Watershed Physiography, Land Use, and Sediment Yield: A Case Study from Northwest Arkansas, USA

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ABSTRACT
Precision echo sounder surveys of bathymetry and sediment thickness of Lee Creek Reservoir and Lake Shepherd Springs (northwest Arkansas) were combined with Geographic Information Systems (GIS) analyses of watershed digital elevation data and land use/land cover data to evaluate the relative importance of watershed area, watershed physiography, and land use/land cover on sediment yield and reservoir sedimentation. Both reservoirs have comparable surface areas, though Lee Creek Reservoir has approximately one-half the storage capacity of Lake Shepherd Springs (9.47 x 10⁶ m³ versus 18.8 x 10⁶ m³) due to the fact that its average depth is approximately 5 m versus an average depth of 9 m for Lake Shepherd Springs. Physiographically, Lee Creek watershed occupies less rugged terrain (94% of slopes <10°) than Lake Shepherd Springs watershed (33% of slopes >10°). Land cover and land use in both watersheds were dominated by forest (83% for Lee Creek Reservoir Watershed; 90% for Lake Shepherd Springs Watershed) and agriculture, though agricultural land use in Lee Creek watershed is nearly twice (15%) that in Lake Shepherd Springs watershed (8%).

Long-term average annual sediment flux to Lee Creek Reservoir was estimated from observed lacustrine sediment volume to be approximately 1.87 x 10⁴ m³, three times greater than for Lake Shepherd Springs (6.18 x 10³ m³). However, normalizing long-term average sediment accumulation to watershed area (1,163 km² for Lee Creek Reservoir versus 173 km² for Lake Shepherd Springs) showed that the sediment yield (mm m⁻² y⁻¹) from Lee Creek watershed (0.16 mm m⁻² y⁻¹) was only one-half that from Lake Shepherd Springs watershed (0.35 mm m⁻² y⁻¹). This result indicates that slope, rather than land cover and land use, was the dominant control on sediment yield within these two watersheds. Additionally, this study reinforces the importance of considering watershed-scale geomorphic processes in the interpretation of reservoir sedimentation and suggests that simple estimates of reservoir infilling can be misleading indicators of watershed processes.

Keywords: Reservoir; Sedimentation; Watershed; Sediment yield; Land use; Slope

INTRODUCTION
Any reservoir on a sediment-bearing water-course will eventually infill with sediment (Chen, 1998). Therefore, it is important to estimate sedimentation rates for quantifying design life of reservoirs. Sediment fluxes in lakes and reservoirs often reflect the interplay of watershed physiographic characteristics such as degree of topographical steepness, slope orientation, climate, geology, watershed area, surface runoff, soil characteristics, sediment grain size, etc. (Gilbert, 1980; Dendy et al., 1973; Abrahams and Parsons, 1991; Pemberton, 1980). In addition, watershed land cover and land use can greatly influence rates of surface denudation, sediment yield, and ultimately sedimentation in reservoirs (Chen, 1998; Canfield et al., 2001; Young et al., 2001).

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This paper presents results of a study to examine the relative influences of watershed area, watershed physiography, and land-use and land cover on watershed sediment yield and resultant sedimentation in two multi-purpose reservoirs in northwest Arkansas. Lee Creek Reservoir and Lake Shepherd Springs (Fig. 1) are maintained and monitored by the Utility Department of the City of Fort Smith, Arkansas for domestic water provision, flood control, and limited recreation (boating and fishing). Both reservoirs and their watersheds are located in similar physiographic provinces (the Boston Mountains of northwest Arkansas) and are underlain by similar geological formations (interbedded sandstone, siltstone, and shale of the Pennsylvanian Atoka Formation; Andersen, 2001; Cooper, 2001; Brown, 2000; Valek, 1999; Haley et al., 1976). In addition, these adjacent watersheds are in the same climate zone. Thus, comparing these two reservoirs provided an excellent opportunity to examine the influence of natural processes (watershed physiographic phenomena) relative to anthropogenic impacts (land cover and land use) on sediment yield and resultant reservoir sedimentation.

Fig - 1. A) Location map Lee Creek Reservoir watershed in Oklahoma and Arkansas and Lake Shepherd Springs watershed in Arkansas; B) Detail showing locations of Lee Creek Reservoir and Lake Shepherd Springs relative to their respective watersheds.
Background and Regional Setting
Surface water resources of northwest Arkansas serve as important sources of drinking water supplies for the rapidly growing metropolitan area of Fort Smith (second largest municipality in Arkansas) and surrounding suburban and rural areas of Sebastian County and Crawford County. Census statistics show that the populations of Crawford County and Sebastian County increased 120% and 95% respectively since World War II, and population continues to increase at an average rate of 2% to 3% per year (Brown, 2000; U.S. Census Bureau, 2000). This rapid population growth is associated with urbanization, industrialization, and increased agriculture with the potential to affect watershed-scale processes responsible for sediment yield and reservoir sedimentation.

