Comparative Analysis of Watershed Erosion, Reservoir Sedimentation and Sediment Trace Metals in Two Virginia Lakes

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Introduction

Two contrasting reservoirs in Virginia were studied to compare their environmental evolution based on watershed erosion, reservoir sedimentation and trace metals variations. Lake Moomaw, located in the Blue Ridge Mountains, is a pristine reservoir with extreme slopes surrounded by undeveloped, protected land. Lake Pelham, located in Culpeper County, has a more developed area consisting of agriculture, industry, and numerous human developments. Watershed erosion rates in the two basins were estimated by the Revised Universal Soil Loss Equation (RUSLE) and sediment delivery ratios (SDRs). Three sediment cores from each reservoir were used for ^{210}Pb based sediment accumulation rates estimates, as well as trace metal analysis. Metals sediment Enrichments was calculated relative to background concentrations. Acoustic geophysical surveys were also conducted to quantify spatial variations in sediment thicknesses and bathymetry of the reservoirs.

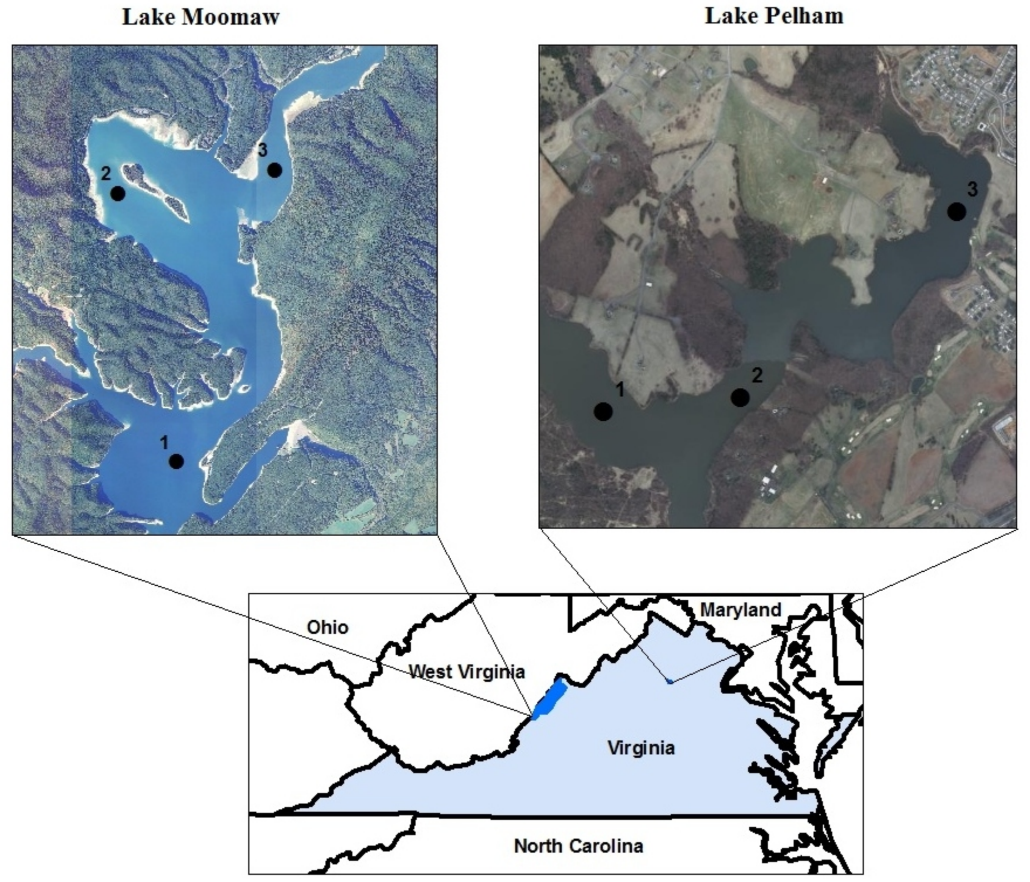

Figure 1. Location map for the two study areas. Lake Moomaw lies close to West Virginia in the George Washington National Forest and Lake Pelham lies within Culpeper County. The numbers 1-3 correspond to core sampling sites.

