locke *et al.* 2008; McCarty *et al.* 2008). In watersheds where artificial subsurface (tile) drainage is dominant, riparian buffers cannot treat drainage from tile-drained uplands, but do provide a setback that reduces direct losses of nutrients and sediment from cropland adjacent to waterways (Smith *et al.* 2008). Benefits of riparian buffers have not been measured directly through the CEAP studies, partly because the literature includes many field evaluations (Lovell & Sullivan 2006). However two modeling studies have been conducted that simulated water quality benefits of buffers in CEAP watersheds (Table 1; Cho *et al.* 2010; Moriasi *et al.* 2010).

Natural wetlands are often transition zones between agricultural areas and water bodies and can serve as areas for processing contaminants moving through the system. Placing artificial wetlands in areas where wetlands do not naturally exist can also provide a protective buffer for vulnerable water bodies. A wetland was constructed in CEAP Beasley Lake watershed and its potential for mitigating pesticide in runoff was demonstrated (Moore *et al.* 2009; Locke *et al.* 2011). Methods to locate sites most appropriate for installation of riparian buffers and constructed wetlands, based on terrain analysis, were proposed for a tile drained watershed (Tomer *et al.* 2003).

Ditches have been installed to receive water draining from cropland in many agricultural watersheds, providing a conduit for rapid transport of contaminants to downstream water bodies. Therefore, improving the management of ditches can be an important component of watershed protection. In tile-drained watersheds across the Midwest, drainage ditches are shaped with berms or weirs to prevent runoff from eroding shaped ditch banks (Smith *et al.* 2008). In CEAP's Beasley Lake watershed in Mississippi, vegetation in a ditch draining agricultural fields was shown to be effective in retaining pesticides (Moore *et al.* 2001). This and other research (Moore *et al.* 2008) led to establishment of NRCS guidelines for vegetative ditches in California and Mississippi.

Nitrogen fertilizer rate and timing

A paired watershed study on nitrogen management, which included soil testing in late spring to identify split-N application rates to corn (maize), showed the practice could reduce nitrate concentration in tile drainage by 30% within four years (Jaynes *et al.* 2004). This study provides a rare example of the use of a control watershed and a pre-treatment calibration period in watershed-scale agricultural research.

Sediment control structures

Sediment and floodwater control structures have been evaluated through modeling studies in CEAP watersheds in Mississippi (Kuhnle *et al.* 2008) and Oklahoma (Van Liew *et al.* 2003). Erosion and sediment movement are natural geomorphic processes that are impacted by land cover, agricultural practices, and river corridor management, and this topic is revisited below.

WATERSHED MODELING

Models are important tools in watershed management to help assess our understanding of watershed processes and evaluate how proposed changes in land use and agricultural practices might impact hydrology and water quality. Two watershed models, AnnAGNPS (Annualized Agricultural Non-Point Source) (Bingner *et al.* 2009) and SWAT (Soil and Water Assessment Tool) (Arnold *et al.* 1998), were employed throughout CEAP, and have seen broad, international application (Gassman *et al.* 2007; Licciardello *et al.* 2007; Zema *et al.* 2010). SWAT was also part of the modeling effort for the CEAP National Cropland Assessment (USDA 2010).

Collectively, watershed modeling efforts in the CEAP watersheds have led to a number of advances. In watershed modeling, the issues of calibration and validation in identifying optimal parameter sets and determining parameter sensitivities have received a variety of treatments, and one contribution of the CEAP studies has been a set of recommended guidelines to follow to ensure consistency in watershed modeling efforts (Moriasi *et al.* 2007). These guidelines, which recommend performance statistics and targets to deem model results 'satisfactory', are critical because policy and legal decisions can hinge on realistic modeling results and confidence in the modeling process.

The first goal of watershed modeling is to achieve an accurate hydrologic calibration: water quality responses to management cannot be accurately simulated if hydrologic timings and pathways are not accurately simulated by the model. SWAT was shown to be an effective tool for capturing the dynamics of streamflow and atrazine concentrations of the St. Joseph River watershed (Larose *et al.* 2007; Heathman *et al.* 2008). In a cross-basin comparison of CEAP watershed SWAT calibrations, Veith *et al.* (2010) showed that parameters governing surface runoff were most sensitive, and that SWAT appears to perform best in humid environments. In Midwest watersheds, subsurface (tile) drainage has been widely installed, substantially altering watershed hydrology and providing a critical pathway for nitrate losses (Dinnes *et al.* 2002). A routine to represent tile drainage in the SWAT model was developed and tested (Du *et al.* 2005), and calibrated for the Iowa River's South Fork watershed (Green *et al.* 2006). The driving input variable for any hydrologic calibration is precipitation, and the spatial and temporal resolutions of precipitation data can impact the sensitivity of parameters driving key hydrologic processes, specifically groundwater recharge (Starks & Moriasi 2009). The AnnAGNPS model was used on CEAP Beasley Lake watershed in Mississippi to simulate water and sediment produced on each field and the resulting impact on lake water quality (Yuan *et al.* 2008). The model was applied without calibration, and the simulated runoff and sediment yield compared well with observed data. AnnAGNPS was used to identify high sediment-producing areas and to simulate the impacts on water quality of targeting conservation practices to these areas.