Human population growth commonly impacts surface water resources by influencing watershed-scale processes (such as sediment yield and reservoir sedimentation) that can dramatically alter surface water quality (Kikkawa, 1980; Trimble, 1982; Lin, 2000). Remedies for reservoir sedimentation are costly, hence proper evaluation of the vulnerability of reservoirs to sedimentation effects is imperative to long-term management of these finite resources. Primary responsibility for managing surface water resources in the Fort Smith metropolitan area resides with the Utility Department of the City of Fort Smith. Presently, the Utility Department manages three reservoirs as municipal water supplies: 1) Lee Creek Reservoir, 2) Lake Shepherd Springs, and 3) Lake Fort Smith. Since 1999, the Utility Department has authorized baseline surveys of all three reservoirs in an effort to evaluate long-term sedimentation trends and develop 50-year watershed management plans to protect water quality in these reservoirs. The subjects of the present study are Lee Creek Reservoir and Lake Shepherd Springs. Lake Fort Smith was studied by Brown (2000).

Geographic Setting
Both reservoirs lie near the terminus of fourth order streams (Fetter, 1980), within a few kilometers of the stream’s confluence with the Arkansas River. Both watersheds have well-developed dendritic drainage systems (Fig. 1b). Brief descriptions of the history and physiographic setting of Lee Creek Reservoir and Lake Shepherd Springs are presented below.

Lee Creek Reservoir
Lee Creek watershed is located in northwest Arkansas and eastern Oklahoma, U.S.A. (Fig. 1a). The watershed is approximately 52 km long and averages approximately 23 km in width, occupying a total area of 1,163 km² (Table 1). Lee Creek Reservoir (Fig. 1b) was created in 1992 by construction of an earthen dam across the valley of Lee Creek approximately 5 km north of Van Buren, Arkansas. At its normal pool elevation of 128 m above mean sea-level, Lee Creek Reservoir has a surface area of 2.47 km².

Management of this watershed is complicated because it straddles the border separating Arkansas and Oklahoma; 692 km² are located in Washington and Crawford Counties, Arkansas, and 474 km² are located in Adair and Sequoyah Counties, Oklahoma (United States Army Corps of Engineers, 1965, 1979). Elevation within the Lee Creek watershed ranges from 640 m above mean sea-level in the northeast highlands to 121 m above mean sea-level at the dam of Lee Creek Reservoir. Surface slopes within Lee Creek watershed vary from relatively steep (>30°) in the northeastern highlands of the Boston Mountains to low hills with gentle slopes (dominantly <10°) in the southern portion of the watershed.
Table 1. Lee Creek Reservoir and Lake Shepherd Springs Bathymetric, Sedimentological and Watershed Physiographic Parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Lake Shepherd Springs</th>
<th>Lee Creek Reservoir</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (at time of survey)</td>
<td>44</td>
<td>8</td>
</tr>
<tr>
<td>Lakes surface area</td>
<td>2.2 km²</td>
<td>2.5 km²</td>
</tr>
<tr>
<td>Capacity (volume)</td>
<td>$1.88 \times 10^7$ m³</td>
<td>$9.47 \times 10^6$ m³</td>
</tr>
<tr>
<td>Sediment volume</td>
<td>$2.7 \times 10^5$ m³</td>
<td>$1.5 \times 10^5$ m³</td>
</tr>
<tr>
<td>Average sediment accumulation rate</td>
<td>0.004 m y⁻¹ (0.4 cm y⁻¹)</td>
<td>0.016 m y⁻¹ (1.6 cm y⁻¹)</td>
</tr>
<tr>
<td>Maximum watershed elevation</td>
<td>731 m</td>
<td>640 m</td>
</tr>
<tr>
<td>Minimum watershed elevation</td>
<td>274 m</td>
<td>121 m</td>
</tr>
<tr>
<td>Watershed area</td>
<td>173 km²</td>
<td>1163 km²</td>
</tr>
</tbody>
</table>

*long-term average annual sediment flux = Sediment volume (m³) ÷ age of lake (y)

**Lake Shepherd Springs**

The Lake Shepherd Springs watershed has an area of 173 km² (Fig. 1a). Lake Shepherd Springs (Fig. 1b) was created in 1956 by construction of an earthen dam across the valley of Frog Bayou, in Crawford County, Arkansas. It is located approximately 45 km northeast of the city of Fort Smith. At its normal pool elevation of 277 m, Lake Shepherd Springs has a surface area of 2.2 km² (Table 1). Elevation within the Lake Shepherd Springs watershed ranges from 731 m above mean sea-level in the Boston Mountain highlands of the northeastern watershed to 274 m above mean sea-level at the dam site. Surface slopes within the watershed are generally steep (33% of slopes >10°).

Lake Shepherd Springs originally served as a sediment trap and regulatory pool for Lake Fort Smith (another municipal water supply for the City of Fort Smith). However, in 2006 the pool elevation of Lake Fort Smith will be raised approximately 27 m, and this will result in Lake Fort Smith joining Lake Shepherd Springs to form a single large reservoir. Therefore, watershed analysis in relation to sedimentation in Lake Shepherd Springs provides a timely contribution to aid planners in developing environmental management and monitoring policies for the expanded lake basin as well as providing baseline data prior to joining of the two lake basins.

