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Impacts of land-use change and best management practice implementation in a Conservation Effects Assessment Project watershed: Northwest Arkansas

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Abstract: A study was conducted to quantify land use and management changes and their effects on water quality as part of an effort to evaluate the effects of best management practices under the Conservation Effects Assessment Project. This study was focused on the Lincoln Lake watershed, a primarily pastured watershed in northwest Arkansas and one of the watersheds funded under the Conservation Effects Assessment Project competitive grants program. As with a number of other Conservation Effects Assessment Project watersheds, this watershed has undergone substantial land-use change over the past few years. These changes have occurred concurrently with best management practice implementation. Thus, the need has arisen to determine their impacts on watershed water quality. Land-use analyses covering a 12-year period revealed a rapidly changing landscape, with the various land uses experiencing gains and losses at different times. Furthermore, a systematic trend for pastured areas to be replaced by urban land uses was identified, with pastures experiencing a net decline of about 12% during the analyses period. With regard to water quality, downward trends were observed under base and storm flow conditions in the upper reaches (Upper Moores Creek) with significant changes in total phosphorus and total suspended solids (p-values = 0.0153 and 0.0135, respectively). Significant increases in flow and nitrate-nitrogen (p-values = 0.0465 and 0.0927, respectively) were observed in the lower reaches (Lower Moores Creek), while no appreciable changes were observed in one part of the watershed. We conclude that the concurrent implementation of best management practices served to protect water quality from otherwise adverse effects that might have occurred due to a rapid urbanization in the watershed.

Key words: best management practice—Conservation Effects Assessment Project (CEAP)—land-use analyses—land-use change—water quality

In 2003, the Conservation Effects Assessment Project (CEAP) was initiated to quantify the benefits of best management practices (BMPs) implemented under various conservation programs within the United States. Several watersheds were selected, and currently, studies are being conducted at 37 locations throughout the United States. For many of these watersheds, there is a concern about the possible water quality impacts of land-use changes (Turco et al. n.d.; Brooks et al. n.d.; Chaubey and Popp n.d.; Boll et al. n.d.), in addition to the question on BMP effectiveness. The simultaneous presence of land-use changes and BMP implementation presents a number of challenges with regard to evaluating BMP impacts as changes observed in water quality cannot be attributed solely to the BMPs. Changes in land use can have either positive or negative impacts on water quality. For example, where pastures or arable land are replaced with forests, positive impacts might result due to associated reductions in soil and nutrient losses. Similarly, negative impacts might result where urbanization is occurring and/or forests have been cleared to make way for pasture and cropland. Thus, water quality impacts of land-use change can either serve to complement or to counteract the effects of BMPs.

A number of studies have been conducted developing methods to quantify land-use changes in mixed land-use watersheds. These methods generally combine data from remote sensing, including satellite imagery, aerial photographs with the ground-truthing data, and a geographic information system (GIS) to evaluate the extent of land-use changes from one category into another. For example, Paegelow and Olmedo (2005) combined a variety of tools with the GIS and historical land-use data in evaluating possibilities for land use/land cover modeling. Pontius et al. (2004) suggested that more information was discernable from land-use maps than what could be derived using standard land-use change analyses methods. Similarly, Pontius and Lippitt (2006) have presented methods that can be used to determine the extent to which error can explain differences observed in maps from different time periods.

The land-use change data are subsequently used to evaluate the impacts on hydrology/water quality response of the study watersheds. For example, Yang and Lo (2002) studied land-use/land cover change over time in the Atlanta metro area and found that rapid urbanization and loss of forest presented a major problem in the area. Similarly, Mattikalli and Richards (1996), working in eastern England, and Ierodiaconou et al. (2005) working in southwest Victoria (Australia) combined land-use change data with an export coefficient model to determine land-use change impacts on nutrient exports. Fohrer et al. (2005) reported a similar approach to combine watershed models with land-use change analyses to quantify the hydrologic/water quality response of mixed land-use watersheds in Germany.

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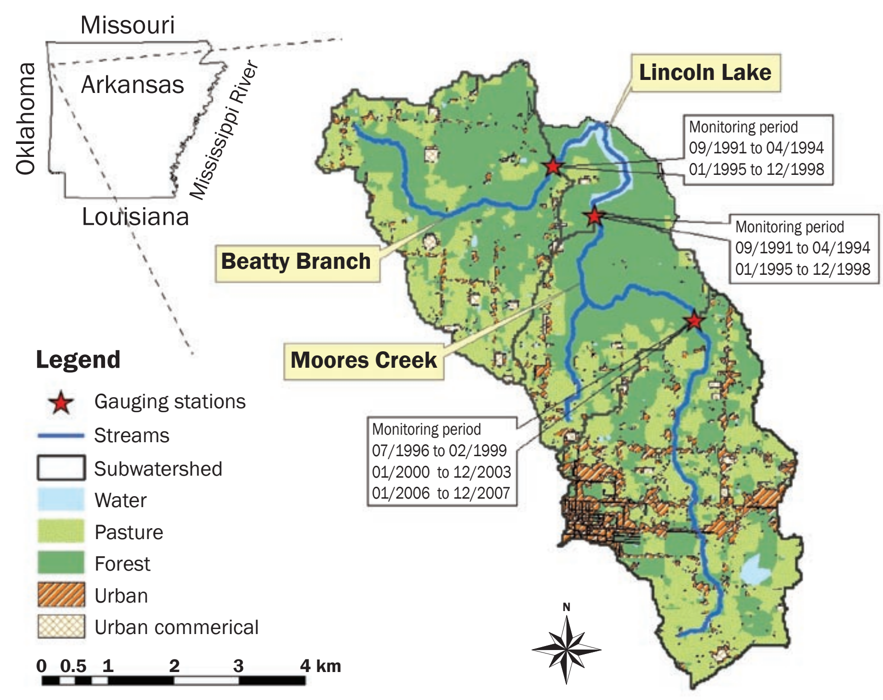
This study seeks to quantify the nature and extent of land use and management (BMP) changes within the Lincoln Lake watershed, a 32 km² (12.4 mi²) mixed land-use watershed in northwest Arkansas, and further, to determine those changes affect flow, sediment, and nutrient losses. The Lincoln Lake watershed is one of 13 watersheds funded under the CEAP competitive grants program. This watershed has undergone dramatic land-use changes over the past 12 years, including rapid urbanization and loss of pastures. The study quantifies the extent and nature of land-use changes occurring within the watershed during the 12-year period between 1992 and 2004 and evaluates the extent and distribution of BMP implementation during the same period as well as the corresponding historical water quality data.

Figure 1

Lincoln Lake watershed location and land use. Land-use data represents conditions as of 2004.



Materials and Methods

Site Description. The Lincoln Lake watershed (figure 1) is located in Washington County, in northwest Arkansas (Latitude 35°58'29"N, Longitude 94°25'05"W). The primary industries in this region are poultry and beef cattle production. Rapid urbanization in the region has resulted in changes in forest and pasture lands leading to concerns regarding its impact on water quality in the area. Also of major concern is nonpoint source transport of nutrients, sediment, and pathogens from agricultural activities. Despite the tendency towards urbanization, rolling hills in the region are home to thousands of poultry farms and pastures that produce forage for numerous beef and dairy cattle, resulting in an abundance of animal manure. The predominant use of manure in the area has been as a fertilizer for perennial forage crops. There is a growing concern that excess land applications of manure can lead to surface and groundwater pollution due to increased runoff losses of sediment, nutrients, and pathogens (Edwards and Daniel 1992; Edwards et al. 1997) and leaching of contaminants. In this region, the primary nutrient of concern is phosphorus (P).

As with the larger northwest Arkansas region, the Lincoln Lake watershed has also been impacted by land use and management changes. As of 2004, 12% of the land-use area in the watershed was occupied by urban areas compared to 3% in 1992. There has also been BMP implementation within the watershed since 1992 to address the phosphorus pollution problem.

The Lincoln Lake watershed comprises three main subwatersheds (figure 1): Moores Creek, which covers 21 km² (8.1 mi²), Beatty Branch, which covers 11 km² (4.2 mi²), and Upper Moores Creek, which is nested within the Moores Creek watershed. The Lincoln Lake watershed has had a long history of water quality monitoring; nutrient and sediment data were initially collected between September 1991 and April 1994 in Lower Moores Creek and Beatty Branch (Edwards et al. 1996, 1997). Monitoring at these sites was discontinued in May 1994 but was resumed in January 1995. In July 1996, a third site was added to the monitoring network on the Moores Creek subwatershed (Upper Moores Creek). This site was located just above a 3.2 km² (1.2 mi²) parcel of land surrounding the creek that has been selectively logged since the fall of 1995. Monitoring continued at the three sites until December 1998 (Vendrell et al. 1997). Monitoring at the Upper Moores Creek site resumed in January 1999 (Nelson et al. 2000). Surface and groundwater monitoring at this site continued until March 2004. Flow and water quality in all three subwatersheds were also monitored as part of the CEAP project between 2005 and 2006.

