Use of Reservoir Sediments to Determine Sediment Yield

A Research Paper Presented

By

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Abstract

The Waterbury Reservoir, located in Waterbury, Vermont, was drained in the summer of 2002 for dam repairs, providing a unique opportunity to study reservoir deposits. A pilot study was conducted on the East Branch to determine sediment yield from the surrounding watershed. With the low water level I was able to take transects of cores across the reservoir floor and calculate a rate of sediment yield. Samples taken from the reservoir were also used to determine bulk densities. A map interpolation program was used to estimate volume of the reservoir deposits and a geographic information system was used to delineate the watershed for the study area. Net volume of reservoir sediment was calculated to be 434225m^3. The sediment yield rate for this reservoir was found to be 215t/km^2/year, which is high in comparison to other studies of watersheds of similar area. Land use and precipitation were assumed to be the dominant sediment sources, thus impacting erosion rates and sedimentation.

Introduction

Reservoirs have the potential for a variety of uses, including flood control, water supply, recreational activities, and water power, but are susceptible to filling with sediment due to erosion in the watersheds they impound. Erosion rates are significant when looking at reservoirs because they determine how much sediment gets deposited into the reservoir and how quickly. However, there are multiple factors that affect rates of erosion, particularly land use changes and precipitation, which greatly influences the type of sediment that gets deposited. Ultimately, the sediment that reaches the reservoir bed will reflect the transport energy in the catchment, availability of sediment for erosion, and any time lags in the system as material moves toward the reservoir via temporary sediment storage zones such as floodplains and deltas (Dearing, 1991). There are several ways to document rates of sedimentation into reservoirs, including isotopic dating and coring studies. This information can then in turn be used to mitigate erosional processes so as to prevent the reservoir from filling to its storage capacity.

Consequently, erosion and sedimentation are topics of interest to many scientists and land managers because they are ongoing processes that can be potentially harmful to ecosystems. Studies are needed to better understand erosion and sedimentation in order to figure out aspects or practices that increase these processes. Reservoirs are particularly useful for this because often they maintain an intact record of sediment deposition for the surrounding watershed that can be explored further and studied in great detail

Factors Affecting Rates of Erosion

Many scientists have considered reservoir sedimentation and land use in order to determine chronologies of sediment deposition and identify any major land use changes. Consequently, a major cause of sedimentation in small rural reservoirs (<100 ha) is the use of land for agricultural purposes (McIntyre, 1993). In a study by McIntyre (1993), several land use categories were compared from an Oklahoma agricultural reservoir watershed system as potential sediment sources. The study concluded that abandoned fields with gullied bare-soil areas were considered to have the greatest potential as sediment sources, whereas perennial pasture and forest lands were not considered to be significant sediment sources (McIntyre, 1993). Royall (2000) looked at a small Appalachian watershed where a small patch of forest had been cleared but did not appear to alter sediment yield; thus also concluding that forestlands are not significant sediment sources.

On the other hand, other studies that have explored the impact of land use on sedimentation have contradictory results. According to Foster and Walling (1994), pasture areas represented the dominant source of sediment due to an increase in livestock numbers and grazing intensity in the catchment of the reservoir. In addition, an increase in sediment delivery is also the result of documented hedgerow removal that has taken place since 1973 because it has increased the average field size (Foster and Walling, 1994). In another study, where the dominant land use is forestry, activities associated with logging are one major source of sediment since logged land is susceptible to erosion (Ambers, 2001).

Consequently, land use is not the only factor that affects rates of erosion. Many studies have been conducted that suggest precipitation is a leading cause of increased rates of erosion and sedimentation. In a study by Royall (2000) for example, land use effects on sediment yield were found to be inconsequential in comparison to those related to hydrologic event history. By looking at precipitation records, Royall (2000) was able to conclude that high magnitude events are more important to total sediment yield in small basins where discharge and velocity remain below the sediment transport threshold for a larger part of the year and moderate events accomplish most geomorphic work over the long run. Ambers (2001) also found that sediment yield is controlled primarily by flood magnitude and frequency, with the bulk of sediment transportation to the reservoir occurring during large floods. Conversely, Foster and Walling (1994) have found that high magnitude, low frequency events are of relatively limited importance to the pattern of sediment yield from the catchment.