**METHODS**

**Echo Sounding Surveys**

Echo sounder surveys of Lee Creek Reservoir and Lake Shepherd Springs were conducted during June and July 2000. A Knudsen Engineering 320 B/P echo sounder system was mounted on the bow of R/V *Ozark Traveler* (an 8-meter pontoon boat maintained for limnological research by the Department of Geosciences, University of Arkansas) and the vessel was steered in an overlapping orthogonal grid survey pattern (Fig. 2) at a survey speed of approximately 2 m s⁻¹. Survey lines consisted of north-south, east-west, northeast-southwest, and northwest-southeast trending tracks with approximately 20-meter offset (Fig. 2). The total track line distance of the surveys in Lee Creek Reservoir and Lake Shepherd Springs were 215 km and 138 km respectively.
Fig. 2. Portion of 7.5-minute topographic quadrangle showing A) Lee Creek Reservoir (Fort Smith Quadrangle) and B) Lake Shepherd Springs (Fern Quadrangle). The overlain survey trackline yielded 68,110 soundings (total trackline distance = 215 km) in Lee Creek reservoir and 41,386 soundings (total trackline distance = 138 km) in Lake Shepherd Springs.
Navigation data were acquired with a Trimble Pathfinder Pro XRS Global Positioning System (GPS) receiver. Location and time according to the GPS were automatically logged every 5 seconds during the survey. Other pertinent information, such as vessel heading, bottom features, and landmarks, were recorded where appropriate. Following the field survey, echo sounder data and GPS navigation were merged using spreadsheet software, and geographic positions were interpolated between 5-second navigation fixes to yield a database with navigation data merged to echo profile data at 1-second intervals. This procedure yielded a total of 68,110 soundings and 41,386 soundings for Lee Creek Reservoir and Lake Shepherd Springs, respectively. Thus, the data density was such that there was one sounding for every 6 - 7 m of lake surface area on average for both reservoirs.

The Knudsen Engineering Model 320 B/P echo sounder transmits acoustic energy with two distinct frequencies, 200 kHz and 28 kHz (Anonymous, 1998). The theoretical vertical resolution of the 200 kHz pulse (i.e. one-quarter $\lambda$) is 1.85 mm. The 200 kHz (high frequency) band has sufficient energy to penetrate the water column but reflects from the water/sediment interface. Data derived from this frequency provide an image of the present-day bathymetry of a lake. The theoretical vertical resolution of the 28 kHz pulse (i.e. one-quarter $\lambda$) is 13.2 mm. The 28 kHz (low frequency) band has sufficient energy to penetrate both the water column and recent lacustrine sediment, but reflects from the sediment/pre-impoundment land surface (compacted soil or rock). The low frequency data provide an image of the land surface prior to inundation by the lake. The difference in depth detected by the high and low frequencies at each ping represents the total thickness of lacustrine sediment deposited since impoundment.

Accuracy of the echo sounder and GPS data was evaluated by comparing survey 28 kHz echo sounder results to the pre-impoundment topography as represented on the USGS digital raster graphic of Fort Smith, Arkansas 7.5-minute quadrangle map (Odhiambo and Boss, 2004, Fig.3). Examination of 28 kHz echo sounder data and the topographic map shows that the echo data accurately depicts pre-impoundment topography including complex bathymetry formed by submerged sandstone blocks near the dam.
Fig - 3. Maps comparing A) pre-impoundment contours and B) 28 kHz echo sounder survey of Lee Creek Reservoir. Pre-impoundment contours represented on USGS digital raster graphic of Fort Smith, Arkansas 7.5” topographic quadrangle. Note excellent correlation of echo sounder results with topographic map, indicating that 28 kHz echo data are effective in recovering pre-impoundment surface of Lee Creek area (after Odhiambo and Boss, 2004).

**Bathymetry and Sedimentation**

High frequency (200 kHz) echo sounder data were used to develop a digital map of present-day bathymetry for both reservoirs (Figs. 4a, 5a). Low frequency (28 kHz) echo sounder data (which penetrate lacustrine sediment) were used to map the pre-impoundment surface of each reservoir. Every sounding for each survey had a corresponding high frequency depth (present-day bathymetry) and low frequency depth (pre-impoundment surface). The difference in these two values represented lacustrine
Fig - 4. A) Bathymetric map of Lee Creek Reservoir derived from 200 kHz echo sounder survey. B) Sediment thickness map of Lee Creek. Reservoir derived from difference in measured first-arriving acoustic impulse from 200 kHz and 28 kHz echo sounder survey. Contour interval is 0.1 meter.
Fig - 5. A) Bathymetric map of Lake Shepherd Springs derived from 200 kHz echo sounder survey. Contour interval is 4 m. B) Sediment thickness map of Lake Shepherd Springs derived from difference in measured first-arriving acoustic impulse from 200 kHz and 28 kHz echo sounder survey.
sediment thickness deposited since the time the lake was inundated. Using the GIS, this difference was calculated for every survey point in each survey, and maps showing sediment thickness were developed (Figs. 4b, 5b).