Once hydrologic calibration of a watershed model is satisfactorily achieved, simulation of water quality is possible, but progress has been slower than for hydrologic calibration during CEAP's first five years. Water quality assessments of conservation practices through watershed scale modeling in CEAP have dominantly, but not solely, focused on sediment reduction effects (Table 1). Cho *et al.* (2010) assessed trapping of nutrients along with sediment in simulating effects of riparian buffers in Georgia, and Saleh *et al.* (2007) demonstrated that SWAT can simulate reduced loadings of nitrate-N in tile drainage resulting from use of split N fertilizer applications, and from winter cover crops. SWAT is undergoing changes to nitrogen cycling and soil phosphorus routines to enable greater progress in this area (Gassman *et al.* 2007). The SWAT and AnnAGNPS models have been used to quantify the environmental benefits of implementing cover crops and riparian buffers on the Choptank watershed, and data from a sub-basin were used to calibrate and validate the models. The models showed a direct relationship between degree of implementation of cover crops and the reduction in nitrate loading to the stream. SWAT showed marked improvement in load reduction when cover crops were targeted to areas with the greatest nitrate loads rather than randomly applied. AnnAGNPS was used to identify the spatial location for specific pollutant loads within the watershed (McCarty *et al.* 2008). The SWAT and AnnAGNPS models were applied without calibration to the Cedar Creek watershed, a 708 km^2 sub-watershed of the St. Joseph River in Indiana, to simulate streamflow, sediment transport, and atrazine losses. SWAT performed better than AnnAGNPS in estimating monthly and annual streamflow, while AnnAGNPS predicted greater sediment loss than SWAT.

As a result of CEAP studies, improvements were identified for both SWAT and AnnAGNPS. Components of subsurface drainage control practices of Midwestern conditions were incorporated into AnnAGNPS to allow evaluations of these improvements for their effect on water, sediment, and chemical loadings in a watershed (Yuan *et al.* 2006). Enhancements were also completed within AnnAGNPS to account for ephemeral gully erosion sources within a watershed (Gordon *et al.* 2007), as well as riparian buffer systems (Yuan *et al.* 2007). New modeling technologies (genetic algorithms) are also being combined with SWAT to evaluate how combinations of practices can be targeted within watersheds, and indeed must be to achieve maximum water quality benefits, as demonstrated in New York's Town Brook watershed (Gitau *et al.* 2006). Gassman *et al.* (2007) provide tables summarizing SWAT watershed modeling performance for hydrologic and water quality variables. Arabi *et al.* (2008) and Gassman *et al.* (2007) provided suggestions of parameter adjustments that best represent a variety of conservation practices, and parameters found to be most sensitive for calibration on different water quality constituents. This progress in watershed modeling has been important in enabling progress in regional modeling efforts for CEAP (USDA 2010). A remaining challenge is simulating not only water quality responses to conservation, but response of aquatic habitat quality to conservation efforts (Shields *et al.* 2006).

These modeling accomplishments are consequential but the broad goal of documenting conservation practice effects on water quality at watershed scales has remained elusive. Few efforts have included a watershed-scale study to monitor and quantity a conservation-practice benefit for water quality, followed by a successfully validated model simulation of that practice's water quality response in the same watershed. Demonstration of fertilizer management (late spring nitrate test) benefits for nitrate reduction in a paired watershed experiment (Jaynes *et al.* 2004), followed by model validation (Saleh *et al.* 2007) is one example that illustrates a successful effort to combine field and modeling efforts, yet demonstrates the level of effort required to demonstrate and simulate an impact of only one practice on one contaminant in one watershed. Beyond that, watershed modeling remains a semi-empirical process including representational functionality as well as specific governing biophysical processes. Hence watershed simulations may simply estimate the *potential* benefits of conservation based on our understanding of how a practice *should* function to improve water quality. However, design and intent do not necessarily dictate outcome. Therefore, more combined efforts to both measure and simulate benefits of conservation practices accurately will be necessary to improve our confidence in watershed modeling. Accomplishing this for small watersheds would provide experience to better assess large basins.