Other small watershed studies indicate that the condition of a watershed at the time of a storm event strongly influences the amount of erosion that occurs because hillslopes can be pushed over the failure threshold, which triggers mass movement (Ambers, 2001   Noren and Bierman (2001) observed distinctive characteristic coarse layers in multiple cores that correspond to approximate dates of large storms that passed over the lake's drainage basin, ultimately leading them to believe that they originated as terrestrial sediment that eroded from uplands during severe storm events. In general, the ages of terrigenous layer deposition in separate lakes suggest that most storms of great intensity or duration affected localized areas and that the most severe Holocene storms for the northeast region were probably small, highly intense storm cells capable of devastating effects (Noren and Bierman, 2001). Bosley et al. (2001) discovered through analyses of sediment cored from Lake Morey in Fairlee, Vermont that storms happen in a cyclical manner, separated by long periods of relatively quiet, low energy depositional environments. In addition, through research conducted at the Coweeta Experimental Forest in Virginia, it was discovered that in trunk streams the majority of sediment gets transported in effective discharge events that recur on average every 1.5 years and headwater streams require extreme and infrequent precipitation events to generate effective discharge (Kavage, 2001).

Methods for Documenting Sedimentation into Reservoirs

Physical, chemical, biological, and magnetic analyses, with data for accumulation rates, have been used in a range of environmental settings to infer the rate, form, cause, and source of erosion (Dearing, 1991). More specifically, mineral magnetic characteristics and Cesium (Cs)-137 activity are the two most widely used methods for dating sediment and determining sediment sources. There are however several other approaches for analyzing sediment deposition such as the spud survey, examining core stratigraphy, and using bathymetry. In general though, all analyses begin by taking cores, or vertical, tubular samples of the sediment.

Coring and sediment profile stratigraphy have been widely used to study sediment deposition in lakes, ponds, and reservoirs. In one case, by examining the stratigraphy of sediment cores, information was obtained about variations in the sediment yield of the watershed (Ambers, 2001). In a study by Royall (2000) sediment cores were collected in 5.8 cm diameter plexiglass tubes at 28 locations across the lake surface and bulk density was measured using loss on ignition for three master cores. In order to obtain representative coverage of the sediments in Gallie Pond, sampling sites were selected systematically using a series of transects two meters apart (Souch and Slaymaker, 1986). Similarly, a coring apparatus consisting of a 1.83-meter length of extruded plastic piping was driven into the sediment using a mallet in order to obtain sediment samples. In total, 26 cores were collected and bulk densities were determined in the lab for a number of the cores (Souch and Slaymaker, 1986). Royall (2000) used functions in Surfer to calculate volume and mass whereas Souch and Slaymaker (1986) used the more traditional method of using different grid sizes to base calculations.

Bathymetric surveys provide a mean for determining sediment deposition in lakes and reservoirs, which depends on measuring changes in contours of a water body over time and linking them to an accurate base map. Bottom contours can be measured with a sonic depth recorder and then compared to prior contours to estimate changes (Ritchie et al., 1985). This method also has some advantages but has not been seen as widely used given the literature. One example is in a study by Royall (2000), where routine water depth measurements were made at grid intersections so the lakes bathymetry could be mapped.

Ritchie and McHenry (1985) propose another method that they perceive to be commonly used, known as the spud survey, which involves throwing the "spud" with enough force so it penetrates vertically through the deposited sediment. The spud is a steel rod six feet long and 1.5 inches in diameter at the rim with grooves spaced at intervals one-tenth of a foot, then each groove tapers outward. As the spud is pulled from the ground, sediment is collected in the grooves and then later examined to determine depth to interface between the deposited sediment and underlying soils (Ritchie et al., 1985). There are several advantages to this method that include: it can be carried out in any water covered sediment; no other information is essential for interpreting the results; and it is a quick and simple method for measuring the total depth of sediment accumulation (Ritchie and McHenry, 1985). There are however limitations with this approach as well. For instance, experience is needed in order to discern the interface between deposited sediment and underlying soils, the spud cannot penetrate sediments that have dried, and sample sizes are insufficient for physical measurements (Ritchie and McHenry, 1985). In a study by Ambers (2001) a spud was used from a boat on the low pool with a grid spacing of approximately 120 meters and thickness on the exposed lake bottom was measured with a coring device.