Once sediment thickness values were determined for each reservoir, the GIS program was used to calculate the volume of sediment within each reservoir. Given the known age of each reservoir, it was then possible to determine a long-term average annual sediment flux \( (m^3 \cdot y^{-1}) \) by dividing the observed sediment volume by the age of the lake (8 y for Lee Creek Reservoir, 44 y for Lake Shepherd Springs).

\[
Q_s = \frac{V_s}{t}
\]  

(1)

where \( Q_s \) is long-term average annual sediment flux \( (m^3 \cdot y^{-1}) \), \( V_s \) = observed sediment volume \( (m^3) \), and \( t \) = age of reservoir \( (y) \). The ages of the reservoirs at the time of the survey were 8 years (Lee Creek Reservoir) and 44 years (Lake Shepherd Springs), corresponding to the year during which each was inundated (1992 and 1956, respectively).

**Watershed Sediment Yield and Terrain Analyses**

Calculation of long-term average annual sediment flux naturally leads to an assessment of sediment yield from each watershed. Traditionally, sediment yield is defined as the mass of sediment eroded from each square meter of a watershed annually (Verstraeten and Poesen, 2001). For this study, sediment yield was defined as the annual thickness of sediment eroded from each meter of the watershed in mm m\(^{-2} \cdot y^{-1}\) and was calculated by dividing the long-term average annual sediment flux (converted to mm\(^3 \cdot y^{-1}\)) by watershed area. Thus,

\[
Y_s = \frac{Q_s}{A_w}
\]  

(2)

where \( Y_s \) = average annual sediment yield \( (mm \cdot m^{-2} \cdot y^{-1}) \), \( Q_s \) is long-term average annual sediment flux \( (mm^3 \cdot y^{-1}) \), and \( A_w \) = watershed area \( (m^2) \).

The value obtained for sediment yield could be converted to mass if the bulk sediment density or soil density were known throughout the watershed. Unfortunately, these data are not available throughout the watershed. A different strategy was employed here defining sediment yield according to sediment volume. A limitation of this method is that lacustrine sediments are typically uncompacted and thixotropic, being characterized by very high fluid (water) filled porosity. Thus, the calculated sediment volume represents a maximum volume of sediment derived from the watershed. Dividing the calculated volumetric sediment flux by the watershed area provides an estimate of the maximum average rate of surface lowering throughout the watershed. In addition, it is assumed the reservoir is a closed system with respect to sediment, such that sediment losses from the reservoir (primarily through discharge of suspended sediment) are negligible. The sediment yields for each watershed are presented in Table 2.

For terrain analyses, United States Geological Survey 3 arc-second (30-m) digital elevation models (DEMs) at 1:24,000 scales were obtained for all quadrangles encompassing Lee Creek and Lake
Shepherd Springs watersheds. Individual DEMs were merged within the GIS software and contour maps showing surface relief within the watershed were generated.

Using the GIS, slope maps comparing both watersheds were derived from digital elevation data. Slope maps were contoured to show slope in angular degrees (Fig. 6). Finally, watershed stream densities were calculated using the GIS to measure the length of each stream within each watershed, then dividing the total length of streams within each watershed (Fig. 1b) by watershed area. Thus,

\[ s = \frac{\Sigma l_s}{A_w} \]  

where \( s = \) stream density (m of stream reach per m\(^2\) of watershed), \( \Sigma l_s = \) total length of watershed streams (m), \( A_w = \) watershed area (m\(^2\)).

![Fig - 6. Slope maps of Lee Creek Reservoir and Lake Shepherd Springs watersheds derived from digital elevation data and analyzed using GIS. (DEM data from USGS digital elevation data).](image-url)
Table - 2. Lee Creek Reservoir and Lake Shepherd Spring watershed area (km²), long-term average annual sediment flux to reservoirs (m³/y), sediment yield from watershed (mm/y/m²), and percent slope of watershed area (degrees).

<table>
<thead>
<tr>
<th>Watershed Area (km²)</th>
<th>*Sediment flux (m³/y)</th>
<th>†Sediment Yield (mm/y/m²)</th>
<th>Watershed Stream Density m/m²</th>
<th>Percent slope of watershed area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lee Creek Reservoir</td>
<td>1,163</td>
<td>18,749</td>
<td>0.16</td>
<td>0.00089</td>
</tr>
<tr>
<td>Lake Shepherd Springs</td>
<td>173.38</td>
<td>6181</td>
<td>0.35</td>
<td>0.00076</td>
</tr>
</tbody>
</table>

*long-term average annual sediment flux = Sediment volume (m³) ÷ age of lake (y)

†Sediment yield = sediment flux (m³/y) ÷ watershed area (km²).

Stream density = total stream length ÷ watershed area (m²).