Methodology

Watershed Spatial Erosion Analysis

The watershed erosion analysis was based on the widely used Revised Universal Soil Loss Equation (RUSLE) (Jones et al 1996; Renard et al. 1997). The RUSLE model is expressed in the following equation:

$A = R x K x L x S x C x P$

Where A is the annual soil loss in tons /acre/ year from sheet, rill, and interrill erosion, R is the rainfall-runoff erosivity factor, K is the soil erodability factor, LS is the slope length/gradient factor, C is the land use land cover factor, and P is the support practice factor.

The LS factor for watershed slopes was computed using the following equations:

$L = (k / 22.1)^m$

where k is the projected distance in meters between the onset of runoff and the point where deposition or flow channelization occurs, 22.1 is the RUSLE unit plot length (in meters), and the m superscript is a variable slope-length exponent.

$S = 10.0 \sin \theta + 0.03$ for slopes <9%

$S = 16.8 \sin \theta - 0.50$ for slopes ≥9%

where θ is the slope angle (Renard et al. 1997).

Geophysical Survey

The geophysical survey of the lakes was conducted using an EdgeTech SB-216S Full Spectrum Sub-Bottom Tow Vehicle coupled with the EdgeTech 3100 Portable System using CHIRP (Compressed High Intensity Radar Pulse) technology over a range of frequencies (2-16kHz). The multi-frequency system allows for wave penetration to different depths to estimate sediment thicknesses and sediment accumulation rates. Each ping records a GPS location and GIS was utilize to analyze and map the data.

Isotopic Sediment Accumulation Rates Analysis

The ^{210}Pb analysis is based on the method of Eakins and Morrison (1978) in which ^{210}Po is distilled out of sediments at a high temperature, digested by acid, and then plated onto silver discs for alpha spectrometry analysis. The regression model based on Matsumoto and Wong (1977) and Odhiambo and Ricker (2012) was used in sediment accumulation rates and chronology estimates. The model is based on the following assumptions: ^{210}Pb flux to the sediments is constant over the time interval being considered; ^{210}Pb does not or minimally migrates after deposition; the accumulation rate of sediments is constant over time. The constant rate supply (CRS) model was also applied, which allows for variable sedimentation rates at different depths and dates. CRS model is detailed in Nriagu et al. (1979) and Appleby and Oldfield (1978).

Trace Metal Analysis

The concentrations of sediment trace metals were analyzed based on the method of Zwolsman et al. (1993), where one gram of dry sediment was digested in 20mL of aqua regia acid solution (3HCl: 1NO3: 3H2O) in a 90°F water bath for 2 hours, left on a shaker overnight, and centrifuged for 3 hours. The leachate for each sample was then diluted to 3% solution using nanopure ultra deionized water. Analysis of nine trace metals, Fe, Al, Ba, Cd, Cr, Cu, Pb, Mn, and Zn was done using a Thermoscientific iCAP 6000Series ICP-OES set at the appropriate wavelength.