MEASURING CONSERVATION EFFECTS IN LARGE WATERSHEDS

Efforts to quantify conservation benefits in large watersheds using monitoring studies comprise the minority of practice assessments listed in Table 1, compared to the number of modeling studies. This is a natural consequence of the focus on large watershed studies under CEAP. Assessments of single practices have been conducted at field scale many times and shown water quality benefits, but the level of experimental control required to accomplish this is seldom possible. So what is the point of using monitoring studies to undertake conservation assessments at the large watershed scale? What lessons can be leveraged from these watershed assessments to move conservation and watershed science forward? This question is apt especially given that watershed and water quality monitoring efforts are subject to gauging, sampling, and analytical errors that are unavoidable and, for stormflow load estimates, combine to become 7–11% under ideal measurement and analytical conditions, depending on the contaminant, and significantly larger if monitoring protocols are not established and adequately followed (Harmel *et al.* 2006). Yet, measured real world data will be necessary to validate future advances in modeling and ensure we can simulate the effects of changes in land use and climate on hydrology and water quality. In addition, through the CEAP effort, several critical issues that impact watershed water quality dynamics and responsiveness to varying management and climate have been highlighted by these studies, which would remain under-appreciated without them. These issues address the difficulties involved with documenting conservation benefits in watersheds and, at least in part, with validating models that can simulate conservation benefits for water quality. They also help address the basic question of how the USDA could be spending \$3.5B per year on conservation efforts and yet not be adequately addressing agricultural water quality problems.

Issues that mitigate our ability to measure benefits of conservation practices in large watersheds can be expressed as follows:

First, conservation practices that are implemented may not address critical sources, timings, and pathways of contaminants. Clearly, targeted placement of conservation practices to mitigate contaminant sources is a useful approach for water quality management, based on environmental benefits and cost effectiveness (Gitau *et al.* 2006; Walter *et al.* 2007). However, water quality monitoring can reveal the extent of water quality problems in a stream and yet provide very little information about non-point contaminant sources. Making assumptions about contaminant sources without data-based evidence can lead to ineffective recommendations and loss of stakeholder trust in the process of water quality management. Perhaps the clearest example illustrating the need for critical knowledge of contaminant source is that of *E. coli* as an indicator of fecal contamination. Livestock are an obvious source of bacterial contamination, but not the only source, as shown in Iowa (Tomer *et al.* 2008a), and Texas (Harmel *et al.* 2010). Measures to reduce fecal contamination by livestock are certainly appropriate in impaired watersheds, but the adequacy of those measures where background levels include multiple sources will be difficult to prove or disprove (Harmel *et al.* 2010). Another example of complications involved in accurately identifying contaminant source relates to sub-surface contaminant transport in tile drainage systems. Tile drainage is a known source of nitrate loads to streams in the Midwest and has also contributed to phosphorus losses in CEAP watersheds in Indiana (Smith *et al.* 2008) and Iowa (Tomer *et al.* 2008a). Some of these losses may be occurring through surface inlets that drain runoff from depressions. Watershed models do not adequately simulate processes governing bacterial transport and survival, nor subsurface movement of phosphorus (Gassman *et al.* 2007). Conservation practices implemented to improve water quality will need to be supported by flexible policies that allow stakeholders to respond to new information on contaminant sources. Conservation practices also need to be designed and implemented recognizing the importance of timing issues; e.g., the importance of planting date for winter cover crops (Hively *et al.* 2009).

Second, sediment in streams mostly originated from channel and bank erosion, not from erosion of soil in fields. The importance of natural processes of channel widening and movement for degradation and sediment loads in streams in the context of CEAP research was reviewed by Simon & Klimetz (2008). Many streams in the U.S. are undergoing geomorphic change as fluvial systems respond to hydrologic alterations that accompanied settlement and agricultural development across the North American continent. Downcutting, aggradation, and widening are examples of the processes that keep streambanks unstable over many decades and even centuries. Wilson *et al.* (2008a) found most (54 to 80%) of sediment loads were derived from channel sources as opposed to eroded surface soils, in a study of five Benchmark CEAP watersheds. If erosion-control practices reduce sediment concentration without attenuating hydrologic discharge, then runoff water may enter the stream with a capacity to increase the sediment load by eroding the bed and banks, which may mask the impact of the conservation practice on runoff sediment. Practices that attenuate surface runoff as well as erosion are therefore most effective. Conversion of cropland to perennial cover is one example of a practice that can reduce peak discharge and erosion, and thereby reduce sediment loads, as shown in two CEAP watersheds in Mississippi (Kuhnle *et al.* 2008; Cullum *et al.* 2010). Another important cause of bank erosion is past accretion of sediment. Sediment accretion in river valleys has resulted from historical erosion, and has led to channelization, loss of floodplain water storage capacities, and accelerated bank erosion (Yan *et al.* 2010). Hence sediments derived from bank erosion may be a legacy of pre-conservation (pre-1950) agriculture.