Land Use and Land Cover Analyses

Land use and land cover (LULC) data were obtained from the United States Geological Survey National Land Cover Data (NLCD) for Arkansas and Oklahoma. These digital LULC maps were derived from 1992 Landsat Thematic Mapper scenes using spectral characteristics of image pixels to classify land uses or land cover according to criteria developed by Anderson et al (1976). These data were imported into the GIS and examined to determine the relative proportions of different land uses and land cover present within each watershed. Results of LULC analyses are illustrated in Figure 7 and tabulated in Table 3. A possible limitation of these data was that it dates from 1992, the same year that Lee Creek Reservoir was inundated. Thus, it is possible that LULC changed somewhat during the last decade, especially in view of the rapid population growth in northwest Arkansas and eastern Oklahoma. Census data indicate that population growth from 1990 – 2000 ranged from 14 – 25% in the two Oklahoma and Arkansas counties in which the watersheds were located (U.S. Census Bureau, 2000). However, most of this population growth occurred proximal to the large urban center of Fort Smith, Arkansas which is outside the watershed area of Lee Creek and Lake Shepherd Springs. Therefore, it is unlikely that dramatic changes in LULC have occurred. Field visits to both watersheds showed that there has been little new, large-scale construction and that the concentration of inhabitants does not appear to have increased dramatically in recent years. Furthermore, much of Lee Creek watershed and all of Lake Shepherd Springs watershed are dominantly forested as part of the Ozark National Forest.
Fig - 7. Land-use and land-cover maps of Lee Creek and Lake Shepherd Springs watersheds derived from 1992 Landsat Thematic Mapper scenes and obtained from United States Geological Survey National Land Cover Data (http://www.usgs.gov).

Table 3: Land use and land cover characteristics of Lee Creek Reservoir and Lake Shepherd Springs watershed

<table>
<thead>
<tr>
<th>Land-use and Land-cover type</th>
<th>Lake Shepherd Springs</th>
<th>Lee Creek Reservoir</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Area (km²)</td>
<td>Percentage</td>
</tr>
<tr>
<td>Forest cover (Deciduous, Evergreen, and Mixed forest)</td>
<td>155.77</td>
<td>89.84</td>
</tr>
<tr>
<td>Pasture/Hay</td>
<td>13.81</td>
<td>7.96</td>
</tr>
<tr>
<td>Row Crops and Small Grains</td>
<td>0.52</td>
<td>0.30</td>
</tr>
<tr>
<td>Residential</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>Commercial/industrial/transportation</td>
<td>0.10</td>
<td>0.06</td>
</tr>
<tr>
<td>Urban/Recreation Grasses (Parks/Golf courses)</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Others</td>
<td>3.15</td>
<td>1.67</td>
</tr>
<tr>
<td>TOTALs</td>
<td>173.37</td>
<td>100</td>
</tr>
</tbody>
</table>
RESULTS
Results from echo sounder surveys of each reservoir, estimates of long-term average annual sediment flux, watershed sediment yield, and watershed terrain analyses are presented below. These results illustrate the complexity of watershed processes and the necessity of monitoring processes at watershed scales in order to better understand reservoir sedimentation.

Bathymetry and sedimentation
The bathymetric map of Lee Creek derived from 200 kHz echo sounder surveys is illustrated in Figure 4a. As can be seen, Lee Creek Reservoir occupies a bathymetrically diverse basin, with clear evidence of its fluvial origin (Fig. 4a). The maximum present-day depth of Lee Creek Reservoir was approximately 12 m, with an average depth of only 5 m. In the central portion of the lake basin, there exists a broad, flat terrace that was pasture prior to inundation of the reservoir (Mr. Steve Parke, personal communication, 2000). Within the lake basin, there are several fluvial channels that meander among outliers of sandstone. These sandstone blocks rise up from the surrounding lake floor as much as 4 m in some areas. The map also clearly depicts the former main channel of Lee Creek, and this narrow channel constitutes the principal volume for water storage within the reservoir. The total volume or storage capacity of Lee Creek Reservoir was estimated at $9.47 \times 10^6$ m$^3$, whereas Lake Shepherd Springs occupies a relatively much simpler basin with a storage capacity of $18.8 \times 10^6$ m$^3$. At the time of the survey, July 2000, the maximum depth of Lake Shepherd Springs was approximately 23 m and its average depth was approximately 9 m, almost twice as deep as Lee Creek Reservoir. The primary channel of Frog Bayou is evident on the bathymetric map, though it is not as pronounced as the main channel of Lee Creek in Lee Creek Reservoir.

Observed sediment thickness in Lee Creek Reservoir (Fig. 4b) was quite variable throughout the basin, commonly ranging from 0.0 m to about 0.4 m. However, extreme sediment thickness values (>0.5 m) were restricted to the broad, flat terrace in the central portion of the reservoir, and it is believed these values represent the thickness of fluvial deposits and soil creating this terrace prior to inundation rather than lacustrine sediment deposited since 1992. Geomorphically, this terrace appears to represent a point bar sequence, and it is known that this terrace was pasture prior to formation of the lake. In addition, the acoustic signature of sediments across this terrace is distinctly different from that of sediment interpreted to be lacustrine fill throughout the basin (Fig. 8). Thus, the geomorphology, land use history, and sediment physical properties provide the primary evidence that these anomalously thick deposits predate inundation of the reservoir. Excluding these anomalously thick sediments, the average sediment thickness observed in Lee Creek Reservoir was 0.13 m. The thickest lacustrine sediment was observed in a broad, looping meander in the south-central portion of the basin where sediments reach a maximum thickness of approximately 0.40 m (Fig. 4b).

