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History of Sedimentation and Contamination in Valley Mill Reservoir, Springfield, Missouri

Susan S. Licher

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**HISTORY OF SEDIMENTATION AND CONTAMINATION IN VALLEY MILL
RESERVOIR; SPRINGFIELD, MISSOURI**

A Thesis

Presented to

The Graduate College of
Southwest Missouri State University

In Partial Fulfillment

Of the Requirements for the Degree
Master of Science, Resource Planning

By

Susan S. Licher

December 2003

HISTORY OF SEDIMENTATION AND CONTAMINATION IN VALLEY MILL RESERVOIR; SPRINGFIELD, MISSOURI

Geography, Geology, and Planning

Southwest Missouri State University, December 2003

Master of Science

Susan S. Licher

ABSTRACT

The Valley Mill Reservoir (VMR) was constructed between 1851 and 1871 and drains an important recharge area of the drinking water watershed for Springfield, Missouri. Presently, management efforts to protect downstream water quality are aimed at using VMR as a non-point pollution and sedimentation basin since its watershed is planned for continued urban development. The morphometry of VMR is typical of most reservoirs with an elongated basin and the deepest point being near the dam. Sedimentation within the reservoir has created a delta formation with upstream wetlands and floodplains acting as part of the delta especially during the past. Little evidence is found to indicate that resuspension and sediment focusing is occurring after initial deposition. Sedimentation rates ranged from 0.4 to 1.6 cm/yr from 1871 to 1954, while from 1954 to 1964 sedimentation rates increased dramatically ranging from 2.0 to 5.5 cm/yr. Then from 1964/69 to 1978, rates decreased to 0.7 to 1.9 cm/yr. From 1978 to 2000, sedimentation rates ranged from 0.3 to 2.1 cm/yr. During 2000, a large storm event left a 2 to 5 cm thick sediment deposit. Post-2000 sedimentation rates stayed high with a range of 2 to 4.5 cm/yr. Core sediments within VMR indicate that land use changes within the watershed have increased P and Zn concentrations in the upper 5 to 65 cm. Lead also increased over background levels but since the late 1970's began decreasing due to the banning of Pb in the environment. Around 1970, after the construction of major highways and increased urban land uses, P, Pb and Zn became enriched over background levels. Initial enrichment of Cu and Hg began much earlier than 1970.

KEYWORDS: reservoirs, sedimentation, contamination, sedimentation rates, and environmental history

This abstract is approved as to form and content

Robert T. Pavlowsky, PhD.
Chairperson, Advisory Committee
Southwest Missouri State University

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CHAPTER ONE – INTRODUCTION

OVERVIEW AND PROBLEM STATEMENT

The effects of human-induced changes on lake sedimentation have been of interest to environmental scientists and managers for quite some time (Brune, 1953; Gottschalk, 1964). It is widely known that lakes function as sediment traps and that agriculture and urbanization tend to increase sediment and pollutant delivery to lakes (Trimble, 1997; Walling, 1999). Thus, lake bottom deposits often contain a stratigraphic record of watershed disturbances and land use changes. Measurements of lake sediment distribution and composition are commonly collected in lake monitoring studies. First, sediments reduce the useful life of the reservoir (Morris and Fan, 1998). Secondly, lake bottom sediments record the pollutants of the watershed because pollutants are adsorbed and incorporated into sediments (Mau and Christensen, 2000). Finally, reservoir sediments are of interest because they record anthropogenic changes within the lake and watershed (Wetzel, 2001).

While water quality data describes watershed conditions at the time of sampling, lake sediment core studies can be used to examine the history of water quality changes over periods spanning years to centuries (Brenner et al., 1999; Wetzel, 2001). In most cases, the sedimentation record of a lake can be easily dated with ^{137}Cs , ^{210}Pb , or ^{14}C (Ritchie and McHenry, 1990; Wetzel, 2001). Sediments and pollutants are relatively stable and immobile in deposits. Thus, lake and reservoir sediments can be used to gain a better understanding of the depositional patterns and processes occurring within the lake and to evaluate the watershed sources and history of contamination. While, lake and reservoir sediments are generally well studied, most of these studies were conducted on

moderately large basins and less is known about shallow lakes and even less about small, shallow reservoirs (Wetzel, 2001). The Valley Mill Reservoir (VMR) is the focus of this study and is unique in that the watershed is a developing watershed in the Ozarks where few scientific studies have been conducted on lake sedimentation and non-point pollutant issues.

This study focuses on describing the temporal distribution and contamination of bottom sediments of the VMR, a small, shallow reservoir. The VMR was constructed in mid-1800 as a wheat mill and was one of the original public drinking water sources for Springfield (L. Bullard, personal communication, 2003). Currently, this area drains an important recharge area of the drinking water watershed for Springfield, Missouri and the reservoir and adjacent land is being planned as an outdoor water quality classroom with the impoundment acting as a pollutant and sediment control (L. Bullard, personal communication, 2003). However, the dynamics of sedimentation and pollutant storage were unknown. Thus, determining the sedimentation rates, patterns, and processes was essential in order to understand how the system was affecting water quality downstream of the reservoir. There were also management concerns related to the in filling of the VMR with fine-grained sediments and the destabilization of channels and the delta area. The VMR reservoir was drained providing a unique opportunity to study the bottom sediments. Assessment of sedimentation processes in VMR is important because sediment quality closely approximates water quality and the pollutant and sediment record for understanding long-term environmental history is contained within the sediments.