Third, historical legacies and shifting climate combined to mask water quality effects of practices that generally lag practice implementation. As rivers respond to legacy impacts of past erosion through natural geomorphic processes of channel evolution (Simon & Klimetz 2008), other changes are taking place within our watersheds. Implementation of conservation practices is but one of many changes that are occurring in watersheds simultaneously. Water quality trends need to be evaluated in the context of historical shifts in agricultural land use and the application of new technologies such as improved crop genetics and changing crop rotations, as well as conservation-tillage and nutrient management (Locke *et al.* 2010). In addition to geomorphic and land use changes, climatic trends and cycles can also have a large effect on water quality observations; in Oklahoma's Ft. Cobb Reservoir, sediment yield increased 183% from dry to wet periods (Garbrecht 2008). Changes in the balance of precipitation and evaporative demand has led to increased stream flows in the Midwest, which increases potential losses of nutrients and sediment if all else is equal (Tomer & Schilling 2009). Against these changes that constantly occur in watersheds, conservation practices often require several years to become effective. The phenomenon of lag effects is critical to understanding how the impacts of conservation practices on water quality need to be evaluated over multiple years, and often decades. This was shown in Walnut Creek Iowa where soil testing and split N-fertilizer applications were trialed in a paired watershed study, in which several years were required to document a response in tile nitrate losses (Jaynes *et al.* 2004). A significant literature on lag effects has evolved during the past 10 to 15 years, as reviewed by Meals *et al.* (2010).

Against changing 'background' conditions, how much conservation is required to document water quality change? Those instances where water quality improvement in CEAP watersheds was attributed to conservation practices occurred in Mississippi, where a significant portion of two watersheds (20–33%) was converted to permanent cover (CRP) from cropland (Kuhnle *et al.* 2008; Cullum *et al.* 2010). However, Feyereisen *et al.* (2008) found no trend in water quality during a period when 11% of a mixed land-use watershed in Georgia was converted to conservation practices.

Fourth, water quality management strategies address single contaminants rather than comprehensive approaches including inherent trade-offs among contaminants. This is not an easy issue to address because multiple practices may be required to adequately mitigate a single contaminant, even at a small-watershed scale (Gitau *et al.* 2004; Gitau *et al.* 2006). That is, a single contaminant may have several key sources that need to be addressed through a set of targeted conservation practices. While a conservation practice may influence runoff and the contaminants it carries relatively quickly, impacts on other contaminants impacting subsurface water quality may take many years to be detected. Therefore our understanding of tradeoffs among contaminants is evolving slowly. Hydrograph separation studies offer one approach to identify major pathways that each critical contaminant follows; Tomer *et al.* (2010) concluded that practices to address tile drainage, surface intakes, and riparian management all need to be addressed to comprehensively address water quality in an Iowa watershed. The importance of both upland and riparian management for water quality improvement is therefore highlighted here. While a mix of well targeted practices may be necessary for upland management, well managed riparian buffer can have multiple benefits not only for water quality and bank stability, but for a range of physical benefits for the stream environment that can improve the quality of aquatic habitat (Shields *et al.* 2006).

CONCLUSION

The Conservation Effects Assessment Project Benchmark watershed studies have facilitated significant progress in watershed and conservation science through modeling and observational studies. Progress during the first five years of this effort could be characterized as achieving critical steps in moving watershed modeling capabilities forwards, and recognizing key lessons that begin to capture the complexity and dynamic nature of watersheds through observational studies. Long term studies have demonstrated the impact of climatic variation, and lagged effects of practice implementation. Continued efforts that integrate observational and modeling studies offer the best opportunity to expand on this progress and move conservation science and policy forward, in cooperation and partnership with landowners and other stakeholders who recognize the critical importance of managing water quality. In this effort, it will be important to develop an understanding of linkages between water quality, conservation practices, and indicators of ecological integrity if conservation science is to recognize the full range of ecosystem services that agricultural landscapes and their associated aquatic environments can provide.

REFERENCES

Arabi, M., Frankenberger, J. R., Engel, B. A. & Arnold, J. G. 2008 Representation of agricultural conservation practices with SWAT. *Hydrological Processes* **22**, 3042–3055.

Arnold, J. G., Srinivasan, R., Muttiah, R. S. & Williams, J. R. 1998 Large area hydrologic modeling and assessment: part 1.

Model development. *Journal American Water Resources Association* **34** (1), 73–89.

Becker, G. S. 2002 The 2002 farm law at a glance. Congressional Research Service. RS21233. Washington DC.