RUSLE/SDR Results

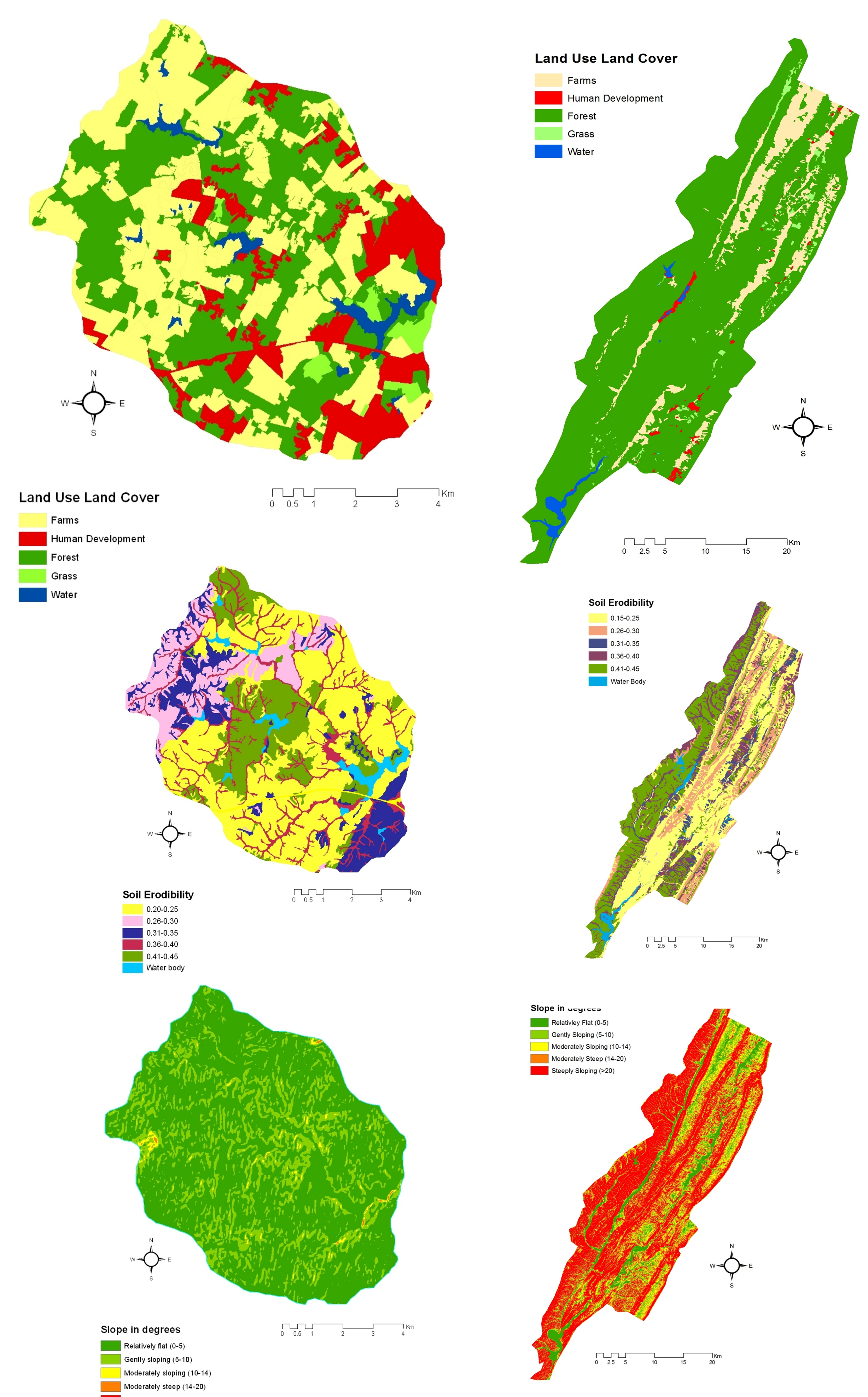

Figure 2. A-B. LULC maps for both watersheds, created from 2008 Digital Orthographic Images (DOQs) from USGS Seamless Data Warehouse. C-D. Soil erodibility maps for both watersheds, created from USDA Soil Data Mart soil surveys. E-F. Slope maps for both watersheds, created using Digital Elevation Models (DEMs) from USGS Seamless Data Warehouse.

Table 1a RUSLE/SDR* sediment flux estimates: Lake Pelham, VA

Land use designation	2008 land use		Pristine land use	
	LULC (%)	Annual sediment flux (Mg/y)	LULC (%)	Annual Sediment flux (Mg/y)
Forest	41.2	1463.1	100.0	2739.8
Agriculture/Pasture	40.5	10123.7	0.0	0.0
Human Development	14.3	1416.9	0.0	0.0
Grass	4.1	900.1	0.0	0.0
Totals	100.0	13903.3	100.0	2739.8
Totals per unit area (ha)	6470.7 ha	2.15 Mg/ha/y	6470.7 ha	0.42 Mg/ha/y

Table 1b RUSLE/SDR* sediment flux estimates: Lake Moomaw, VA

Land use designation	2008 land use		Pristine land use	
	LULC (%)	Annual sediment flux (Mg/y)	LULC (%)	Annual Sediment flux (Mg/y)
Forest	85.9	203041.8	100.0	208971.0
Agriculture/Pasture	11.9	22192.7	0.0	0.0
Human Development	1.0	2702.2	0.0	0.0
Grass	1.2	11877.8	0.0	0.0
Totals	100.0	239814.6	100.0	208971.0
Totals per unit area (ha)	88255.00 ha	2.72 Mg/ha/y	88255 ha	2.37 Mg/ha/y