A programmable datalogger was used in conjunction with a pressure transducer to measure and record water depth (stage). It converted the stage to discharge using a stage/discharge-rating curve developed for each site. The datalogger initiated sampling by triggering the autosampler as soon as the stage reached a depth of 21 in (533 mm). This trigger level was chosen initially in previous years to cause the upper sampler to begin taking samples at the same point in a storm hydrograph as the lower sampler. Once sampling had been initiated, the datalogger began calculating discharge and summing the total volume passing the sampler. Each time 10,000 m³ (353,147 ft³) had passed, the sampler took a discrete sample until it had taken 24 samples or samples were retrieved. Once per day during storm events, samples were retrieved from the sampler and it was reset to continue sampling until the stage had fallen below the trigger level. Each time samples were collected, equal volumes from each discrete sample were combined into one composite sample for analysis. These flow-weighted composite samples gave an accurate picture of the average concentrations for the entire storm event. In addition to sampling all storm events, grab samples were taken manually every two weeks during the year. All samples were taken immediately upon collection to the Arkansas Water Resources Center Water Quality Lab and were analyzed for nitrate-nitrogen, ammonia-nitrogen, total nitrogen, total phosphorus, ortho-phosphate, and total suspended solids. All samples were analyzed using approved and certified methods, and all laboratory and field-sampling procedures adhered to the laboratory quality management plan. In addition, field blanks and duplicates were used as field-sampling quality control. Stage, time, and discharge data were downloaded from the dataloggers once per month. These data were combined with the analytical results for the samples in a spreadsheet and were used to calculate total nutrient and solids loads for the year. Loads were calculated by assigning a concentration to every thirty-minute time interval, multiplying the concentration by the volume passing during the time interval, and summing each thirty-minute load over the year. Flow-weighted mean concentrations were calculated by dividing the year's total load for each parameter by the year's total discharge.

Land-Use Data Development. Land-Use/Land Cover classification maps were developed for the years 1992, 1994, 1996, 1999, 2001, and 2004, for the Lincoln Lake watershed. Data from these years covered periods in which major land-use changes occurred in the watershed. The final maps included nine landscape classes: low intensity urban, high intensity urban, barren land, water, woody/herbaceous, forest/woodland, poultry houses, warm season pasture, and cool season pasture. For each of the aforementioned years, two moderate spatial resolution (28.5 × 28.5 m [93.5 × 93.5 ft]) Landsat Thematic Mapper satellite images were selected. To improve categorical separation in the classification process, two dates of imagery within each year were chosen. A comparison of images acquired in both cool and warm seasons allowed us to more easily differentiate between warm and cool season pastures and between woody shrubland and forest. Additionally, the leaf-off nature of the cool season imagery allowed us to better distinguish woodland from low intensity (residential) urban areas, as we were able to see more ground area.

All image processing and classification was performed using PCI Geomatica (PCI Geomatics 2006). The Landsat scenes were imported from GeoTiff format to Geomatica, were then inspected for quality, and were clipped to a rectangular region surrounding the Lincoln Lake watershed for faster processing. Each clipped image was then geometrically corrected and rectified to overlay a single orthocorrected, high resolution aerial photograph, which served as the project basemap. The resulting geometrically corrected raster images had a positional accuracy of less than one pixel (root mean square error). The corrected images were then clipped once again to the boundary of the Lincoln Lake watershed with an additional 250 m (820 ft) buffer and were combined into Geomatica-accessible files with two Landsat scenes for each year. Project personnel spent approximately two days (16 hours) touring the study area, taking field notes, and collecting complimentary global positioning system coordinates for historic features such as farmhouses, well-defined field boundaries, and established urban features. The field data were useful for image analyses as they allowed a better understanding of the relationships between the satellite images and actual ground conditions. The global positioning system positions were also used to make additional measurements of positional accuracy.

An initial "maximum likelihood" supervised image classification was performed on all of the spectral data (pixel by pixel) for each year for both cool and warm seasons. Training sites for the classification were selected for all landscape classes, except poultry houses, from high resolution aerial photography. If photographs were not available for a given year, training sites from the previous year were overlain on satellite imagery for the year being analyzed. Image interpretation was used to determine if there was a change in land-cover or land-use for each site. If the site clearly had no change, the site was reused. If a change of land-cover type was detected, and the type of change could be clearly determined, the site was relabeled with the new category and was used as a training site. When a new photograph was available, all new ground-truth sites were collected. Data from the resulting classifications were used only if the pixel fit into a category with a 90% certainty. This "first pass" supervised classification normally accounted for approximately 80% to 85% of the study area for each of the years in question. Based on the results of the first pass, all pixels in which no change occurred between 1992 and 2004 were applied to the map layer for each year. Those areas for which classes were not common to all images were set aside for further processing. The unclassified areas from the first pass were classified a second time using an "Isoclustering" unsupervised classification algorithm. The resulting raster images each contained 60 undefined classes. Image analysis was used to assign each of these 60 classes into one of the eight landscape classes. The supervised and unsupervised classifications were then combined into a single classification dataset for each year.

The combined classifications were further processed by aggregating urban areas, using 1992 as a baseline for urban extent, with the assumption that the urban areas remained urban in all subsequent years. Attention was also given to water classification, especially extracting small ponds, by querying the Landsat data. Poultry houses were digitized from high resolution aerial photography for 2004 to create a unique land class. The data for each year were examined, and poultry houses that did not exist were removed from that year's dataset. Lastly, a three by three mode filter was applied to all classifications, and each was clipped precisely to the Lincoln Lake watershed boundary. The mode filter computes the most frequently occurring category value within an N × N filter window surrounding each pixel and replaces small "island" categories with larger (more frequently occurring) ones that surround them. The clipped classification data were then exported to Environmental Systems Research Shapefile Format, with one map developed for each year of land-use data.

Finally, the accuracy for each of the maps in the series was measured. A standard error confusion matrix analysis was employed (Congalton and Green 1999). First, a set of random points was selected from each classified map. Next, using aerial photo/satellite image interpretation methods, a category was assigned to each ground-truth point. These points were overlain on the image, and the categorical value of the point was compared to the categorical value of the corresponding pixel. In each year, the water category had the highest average accuracy: 97.4%. The forest category was next with an average accuracy of 92.9%. Barren land had an average accuracy of 85%. Warm and cool season pasture categories had relatively low accuracies, these being 71% and 83%, respectively. Eighty percent of the associated confusion was cross-categorical with the other pasture category (i.e., cool pasture confused with warm pasture and warm pasture confused with cool pasture). When cool and warm season grasses were combined, for the sake of accuracy analysis, the accuracy for that combined category increased to 84%. There was a similar confusion between the high and low intensity urban categories. The average accuracy of the low intensity urban category was 76% and 92% for high density, respectively. The accuracy for a combined urban category was 91%. The woody/herbaceous category had the lowest accuracy at 71%, but that category typically comprised less than 10% of the study area. Since poultry houses were digitized from photographic sources and other "known" sources, that category was assumed to be 100% accurate. With combined pasture and urban categories, the overall accuracy for the maps ranged from 86.6% to 92.5%.

In this study, all base maps were developed by the same person using the same protocol. This was particularly important as it served to maintain overall high accuracy and repeatability in the analyses, by minimizing the uncertainties that are typically magnified when datasets developed by different persons are used (Pontius and Lippitt 2006). The same protocol was used in developing the base maps, thus eliminating errors due to differences in classification methods. Accuracies for combined land uses and for the base maps were above the standard threshold of 85% (Bottomley 1998) and greatly exceeded the 77% threshold reported by Pontius and Lippitt (2006) below which all of the differences between land uses in each of the periods analyzed could be attributed to error.

Land-Use Data Analyses. Processed land-use data were analyzed to determine gains, losses, and the net change in land-use areas. The data were also subjected to spatial analyses to determine the spatial distribution of the changes that had occurred, as well as to discern any patterns in the land-use changes. For these analyses, warm and cool season pastures were combined into one category called pasture. Similarly, low and high density urban areas were combined together into a single category called urban. In addition to simplifying the analyses, the accuracies of the base maps were much improved when these respective land uses were combined. Other land uses included in the analyses were forest and woody/herbaceous categories. Water and barren land were not included in the analyses as these categories occupied a relatively small portion of the watershed area (≈2%). Furthermore, ponds and lakes (water classification) were not expected to change as land uses from one period to another, although their exact areal coverage was dependent on their water levels at the time of the image acquisition. The barren land-use category was only present in the 1992 dataset and occupied about 0.3% of the watershed area. The land use designated as woody/herbaceous represented a transitional land use, comprising recently cleared forests and abandoned pastures. For the analyses, this land use was renamed to transitional. Analyses were carried out for each of the periods, 1992 to 1994, 1994 to 1996, 1996 to 1999, 1999 to 2001, and 2001 to 2004, and for the whole evaluation period (1992 to 2004). These periods were chosen to correspond to the years for which land-cover maps were developed (1992, 1994, 1996, 1999, 2001, and 2004), as explained in the preceding section, and thus represented periods in which major land-use changes occurred in the watershed.

Changes occurring in the various land uses were determined by sequentially overlaying the land-use grids developed with the grid from the immediately preceding overlay. The analyses were carried out starting with the 1992 and 1994 grids and ending with the 2004 land-use grid. Resulting land-use data were processed to determine specific changes occurring in the various land uses within the watershed. For example, data were processed to determine what proportion of the analyzed area that was originally forested remained forested or was changed to pasture, urban, or any of the other land uses. The same information was determined for each of the other land-use classes.

The resulting proportions were entered into transition matrices (Pontius et al. 2004). These matrices allow one to track the changes in the various land uses between two different periods. Based on Pontius et al. (2004), gains (G_j) and losses (L_i) occurring during a period bounded between years one and two were determined as

$$G_j = T_j - P_{ij} \quad (1)$$

and

$$L_i = T_i - P_{ij} \quad . \quad (2)$$

Further, the net change (N_{ij}) occurring in any one land use between the two years was computed as

$$N_{ij} = T_j - T_i \, , \quad (3)$$

where i is the land-use category during year one for a total of I land uses, j is the land-use category in year two for a total of J land uses, T_i is the total proportion of the watershed in the ith land use during year one, T_j is the total proportion of the analyzed area in the jth land use during year two, and P_{ij} is the proportion of the analyzed area that changed from land use i to land use j between years one and two. For $j = i$, P_{ij} is known as the persistence and denotes the proportion of analyzed area in land use i that remains unchanged between years one and two. Separate transition matrices were computed for each of the aforementioned periods, as well as for the whole period 1992 to 2004. Results from the analyses were then compiled in a single table to allow concurrent evaluation of changes occurring during various periods.