The two most common dating techniques include magnetic susceptibility and Cs-137. Magnetic susceptibility is the measure of the concentration of magnetic minerals in a substance and can be used as a tracer and correlation tool (Royall, 200). It works primarily by establishing a relationship between sediment magnetism and particle size, which allows for evaluation of sediment yield frequency and magnitude. In a study by Royall (2000), magnetic profiles from the sediment cores were used to correlate sediment sequences from different parts of the lake and magnetic susceptibility was used to measure particle size distributions. Cs-137 is a radioactive isotope produced during nuclear fission and has been distributed around the world by fallout from above ground nuclear weapons tests (Ritchie and McHenry, 1985). It acts as a tracer and is especially unique because there are no natural sources. It works by measuring spatial patterns of Cs-137 in vertical and horizontal planes across the landscape so rates of soil loss or depletion can in turn be measured for different parts of the watershed (Ritchie and McHenry, 1990). Cs-137 is used ubiquitously in scientific research (Foster and Walling, 1995; McIntyre, 1993) as a means of dating sediment horizons and correlating cores.

Rates of Sediment Yield

Originally sediments were well sorted and primarily derived from instream sources or hillslope failures, such as debris flows and landslides; but this changed as humans altered their land use patterns on local and regional levels, so that now increased sediment from surface runoff and erosion produces a major impact on rates of sediment yield within watersheds (Kavage, 2001). During the 29-year life of Thompson Lake Reservoir, a small reservoir in northern Virginia, a low value sediment yield was established, which is consistent with low values for fully forested watersheds in the eastern United States (Table 1) (Royall, 2000). In addition, this value is also consistent with other estimates for nearby areas of the Maryland Piedmont (Table 1). However, Allmendinger and Pizzuto (2000) determined an annual sediment yield that is slightly higher (Table 1 Conversely, in the Good Hope watershed, urbanization is the major cause of sedimentation, thus accounting for the higher rate of sedimentation. Other studies were also done that produced a wide range of sediment yield values (Table 1). The Thompson Lake reservoir was sectioned into three zones, zone 1, 2, and 3, with corresponding volumes of 1758m^3, 945m^3, and 532m^3 respectively and bulk density was around 0.3 to 0.4g/cm^3 (Royall, 2000). The low sediment yields for zone two correspond to below average precipitation for that time as well as a low maxima 24-hour precipitation (Royall, 2000).

Statement of Objectives

The purpose of this report is to determine a rate of reservoir sediment deposition for a flood control reservoir in Northeastern Vermont and compare this value to other drainage basins. Understanding and knowing sedimentation rates is useful at the Waterbury Reservoir because few local records exist documenting decadal scale sedimentation rates, and development in the region will likely increase erosion rates in the watershed. Also, having a volume estimate for sediment currently stored in the reservoir will enable scientists, planners, and land managers to determine storage capacity and the life of the reservoir.

Methods

The Waterbury Reservoir is located in Waterbury, Vermont and can be accessed by Reservoir Road or Moscow Road (Figure 1). It is located approximately 30 miles south of Burlington, Vermont and a quarter mile west of route 100. The reservoir was formed by an earth filled dam, which was originally built in the summer of 1937 by the U.S. Army Corps of Engineers partly for flood control but mostly as a make work project during the depression. The dam impounds a drainage area of 282.3km^2. The reservoir includes the main lake, which impounds water from the Little River, draining the eastern slope of Mount Mansfield and the Stowe valley, and the East Branch, which drains several tributaries to the southeast. This study focused on the East Branch of the reservoir.

From late spring to early fall, the reservoir is maintained to a surface area of 860 acres and a maximum depth of 100 feet. This surface area is reduced to between 250-300 acres in winter to prepare for spring snow melt (Vermont State Parks, 2003). The reservoir was drained in the summer of 2002 so construction could be undertaken on the dam, affording us the unique opportunity of measuring the amount of reservoir sediment in order to calculate an overall deposition rate. There is still some water flowing through the channel, but this river is extremely shallow and only two to three meters wide. The reservoir sediment itself is dark gray clay that is extremely smooth, fine grained, and uniform in color and texture.