Lee Creek Reservoir’s total sediment volume calculated from the sediment contour map (Fig. 5b) yielded a total sediment volume of 149,991 m$^3$. Using observed sediment thickness throughout the basin and dividing these observations by the age of the lake (8 y) provided estimates of the long-term average accumulation rate for the lake ranging from 0.0 m y$^{-1}$ to 0.05 m y$^{-1}$, with a basin-wide average of 0.015 m y$^{-1}$. This value is 50% greater than the average (0.01 m y$^{-1}$) observed in four other northwest Arkansas reservoirs (Lake Wedington; Polly, 2001; Beaver Reservoir, Hansen, 1999; Lake
Alma, Boss and Brown, 2000; Lake Fort Smith, Brown, 2000; Brown and Boss, 2000) and 3-times greater than that determined for Lake Shepherd Springs (see below).

Fig - 8. Sample echograms from survey of Lee Creek Reservoir, July 2000. A) Sediment overlying the pre-impoundment surface (arrow) in the former main channel of Lee Creek. (Note that the sediment surface was obtained from 200 kHz echo pulse whereas the 28 kHz echo pulse penetrates lacustrine sediment to yield a strong reflection from the pre-impoundment surface (Anonymous, 1998). The difference in measured depth to these reflectors is the sediment thickness at any point in the lake. B) Sample echogram illustrating acoustic signature of sediment interpreted to be compact soil that existed on broad terrace prior to inundation).

Observed sediment thickness for Lake Shepherd Springs (Fig. 5b) was variable throughout the basin ranging from 0.0 m to >0.50 m, with an estimated average of 0.18 m. The generally diffuse distribution of sediment throughout this basin suggests that most sediment settled from suspension. Slightly thicker sediments appeared to be common within the former main channel of Frog Bayou (Fig. 5b), and it is possible that some of this sediment represented original fluvial deposition or was deposited during the earliest stages of reservoir inundation.
Total sediment volume for Lake Shepherd Springs calculated under each sediment thickness contour (Fig. 5b) yielded a total sediment volume of 269,332 m$^3$. Based on the age of the lake at the time of survey (44 y), long-term average accumulation rate for Lake Shepherd Springs ranged from 0.0 m y$^{-1}$ to 0.01 m y$^{-1}$, with a basin-wide average of 0.0042 m y$^{-1}$. This value was relatively low for the northwest Arkansas reservoirs studied to date (Lee Creek Reservoir, this paper; Lake Wedington; Polly, 2001; Beaver Reservoir, Hansen, 1999; Lake Alma, Boss and Brown, 2000).

The total volume of lacustrine sediment calculated from the sediment thickness map (Fig. 4b) for Lee Creek Reservoir was 149,991 m$^3$. Dividing this value by the age of the lake (8 y) gives a long-term average annual sediment flux of 18.7 x 10$^3$ m$^3$ y$^{-1}$. Whereas, the total volume of lacustrine sediment calculated for Lake Shepherd Springs was 269,332 m$^3$, divided by the 44 year period gives a long-term average annual sediment flux of 6.18 x 10$^3$ m$^3$ y$^{-1}$.

**Watershed Sediment Yield and Terrain Analyses**

Table 2 presents calculations of long-term average annual sediment yield for both Lee Creek watershed and Lake Shepherd Springs watershed. This value was determined by dividing estimated long-term average annual sediment flux to each reservoir by the area of the watershed. Thus, sediment yield (as defined in this paper) provides an estimate of the average thickness of sediment eroded from each square meter of watershed annually. For Lee Creek watershed, the long-term average annual sediment yield was calculated to be 0.16 mm m$^{-2}$ y$^{-1}$. For Lake Shepherd Springs watershed, the calculated long-term average annual sediment yield was 0.35 mm m$^{-2}$ y$^{-1}$, twice as much as for Lee Creek watershed.

The GIS derived maps depicting slope angles from digital elevation data throughout both watersheds are shown in figure 6. Results of slope analyses show that the terrain of Lee Creek watershed is much subdued relative to that of Lake Shepherd Springs watershed. Despite some relatively rugged highland areas of the Boston Mountains in the northeastern portion of Lee Creek Watershed where local slopes may exceed 30$^\circ$, 94% of slopes throughout the watershed are <10$^\circ$ with 50% of slopes <4$^\circ$. In contrast, 33% of slopes within Lake Shepherd Springs watershed are >10$^\circ$.

Stream densities for each watershed (Fig. 1b) were determined to be somewhat similar. For Lee Creek watershed, the calculated stream density was 0.0009 m m$^{-2}$ whereas stream density in the Lake Shepherd Springs watershed was 0.0008 m m$^{-2}$. The similarity in stream density for both watersheds reflects the well-developed dendritic drainage pattern of northwest Arkansas and eastern Oklahoma.