Gains and losses obtained through transitional matrices were further analyzed to determine if there were patterns in the way the land uses were changing. These analyses were also carried out based on methods outlined in Pontius et al. (2004). As an initial step, gains (PG_{ij}) and losses (PL_{ij}) that would occur if random changes occurred in the watershed were determined (equations 4 and 5). Values obtained were then used to compute differences (D_{ij}) and bias (B_{ij}). These latter values were used to determine the tendency of land use *"j"* to gain from land use *"i"* (focus on gains) and the tendency of land use *"i"* to convert to land use *"j"* (focus on losses). Thus, based on Pontius et al. (2004)

$$PG_{ij} = G_j \left(\frac{T_i}{\sum_{i=1}^{J} i \neq j T_i} \right), \quad (4)$$

$$PL_{ij} = L_i \left(\frac{T_j}{\sum_{i=1}^{J} j \neq i T_j} \right), \quad (5)$$

$$D_{ij} = P_{ij} - PR_{ij} \, , \quad (6)$$

and

$$B_{ij} = \frac{P_{ij} - PR_{ij}}{PR_{ij}}, \quad (7)$$

where PR_{ij} is the proportion of the analyzed area that could have changed from land use i to land use j between years one and two if the changes had been random. $PR_{ij} = PG_{ij}$ for gains-based assessments and $PR_{ij} = PL_{ij}$ for loss-based assessments. By definition, values of PG_{ij} and PL_{ij} for the prime diagonal were set to be equal to the corresponding persistence.

The persistence for each land use, as determined from the transition matrices, was also further analyzed. A normalized persistence (NP_{ij}) was defined to allow an intercomparison of changes occurring within the various land uses. The normalized persistence represented the proportion of a particular land use that remained unchanged between years one and two and was computed as

$$NP_{ii} = \frac{P_{ii}}{T_i}, \quad (8)$$

where NP_{ii} is normalized persistence, i.e., persistence normalized by the total proportion of the watershed in the ith land use during year one, and P_{ii} is the persistence, i.e., the proportion of analyzed area in land use i that remains unchanged between years one and two.

The normalized persistence was computed for each of the aforementioned time periods as well as for the whole period (1992 to 2004). Values could range from zero to one, with zero indicating that none of the original land use remained, and values close to one indicating that the original land-use area remained virtually unchanged.

In order to determine the spatial nature of the changes taking place in the watershed, maps were developed showing the areas of gains, losses, and persistence for each of the land uses. These maps were further examined to determine the spatial distribution of changes among the land uses and the patterns of change from one period to another, for each of the land uses analyzed.

Best Management Practice Implementation Analyses. Historical BMP data were initially obtained from a preexisting database. This database had been constructed by Washington County extension personnel using a county parcel plot map that identified all the property and property owners living within the watershed and available soil, forage, manure, and water records. Furthermore, farm visits were conducted to meet with farmers whose records were not readily available and to obtain additional information for those farms for which base data were already available. A similar protocol was used to add new data to the existing database with the only difference being that data collection utilized the farms' nutrient management plans rather than conservation plans as were employed in the historical database. In addition to BMPs, the nutrient management plans contained additional information such as estimated forage yield and grazing rates.

Recommendations for BMP implementation in the watershed have changed over the years. For example, in the early 1990s, recommendations for poultry litter application in the watershed were primarily based on meeting nitrogen (N) requirements for pasture growth. In 2000, the focus shifted from N based applications to phosphorus (P) based application of poultry litter. Currently, every farmer is encouraged to develop a nutrient management plan based on the Arkansas Phosphorus Index (DeLaune et al. 2004; Moore et al. 2000). Some of the BMPs considered in the Arkansas P Index are alum treatment of poultry litter to reduce soluble P concentration in the litter, timing of application, incorporation of litter into the soil, and maintenance of buffer strips. The database developed contains information on BMPs contained in the P Index.

The proportion of farms with BMPs installed during any particular year was determined based on farm plan dates as documented in the watershed's BMP database. Where multiple years were recorded, the earliest year recorded was taken as "effective BMP year" for that farm. For example, if a farm had a comprehensive nutrient management plan developed in 1999 and filter strips installed in 2001, the farm was taken to have had BMPs installed effective from 1999. Where records showed that BMPs had been installed but no installation date was given, BMP implementation was assumed to represent 2006 conditions. In some cases, dates given were not specific (for example, a date given as "before 1996"). In such cases, the effective year of BMP implementation was taken as the year recorded, in this case 1996. In addition to computing the proportion of the watershed in BMPs in any given year, the data were displayed spatially so as to determine distribution of BMPs within the watershed from one year to another.

Historical Water Quality Data. Historical water quality data from the Lincoln Lake watershed were analyzed in relation to land-use changes, BMP implementation, and precipitation occurring during the analysis period. Preliminary analyses of historical data were carried out for the Upper Moores Creek subwatershed, as this subwatershed had the longest and most consistent period of data. The proportion of farms with BMPs installed during any particular year and the proportion of watershed area under a particular land use were determined in the same way as for the entire Lincoln Lake watershed as previously described. These data were plotted in three separate figures (precipitation, land use and BMPs, and historical water quality) with a common horizontal axis in order to allow assessments to be made.

Statistical analyses were then carried out for all three subwatersheds within the Lincoln Lake watershed. The analyses were carried out for periods for which data were available: the years 1996 to 2007 for the Upper Moores Creek subwatershed and the years 1991 to 1998 for the Lower Moores Creek and Beatty Branch subwatersheds. Depending on the year and location, these data were collected by different individuals as a part of different projects. In some cases, only secondary data at the monthly level were available from published reports. For Beatty Branch and Lower Moores Creek, data for all 12 months were available in only three of the eight years, and for Upper Moores Creek, data were available in eight of the ten years. Raw water quality data were used to calculate monthly flow-weighted means which, in turn, were used to calculate yearly flow-weighted means. The variables included in the analyses were flow volume (L), nitrate nitrogen concentrations (mg L^{-1}), total phosphorus concentration (mg L^{-1}), and total suspended solids concentrations (mg L^{-1}). A straight line regression model was fitted to each of the four variables as a function of time expressed as number of years since 1990 for base flow and storm flow, separately. Years in which data were available for only four months or less (e.g., October to December 1991) were removed from the analyses if they were identified as outliers in the initial regression modeling. For these analyses, a significance level of 0.10 was used. All analyses were carried out using SAS Version 9.1 (SAS Institute, Inc., Cary, North Carolina).

Results and Discussion

Land-Use Analyses. Table 1 shows the historic trend in land-use distribution within the study watershed. In general, there was a steady increase in urban areas over the years, while pastures experienced a decline over the same period. While there were changes in forested land use in the various years, the proportion of the watershed in forests remained relatively constant when considered over the period 1992 to 2004. The transitional land use experienced both increases and decreases, while the number of poultry houses increased over the years.

Table 1
Historic land-use distribution (percentage of analyzed area) in the Lincoln Lake watershed as determined from synthesis of historical data.

Land-use category	Year 1992	1994	1996	1999	2001	2004
Urban	3.1	4.0	6.7	8.0	10.3	11.6
Forest	39.9	44.5	40.4	37.3	45.5	39.7
Transitional*	7.4	6.6	9.5	14.2	5.5	10.2
Pasture	48.8	43.8	42.2	39.3	37.4	37.0
Poultry†	0.9	0.9	1.1	1.2	1.3	1.6

* Transitional land use—newly cleared forests and abandoned pastures.
† Poultry houses.

Table 2 summarizes the gains, losses, and net changes for various land uses as determined using period-specific transitional matrices. The highest gain in forest (10.5%) was experienced between 1999 and 2001, while the highest losses (8.0%) were experienced between 2001 and 2004. Forest experienced losses in each of the periods assessed, with an overall loss of close to 6% being experienced over the entire period of analysis. These losses were, however, countered by gains of almost equal amounts over the entire period, thus the seeming lack of change in forests over the 1992 to 2004 period. While pasture land use also experienced both gains and losses during the periods assessed, this land use experienced a net decline (close to 12%) over the years, as losses greatly exceeded gains. For pastures, the highest gains (6.4%) were experienced between 1999 and 2001, while the greatest losses (9.2%) were experienced between 1992 and 1994. The transitional land use experienced its largest losses (12.6%) between 1999 and 2001. This coincided with the largest gains experienced in both forests and urban areas, suggesting that areas in this land use may have gone to both forests and urban land uses. While both urban and poultry house land uses experienced gains, these land uses experienced relatively few or no losses, suggesting an inherent tendency towards persistence.

Table 2
Gains, losses, and net change for various land uses as determined using period-specific transitional matrices.