* SDR 0.341 for Lake Pelham and 0.237 for Lake Moomaw

The RUSLE/SDR erosion model estimates 2.149 Mg/ha/yr for Lake Pelham, which is a 410% increase from pristine conditions. For Lake Moomaw, 2.717 Mg/ha/yr of erosion was estimates, which is a 13% increase from pristine conditions.

Geophysical Sediment Accumulation Results

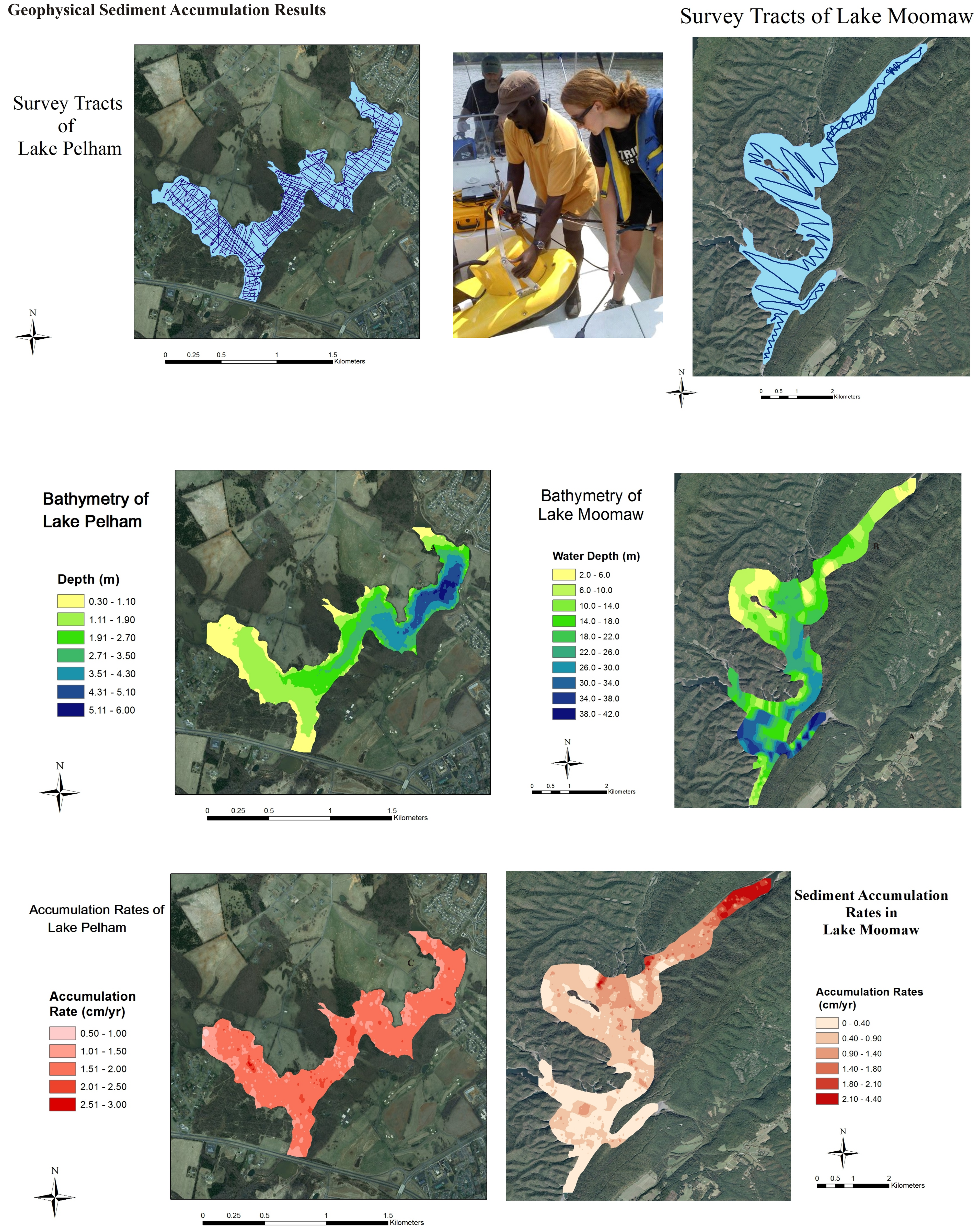

Figure 3. A-B. Survey tracts for the two reservoirs showing lake survey coverage. C-D. Bathymetric maps of the two reservoirs, created using 2500 data points for Lake Moomaw and 3500 data points for Lake Pelham. E-F. Sediment accumulation maps of the two reservoirs produced by dividing the sediment thickness by the reservoir age in years.

Table 2. Comparison of common characteristics for the two reservoirs.

	Lake Pelham	Lake Moomaw
Age (at survey)	40 years	34 years
Surface Area	0.896 km^2	10.23 km^2
Average Depth	2.3m	15.9m
Average Sediment Thickness	60.5cm	20.3cm