PURPOSE AND OBJECTIVES

The purpose of this study is to use sediment properties to determine spatial and temporal distribution of sediments and associated contaminants in VMR. The three main objectives in this thesis research are:

1. *Calculate sediment trap efficiency of VMR.*

The trap efficiency of VMR is important in understanding how the reservoir is acting as a Best Management Practice (BMP) within the watershed and protecting downstream water quality. Trap efficiency, the percent of inflowing sediment that is deposited within the reservoir, was calculated using empirical methods described by Brune (1953) and Heinemann (1981). It is hypothesized that trap efficiency of the reservoir will be high during baseflow conditions due to the fact that no water flows over the dam (Brune, 1953; Heinemann, 1981). During storm events, which produce runoff, the trap efficiency of the reservoir is expected to decrease rapidly (Bhaduri et al., 1995).

2. *Determine the spatial distribution of sediments in VMR.*

Sedimentation patterns and processes are less well understood in small, shallow reservoirs than in larger reservoirs. Determining the spatial distribution of sediments in VMR will indicate the processes of sedimentation. Maps of sediment thickness are utilized in order to understand patterns of sedimentation in the reservoir. It is hypothesized that the spatial distribution of sediments will display a longitudinal delta deposition pattern (Hilton et al., 1986; Morris and Fan, 1998; Striegl, 1987). It is also hypothesized that sediment focusing will occur horizontally and will be a source of redistribution after initial deposition (Crusius and Anderson, 1995; Hilton et al., 1986; Longmore, 1986; Odgaard, 1993).

3. *Evaluate contaminant trends to develop an understanding of the subsurface sedimentation record and sediment properties in VMR.*

Understanding geochemistry and sedimentation of the subsurface sediments is important because it allowed an understanding of how watershed changes have influenced sedimentation rates and properties. The subsurface sedimentation record is analyzed using ^{137}Cs and geochemical signatures. Particle size analysis, organic matter content, pH, geochemistry, and Munsell color are utilized in order to understand how sediment properties have changed through time. First, it is hypothesized that sedimentation rates would decrease over time (Hyatt and Gilbert, 2000; Van Metre et al., 1996). A second hypothesis is that metal and element concentrations would increase over time (Brenner et al., 1999; Charlesworth and Foster, 1993; McCall et al., 1984; Thomas et al., 1984; Williams, 1991).

BENEFITS OF STUDY

The results of this study provide benefits to the Springfield area and to the larger scientific community. This study determines the sedimentation rates and patterns in VMR and reconstructs the sedimentation history of the reservoir over the past 100 years, including temporal variability and disturbances. Locally this study will provide data for educators and help managers implement management strategies to reduce sedimentation, understand the environmental history of VMR, and provide an estimate on the amount and characteristics of fine-grained sediment. It also aids in the understanding of how the VMR is affecting downstream water quality by estimated the amount of sediment trapped from upstream sources. In a broader context, this study will help further the

understanding of the spatial distribution of sediments in shallow reservoirs, which will help managers understand how sedimentation is affecting small reservoirs. Additionally, the use of lake sediments as environmental indicators and as a way to understand the environmental history of a reservoir will be increased.

CHAPTER TWO – LITERATURE REVIEW

The literature review presented here reflects the theory and field methodology used for the research conducted in VMR. The three main topics relevant to VMR and discussed in the following sections are watershed inputs, trap efficiency, and lake sedimentation.

WATERSHED INPUTS

Sediment Sources

Sediment carried in streams and to receiving water bodies is derived from the watershed. There are two main sources of sediment: upland soil erosion and stream bed and bank erosion. Erosion from upland sources is one of the most widely recognized sources of sediments water bodies. Upland erosion occurs when water or wind detaches soil from the land. These eroded sediments carry nutrients and pollutants to waterways and ultimately to the receiving water body (Elliot and Ward, 1995). Stream banks and beds are another source of sediment from within the watershed. Streams naturally oscillate between cutting into banks and channels and depositing these eroded sediments within the same system (Humphrey and Heller, 1995). As the erosion/deposition process occurs, sediment is carried from the sources to the receiving water body.

While erosion occurs naturally, human activities such as agriculture and urbanization can increase or “accelerate” sediment erosion rates by 3 to 100 times or more (Shen and Julien, 1993; Trimble, 1997; Walling, 1995; Walling, 1999). Upland erosion rates can increase due to poor agricultural practices and bare soil exposure during construction phases of development. Human-induced changes within the watershed can also cause streams to readjust to differing sediment load and water velocities which can

increase stream bank, channel, and floodplain erosion (Trimble, 1983; Trimble, 1997). When streams readjust, sediment stored in the channel and on floodplains can become an important sediment source. Additionally, flood frequency and magnitude changes can also affect sediment loads.

Sediment budgets, an accounting of sediment mass and transport within a system, are used to understand the dynamics of the above mentioned sediment erosion, transport, and storage. In a 17 km² agricultural watershed in Minnesota, Beach (1994) found that of the material eroded since the mid-1800's, 47 % was stored in colluvium, 18% was stored in the floodplain, and <35% left the watershed entirely. Historically it has been assumed that the majority of the erosion comes from hill slopes and uplands. For example, in Australia Loughran et al. (1992) found that 97% of the eroded sediment came from cultivated land, with channel sedimentation storing 56% of the eroded soil, and a net sediment yield of 34% in a small drainage basin (1.7 km²). The storage and yield percentages found by Loughran et al. (1992) are very similar to those found by Beach (1994).

However, Neil and Mazari (1993) used empirical sediment yield equations to conclude that approximately 75% of the total sediment yield in Southern Tablelands, New South Wales could be traced back to bank erosion. They conclude that the high sediment erosion rates from channel banks is due to the historical increase in floodplain deposition initially and then channel incision, which increased the surface area of the channel wall susceptible to erosional forces. This increased surface area brought about an increase in the contribution of eroded material from the channel banks. Duijsings

(1987) also looked at stream banks as a sediment source and found that 54% of the sediment yield came from stream banks with 47% came from valley slopes.