Land-use category	Period 1992 to 1994 (%)	1994 to 1996 (%)	1996 to 1999 (%)	1999 to 2001 (%)	2001 to 2004 (%)	1992 to 2004 (%)
Forest						
Gains	7.5	3.0	3.9	10.5	2.1	5.7
Losses	2.8	7.1	7.1	2.1	8.0	5.9
Net change*	4.7	–4.1	–3.2	8.4	–5.9	–0.2
Pasture						
Gains	4.2	5.9	6.0	6.4	4.6	3.9
Losses	9.2	7.6	8.9	8.4	5.0	15.6
Net change	–5.0	–1.7	–2.9	–2.0	–0.4	–11.8
Poultry						
Gains	0.1	0.2	0.1	0.1	0.3	0.7
Losses	0.0	0.0	0.0	0.0	0.0	0.0
Net change	0.1	0.2	0.1	0.1	0.3	0.7
Transitional						
Gains	5.3	7.6	10.9	3.8	8.1	8.3
Losses	6.1	4.6	6.2	12.6	3.4	5.5
Net change	–0.9	3.0	4.7	–8.8	4.7	2.7
Urban						
Gains	1.7	2.7	1.5	3.2	1.5	8.8
Losses	0.7	0.0	0.2	1.0	0.1	0.2
Net change	1.0	2.7	1.3	2.2	1.4	8.5

* Negative values denote a net decrease in land-use area.

Table 3
Interland-use changes in the Lincoln Lake watershed during the period 1992 to 2004—focus on gains.

		2004					
Land-use category	Variable	Forest (%)	Pasture (%)	Poultry (%)	Transitional (%)	Urban (%)	1992 summary (%)
1992							
Forest	P_{ij}	34.00	1.80	0.19	2.98	0.92	39.89*
	PR_{ij}	34.00	3.00	0.29	3.56	3.61	44.45†
	D_{ij}	0.00	−1.20	−0.10	−0.57	−2.68	−4.55‡
	B_{ij}	0.00	−0.40	−0.34	−0.16	−0.74	−0.10§
Pasture	P_{ij}	2.99	33.11	0.51	5.23	6.92	48.75
	PR_{ij}	4.63	33.11	0.35	4.35	4.41	46.85
	D_{ij}	−1.65	0.00	0.16	0.88	2.51	1.90
	B_{ij}	−0.36	0.00	0.46	0.20	0.57	0.04
Poultry	P_{ij}	0.00	0.00	0.85	0.00	0.01	0.85
	PR_{ij}	0.08	0.06	0.85	0.08	0.08	1.14
	D_{ij}	−0.08	−0.06	0.00	−0.08	−0.07	−0.29
	B_{ij}	−1.00	−1.00	0.00	−1.00	−0.93	−0.26
Transitional	P_{ij}	2.70	1.88	0.01	1.93	0.91	7.44
	PR_{ij}	0.71	0.56	0.05	1.93	0.67	3.92
	D_{ij}	1.99	1.32	−0.04	0.00	0.24	3.52
	B_{ij}	2.82	2.37	−0.75	0.00	0.36	0.90
Urban	P_{ij}	0.03	0.17	0.00	0.04	2.82	3.06
	PR_{ij}	0.29	0.23	0.02	0.27	2.82	3.63
	D_{ij}	−0.26	−0.06	−0.02	−0.23	0.00	−0.58
	B_{ij}	−0.91	−0.26	−1.00	−0.85	0.00	−0.16
Summary	T_j	39.72	36.96	1.56	10.18	11.58	
	‖ΣPR_{ij}(2004)	39.72	36.96	1.56	10.18	11.58	
	‖$T_j - \Sigma PR_{ij}$(2004)	0.00	0.00	0.00	0.00	0.00	
	‖$\Sigma D_{ij} \div \Sigma PR_{ij}$	0.00	0.00	0.00	0.00	0.00	

Notes: P_{ij} = the proportion of analyzed area in land *i* that converts to land use *j* between time one and time two (for this table, time one is 1992 and time two is 2004). PR_{ij} = the proportion of analyzed area in land *I* that converts to land use *j* between times one and two if changes were random. Values of P_{ij} and PR_{ij} on the principal diagonal denote the persistence of land use areas that is the proportion of analyzed area in land use *i* that remains unchanged between years one and two. $D_{ij} = P_{ij} - PR_{ij}$. $B_{ij} = D_{ij} \div PR_{ij}$. B_{ij} is a unitless variable. Positive values of D_{ij} and B_{ij} show that the land use as it existed in time two tended to gain from the corresponding land use in time one. T_j = the total proportion of the analyzed area in the *j*th land use during year two (2004). Totals T_j and T_i are used directly in equations 4 and 5, results from which are necessary for equations 6 and 7.

* This total is T_i, the total proportion of the watershed in the *i*th land use during year one (1992).

† This denotes ΣPR_{ij} (1992) and shows the proportion of analyzed area that would have been in land use *i* had changes been random.

‡ This denotes $T_i - \Sigma PR_{ij}$ (1992), also ΣD_{ij} (1992). Positive values indicate an overall tendency towards gains from the land use as it was in time one.

§ This denotes $\Sigma D_{ij} \div \Sigma PR_{ij}$ (1992). Positive values indicate an overall tendency towards gains from the land use as it was in time one.

‖ Values serve as checks and are not included in any calculations.

Tables 3 and 4 show the tendency for change in the various land uses, as determined based on biases computed for gains and losses, respectively. Values of P_{ij} and PR_{ij} on the principal diagonal denote the persistence of land use. In table 3, positive values of D_{ij} and B_{ij} imply that land use *j* (time 2) tended to gain from a land use *i* (time 1), while in table 4, positive values of D_{ij} and B_{ij} imply that the land use *i* (time 1) tended to lose to a land use *j* (time 2) during the period between time 1 and time 2. For example, based on table 3, during the period 1992 to 2004, forest, pasture, and urban land uses tended to gain from transitional land use, while the transitional land use tended to gain from pastures. Urban land use also tended to gain from pastures, based on the computed difference and bias (4.4, 0.6, respectively). Also based on data in table 3, it appeared that when poultry houses were built, the associated land was taken out of pasture (D_{23}= 0.16; B_{23}= 0.46). None of the land uses had the tendency to gain from either urban or poultry house land uses, confirming the initial deduction about the permanence of these land uses. In addition, none of the land uses showed a tendency to gain from forested land uses. This was not surprising given the overall small net change determined for forests (table 2). In general, changes occurring in the watershed were inclined towards the replacement of pastured and transitional land

Table 4
Interland-use changes in the Lincoln Lake watershed during the period 1992 to 2004—focus on losses.

	Land-use category	Variable	2004 Forest (%)	Pasture (%)	Poultry (%)	Transitional (%)	Urban (%)	1992 summary (%)
1992								
	Forest	P_{ij}	34.00	1.80	0.19	2.98	0.92	39.89*
		PR_{ij}	34.00	3.62	0.15	1.00	1.13	39.90† ‖
		D_{ij}	0.00	−1.82	0.04	1.99	−0.21	0.00‡ ‖
		B_{ij}	0.00	−0.50	0.24	2.00	−0.18	0.00§ ‖
	Pasture	P_{ij}	2.99	33.11	0.51	5.23	6.92	48.75
		PR_{ij}	9.86	33.11	0.39	2.53	2.87	48.75
		D_{ij}	−6.87	0.00	0.12	2.70	4.05	0.00
		B_{ij}	−0.70	0.00	0.32	1.07	1.41	0.00
	Poultry	P_{ij}	0.00	0.00	0.85	0.00	0.01	0.86
		PR_{ij}	0.00	0.00	0.85	0.00	0.00	0.86
		D_{ij}	0.00	0.00	0.00	0.00	0.00	0.00
		B_{ij}	−1.00	−1.00	0.00	−1.00	7.50	0.00
	Transitional	P_{ij}	2.70	1.88	0.01	1.93	0.91	7.44
		PR_{ij}	2.44	2.27	0.10	1.93	0.71	7.44
		D_{ij}	0.27	−0.39	−0.08	0.00	0.20	0.00
		B_{ij}	0.11	−0.17	−0.86	0.00	0.28	0.00
	Urban	P_{ij}	0.03	0.17	0.00	0.04	2.82	3.06
		PR_{ij}	0.11	0.10	0.00	0.03	2.82	3.06
		D_{ij}	−0.08	0.07	0.00	0.01	0.00	0.00
		B_{ij}	−0.76	0.71	−1.00	0.53	0.00	0.00
	Summary	T_j	39.72	36.96	1.56	10.18	11.58	
		ΣPR_{ij}(2004)	46.40	39.09	1.48	5.48	7.53	
		$T_j - \Sigma PR_{ij}$(2004)#	−6.69	−2.13	0.07	4.70	4.05	
		$\Sigma D_{ij} \div \Sigma PR_{ij}$#	−0.14	−0.05	0.05	0.86	0.54	

P_{ij} = the proportion of analyzed area in land *i* that converts to land use *j* between times one and two (for this table, time one is 1992, and time two is 2004). PR_{ij} = the proportion of analyzed area in land *I* that converts to land use *j* between times one and two if changes were random. Values of P_{ij} and PR_{ij} on the principal diagonal denote the persistence of land-use areas that is the proportion of analyzed area in land use *i* that remains unchanged between years one and two. $D_{ij} = P_{ij} - PR_{ij}$. $B_{ij} = D_{ij} \div PR_{ij}$. B_{ij} is a unitless variable. Positive values of D_{ij} and B_{ij} show that the land use as it existed in time one tended to lose to the corresponding land use in time two. T_j = the total proportion of the analyzed area in the *j*th land use during year two (2004). Totals T_j and T_i are used directly in equations 4 and 5, results from which are necessary for equations 6 and 7.

* This total is T_i, the total proportion of the watershed in the *i*th land use during year one (1992).

† This denotes ΣPR_{ij} (1992) and shows the proportion of analyzed area that would have been in land use *i* had changes been random.

‡ This denotes $T_i - \Sigma PR_{ij}$ (1992), also ΣD_{ij} (1992).

§ This denotes $\Sigma D_{ij} \div \Sigma PR_{ij}$ (1992).

‖ Values serve as checks and are not included in any calculations.

\# Positive values indicate an overall tendency towards losses from the land use to the corresponding land use (time two).

uses but not towards the replacement of forest and urban land uses (table 3).