Capacity	2.53x10^6 m^3	1.42x10^8 m^3
Sediment Volume	4.94x10^5 m^3	2.28x10^6 m^3
Sediment Flux	12,350.5m^3/yr	67,007.6m^3/yr
Average Sediment Accumulation Rate	1.514cm/yr	0.599cm/yr

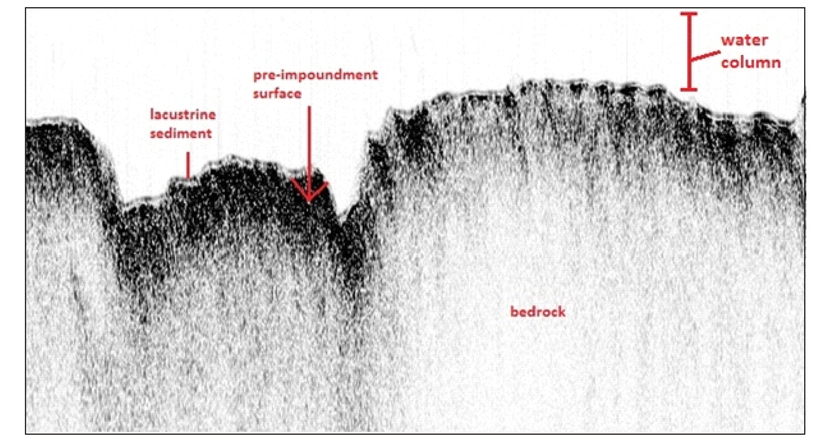

Figure 4. Sample of survey output from Lake Moomaw showing sediment thicknesses, pre-impoundment soil horizon, and bedrock.

^{210}Pb Sediment Accumulation Results

Table 3a Pb-210 Sediment Accumulation Rate Models: Lake Pelham, VA (units are g/cm²/yr)

Lake Pelham	Core 1	Core 2	Core 3	Average
Pb-210 Regression Model	0.343	0.692	0.482	0.506
Pb-210 CRS Model	0.288	0.386	0.371	0.348

Table 3b Pb-210 Sediment Accumulation Rate Models: Lake Moomaw, VA (units are g/cm²/yr)

Lake Moomaw	Core 1	Core 2	Core 3	Average
Pb-210 Regression Model	0.604	0.335	0.402	0.447
Pb-210 CRS Model	0.295	0.230	0.212	0.246

The average ^{210}Pb-based sediment accumulation rates were 0.348 ±0.053 g/cm²/yr for Lake Pelham and 0.246±0.043 g/cm²/yr for Lake Moomaw.