Pollution Sources

Pollutants are any substance that may cause environmental or human health harm and may come from either natural or anthropogenic sources. Table 1 shows some common pollutants and their sources. Sediment, metals, and nutrients all occur naturally within the environment. Sediments are derived from the local watershed, streams, and even within the receiving water bodies. Local geology and climate contributes to background levels of trace metals. Nutrients naturally occur in plant and animal tissues and are released to the system through decomposition.

Anthropogenic sources can increase pollution or introduce new contaminants to the system. While nutrients, sediments, and metals occur naturally, anthropogenic factors can lead to increased sediment and increased concentrations of trace metals and nutrients (Hakanson and Jansson, 1983). Anthropogenic sources of contaminants include both non-point and point sources. Non-point pollutants cannot be traced to a single source but rather originate from diffuse areas and are related to land-use and event runoff rates. Sediment is the biggest non-point pollutant and associated with sediments are other pollutants such as trace metals and nutrients (Julien, 1995). Some sources of non-point pollution include vehicular traffic, animal wastes, fertilizers, sediment erosion, and atmospheric deposition (Brinkmann and Goethe, 1985; Charlesworth and Foster, 1993). Point pollution is that pollution which can be traced back to a single, known source. Sources of some point pollution include industrial processing plants, mining, municipal wastes, and landfill sites (Charlesworth and Foster, 1993).

Table 1. Contaminants of Concern and Common Sources

Contaminant	Common sources or uses
<u>Aluminum</u> ^d	One of the most abundant elements in the earth's crust, acid rain and acid mine drainage can cause increases to toxic levels.
<u>Arsenic</u> ^{c,d}	Orchard and forest sprays, naturally occurring in some areas, smelting of copper, lead, and zinc ores.
Benzene ^d	Natural component of crude oil and natural gas.
<u>Cadmium</u> ^{c,d}	Batteries, ceramics, metal coatings, sludge disposal, lead-zinc mines, industrial effluents.
Carbon Tetrachloride ^d	Used in the manufacturing of chlorofluorocarbons.
Chlorinated benzenes ^d	Used in the production of herbicides, pesticides, fungicides, and other organic chemicals.
<u>Chromium</u> ^d	Electroplating and metal-finishing industrial effluents, sewage treatment discharge, chromates from cooling water.
<u>Copper</u> ^c	Electrical industry, plumbing, fungicides and algal control.
<u>Iron</u> ^d	Acid mine drainage, steel and steel alloys, dyes, and abrasives.
<u>Lead</u> ^{c,d}	Leaded gasoline, batteries, plumbing, pigments in paint, insecticides, effluents from industry and mining.
<u>Mercury</u> ^c	Coal and waste combustion, batteries, paint, industrial uses.
<u>Nickel</u> ^{a,d}	Asphalt pavement, brake linings, tires, industrial water discharges.
Nitrate ^d	Fertilizer, sewage, feedlots.
Organochlorine compounds ^e	Used in insecticides.
<u>Phosphorous</u> ^{b,d}	Naturally occurring, fertilizers, municipal and industrial wastewater.
Polychlorinated biphenyls (PCB) ^e	Used in the manufacturing of electrical transformers, plasticizers, hydraulic lubricants, heat transfer systems.
<u>Silver</u> ^d	Mining, electroplating, film processing, batteries.
<u>Zinc</u> ^c	Galvanizing, dyes, paints, pesticides, fertilizers, wood preservatives.

Note: Underlined contaminants were measured in this study.

^a From Brinkmann and Goethe, (1985); ^b Hakanson and Jansson, (1983); ^c Rheume et al., (2001); ^d Evangelou, (1998); ^e Kalkhoff and Van Metre (1997).

Currently, there are no regulations set out in the United States which govern sediment quality. However, several different agencies have set forth guidelines, which can be used when evaluating the level of pollution found in any given sediment. Table 2 lists five different agencies, which have set out guidelines for understanding pollution levels in sediments. Some elements, such as aluminum, do not have guidelines while other elemental guidelines are very similar in concentration levels. The Ontario Ministry of the Environment (OME) guidelines in general included higher ranges because the criteria incorporate all methods of disposal from open water to unrestricted land use. The VMR study used OME criteria to classify pollution levels because these are the only criteria that specifically deal with dredged sediment.

Sediment contaminant levels vary greatly between different lakes and regions. Table 3 lists several small lake studies, done over the past 30 years, and the contaminant levels found in those sediments. The high clay content found in many lakes is expected to concentrate contaminants and a relationship between clay percentages and metals was found by Nightingale (1987).

Since lacustrine deposits are derived from the watershed, contaminant inputs found within the watershed should be reflected in reservoir deposits. The VMR sub-watershed lies within the Little Sac River watershed. Table 4 shows the range and mean concentrations of contaminants found in the stream channels of the Little Sac River and its tributaries. These values may be higher than levels found within VMR because the sub-watershed is smaller than the larger watershed and local pollution sources may influence the extreme levels measured.

Table 2. Sediment Quality Guidelines

Contaminant	NOAA*	EPA Region V†	NSQS‡	WIDNR~	OME§
As	5.9	3-8	7.2	10	8-20
Benzene	—	—	5.7	—	—
Cd	6	—	6.8	10	1-4
Cr	37	25-75	52	100	25-120
Cu	36	25-50	19	100	25-100
Fe (%)	—	17-25	—	—	1-35
Pb	35	40-60	30	50	50-500
Hg	0.174	—	0.13	0.1	0.3-0.5
Ni	18	20-50	16	100	25-60
Nitrate	—	—	—	—	2,000
PCB's	—	—	0.022	0.05	0.05->2.0
P	—	420-650	—	—	1,000
Ag	—	—	0.733	—	0.5
Zn	123	90-200	124	100	100-500

Note: Units are ppm, except where indicated.