Pasture land use tended to lose to poultry housing, to transitional land use (implying that they were abandoned), and to urban areas (positive D_{ij} and B_{ij} [table 4]). Some of the other observations made from table 4 were, however, in conflict with those made based on table 3. For example, from table 4, transitional land use tended to lose to only forests and pastures, whereas table 3 suggests the inclination toward converting transitional land use into pasture. Additionally, table 4 suggests that forests tended to lose directly to poultry houses and the tendency for losses from urban areas, contrary to observations in table 3.

In addition, table 4 suggests the tendency for forest to lose to transitional land use, while table 3 does not suggest the tendency for transitional land use to gain from forest. These are indeed conflicting results given that the transitional land use comprises recently cleared forests (suggesting tendency for forests to lose to transitional) and abandoned pastures (which may or may not be allowed to revert to forest). The strong signal (B_{35} = 7.5) suggesting a change from poultry housing to urban areas was attributable to the relatively low value of PR_{35} (0.0006) and thus was not taken to indicate a tendency for loss. In general, values in table 4 suggest the tendency for land use to lose to transitional and urban land uses and poultry houses but not to forests or pastures. This is not surprising as the observed net change in forest was very low, while a steady decrease was observed in pastures over the years, and at the same time, a steady increase was observed in urban land use.

Table 5 shows the normalized persistence computed for the various time periods assessed. Values in this table confirm some of the observations made from the earlier tables. On average, about 90% of the forested area in the watershed remained unchanged in each of the periods assessed and over the entire (1992 to 2004) period. Overall, changes in pastures occurred in about 30% of the pastured areas, leaving 70% of the pastures unchanged. For the most part, the amount of land originally in urban areas and poultry housing that remained unchanged was close to 100%, confirming the conclusion about the permanent nature of these land uses. The amount of land in transitional land use that remained unchanged averaged only about 30%, suggesting a highly dynamic land use. This confirms previous observations regarding the tendency of this land use to gain from and lose to other land uses.

Figure 2 shows the extent of gains and losses, as well as the level of persistence (areas not experiencing changes) in the various land uses within the three subwatersheds of Lincoln Lake watershed over the period 1992 to 2004. Relatively large losses were experienced in pastures over the 12-year period (figure 2). In contrast, there were substantial gains in urban areas during the same 12-year period. Generally, areas lost from pastures corresponded to areas added to the existing urban land use, confirming previous observations that pastured areas tended to change to urban areas. Some of the areas of gains in pastures corresponded to areas of loss in forests, suggesting that some of the forested areas had transitioned into pasture during the period 1992 to 2004. This was likely to have been an indirect transition, with an intermediate stage in which the changing units were in transitional land use (table 5). While urban areas were only 3% in 1992, areas of persistence show where these urban areas were initially located. Areas of gain show the extent of growth in area roads and urban land use, which now extend to cover a substantial part of nonforested areas

Figure 2
Spatial representation of the gains, losses, and persistence experienced in (a) pasture, (b) urban, (c) transitional, and (d) forest land uses in Lincoln Lake watershed over the period 1992 to 2004.

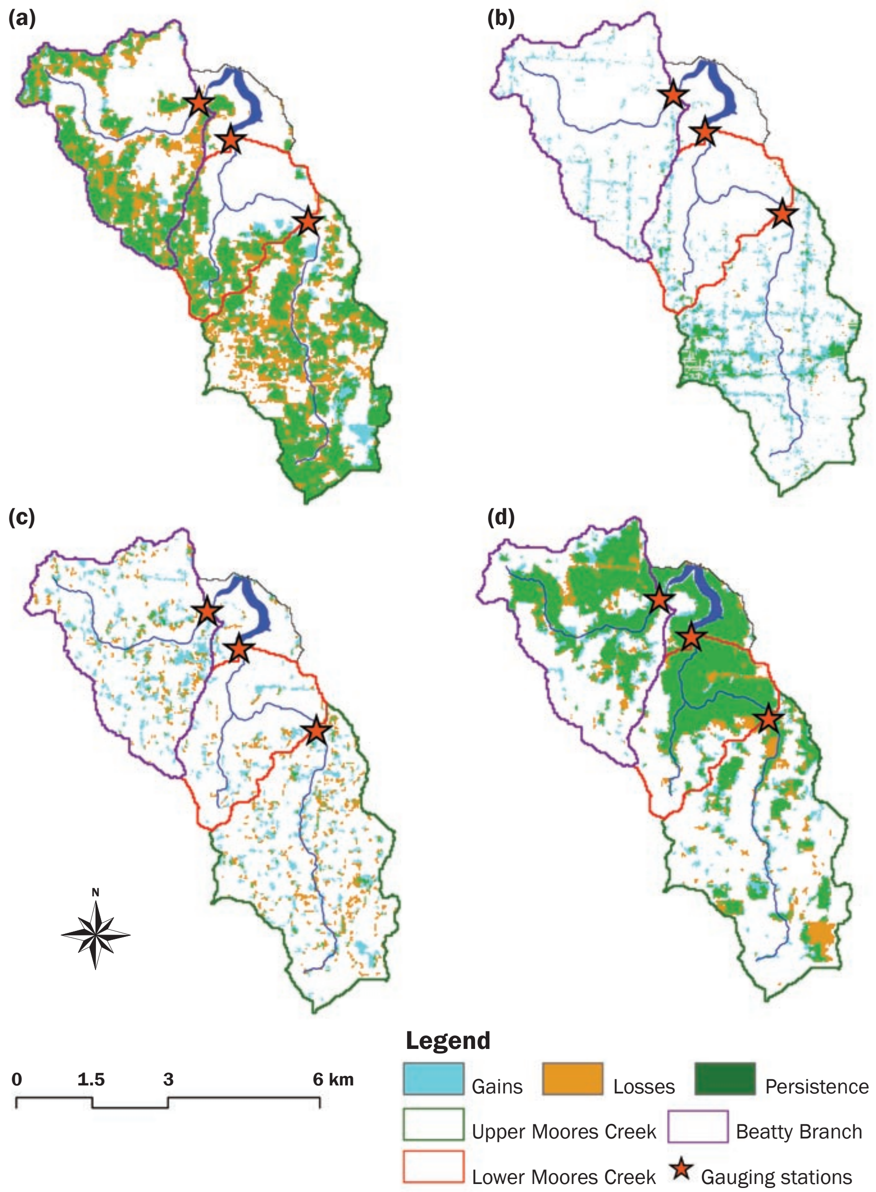


Table 5
Normalized persistence expressed as a percentage; values represent percentage of land-use area that did not change during the specified period.

	Period					
Land-use category	1992 to 1994 (%)	1994 to 1996 (%)	1996 to 1999 (%)	1999 to 2001 (%)	2001 to 2004 (%)	1992 to 2004 (%)
Forest	93	84	82	94	82	85
Pasture	81	83	79	79	87	68
Poultry	100	99	100	100	100	99
Transitional	18	30	34	12	38	26
Urban	76	99	97	88	99	92

in the watershed. Loss in forests tended to occur along the edges of the forested areas (figure 2). This is particularly evident in the Lower Moores Creek and Beatty Branch subwatersheds, where most of the forests are located. Areas of gain in forest were spatially distributed throughout the watershed. Areas of loss and gain in transitional land use were also experienced throughout the watershed and corresponded more closely with pasture and urban areas than with forested areas. This was not surprising as forested land use had a high tendency for persistence (table 5). However, some of the areas of loss in forest corresponded to areas of gain in transitional land use. Areas of persistence were hardly visible within transitional land use, while areas of gains and losses were almost evenly matched. This confirmed initial deductions about a highly dynamic land use in the watershed.

Figures 3 and 4 show a breakdown of the gains, losses, and persistence experienced in pastures and urban land uses, respectively. Changes occurring in pastures were spread throughout the watershed (figure 3). However, there were some distinctly discernable areas in which losses in pasture areas occurred. For example, during the period 1996 to 1999, there were some isolated large areas in the Upper Moores Creek subwatershed within which losses occurred. These areas were mostly in the vicinity of Lincoln, a small town located in the southern part of the watershed (Upper Moores Creek, figure 1), suggesting a rapid expansion of the town during this period. However, some of the areas of loss reverted to pastures during subsequent periods. Areas experiencing changes were substantially reduced between 2001 and 2004, with changes mainly occurring along the edges of existing pastures. Figure 4 confirms observations from figure 3 regarding the areas in which pastures were converted into urban areas, while also serving to validate the findings from interland-use change analyses (tables 3 and 4). Figure 4 shows that a relatively rapid growth occurred in urban areas within the watershed during 1999 to 2001 in comparison to other time periods. Areas of gain in urban land use were closely matched to the areas of loss in pastures (figure 3), with greater growth occurring within the Upper Moores Creek subwatershed (figure 3, table 6) and particularly in the vicinity of Lincoln. The urban land development rate was reduced during 2001 to 2004, with most of the areas already developed remaining persistent. Because the study area is a rural watershed, development occurred mainly along countryside roads as opposed to, e.g., subdivisions, as is the case in more urbanized watersheds. Growth in urban areas occurred along the same areas in which there were already some amount of built-up land (1992 to 1994), suggesting a systematic expansion of these areas rather than establishment of new areas.

Figure 3
Spatial representation of the gains, losses, and persistence experienced in pastures in the Lincoln Lake watershed during (a) 1992 to 1994, (b) 1996 to 1999, (c) 1999 to 2001, and (d) 2001 to 2004.