**Land-use and land-cover**

Mapping and analyses of land-use and land-cover (Fig. 7 and Table 3) demonstrated that both watersheds were dominated by forest cover. Forests of all types (deciduous, conifer, mixed) accounted for 83% of the land cover in Lee Creek Reservoir whereas forest cover within the Lake Shepherd Springs watershed was 90%. Agricultural land uses (pasture and hay, row crops, grains) constituted the next largest land use category in both watersheds. Agricultural land use accounted for nearly 15% in Lee Creek watershed while agricultural land use composed slightly more than 8% of Lake Shepherd Springs watershed. All other land use and land cover categories composed less than 2.5% of each watershed, and were considered to be unimportant as determinants of sediment yield or controls on sedimentation in the respective reservoirs.
DISCUSSION

Lee Creek Reservoir and Lake Shepherd Springs are located in an area where climatological and geological conditions are very similar. Both reservoirs are located near the terminus of fourth order streams and therefore serve as repositories of sediment derived from a variety of processes throughout their respective watersheds (Fig. 1b). Since climatological and geological settings of Lake Shepherd Springs and Lee Creek Reservoir watersheds were nearly identical because of their close proximity to each other, comparison of sedimentation and watershed properties of these two reservoirs provided an opportunity to evaluate concepts relating to sediment yield and sediment transport through watersheds with respect to other geomorphic parameters (e.g. watershed area, slope, stream density, etc.; Gilbert, 1880; Lobeck, 1939; Abrahams and Parsons, 1991; Graf, 1993; Maneux et al., 2001), and LULC (Chen, 1998; Young et al., 2001).

Based on results of this study, a simple estimate of the rate of sediment infilling calculated from observed sediment volume divided by reservoir age indicated that Lee Creek Reservoir was infilling with sediment approximately 3-times faster than Lake Shepherd Springs (18.7 x 10^3 m^3 y^-1 versus 6.18 x 10^3 m^3 y^-1). In determining possible causes of the 3-fold greater long-term average accumulation rate in Lee Creek Reservoir, it could be concluded that LULC differences between the watersheds played a significant role. Examination of LULC distributions within the two watersheds (Table 3) showed that agricultural land use was the only significant difference, and it is well documented that agricultural activities impact surface erosion processes by exposing terrain to direct impacts of rainfall, accelerating sheet erosion and other forms of mass wasting (Matyas and Rothenburg, 1986; Lane et al., 1997). Within Lee Creek watershed, agricultural land use was almost twice that observed for the Lake Shepherd Springs watershed (15% versus 8%). However, this simple conclusion belies that fact that the Lee Creek watershed is nearly 7-times larger than the Lake Shepherd Springs watershed (1,163 km^2 versus 173 km^2; Table 1). Thus, long-term average sediment flux may be higher at Lee Creek Reservoir because it is the repository of sediments from a much larger area. Normalizing estimated long-term average sediment flux to watershed area provided a new parameter, sediment yield, which was defined for this study as a measure of the annual thickness of sediment eroded from each square meter of watershed area. Owing to the relatively large size of the Lee Creek watershed, the sediment yield from this watershed (0.16 mm m^-2 y^-1) was only one-half the sediment yield from Lake Shepherd Springs watershed (0.35 mm m^-2 y^-1). Thus, somewhat paradoxically, Lee Creek watershed, with less forest cover (83% versus 90%) and greater agricultural land use (15% versus 8%) yielded only one-half the sediment of Lake Shepherd Springs watershed. Clearly, long-term average annual sediment fluxes calculated from sediment thickness maps of the two reservoirs were somewhat misleading indicators of watershed-scale sedimentological processes.

In geomorphic analyses, it was determined over 100 years ago that erosion and sediment yield in watersheds was most rapid where the slope was steepest; even though weathering and downslope transport of materials were affected to different degrees by climatological, geological, and biological (i.e. vegetation) conditions (Gilbert, 1880; Bondu rant and Liversey, 1973). Thus, increase of topographical slope (declivity) increases the velocity of running water (somewhat irrespective of other factors) with corresponding increase in power to transport detrital material. Analyses of slopes within each watershed (Fig. 6) showed dramatic differences in the terrain of the two watersheds. Over 94% of slopes within Lee Creek Reservoir watershed were <10°, and 50% of slopes were <4°. In contrast,
slopes within the Lake Shepherd Springs watershed were substantially steeper; 33% of slopes were >10°. The observed difference in watershed slopes provides a likely explanation of the observed difference in sediment yield. Despite more extensive forest cover in the Lake Shepherd Springs watershed relative to the Lee Creek watershed, sediment yield within Lake Shepherd Springs watershed was twice that of Lee Creek watershed due to the greater proportion of steep slopes.