* National Oceanic and Atmospheric Administration's Threshold Effect Level for freshwater sediment (NOAA, 1999).

† U.S. EPA, Region V, guidelines for classifying sediments as moderately polluted for Great Lakes Harbors (Baudo et al., 1990).

‡ National Sediment Quality Survey's Threshold Effect Level for sediment concentration and **bold number** is sediment quality advisory level (U. S. Environmental Protection Agency, 1997).

~ Wisconsin Department of Natural Resources sediment quality criteria (Baudo et al., 1990).

§ Dredged material disposal criteria used by the Ontario Ministry of the Environment (Baudo et al., 1990).

Table 3. Sediment Characteristics of Small Lakes

Lake	Location	Sample Size	Extraction Method	Texture	Organic Matter (%)	Contaminants (ppm)	Reference
St. Elmo Pond	Austin, TX	5	NR	NR	NR	Cu – 46.7 Pb – 21.5 Zn – 471	(Schueler, 2000)
Retention Pond	Sologne, France	8	Sequential with MgCl ₂ , sodium acetate, hydroxylamine hydrochloric acid, H ₂ O ₂ , HNO ₃ , and concentrated HNO ₃ and HClO ₄	Mainly silt with a minor clay fraction	2.5	Cd: 0.39 Fe: 18.36 Mn: 681.7 Pb: 55.4 Zn: 141	(Lee et al., 1997)
Basin MM	Fresno, CA	3	Concentrated Nitric Acid	1% clay	0.1	As – 2 Cu – 7.7 Ni – 6.9 Pb – 130	(Nightingale, 1987)
Basin G	Fresno, CA	3	Concentrated Nitric Acid	14% clay	8.57	As – 5.9 Cu – 24 Ni – 36 Pb – 570	(Nightingale, 1987)
Basin F	Fresno, CA	3	Concentrated Nitric Acid	24% clay	15.81	As – 16 Cu – 31 Ni – 27 Pb – 670	(Nightingale, 1987)
Basin M	Fresno, CA	3	Concentrated Nitric Acid	34% clay	7.5	As – 29 Cu – 39 Ni – 40 Pb – 1400	(Nightingale, 1987)
Lake Ellyn	DuPage County, IL	16	NR	34 – 48% clay	NR	Cu – 250 Pb – 1,590 Zn – 210	(Striegl, 1987)
Eau Galle Lake	Central Wisconsin	19	NR	<1% clay	NR	Fe: 18.76-31.52 Mn: 0.76-1.09 TN: 2.03-3.14 TP: 0.72-1.35	(Gunkel et al., 1983)
Murphey	Northern Mississippi	55	Sequential with HCl and NaOH	32% clay	NR	Inorganic P – 274 Organic P – 31	(Gill et al., 1976)

Note: NR = not reported.

Table 4. Geochemistry of Stream Sediments Found in the Little Sac River Watershed (Pavlowsky, R. T., unpublished data, 2001)

Element	Median	Mean	CV%	Minimum	Maximum
Al (%)	0.92	0.92	38	0.20	1.91
As	10	11	75	2	58
Ba	150	216	178	30	4130
Cr	64	76	85	24	623
Cu	10	16	141	1	136
Fe (%)	2.36	2.56	42	0.98	6.28
Hg	<1	<1	N/A	<1	1
Mn	1255	1688	81	215	7550
Ni	21	29	123	4	332
P	400	438	45	120	1400
Pb	24	33	106	6	304
Zn	34	44	76	4	210

n = 121

Note: Units are ppm, except where indicated.

Sediments, Pollution, and Geochemistry

The critical link between pollution and sediments is that many pollutants are attached to and transported by sediments. Sediments are often considered the principal cause of water pollution in many water bodies (Miller and Gardiner, 1998). In addition, contaminants may adsorb to and become concentrated on sediments. Since soil erosion selectively removes the most chemically reactive materials in soils (i.e. clay-sized particles and organic matter), sediment often has a higher concentration of trace metals and P than intact soil (Logan, 1995). Following, the detection of pollution effects is often easier with sediment monitoring because both bottom and suspended sediments have trace element concentrations that are several orders of magnitude higher than those found dissolved in the water column. For example, Pb levels in the Elbe River were 0.005 mg/L in the water and 500 mg/kg in the bottom sediments, which is about 100,000 times greater concentration in the sediments than in the water (Horowitz, 1991).

Geochemical analyses of sediment can be used to understand anthropogenic influences. Background levels of a contaminant can be determined from diagenetically unaltered sediments and can be used as a comparison to soils contaminated by anthropogenic factors because they naturally hold trace metals at very low concentrations. Williams (1991) found that Cu, Pb, and Zn steadily increased throughout post-industrial sediments. Additionally, increased organic deposition and nutrient burial was correlated with land uses and population growth (Brenner et al., 1999).

Sediment and Pollutant Transport

Because sediments and the pollutants that bind to sediments are so closely interlinked, the transport process for both will be discussed together. After erosion

occurs, particles are transported downstream and into the receiving water body. The transportation of these particles to the receiving water body can occur in a single event or may be deposited and then re-suspended reaching the receiving water body long after initial erosion (Beach, 1994).

Streams transport sediments in two ways: in suspension or along the bed. First, sediment transported in suspension are generally silt- and clay-sized particles, which are easily kept in suspension, and may travel long distances and even reach the receiving water body in a single episode (Ritter, 1978). A second mechanism of transport occurs when coarser-sized particles are transported along the bed of the stream and may only be carried a short distance before being deposited (Ritter, 1978). When another storm event occurs, these particles may be entrained again and deposited further downstream. This cycle will continue until the particles reach the receiving water body.