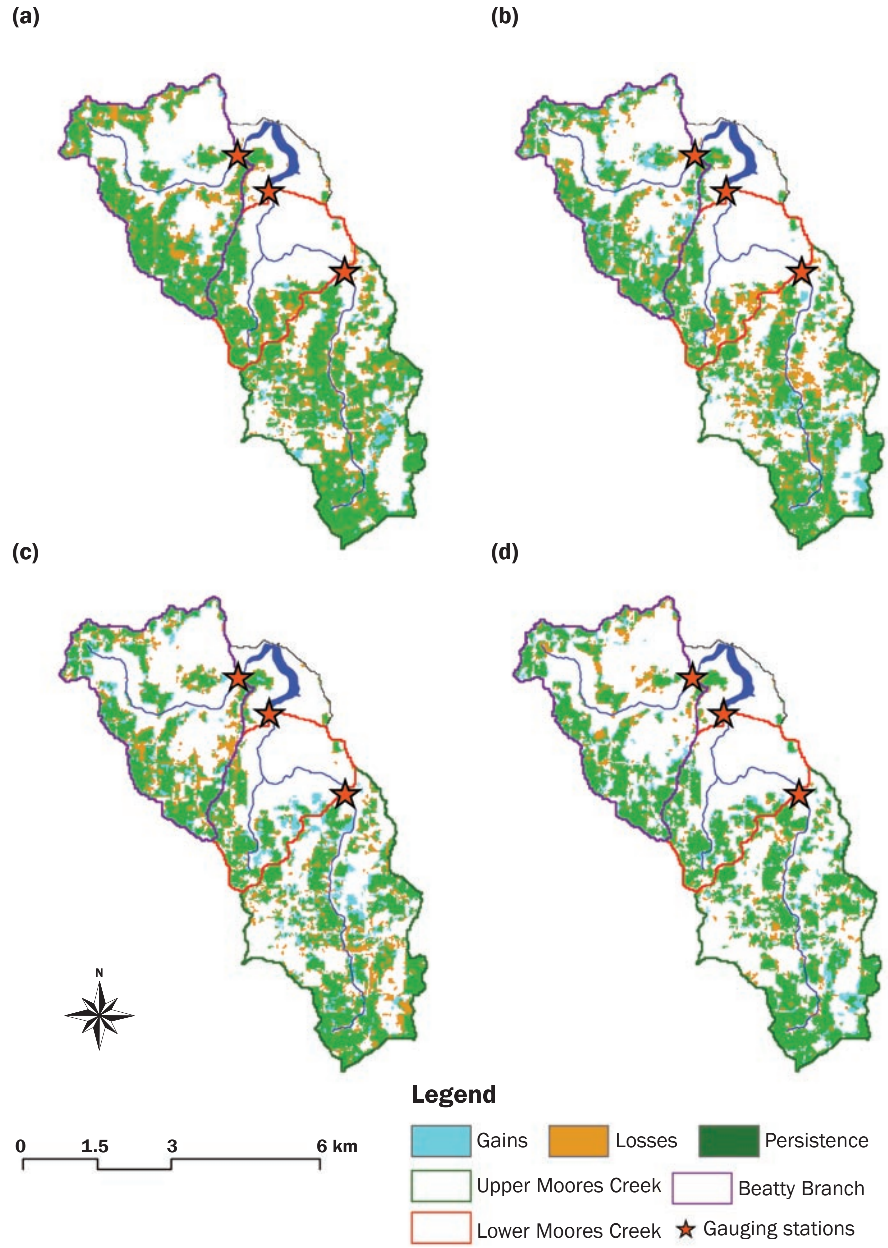
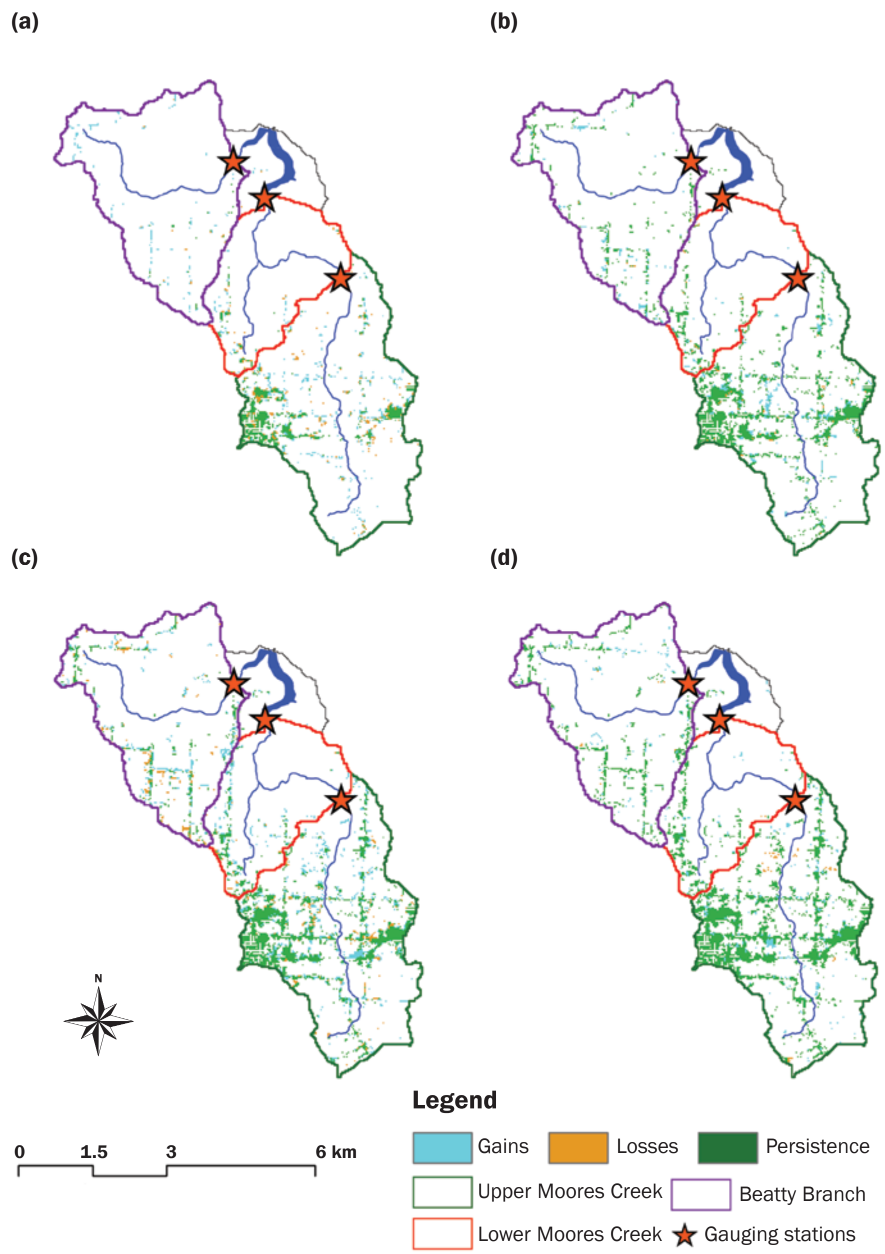


Table 6 shows land-use distribution and net land-use changes in the three subwatersheds of the Lincoln Lake watershed during the period 1992 to 2004. In the Beatty Branch subwatershed, the largest change occurred in the pastures, with 14% being lost primarily to transitional and urban land uses. Losses in pastures also occurred in the Lower Moores Creek subwatershed (5.5%), while a similar gain (4.8%) occurred in urban

Figure 4

Spatial representation of the gains, losses, and persistence experienced in urban land use in the Lincoln Lake watershed during (a) 1992 to 1994, (b) 1996 to 1999, (c) 1999 to 2001, and (d) 2001 to 2004.



areas. In the Upper Moores Creek subwatershed, about 14% of pastures were lost during this period while urban areas experienced a corresponding gain of about 14% during the same period. The subwatershed-level analysis confirms previous deductions that pastures tended to convert to urban areas. In the Upper Moores Creek subwatershed, forest land use experienced a decline of 0.8%, while a corresponding gain in transitional areas was realized. This also confirmed previous observation that forest tended to lose to transitional land use. Larger increases were observed in the areas with poultry houses in Beatty Branch subwatershed than in the other two subwatersheds.

Best Management Practices. Figure 5 shows the spatial distribution of BMPs over the land-use analyses period while table 7 shows the details of BMP implementation over the study period presented as percentage of farms in the watershed with a particular BMP. The BMPs implementation had a slow start in the early years, followed by a dramatic increase after 2001. This is, to a large extent, attributable to extension and education efforts within the watershed by the University of Arkansas Cooperative Extension Service (Pennington et al. 2008). The BMPs implemented in the watershed are primarily those pertaining to pasture and grazing management and include soil testing, reduced manure application, use of manure amendments such as alum (Smith 2002), and rotational grazing. Other BMPs that are implemented in the area include vegetative filter strips, stream fencing, and stream crossing. Based on table 7, soil testing, fertilizer application buffers, and controlled grazing were the most commonly used BMPs having been implemented on 32%, 22%, and 20% of the farms, respectively. Overall, about 40% of the farms in the watershed had BMPs installed by 2007. At the subbasin level, the percentage of farms with at least one BMP installed as of 2006 was 34% in Beatty Branch subwatershed as well as in the Upper Moores Creek subwatershed, while the percentage for Lower Moores Creek subwatershed was 17.5%.