In order to cover an area and get repeated samples, we measured across the river in transects. A transect in this case simply implies a straight line from which points were sampled. Each transect was numbered and then the points taken from those transects were numbered with subscripts, respectively. In order to collect data randomly, sampling was begun at a random point in the middle of the reservoir (systematically) and then additional samples were taken approximately every 20 to 40 feet. To georeference sampling points, a GPS was used to mark the sites where samples were collected and to calculate distance between transects. To collect samples of reservoir sediments, we used a gouge auger, which is a meter long metal semicircular tube with a meter long handle. The corer was thrust into the sediments until a gravel surface was detected or to the point of maximum manual penetration. Visual analysis of the extracted core was used to distinguish post reservoir sediments, such as color and texture.

Samples of 11 cores were retained for determination of bulk density. Samples were collected and brought to a lab where they were weighed, baked over night at 105°C, and then the dry weight was recorded. The bulk densities were calculated by dividing the mass by the volume, where mass is the dry weight minus the initial weight and volume is the length multiplied by the cross sectional area of the corer ($16.78 cm^2$)

A net volume of sediment in the East Branch was calculated using Surfer, a three-dimensional map interpolation program. Net volume is calculated as the average of the three values for volume produced in the output view in Surfer. These volumes were approximated using three classical numerical integration algorithms that include the Trapezoidal Rule, Simpson's Rule, and Simpson's 3/8 Rule, all of which define volume as a function under a double integral (Golden Software Inc., 1999). In Surfer, volume is computed by first integrating over X (columns) to get areas under the individual rows and then by integrating over Y (rows) to get a final volume (Golden Software Inc., 1999). The estimated sediment volume (√) was converted to mass (m) using the average bulk density (ρavg) value for the analyzed cores, according to the following formula: m=ρavg*√

The watershed for the East Branch of the Waterbury Reservoir was delineated using a geographic information system, using a digital elevation model of the study area A digital elevation model (DEM) for the area was downloaded from the Vermont Center for Geographic Information (www.vcgi.org) website. Orthophotographs of the reservoir were used to extract the region surrounding the reservoir. Prepro 04 (Olivera, 1999), an ArcView extension written for hydrologic feature extraction, was used to perform GIS functions. The watershed delineation process involves creating a flow direction grid from the digital elevation model. The flow direction grid was used to derive a flow accumulation grid using standard ArcView algorithms available through Prepro. A stream network was derived from the flow accumulation grid and used to select the outlet along the stream network for delineating the watershed draining the East Branch of the reservoir.

Sediment mass was calculated for the cores chosen to use for bulk density. A basin sediment yield was determined by dividing mass of the reservoir sediments by watershed area. This term was divided by 66 years (time since reservoir construction) to get an annual average yield. Annual yields were compared to other studies conducted in New England and elsewhere

Results

The survey covered an area in the East Branch of Waterbury Reservoir approximately 12000m long using 23 transects that ranged from one to 295 meters wide (Figure 1 and Table 2). Extracted sediment cores showed that sediment deposited since reservoir construction ranged from 8 to 132 centimeters, with thicker deposits in the downstream direction (Table 2). Bulk density of the 1 extracted cores ranged from 0.3 to 1.50 g/cm^3 with an average bulk density of 0.55g/cm^3 (552.9kg/m^3) (Table 3) (DeMayo, 2003).

The watershed area delineated on the digital elevation model is 16.9km^2 (Figure 2). The area includes the main tributary of Thatcher Brook and several smaller tributaries that enter the reservoir from the north and south banks. This watershed area is approximately 6% of the total area drained by the Waterbury Reservoir. Interpolated volumes of sediment using the three Surfer procedures range from 434,181 to 434,226 m^3. This survey and results of the map interpolation analysis indicate there is at least 434,225m^3 of sediment stored in the East Branch of the reservoir. Using the average bulk density of extracted samples, this equates to 240,083,003kg (240,083 tons). Over the 66-year life of the reservoir, these estimates indicate an annual sediment yield of 215t/km^2/year.