TRAP EFFICIENCY

Trap efficiency is the percentage of sediment that is deposited in a reservoir when compared to the incoming sediment. Trap efficiency can also relate to the portion of nutrients that are trapped in the reservoir, but in this paper, only sediment trap efficiency was considered. The trap efficiency of an impoundment is important in order to understand how the impoundment helps reduce pollution and sediment downstream. Trap efficiency can generally be expressed as: $(\text{amount of inflow load} - \text{amount of outflow load}) / \text{amount inflow load}$, expressed as a percent (Bhaduri et al., 1995). The trap efficiency of large impoundments over a long-term basis have been studied and empirical models have been established (Verstraeten and Poesen, 2000). However, even though

there are a large number of small impoundments, few studies have been conducted on small impoundments (Verstraeten and Poesen, 2000).

Trap efficiency can be measured in several different ways including the calculation of sediment loads up and downstream, sediment load up or downstream with sedimentation surveys, empirical equations, or trap efficiency curves. Trujillo (1982) used measurements of runoff, suspended sediment, and reservoir surveys in order to determine the trap efficiency of a large, flood-retarding reservoir in California. Bhaduri et al. (1995) used water volume data and water column samples in order to calculate the trap efficiency in a storm-water retention basin in Ohio. Verstraeten and Poesen (2000) provide three ways in which to estimate trap efficiencies of ponds: 1) reservoir survey with suspended-load measurements downstream, 2) reservoir surveys with suspended-load measurements upstream, and 3) suspended-load measurements up and downstream. Both Brune (1953) and Heinemann (1981) developed trap efficiency curves for indirectly estimating trap efficiency using easily obtainable data.

Trap efficiency is not a consistent value and can fluctuate with storm event, time, or among different chemicals. Verstraeten and Poesen (2000) found that the trap efficiency of small ponds changes for each storm event and thus the prediction of annual trap efficiencies are difficult. When considering the sediment and chemical trap efficiency of small ponds, Bhaduri et al. (1995) found that while ponds do trap sediment, other pollutants were not as effectively removed. Trujillo (1982) found that the large, flood-retarding reservoir he studied had a sediment trap efficiency of 86 percent for the period in which the study was conducted.

Larger reservoirs would be expected to have larger trap efficiencies due to the water having a longer residence time than in small ponds. However, Table 5 shows that trap efficiencies for small water bodies were usually high (66% to 100 %) and similar to large lakes and reservoirs (Trujillo, 1982). Small reservoirs in Missouri had high trap efficiencies which ranged from 88% to 94 % (Rausch and Heinemann, 1975). Only one storm event in Bhaduri et al.'s (1995) study had a low trap efficiency of 19.7 percent. Therefore, it is expected that small reservoirs will collect significant amounts of sediment and associated contaminants.

LAKE SEDIMENTATION

Sediment and pollutants eroded from sources within the watershed are ultimately deposited in a receiving water body. Reservoir and lake sediments record the magnitude and nature of sediment transport and deposition processes in lakes. Both spatial and temporal deposition of sediments were looked at in the VMR.

Spatial Deposition of Sediments

The spatial distribution of sediment thickness in ponds/lakes is usually described in terms of longitudinal and lateral variations and trends. Longitudinal deposition is that deposition which occurs down lake along the main bathymetric flow line. Longitudinal deposition patterns vary among reservoirs and are influenced by basin morphometry, inflow discharge, sediment grain size, and operational regime (Banasik et al., 1993; Brenner et al., 1999; Fan and Morris, 1992). Six general longitudinal deposition patterns are described in the literature and include: delta, wedge, tapering, uniform,

Table 5. Measured Trap Efficiency of Some Small Lakes/Reservoirs

Lake/Reservoir	Drainage Area (km ²)	Lake Volume (m ³)	Method Used	Trap Efficiency (%)	Reference
Retention pond in Belgium	NR	2000	Upstream sediment loads with reservoir survey	66-100	Verstraeten and Poesen, 2000
Lake Ellyn, IL	216	55,280	Up and downstream sediment loads	91-95	Striegl, 1987
Retention basin in northern Ohio	0.35	3200	Up and downstream sediment loads	20 and 89	Bhaduri et al., 1995
Ashland, MO	10.0	189,000	Up and downstream sediment loads	94	Rausch and Heinemann, 1975
Callahan, MO	14.6	1,186,500	Up and downstream sediment loads	88	Rausch and Heinemann, 1975
Bailey, MO	1.0	109,200	Up and downstream sediment loads	88	Rausch and Heinemann, 1975

random, localized effects, and current erosion formations (Hilton et al., 1986; Morris and Fan, 1998). Lateral depositional processes include sediment focusing and peripheral sedimentation (Anderson, 1990a; Hilton et al., 1986; Morris and Fan, 1998).

Longitudinal delta distribution of sediments is the fan-shaped deposition of most sediment at the inflow of the reservoir. Delta formations contain the coarsest materials and form at the inflow due to decreased water velocity and transport capacity (Fan and Morris, 1992). Hilton et al. (1986) found that delta morphology dominated when inflow suspended loads were high. Using a one-dimensional numerical model that utilized the Meyer-Peter & Müller formula, Banasik et al., (1993) also found that sedimentation takes place in the upper part of the reservoir and further upstream in the river.