Trace Metal Enrichment Factors

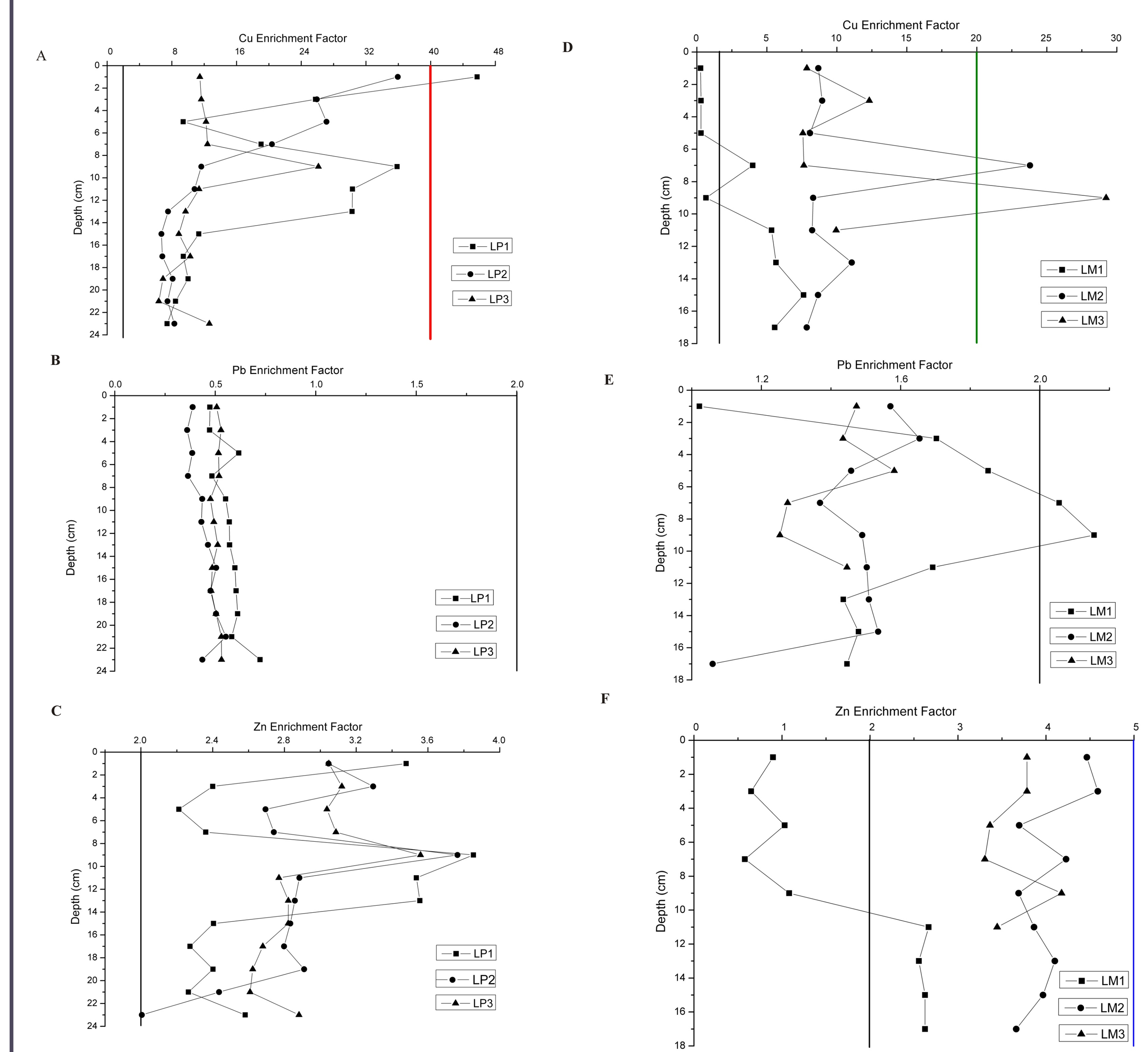

Figure 5. A-f- Plots showing the metal enrichment factors for the main anthropogenically input metals of Cu, Pb, and Zn for the two reservoirs.

<2 Enrichment deficient, 2-5 Moderate enrichment, 5-20 Significant enrichment, 20-40 Very high enrichment, >40 Extreme enrichment (Mmolawa 2011).

Conclusions

Overall, Lake Moomaw has relatively low accumulation rates and erosion rates due to the pristine nature of the watershed, but is also more vulnerable due to the steep slopes that characterize the basin. Comparatively, Lake Pelham has higher erosion rates, sediment accumulation rates and high metal enrichment of Cu and Zn, which directly reflects the impact of human development and industry on reservoir sedimentation.

Acknoweldgements

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