Discussion

The rate of sediment yield for a watershed of this size appears to be unusually large in comparison to other studies, yet average bulk density appears to coincide with values from other studies. There are however other factors that affect erosion and runoff for this watershed that might heavily influence the amount of sedimentation. For instance, this is not a fully forested watershed and land use contributes greatly to erosion; thus, an explanation for the high sediment yield could be gained through exploring land use more closely. One way to do this would be to conduct magnetic susceptibility or Cs-137 analyses on cored samples and make correlations between cores. In addition, precipitation patterns for the area should be studied in greater detail because there is evidence in the cores that suggests several large storm events have occurred in the vicinity. Storm events affect rates of erosion, resulting in increasing sedimentation. Due to the large mountain and geographic location of the region, there is an abundance of precipitation as well as spring snowmelt. All of these conditions do play a part in affecting erosion and ultimately the rate of sediment deposition in the reservoir. Since the rate of sedimentation is already extremely high for this reservoir, future construction will definitely impact erosion and further increase the rate of sedimentation. This in turn will have major consequences for the reservoir because it will fill to storage capacity before it should, thus eliminating its usefulness in flood control

Source	Location	Yield (t/kg^2/yr)
Royall, 2000	Thompson Lake Reservoir, No. Virginia	8.3
Royall, 2000	Maryland Piedmont	40
Allmendinger and Pizzuto, 2000	Good Hope Tributary, Montgomery Co., MD	44
Matmon et al., 2003	Great Smokey Mountains	73
Roberts and Pierce, 1976	Patuxent River	344