The thickest sediments occurring at the dam characterize the wedge sediment feature or form. Wedge sedimentation usually occurs due to density currents, currents driven by the differences in density of the inflow and reservoir water, carrying fine sediments to the dam (Fan and Morris, 1992). Both large reservoirs with low water levels during floods and small reservoirs with large amounts of incoming fine sediments display wedge sedimentation (Morris and Fan, 1998; Valero-Garces et al., 1999).

Tapering sedimentation patterns display progressively thinner sediments down-lake. Tapering deposits generally represent the deposition of fine-grained sediment as the water moves dam ward and continues to deposit material (Effler et al., 2001; Morris and Fan, 1998). Coriolis forces may move these fine-grained sediments toward the right-hand shore in the northern hemisphere (Hilton et al., 1986). Tapering sedimentation depositional pattern generally occurs when long reservoirs are held at a high pool level or

when fine-grained allochthonous inputs are high (Hilton et al., 1986; Morris and Fan, 1998).

Uniform depositional patterns exhibit the same amount of sediment along the entire bed of the reservoir. Morris and Fan (1998) found that the uniform depositional pattern rarely occurs and when uniform morphology does occur it is usually in narrow reservoirs with little sediment inflow and frequent water level changes. Conversely, Brenner (1999) found fairly uniform sediment distribution in wide lakes with large amounts of sediment inflows. Uniform sedimentation has been attributed to macrophytes, small maximum fetches (the length of the water surface exposed to wind), continuous complete mixing of the lake water, and uniform depth with frequent re-suspension (Brenner et al., 1999; Hilton et al., 1986; Whitmore et al., 1996).

When localized effects dominate the depositional pattern, there is no clear overall pattern. Some localized effects include: slumping and sliding on slopes, local sediment inflow from a tributary, and channel erosion during drawdown (Brenner et al., 1999; Hilton et al., 1986; Morris and Fan, 1998). Localized effects will exhibit differing morphology based on the bathymetry, tributary influence, and slopes found within the reservoir and these conditions will change throughout the lake.

A final longitudinal distribution pattern is the random distribution of lake bottom sediments. Random distribution is attributed to the continual resuspension of sediments by wave action (Hilton et al., 1986).

Current erosion/depositional patterns are an additional longitudinal deposition pattern that occurs when wind driven currents dominate the process of bottom deposition. Hilton et al (1986) found studies showing that while the current erosion/deposition

process is often cited as the reason for a depositional pattern, the winds are rarely strong enough to have such a strong effect on bottom sediments. However, Odgaard (1993) and Hilton et al.(1986) both found that in some lakes sediment distribution was determined by waves and currents created from strong winds.

Sediment focusing and peripheral sedimentation are the two main types of lateral sediment depositional patterns. Sediment focusing occurs when sediments are deposited in the deepest portions of the lake, while peripheral sedimentation occurs when most of the sediment is deposited along the edges of the lake.

Sediment focusing is one of the lateral spatial distribution patterns. Sediment focusing is the idea that sediments are preferentially deposited in the deepest portions of the lake. Sediment focusing is the dominant redistribution process when peripheral wave action and annual mixing are the dominant factors (Crusius and Anderson, 1995; Davis et al., 1984; Edwards and Whittington, 1993; Hilton et al., 1986; Whitmore et al., 1996). Using lead (Pb) distribution to study sediment deposition, Evans and Rigler (1985) found lateral deposition to be variable, with deep lakes showing sediment focusing, while shallow lakes did not exhibit sediment focusing.

The second lateral depositional pattern is peripheral deposition. Peripheral deposition is sediment that is deposited in the shallow waters of the lake along the periphery. Anderson (1990a) found littoral macrophytes played a dominant role in peripheral sediment distribution by decreasing water velocities, trapping sediments, and decreasing sediment re-suspension. In some Florida lakes, shorter effective fetches and lower energy regimes in lake embayments allowed greater sediment peripheral deposition (Whitmore et al., 1996). Peripheral deposition is also affected by organic degradation;

greater quantities of organic matter are decomposed in the shallow oxic sediments and may account for greater peripheral deposition (Hilton et al., 1986).

Using GIS to Model Bathymetry and Sediment Patterns

A Geographic Information System (GIS) can be used to model bathymetry and the spatial distribution of sediments (Evans et al., 2002; Heimann, 1995). There are different methods for interpolating raster surfaces from sample points including Inverse Distance Weighted (IDW), Spline, and Kriging. IDW is based upon a basic concept in geography that items closer together are more alike. Thus, IDW estimates cell values by averaging the values of sample data within a specified vicinity of the cell (McCoy and Johnston, 2001). Spline interpolation raises the sample points to their given values and then fits a plane through each of the sample points (McCoy and Johnston, 2001). Finally, Kriging, the interpolation method with the greatest statistical power, quantifies the correlation of the measured values through structural analysis (McCoy and Johnston, 2001).

Once a raster surface (a cell-based surface) has been generated, contours can be calculated based upon the interpolated surface (McCoy and Johnston, 2001).

Additionally, ArcGIS[®] extension, 3D analyst[®], can be used to determine volumes (Booth, 2000). In this study, a raster surface was generated for sediment distribution using Spatial Analyst[®]. 3D Analyst[®] was used to determine both the volume of the lake and the volume of sediment contained in VMR.

Temporal Variations

Sedimentation patterns and rates over time in lakes and reservoirs are another important aspect of lake sedimentation. The temporal deposition of a reservoir reflects

changes in the watershed and changes in the sedimentation processes. Temporal processes can be analyzed through geochemistry and sedimentation rates.