Historical Water Quality Data Analyses. Based on the analyses discussed in preceding paragraphs, the Lincoln Lake watershed has seen a dramatic change in land use in the period between 1992 and 2004. During the same time, a dramatic increase was seen in BMP implementation, particularly in the period between 2001 and 2004. Preliminary analyses of water quality data for the watershed (figure 6) showed that increases were observed in sediment and nutrients during the period 1996 to 1998. While the precipitation pattern did not appreciably change during the study period, significant changes in land-use distribution (figure 6) combined with changed in BMP implementation in the watershed (figure 5) likely resulted in measured changes in water quality. Data from 2000 to 2003 showed mixed results; sediment loads decreased between 2000 and 2001 and then increased during the next year and decreased thereafter. Nitrate loads also showed a somewhat similar pattern, with increases being observed initially, then decreases, and then increases. Total nitrogen and total phosphorus loads did not change appreciably during the period 2000 to 2003 based on these analyses.

Table 6
Land-use distribution and net land-use changes in the Upper Moores Creek, Lower Moores Creek, and Beatty Branch subwatersheds of Lincoln Lake watershed during the period 1992 to 2004.

		Year						Net change
Subbasin	**Land use**	**1992 (%)**	**1994 (%)**	**1996 (%)**	**1999 (%)**	**2001 (%)**	**2004 (%)**	**(1992 to 2004) (%)**
Beatty Branch	Forest	41.9	47.6	42.0	37.4	50.8	43.2	1.2
	Pasture	49.3	43.3	41.4	41.7	37.6	35.3	–14.0
	Poultry	0.6	0.9	1.1	1.5	1.5	2.1	1.5
	Transitional	7.8	6.8	12.5	15.3	4.8	12.7	4.9
	Urban	0.4	1.4	3.0	4.1	5.4	6.7	6.3
Lower Moores Creek	Forest	59.0	62.4	59.0	56.7	61.1	56.9	–2.1
	Pasture	35.3	31.8	30.8	25.4	28.1	29.8	–5.5
	Poultry	1.0	1.0	1.3	1.3	1.3	1.3	0.3
	Transitional	3.3	3.0	5.8	12.9	4.2	5.9	2.5
	Urban	1.4	1.8	3.2	3.6	5.4	6.1	4.8
Upper Moores Creek	Forest	22.5	27.2	23.9	21.1	27.7	21.7	–0.8
	Pasture	59.2	54.3	52.0	47.2	44.7	45.4	–13.8
	Poultry	1.0	1.0	1.1	1.1	1.2	1.2	0.2
	Transitional	9.9	8.9	9.6	15.1	7.3	10.6	0.8
	Urban	7.4	8.6	13.4	15.5	19.1	21.0	13.6

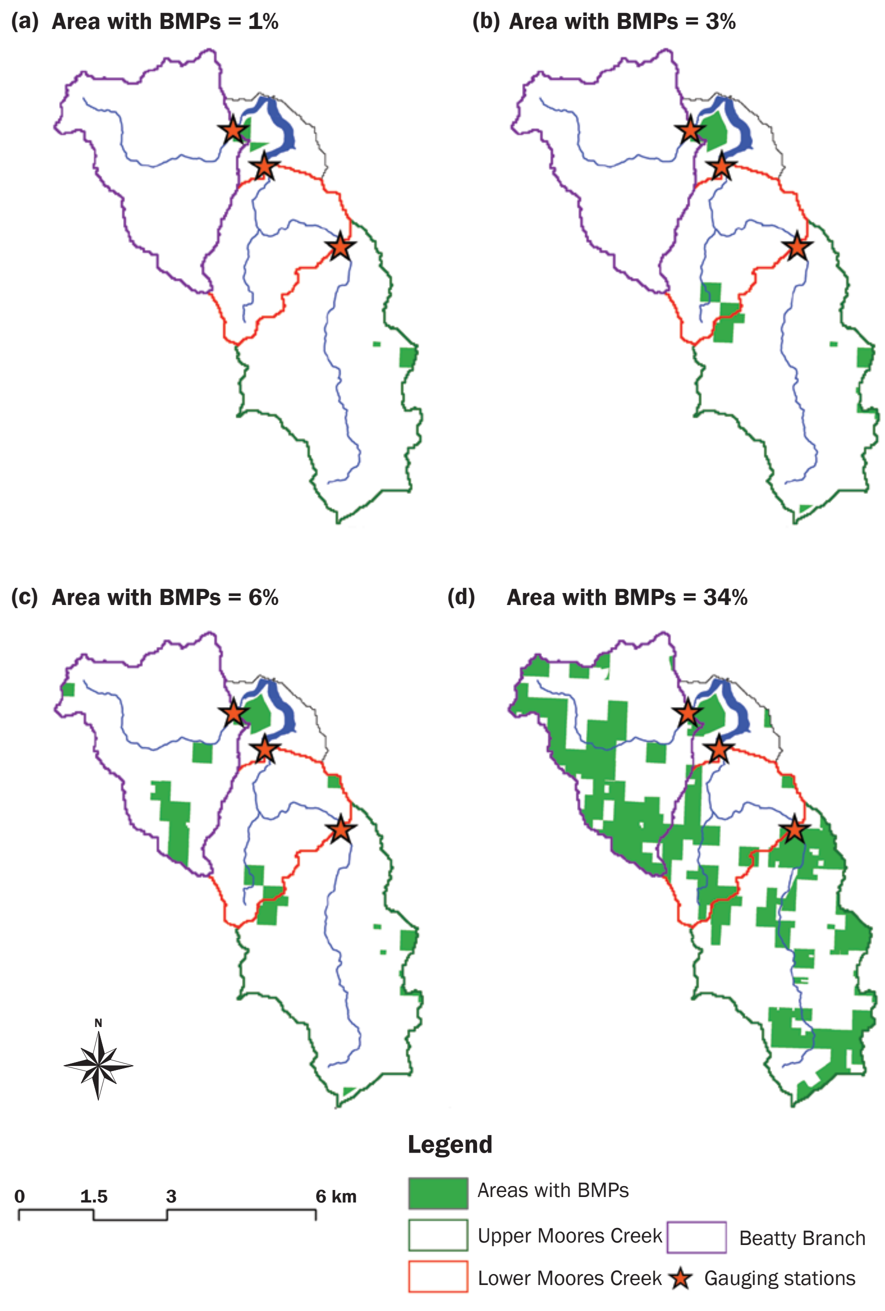
Table 8 shows the results of statistical analyses of the water quality data for the Upper and Lower Moores Creek subwatersheds in the Lincoln Lake watershed. As indicated earlier, the results based on these data, like all statistical analyses based on historical data, must be interpreted with caution. No significant trends were observed from the results of statistical analyses on Beatty Branch data (p-values for tests of zero slope ranged from 0.1471 to 0.9053). This lack of significant trends was not surprising since, for all practical purposes, there was no BMP implementation within this subwatershed during the period 1991 to 1998 for which data were available.

For the Lower Moores Creek, trends under base flow conditions for flow (p-value = 0.0465) and total suspended solids (even though the latter was not significant) could be explained at least partially by the effect of the logging that took place in the fall of 1995. This did not appear to be the case during storm flow conditions, except perhaps for total suspended solids. Significant trends were also found for nitrate N in both base flow and storm flow conditions (p-values = 0.0927 and 0.0026, respectively) and for total P under storm flow conditions (p-value = 0.0133). Using the observed yearly base flows, nitrate N increased by 6.1% prior to 1995 and by 24.5% from 1995 to 1998. In contrast, although not statistically significant, total P decreased 29.2% before 1995 but only by 6.8% after 1995. For the observed storm flows, the percentage increases before and after 1995 dropped dramatically for both

Table 7
Best management practice (BMP) implementation over the study period presented as percentage of farms in the watershed with a particular BMP.

	Period for BMP implementation covering BMPs implemented by year				
BMPs	**1994 (%)**	**1996 (%)**	**1999 (%)**	**2001 (%)**	**2006 (%)**
Comprehensive nutrient management plan			1.4	1.7	13.5
Nutrient management plan					2.4
Stacking shed			1.4	1.4	5.2
Soil test	0.3	1.0	2.8	3.5	32.2
Manure amendments					0.4
Fertilizer application buffer	0.3	2.8	3.8	4.5	21.5
Vegetative filter strips			0.3	0.3	1.7
Incinerator			1.0	1.0	4.2
Controlled grazing		2.4	2.8	2.8	20.4
Stream crossing					1.7
Stream fencing					3.5
Stream bank stabilization					0.7
Percent farm-parcels with at least one BMP	1.0	4.2	6.2	6.9	39.8

Figure 5
Spatial distribution of best management practices (BMPs) implemented in the Lincoln Lake watershed during (a) 1994, (b) 1996, (c) 2001, and (d) 2006 conditions.



nitrate N and total P (from 53.1% to 35.2% for nitrate N and from 67.7% to 0.1% for total P).

For the Upper Moores Creek subwatershed, there was a downward but nonsignificant trend in nitrate N under base flow (p = 0.7865). The trend under storm flow was also nonsignificant (0.1642). For total P, the downward trend was significant under base flow (p = 0.0153) but not under storm flow (p = 0.4760). These downward trends were thought to be related to the impact of the large number of new BMPs implemented between 2005 and 2007.

A substantial amount of BMP effectiveness data are available from previous studies from which estimates of the effectiveness of the various BMPs installed in the watershed can be obtained (Gitau et al. 2005; Merriman et al. 2009). For the most part, these BMPs have been found to have a positive effect in reducing pollutant losses. Likewise, negative impacts of land-use changes have been documented in a number of areas (Ierodiaconou et al. 2005; Fohrer et al. 2005; Mattikalli and Richards 1996). Based on our analyses, and considering the extent of BMP implementation in the watershed, larger decreases in sediment and nutrient losses might have been observed in the Lincoln Lake watershed had land-use changes not occurred in the watershed. By the same token, considering the extent of land-use changes in the watershed, substantial increases in sediment and nutrient losses might have occurred if BMPs had not been implemented in the watershed. Thus the combined analysis of land-use changes and BMP implementation indicate that BMPs were successful in offsetting the negative impacts of land-use changes in the watershed. These analyses also indicate the importance of land-use change analyses in CEAP watersheds in order to get a true picture of BMP performance in improving water quality.