Bingner, R. L., Theurer, F. D. & Yuan, Y. 2009 *AnnAGNPS Technical Processes*. Available from: http://www.ars.usda.gov/Research/docs.htm?docid=5199 (accessed 06 December 2010).

Bryant, R. B., Veith, T. L., Kleinman, P. J. A. & Gburek, W. J. 2008 Cannonsville Reservoir and Town Brook watersheds: documenting conservation efforts to protect New York City's drinking water. *Journal of Soil and Water Conservation* **63** (6), 339–344.

Cho, J., Vellidis, G., Bosch, D. D., Lowrance, R. & Strickland, T. 2010 Water quality effects of simulate conservation practice scenarios in the Little River Experimental Watershed. *Journal of Soil and Water Conservation* **65** (6), 463–473.

Cullum, R. F., Locke, M. A. & Knight, S. S. 2010 Effects of conservation reserve program on runoff and lake water quality in an oxbow lake watershed. *Journal of International Environmental Application & Science* **5**, 318–328.

Dabney, S. M., Delgado, J. A. & Reeves, D. W. 2001 Using winter cover crops to improve soil and water quality. *Communications in Soil Science and Plant Analysis* **32**, 1221–1250.

Dinnes, D. L., Karlen, D. L., Jaynes, D. B., Kaspar, T. C., Hatfield, J. L., Colvin, T. S. & Cambardella, C. A. 2002 Nitrogen management strategies to reduce nitrate leaching in tile-drained Midwestern soils. *Agronomy Journal* **94**, 153–171.

Du, B., Arnold, J. G., Saleh, A. & Jaynes, D. B. 2005 Development and application of SWAT to landscapes with tiles and potholes. *Transactions American Society Agricultural & Biological Engineers* **48** (3), 1121–1133.

Duriancik, L. F., Bucks, D., Dobrowolski, J. P., Drewes, T., Eckles, S. D., Jolley, L., Kellogg, R. L., Lund, D., Makuch, J. R., O'Neill, M. P., Rewa, C. A., Walbridge, M. R., Parry, R. & Weltz, M. A. 2008 The first five years of the Conservation Effects Assessment Project. *Journal of Soil and Water Conservation* **63** (6), 185A–197A.

Feyereisen, G. W., Lowrance, R., Strickland, T. C., Bosch, D. D. & Sheridan, J. M. 2008 Long-term stream chemistry trends in the southern Georgia little river experimental watershed. *Journal of Soil and Water Conservation* **63** (6), 475–486.

Garbrecht, J. D. 2008 Multi-year precipitation variations and watershed sediment yield in a CEAP benchmark watershed. *Journal of Soil and Water Conservation* **63** (2), 70–76.

Gassman, P. W., Reyes, M. R., Green, C. H. & Arnold, J. G. 2007 The soil and water assessment tool: historical development, applications and future research directions. *Transactions American Society Agricultural & Biological Engineers* **50** (4), 1211–1250.

Ghebremichael, L. T., Cerosaletti, P. E., Veith, T. L., Rots, C. A., Hamlett, J. M. & Gburek, W. J. 2007 Economic and phosphorus-related effects of precision feeding and forage management at a farm scale. *Journal of Dairy Science* **90**, 3700–3715.

Gitau, M. W., Veith, T. L. & Gburek, W. J. 2004 Farm-level optimization of BMP placement for cost-effective pollution reduction. *Transactions American Society of Agricultural Engineers* **47** (6), 1923–1931.

Gitau, M. W., Veith, T. L., Gburek, W. J. & Jarrett, A. R. 2006 Watershed level best management practice selection and placement in Town Brook watershed, New York. *Journal American Water Resources Association* **42** (6), 1565–1581.

Gordon, L. M., Bennett, S. J., Bingner, R. L., Theurer, F. D. & Alonso, C. V. 2007 Simulating ephemeral gully erosion in AnnAGNPS. *Transactions American Society Agricultural & Biological Engineers* **50** (3), 857–866.

Green, C. H., Tomer, M. D., DiLuzio, M. & Arnold, J. G. 2006 Hydrologic evaluation of the soil and water assessment tool for a large tile-drained watershed in Iowa. *Transactions American Society Agricultural & Biological Engineers* **49** (2), 413–422.

Hansen, L. 2007 Conservation reserve program: environmental benefits update. *Agricultural & Resource Economics Review* **36** (2), 267–280.

Harmel, R. D., Cooper, R. J., Slade, R. M., Haney, R. L. & Arnold, J. G. 2006 Cumulative uncertainty in measured streamflow and water quality data for small watersheds. *Transactions American Society Agricultural & Biological Engineers* **49** (3), 689–701.