Table 1: Comparative review of sediment yields from various studies

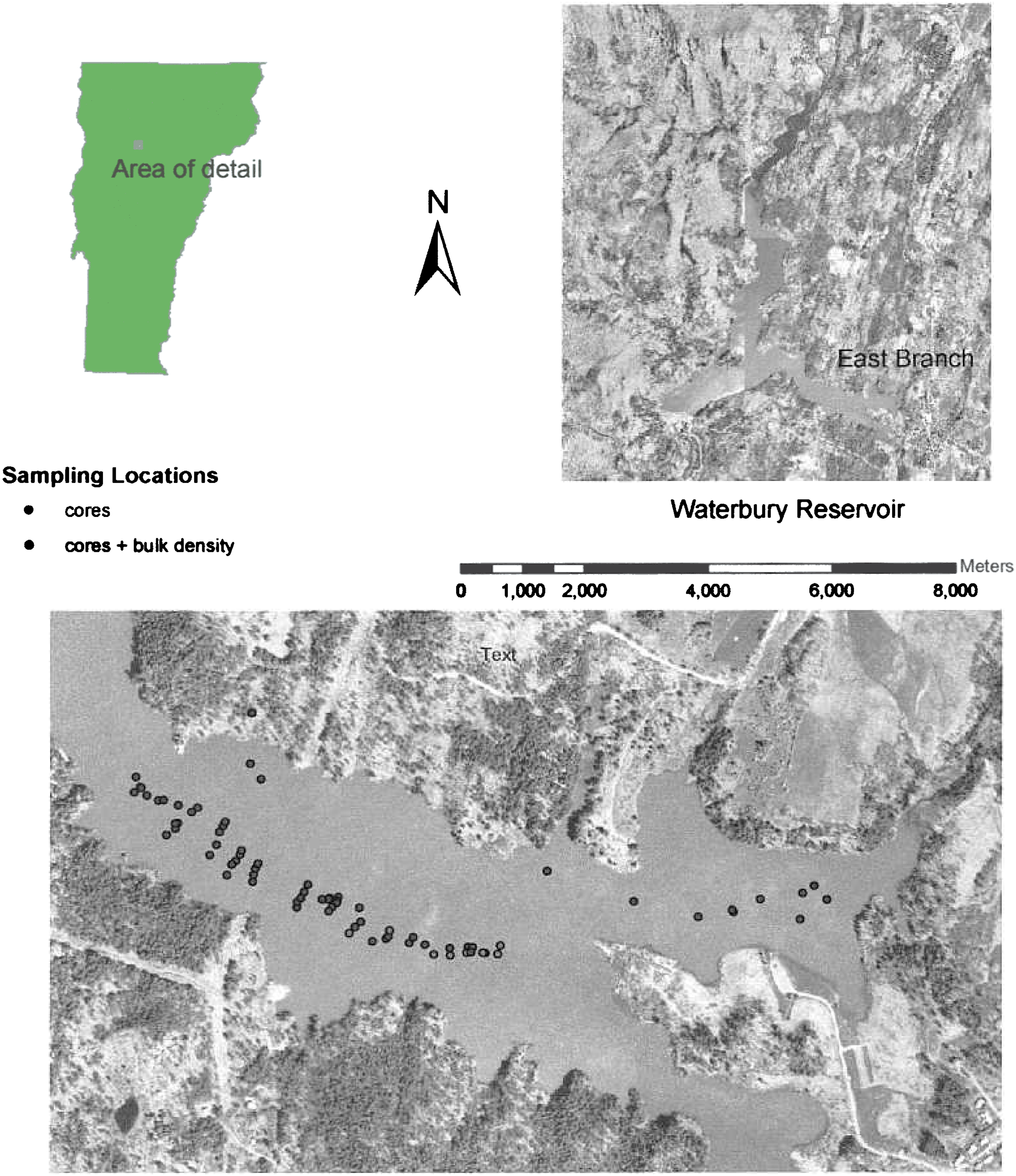

Figure 1: Location map of the East Branch of Waterbury Reservoir in Waterbury, Vermont. Sample points of coring locations are shown.

Point Name	Longitude (utm)	Latitude (utm)	length of reservoir sediment (cm)
1.1	679839	4916789	29
1.2	679849	4917001	35
1.3	679840	4916803	94
1.4	679843	4916816	34.4
1.5	679848	4916826	37.4
2.1	679811	4916844	117
2.2	679814	4916853	64
2.3	679803	4916830	96
2.4	679795	4916823	45
2.5	679826	4917032	31
2.6	679786	4916801	105
3.1	679751	4916841	59
3.2	679763	4916863	61
3.3	679769	4916889	67
3.4	679775	4916902	94
3.5	679779	4916911	72
3.6	679826	4917136	162
4.1	679684	4916905	123
4.2	679679	4916894	153
4.3	679662	4916880	45.6
4.4	679684	4916942	129
4.5	679679	4916904	58
5.1	679597	4916998	93
6.1	679594	4916966	88
6.2	679606	4916978	80
6.3	679608	4916976	105
7.1	679620	4916961	141
8.1	679643	4916951	117
8.2	679654	4916952	50
9.1	679711	4916929	127
9.2	679723	4916938	132
10.1	679929	4916739	117
10.2	679930	4916750	8
10.3	679937	4916759	73
10.4	679943	4916771	61
10.5	679950	4916786	72
11.1	680012	4916763	48
11.2	680011	4916755	23
11.3	680009	4916750	42
11.4	680000	4916741	80
11.5	679994	4916733	27
st1	679995	4916760	116
st2	679992	4916758	109
st3	679980	4916757	125
12.1	680037	4916689	62
12.2	680048	4916702	70
12.3	680055	4916742	23
12.4	680059	4916713	32
13.1	680084	4916674	52
13.2	680111	4916680	26
13.3	680115	4916685	78
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
15.1	680242	[illegible]	[illegible]
15.2	**680240**	[illegible]	[illegible]
16.1	680277	4916668	[illegible]
16.2	**680275**	**4916656**	**33**
17.1	**680286**	**4916668**	**48**
17.2	**680283**	**4916657**	**26**
18.1	680312	[illegible]	[illegible]
18.2	**680308**	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
21.1	680190	4916670	[illegible]
22.1	**680950**	**4916798**	[illegible]
22.2	680972	[illegible]	[illegible]
22.4	**680999**	[illegible]	[illegible]
22.5	680946	4916744	[illegible]
22.7	**680865**	**4916783**	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
23.2	680808	[illegible]	[illegible]
23.3	680740	4916743	[illegible]
23.5	**680609**	**4916771**	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]

Table 2: Table of point names, coordinates (in utm), and thicknesses of reservoir sediment from various surveyed locations at the Waterbury Reservoir in Waterbury, Vermont.

sample id	mass (g)	length (cm)	volume (cm^3)	bulk density
13.4	455.4	55	922.9	0.49
12.1	280.4	35.2	590.7	0.47
n of steve	251.7	50	839	0.3
n of steve	330	50	839	0.39
15.1	165.4	21.5	360.8	0.46
19.2	241.8	29.1	488.3	0.5
16.2	461	57.2	959.8	0.48
18.2	328.1	39.8	667.8	0.49
19.1	637.9	25.4	426.2	1.5
18.1	240	27.6	463.1	0.52
14.1	313	38.8	651.1	0.48

Table 3: Table of core data used to determine bulk density for nine sites along the East Branch of the Waterbury Reservoir. Two samples were taken from Stevenson Brook. Mass and length are measured values. Volume is calculated as length * the cross sectional area of the auger (16.78 cm^2). The average bulk density is 0.55 g/cm^3 (552.9 kg/m^3).