Geochemistry provides one mechanism by which to determine deposition history and environmental history of the lake sediments. Burden et al. (1986) found that land disturbances associated with forestry and agriculture can be identified by decreased organic matter and increased Na, Mg, Ba, Al, and Ti. Increased urbanization, industrialization, and population were temporally correlated with increased nutrient accumulation and increased trace metals (Brenner et al., 1999; Charlesworth and Foster, 1993; McCall et al., 1984; Williams, 1991). In contrast to continually increasing geochemical concentrations, Cole et al. (1990) found that trace metals did increase as industrialization increased, but, since the 1970s, levels have decreased from the peak rates. Cole et al. concludes that the decrease in trace metals, while still above presettlement concentrations, is most likely due to decreased production or emission controls. Hyatt and Gilbert (2000) used ^{210}Pb chronology to show that lacustrine sediments do record recent land-use changes and are valuable in assessing geomorphic, climatic, and human-induced environmental change.

While geochemistry can explain patterns and processes, there are problems with using geochemical methods due to changing sedimentation rates. Charlesworth and Foster (1993) used geochemistry to study the history of the lake but found that using geochemical trends can be problematic because concentration data do not account for changes in sedimentation rates or the changing sediment sources and erosion rates.

Additionally, upon sediment deposition, both physical and chemical factors may affect element and ^{137}Cs composition and profiles. Physically, the sediments may be

disturbed by bioturbation or through the re-suspension of sediments. Both Wetzel (2001) and Salomons and Mook (1980) state that re-suspension and bioturbation can obscure dating chronology and contaminant profiles. However, other authors have found that, while some mixing did occur in shallow reservoirs, based upon the ^{137}Cs activity the mixing was not appreciable and sediment profiles could be used (Calcagno and Ashley, 1984; Verta et al., 1989). Additionally, Faulkner and McIntyre (1996) found in Riecks Lake, Wisconsin, a very shallow lake, that mixing did not affect ^{137}Cs profiles because there was an identifiable 1954 ^{137}Cs boundary and 1964 ^{137}Cs peak.

Chemically, elements may diffuse or go into solution after deposition and thus the true element record may be obscured. Factors which influence the chemical mobility and/or stability of elements includes redox potential, pH, Fe content, and diagenesis (Evangelou, 1998; Wetzel, 2001; Williams, 1992). Williams (1992) found that trace metal profiles interpretations may be difficult due to early diagenesis processes. The Pb, Zn, and Cu down-core profiles were more strongly controlled by redox processes than anthropogenic factors, even though Loch Ba, Scotland, was impacted by anthropogenic activity (Williams, 1992). Phosphorus was released from sediments to the water under reducing conditions in Sobygaard, Denmark, and may obscure the P record (Welch and Cooke, 1995). Another factor, which may reduce the stability of element profiles, is the downward diffusion of some elements. Carignan and Nriagu (1985) found that Fe, Mn, and Ni can be diffused after deposition which may lead to false subsurface peaks.

Sedimentation rates are another way to look at temporal deposition. Hyatt and Gilbert (2000) used sediment stratigraphy to assess sedimentation rates and help in understanding temporal changes. Sedimentation increases are associated with increased

population and mass sedimentation is proportional to exponential growth in population (McCall et al., 1984). As the productivity of the lake changes due to anthropogenic inputs of nutrients, so do the sedimentation rates (Sanei et al., 2000).

Sedimentation rates can also be calculated with radioactive isotopes such as ^{137}Cs . ^{137}Cs is an isotope that is produced during nuclear fission and was distributed to the atmosphere at a global-scale due to nuclear weapons testing. ^{137}Cs strongly adsorbs to fine-grained sediments and is not easily leached (Turnage et al., 1997). In 1954 initial measurable amounts of ^{137}Cs were first present and then in 1964 there was a peak rate of fallout (Mueller et al., 1989; Ritchie and McHenry, 1985; Turnage et al., 1997). Thus, three different periods can be determined: impoundment date to 1954, 1954 to 1964, and 1964 to present.

SUMMARY

Lake sediments are influenced by the upstream dynamics of the watershed. The sediments along with associated contaminants are carried downstream to the receiving water body where they are deposited. The deposition occurs both longitudinally and laterally. Different depositional patterns will occur depending on in lake dynamics and inflowing sediment. In VMR, deposition is expected to display delta formation with sediment focusing. Temporally the deposits may also change due to changing characteristics of the watershed. Sediments in VMR are expected to have increased contaminants in the upper cores due to increased urbanization. Additionally, sedimentation rates are expected increase with time. The trap efficiency of the impoundment will be affected by lake sedimentation. The trap efficiency of VMR is expected to be high (above 60 %).

CHAPTER THREE – STUDY AREA

The VMR watershed is located in Greene County, Missouri and contributes to Springfield, Missouri's water supply (Figure 1). The surface catchment is small (12 km²) and urbanizing. Additional water may drain into VMR through the subsurface karst drainage system.

VMR was initially impounded sometime between 1851 and 1871 for use as a wheat mill and was called McCracken Mill (Rayl, 2000). In 1899, the reservoir and surrounding land were purchased by the Springfield Water Company, which continues to operate the reservoir (L. Bullard, Watershed Committee of the Ozarks, unpublished data). In 1908, the dam was raised to the current height of 5.5 m. In 1969, the reservoir was drained and at least partially excavated but the amount and area excavated are uncertain due to lack of detailed records (J. Parker, Springfield City Utilities, personal communication).

VMR is a small, shallow reservoir with a surface area of 5.9 ha and a maximum depth of 6.1 m. This reservoir is a normally ponded, surface discharged reservoir with a current storage volume of 149,536 m³. The shape of the reservoir is elongated on the north-south transect and shoreline development, the degree of convolution, is low. Residence time of water during baseflow conditions is 48.8 hours.