Harmel, R. D., Rossi, C. G., Dybala, T., Arnold, J., Potter, K., Wolfe, J. & Hoffman, D. 2008 Conservation Effects Assessment Project research in the Leon River and Riesel watersheds. *Journal of Soil and Water Conservation* **63** (6), 453–460.

Harmel, R. D., Karthikeyan, R., Gentry, T. & Srinivasan, R. 2010 Effects of agricultural management, land use, and watershed scale on *E. coli* concentrations in runoff and streamflow. *Transactions American Society Agricultural & Biological Engineers* **53** (6), 1833–1841.

Heathman, G. C., Flanagan, D. C., Larose, M. & Zuercher, B. W. 2008 Application of SWAT and AnnAGNPS in the St. Joseph River watershed. *Journal of Soil and Water Conservation* **63** (6), 552–568.

Hively, W. D., Lang, M., McCarty, G. W., Keppler, J., Dadeghi, A. & McConnell, L. L. 2009 Using satellite remote sensing to estimate winter cover crop nutrient uptake efficiency. *Journal of Soil and Water Conservation* **64** (5), 303–313.

James, E., Kleinman, P., Veith, T., Stedman, R. & Sharpley, A. 2007 Phosphorus contributions from pastured dairy cattle to stream of the Cannonsville Watershed, New York. *Journal of Soil and Water Conservation* **62** (1), 40–47.

Jaynes, D. B., Dinnes, D. L., Meek, D. W., Karlen, D. L., Cambardella, C. A. & Colvin, T. S. 2004 Using the late spring nitrate test to reduce nitrate loss within a watershed. *Journal of Environmental Quality* **33** (2), 669–677.

Karlen, D. L., Dinnes, D. L., Tomer, M. D., Meek, D. W., Cambardella, C. A. & Moorman, T. B. 2009 Is no-tillage enough? A field scale watershed assessment of conservation effects. *Electronic Journal of Integrative Biosciences* **7** (2), 1–24.

Kaspar, T. C., Jaynes, D. B., Parkin, T. B. & Moorman, T. B. 2007 Rye cover crop and gamagrass strip effects on NO_3 concentration and load in tile drainage. *Journal of Environmental Quality* **36**, 1503–1511.

King, K. W., Smiley, P. C., Baker, B. J. & Fausey, N. R. 2008 Validation of paired watersheds for assessing conservation practices in the Upper Big Walnut Creek watershed, Ohio. *Journal of Soil and Water Conservation* **63** (6), 380–395.

Kuhnle, R. A., Bingner, R. L., Alonso, C. V., Wilson, C. G. & Simon, A. 2008 Conservation practice effects on sediment load in the Goodwin Creek experimental watershed. *Journal of Soil and Water Conservation* **63** (6), 496–503.

Lal, R., Reicosky, D. C. & Hanson, J. D. 2007 Evolution of the plow over 10,000 years and the rationale for no-till farming. *Soil and Tillage Research* **93**, 1–12.

Larose, M., Heathman, G. C., Norton, L. D. & Engle, B. 2007 Hydrologic and atrazine simulation on the Cedar Creek watershed using the SWAT model. *Journal of Environmental Quality* **36** (2), 521–531.

Lerch, R. N., Sadler, E. J., Kitchen, N. R., Dudduth, K. A., Kremer, R. J., Myers, D. B., Baffaut, C., Anderson, S. H. & Lin, C.-H. 2008 Overview of the mark Twain Lake/Salt River basin conservation effects assessment project. *Journal of Soil and Water Conservation* **63** (6), 345–359.

Licciardello, F., Zema, D. A., Zimbone, S. M. & Bingner, R. L. 2007 Runoff and soil erosion evaluation by the AnnAGNPS model in a small mediterranean watershed. *Transactions American Society Agricultural & Biological Engineers* **50** (5), 1585–1593.

Locke, M. A., Knight, S. S., Smith, S., Cullum, R. F., Zablotowicz, R. M., Yuan, Y. & Bingner, R. L. 2008 Environmental quality research in the Beasley Lake watershed, 1995 to 2007: succession from conventional to conservation practices. *Journal of Soil and Water Conservation* **63** (6), 430–442.

Locke, M. A., Tyler, D. D. & Gaston, L. A. 2010 Soil and water conservation in the mid-south United States: Lessons learned and a look to the future. In: *Soil and Water Conservation Advances in the United States* (T. Zobeck & W. Schillinger, ed.). SSSA Special Publication 60. Soil Science Society of America, Madison, WI, pp. 201–236.

Locke, M. A., Weaver, M. A., Zablotowicz, R. M., Steinriede, R. W., Bryson, C. T. & Cullum, R. F. 2011 Constructed wetlands as a component of the agricultural landscape: mitigation of herbicides in simulated runoff from upland drainage areas. *Chemosphere*.