The dominant influence of slopes in the overall sediment yield in these two watersheds is even more obvious in USLE (universal soil loss equation) model analysis results of Odhiambo and Boss (2004). That study showed that though more pristine, Lake Shepherd Springs watershed still had comparable USLE sediment yield estimates (3.33 x 10⁻³ tons m⁻² y⁻¹) compared to Lee Creek Reservoir’s watershed (3.15 x 10⁻³ tons m⁻² y⁻¹). USLE model predicted that 80% of the sediments were generated from slopes > 5 degrees in both watersheds. Though gentler slopes (< 5 degrees) had significant slope lengths, these slopes were insignificant contributors to rill-related sediment generation. Thus, the higher sediment yield estimates for Lake Shepherds Spring’s watershed with the relatively higher percentage of steeper slopes. The USLE model results also showed significantly higher sediments generated in the watershed compared to the flux estimates from geophysical analysis. The disparity may be attributed to USLE overestimating the amount of sediment generated in individual watersheds or might reflect the role of other factors such as stream bank sediment storage.

Similar observations on the important role of slopes in sediment yield were made by Oguchi et al. (2001) in their work on fluvial geomorphology and paleohydrology of watersheds in Japan. They observed abundant sediment yields from steep watersheds subjected to frequent heavy rains despite heavily vegetated conditions. In addition, Abrahams and Parsons (1991) study of debris covered hill slopes of Walnut Gulch, Arizona demonstrated that on slopes less than 12°, runoff increased very slowly with gradient such that corresponding sediment yield on gentle slopes was also relatively small, despite poor vegetative cover. Thus, the gentle slopes of Lee Creek watershed were most likely storage sites rather than sediment yield sites.

The foregoing discussion does not negate or ignore contributions of other factors in determining sediment yields within Lee Creek and Lake Shepherd Springs watersheds. As concluded and well documented by many workers, (Gilbert, 1880; Abrahams and Parsons, 1991; Lane et al., 1997; Chen, 1998; Evans and Seamon, 1997, Trimble, 1983) climate, characteristics of parent geological material, soil, land use and land cover changes all influence erosion and sediment production within watersheds. However, the effectiveness and relative contribution to sediment production and transport is either amplified or minimized by the degree of declivity throughout the watershed. This was clearly demonstrated in the comparison of sedimentation and watershed characteristics of Lee Creek Reservoir and Lake Shepherd Springs, where climatological and geological conditions were very similar and the primary observable differences were in LULC and watershed terrain. The watershed displaying greater human impacts due to agricultural activity yielded only one-half the sediment of its more pristine (90% forest cover) counterpart. Given that differences in land cover and land use appeared to have little effect on sediment yield, it must be concluded that slope was the overriding factor in determining the degree of erosion and downslope transport within these watersheds.
Despite the fact that sediment yield from Lee Creek watershed was only one-half the sediment yield from Lake Shepherd Springs watershed (Table 2), the cumulative impact of sediment yield from the 7-times larger watershed was such that annual reservoir sedimentation was estimated to be 3-times greater. Thus, watershed area must also be considered as an important parameter in predicting reservoir sedimentation. This observation validates those of Lane et al. (1997), in their statistical study of watersheds in the United States and Australia where watershed area was an important predictor variable correlated with sediment yield.

The relatively high density of streams in both watersheds contributes to efficiency of sediment transport. In addition, it has been observed that streams (especially in large watersheds) often serve to temporarily store sediment eroded from surrounding slopes, and this can lead to inexact estimates of sediment yield derived from reservoir sediment thickness (Young et al., 2001). However, observations of the streambed entering both Lee Creek Reservoir and Lake Shepherd Springs indicated that little fine-grained sediment (sand-sized or smaller) is being stored in these streams; the streambeds of both Lee Creek and Frog Bayou were bedrock (primarily sandstone) outcrops or very coarse (cobble-sized) gravel.

In comparing sediment yields and sediment fluxes into these two reservoirs relative to watershed physiography, it became clear that simple estimates of long-term average sediment accumulation were poor descriptors of watershed-scale processes. Thus, in developing management schemes for these two reservoirs, the complex interplay of a number of factors must be considered. However, since watershed slopes appeared to be the dominant determinants of sediment yield, management of these reservoirs should include plans to mitigate against significant slope enhancement. For instance, reduction of forest cover is likely to trigger more dramatic increases in sediment flux to Lake Shepherd Springs than Lee Creek Reservoir because 33% of slopes within Lake Shepherd Springs watershed are >10° whereas more modest sediment flux changes would likely accompany reduction of forest cover in Lee Creek watershed where 94% of slopes are <10°.

For the near future, watershed physiography of both Lee Creek Reservoir and Lake Shepherd Springs will remain unchanged. However, continued population growth in northwest Arkansas may be attended by dramatic changes in land use or land cover, especially as development expands into a larger suburban to pseudo-rural base along major transportation corridors. In addition, competing activities on multipurpose forestland, especially timber harvesting within the Ozark National Forest, may have the most impact on future sedimentation trends in these reservoirs. Results of this study provide an important baseline of the sedimentation status of each reservoir, and also provide context for understanding effects of future sedimentation on the evolution of water quality, though discussion of water quality issues are beyond the scope of the present work. Further studies and implementation of long-term monitoring of sediments and water quality will provide bases for development of sound management practices aimed at conserving surface water resources in this environment of rapid population growth.
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REFERENCES