Summary and Conclusions

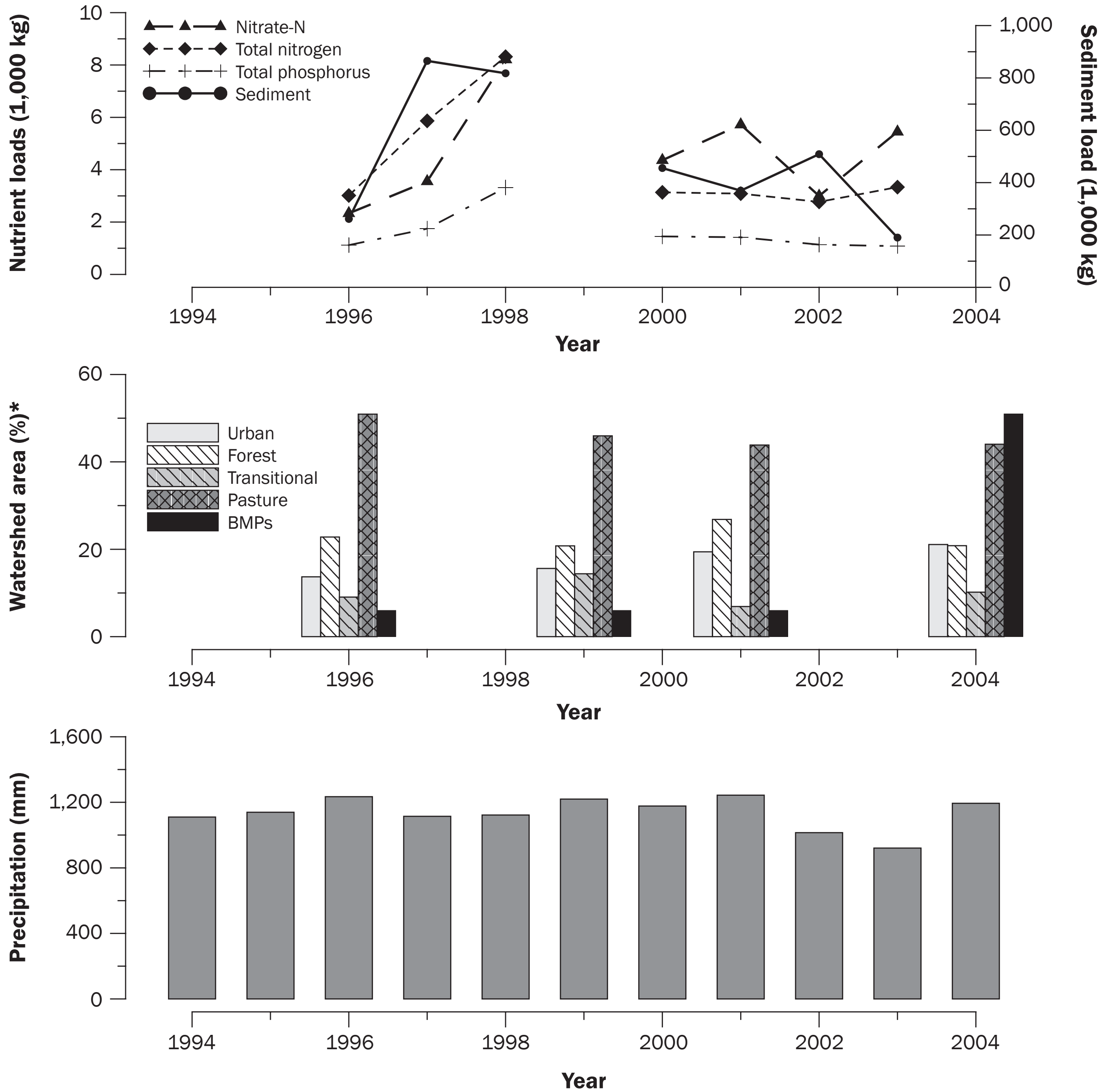
This study quantified land-use and management changes occurring in the Lincoln Lake watershed between 1992 and 2004 and evaluated the linkages among these changes and water quality in the watershed during the same time period. This was accomplished by conducting detailed land-use change analyses, developing a BMP database and analyzing BMP data for the watershed, and conducting trend analyses using the measured water quality data.

Land-use analyses revealed a rapidly changing landscape with the land uses experiencing both gains and losses at different times during the 12-year period considered. Although there were some discrepancies with regard to the interpretation of interland-use changes occurring based on separate assessments of gains and losses, in both cases, results pointed to the systematic gain in urban areas and the corresponding systematic loss in pastures, with the former tending to replace the latter. In both cases, the watershed was found to comprise a highly dynamic transitional land use, suggesting a rapidly changing landscape, the occurrence of which was verified by site visits.

Forests seemed largely unaffected by the changes occurring within the water-

Figure 6

Analyses of historical water quality data in the Upper Moores Creek subwatershed in relation to land use, best management practice (BMP), and precipitation data.



*BMP implementation is presented as percentage of farms with BMPs.

shed, with 90% of the forested remaining unchanged throughout the analyses period. This persistence of forest might be attributed to the location of the forests in the Lincoln Lake watershed; in this watershed, forests are located at and around the watershed outlet and Lincoln Lake, whereas most of the land-use changes have occurred around the upper reaches. Both poultry houses and urban areas displayed a tendency towards permanence based on the high degrees of persistence observed. With the poultry houses, for example, this might indicate that the units are not pulled down once they are constructed, even if they are no longer in use.

A key concern in any land-use analysis is the extent to which map accuracy would affect the results obtained, and as a consequence, the ability to differentiate true change from map error. In this study, all base maps were developed by the same person using the same protocol, thereby minimizing the uncertainties that would occur if the datasets had been developed by different persons and eliminating errors due to differences in classification methods. Accuracies for combined land uses ranged between 84% and

Table 8

Results of regression modeling of water quality data for the Lower and Upper Moores Creek subwatersheds of the Lincoln Lake watershed.

Variable	Intercept	Standard error	Slope	Standard error	*p*-value for H_0: slope = 0
Lower Moores Creek (1991 to 1998)					
Base flow conditions					
Flow (L × 10^8)	6.088	6.236	3.089	1.235	**0.0465**
NO_3-N (mg L^{-1})	0.591	0.209	0.081	0.388	**0.0927**
Total P (mg L^{-1})	0.172	0.033	−0.004	0.006	0.5272
Total suspended solids (mg L^{-1})	8.175	4.04	0.88	0.825	0.3348
Storm flow conditions					
Flow (L × 10^8)	45.549	15.866	−2.735	3.142	0.4174
NO_3-N (mg L^{-1})	0.446	0.073	0.076	0.014	**0.0026**
Total P (mg L^{-1})	0.277	0.05	0.042	0.011	**0.0133**
Total suspended solids (mg L^{-1})	44.64	40.075	12.398	8.961	0.2251
Upper Moores Creek (1996 to 2007)					
Base flow conditions					
Flow (L × 10^8)	11.136	9.387	0.621	0.820	0.4709
NO_3-N (mg L^{-1})	2.027	0.973	−0.024	0.085	0.7865
Total P (mg L^{-1})	0.351	0.059	−0.016	0.005	**0.0153**
Total suspended solids (mg L^{-1})	84.698	19.243	−5.307	1.168	**0.0135**
Storm flow conditions					
Flow (L × 10^8)	13.003	7.141	0.078	0.624	0.9038
NO_3-N (mg L^{-1})	0.789	0.264	0.035	0.023	0.1642
Total P (mg L^{-1})	1.141	0.342	−0.022	0.03	0.4760
Total suspended solids (mg L^{-1})	677.077	246.368	−31.611	21.533	0.1803

Notes: NO_3-N = nitrate-nitrogen. P = phosphorus. Numbers in bold highlight significant trends.

97%, while those for the base maps ranged between 87% and 92%, exceeding the standard threshold of 85%. These accuracies also exceeded the 77% threshold below which all of the differences between land uses in each of the periods analyzed could be attributed to error.

While BMP implementation in the watershed initially got off to a slow start, the extent of implementation increased dramatically after 2001 to the extent that virtually all pastures in the watershed have at least one BMP implemented. With regard to water quality, there were no appreciable changes in flow, sediment, or nutrients over time at the Beatty Branch sampling locations. However, increases in total suspended solids were observed in the Lower Moores Creek subwatershed, these being attributable to logging occurring in the watershed. Furthermore, downward trends were observed under both base and storm flow conditions in the Upper Moores Creek; these were attributed to the large number of BMPs implemented in this part of the watershed. Lack of significant trends observed in some cases could be attributed to the combined effects of land-use changes and BMPs, in which case positive effects of BMPs served to counter negative effects due to land-use change. Land-use changes in the watershed are driven by a variety of socioeconomic factors, the quantification of which is beyond the scope of this study. Given the extent of change occurring in the northwest Arkansas region in general, it can be assumed that land-use changes were imminent in this watershed. This study suggests that the concurrent implementation of BMPs in the Lincoln Lake watershed served to protect water quality from adverse effects that might have occurred due to the changing land use. This study also demonstrates the need to conduct detailed land-use assessment alongside any BMP impact assessments, particularly in areas in which significant land-use changes have occurred. The methodologies utilized can be applied in other CEAP assessments and other watersheds in which BMP implementation and significant land-use change have occurred simultaneously.

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