Loftis, J. C., MacDonald, L. H., Streett, S., Iyer, H. K. & Bunte, K. 2001 Detecting cumulative watershed effects: the statistical power of pairing. *Journal of Hydrology* **251**, 49–64.

Lovell, S. T. & Sullivan, W. C. 2006 Environmental benefits of conservation buffers in the United States: evidence, promise, and open questions. *Agriculture, Ecosystems, & Environment* **112**, 249–260.

Mausbach, M. J. & Dedrick, A. R. 2004 The length we go: measuring environmental benefits of conservation practices. *Journal of Soil and Water Conservation* **59** (5), 96A–103A.

McCarty, G. W., McConnell, L. L., Hapeman, C. J., Sadeghi, A., Graff, C., Hively, W. D., Lang, M. W., Fisher, T. R., Jordan, T., Rice, C. P., Codling, E. E., Whitall, D., Lynn, A., Keppler, J. & Fogel, M. L. 2008 Water quality and conservation practice effects in the Choptank River watershed. *Journal of Soil and Water Conservation* **63** (6), 461–474.

Meals, D. W., Dressing, S. A. & Davenport, T. E. 2010 Lag time in water quality response to best management practices: a review. *Journal of Environmental Quality* **39** (1), 85–96.

Moore, M. T., Bennett, E. R., Cooper, C. M., Smith, S., Shields, F. D., Farris, J. L. & Milam, C. D. 2001 Transport and fate of atrazine and lambda-cyhalothrin in an agricultural drainage ditch in the Mississippi Delta, USA. *Agriculture, Ecosystems & Environment* **87**, 309–314.

Moore, M. T., Denton, D. L., Cooper, C. M., Wrysinski, J., Miller, J. L., Reece, K., Crane, D. & Robins, P. 2008 Mitigation assessment of vegetated drainage ditches for collecting irrigation runoff in California. *Journal of Environmental Quality* **37**, 486–493.

Moore, M. T., Cooper, C. M., Smith, S., Cullum, R. F., Knight, S. S., Locke, M. A. & Bennett, E. R. 2009 Mitigation of two pyrethroid insecticides in a Mississippi Delta constructed wetland. *Environmental Pollution* **157**, 250–256.

Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D. & Veith, T. L. 2007 Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions American Society Agricultural & Biological Engineers* **50** (3), 885–900.

Moriasi, D. N., Steiner, J. L. & Arnold, J. G. 2010 Sediment measurement and transport modeling: impact of riparian and filter strip buffers. *Journal of Environmental Quality* **39**, 1–8.

Osmond, D. L. 2010 USDA water quality projects and the National Institute of Food and Agriculture Conservation Effects Assessment Project watershed studies. *Journal of Soil and Water Conservation* **65** (6), 142A–146A.

Richardson, C. W., Bucks, D. A. & Sadler, E. J. 2008 The Conservation Effects Assessment Project benchmark watersheds: synthesis of preliminary findings. *Journal of Soil and Water Conservation* **63** (6), 590–604.

Russelle, M. P., Entz, M. H. & Franzluebbers, A. J. 2007 Reconsidering integrated crop-livestock systems in North America. *Agronomy Journal* **99**, 325–334.

Saleh, A., Osei, E., Jaynes, D. B., Du, B. & Arnold, J. G. 2007 Economic and environmental impacts of LSNT and cover crops for nitrate-nitrogen reduction in Walnut Creek watershed, Iowa, using FEM and enhanced SWAT models. *Transactions American Society Agricultural & Biological Engineers* **50** (4), 1251–1259.

Shields, F. D., Langendoen, E. J. & Doyle, M. W. 2006 Adapting existing models to examine effects of agricultural conservation programs on stream habitat quality. *Journal American Water Resources Association* **42** (1), 25–33.

Simon, A. & Klimetz, L. 2008 Relative magnitudes and sources of sediment in benchmark watersheds of the conservation effects assessment project. *Journal of Soil and Water Conservation* **63** (6), 504–522.

Smith, D. R., Livingston, S. J., Zuercher, B. W., Larose, M., Heathman, G. C. & Huang, C. 2008 Nutrient losses from row crop agriculture in Indiana. *Journal of Soil and Water Conservation* **63** (6), 396–409.

Starks, P. J. & Moriasi, D. N. 2009 Spatial resolution effect of precipitation data on SWAT calibration and performance: implications for CEAP. *Transactions American Society Agricultural & Biological Engineers* **52** (4), 1171–1180.

Steiner, J. L., Starks, P. J., Daniel, J. A., Garbrecht, J. D., Moriasi, D., McIntyre, S. & Chen, J.-S. 2008 Environmental effects of agricultural conservation: a framework for research in two watersheds in Oklahoma's Upper Washita River basin. *Journal of Soil and Water Conservation* **63** (6), 443–452.