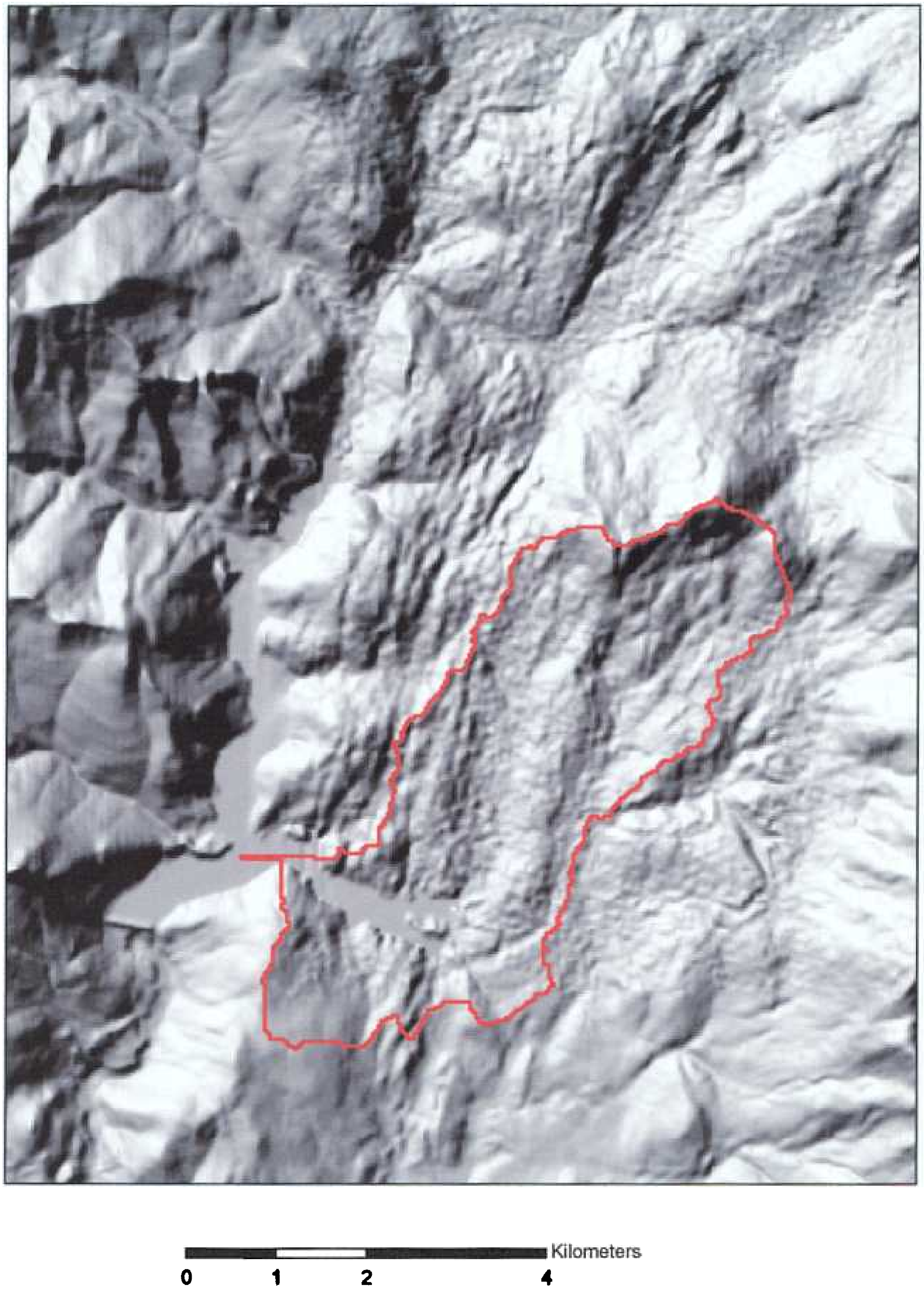

Figure 2: Hillshade map with delineated watershed for the East Branch of Waterbury Reservoir.

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