Tomer, M. D. & Schilling, K. E. 2009 A simple approach to distinguish land-use and climate-change effects on watershed hydrology. *Journal of Hydrology* **376**, 24–33.

Tomer, M. D., James, D. E. & Isenhart, T. M. 2003 Optimizing the placement of riparian practices in a watershed using terrain analysis. *Journal of Soil and Water Conservation* **58** (4), 198–206.

Tomer, M. D., Moorman, T. B. & Rossi, C. G. 2008a Assessment of the Iowa River's south fork watershed: part 1. Water quality. *Journal of Soil and Water Conservation* **63** (6), 360–370.

Tomer, M. D., Moorman, T. B., James, D. E., Hadish, G. & Rossi, C. G. 2008b Assessment of the Iowa River's south fork watershed: part 2: conservation practices. *Journal of Soil and Water Conservation* **63** (6), 371–379.

Tomer, M. D., Wilson, C. G., Moorman, T. B., Cole, K. J., Heer, D. & Isenhart, T. M. 2010 Source-pathway separation of multiple contaminants during a rainfall runoff event in an artificially drained agricultural watershed. *Journal of Environmental Quality* **39** (3), 882–895.

USDA 2010 *Assessment of the Effects of Conservation Practices on Cultivated Cropland in the Upper Mississippi River Basin. U.S. Department. of Agriculture, Natural Resources Conservation Service*. Available from: http://www.nrcs.usda.gov/technical/nri/ceap/umrb/index.html (accessed 08 December 2010).

Van Liew, M. W., Garbrecht, J. D. & Arnold, J. G. 2003 Simulation of the impacts of flood retarding structures on streamflow for a watershed in southwestern Oklahoma under dry, average, and wet climatic conditions. *Journal of Soil and Water Conservation* **58** (6), 340–348.

Vanoni, V. A. (ed.). 2006 *Sedimentation Engineering*. American Society of Civil Engineers, Reston VA.

Veith, T. L., Van Liew, M. W., Bosch, D. D. & Arnold, J. G. 2010 Parameter sensitivity and uncertainty in SWAT: a comparison across five USDA-ARS watersheds. *Transactions American Society Agricultural & Biological Engineers* **53** (5), 1477–1486.

Walter, T., Dosskey, M., Khanna, M., Miller, J., Tomer, M. & Weins, J. 2007 The science of targeting within landscapes and watersheds to improve conservation effectiveness. In: *Managing Agricultural Landscapes for Environmental Quality: Strengthening the Science Base* (M. Schnepf & C. Cox, ed.). Soil & Water Conservation Society Ankeny, Iowa, USA. pp. 63–89.

Wilson, C. G., Kuhnle, R. A., Bosch, D. D., Steiner, J. L., Starks, P. J., Tomer, M. D. & Wilson, G. V. 2008a Quantifying relative contributions from sediment sources in Conservation Effects Assessment Project watersheds. *Journal of Soil and Water Conservation* **63** (6), 523–532.

Wilson, G. V., Shields, F. D., Bingner, R. L., Reid-Rhoades, P., DiCarlo, D. A. & Dabney, S. M. 2008b Conservation practices and gully erosion contributions in the Topashaw Canal Watershed. *Journal of Soil and Water Conservation* **63** (6), 420–429.

Yan, B., Tomer, M. D. & James, D. E. 2010 Historical channel movement and sediment accretion along the South Fork of the Iowa River. *Journal of Soil and Water Conservation* **65** (1), 1–8.

Yuan, Y., Bingner, R. L. & Theurer, F. D. 2006 Subsurface flow component for AnnAGNPS. *Applied Engineering in Agriculture* **22** (2), 231–241.

Yuan, Y., Bingner, R. L., Williams, R. G., Lowrance, R. R., Bosch, D. D. & Sheridan, J. M. 2007 Integration of AnnAGNPS and REMM for watershed riparian buffer system assessment. *International Journal of Sediment Research* **22** (1), 60–69.

Yuan, Y., Locke, M. A. & Bingner, R. L. 2008 Annualized agricultural non-point source pollution model application for Mississippi Delta Beasley Lake watershed conservation practices assessment. *Journal of Soil and Water Conservation* **63** (6), 542–551.

Zema, D. A., Bingner, R. L., Govers, G., Licciardello, F., Denisi, P. & Zimbone, S. M. 2010 Evaluation of runoff, peak flow and sediment yield for events simulated by the AnnAGNPS model in a Belgian agricultural watershed. *Land Degradation & Development*.

First received 6 January 2011; accepted in revised form 14 February 2011