CLIMATE OF THE REGION

Climate within the region is described as a plateau climate with milder winters and cooler summers than in upland, plain, or prairie regions (National Weather Service Forecast Office Springfield MO, 2003). The average temperature for the record period 1971 to

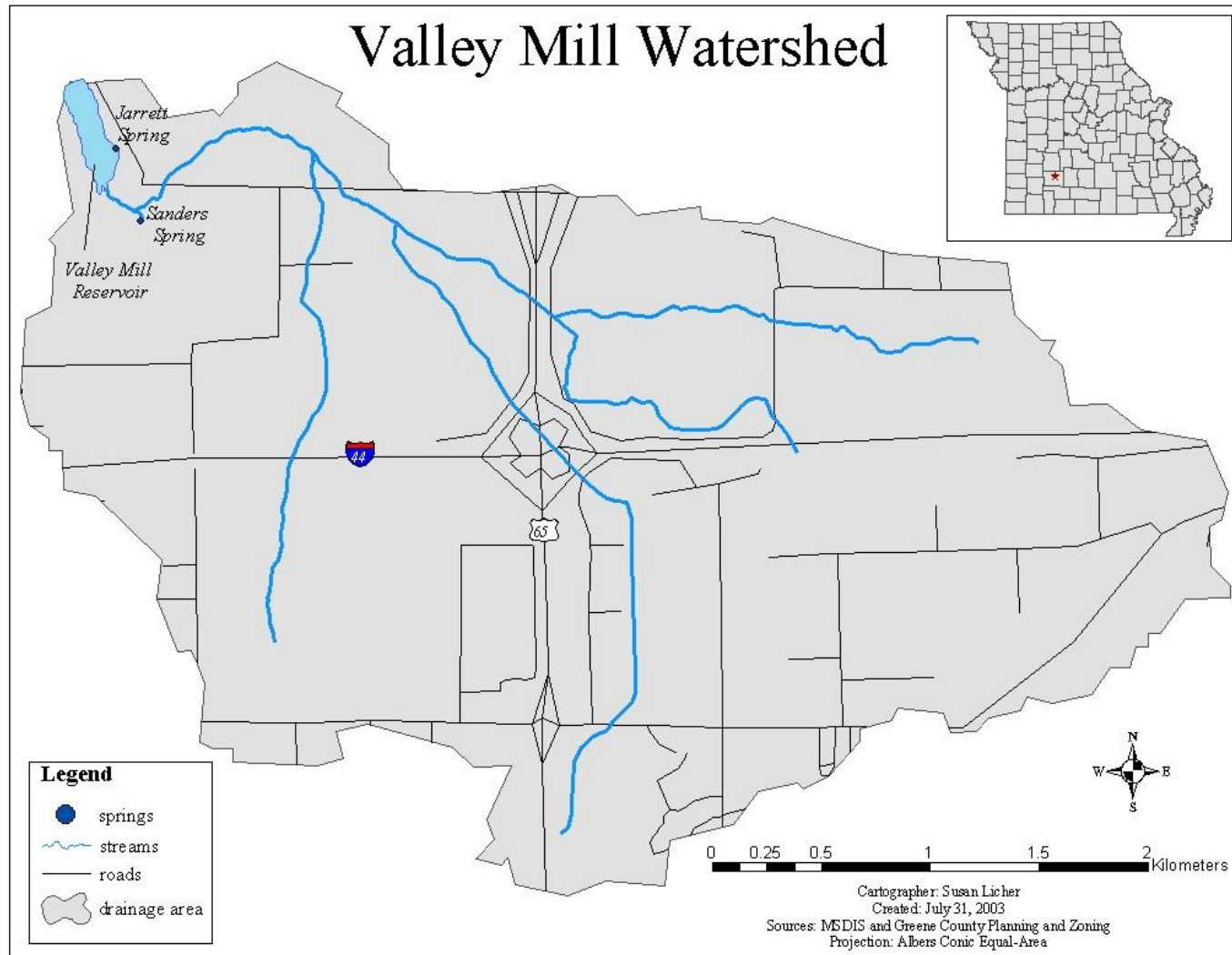


Figure 1. Valley Mill Reservoir watershed

2000 was 13.4° Celsius. During this same period the average monthly temperature ranged from a low, -0.2° Celsius, in January to a high, 25.8° Celsius, in July (Midwestern Regional Climate Center, 2003b). Weather patterns generally move from west to east and are often influenced by moisture generated from the Gulf of Mexico. Precipitation is fairly evenly distributed throughout the year and has a mean annual value of 114.2 cm for the 1971 to 2000 period (Midwestern Regional Climate Center, 2003a). Precipitation is highest in June and lowest in January with 60 percent of the annual rainfall occurring from April to September.

GEOLOGY OF THE WATERSHED

The VMR lies on the western edge of the Springfield Plateau, which lies on Mississippian age rocks. The geological formations within the catchment include Burlington-Keokuk Limestone, Compton Limestone, Elsey Cherty Limestone, and Northview Siltsone/Shale (Wright Water Engineers et al., 1995). The Burlington-Keokuk formation underlies most of the catchment and consists of coarse-grained gray limestone with chert present throughout the formation. Compton Limestone consists of fine to medium-grained crystalline limestone containing small green shale partings, which are exposed in some channel beds. The Elsey formation is a dense gray cherty limestone and generally finely crystalline. The Northview formation has both a lower and upper unit with the upper unit being primarily siltstone with interbedded shales and the lower unit being primarily shale (Wright Water Engineers et al., 1995). The shale found in this formation is also exposed in some channel beds draining into the VMR. There is also a horst, called Valley Mills Horst, which runs between the mouth of the

reservoir and Sanders Spring. This horst consists of two east/west trending faults and terminates just west of Valley Mill Reservoir (Wright Water Engineers et al., 1995).

SOILS IN THE WATERSHED

Topography and soils influence the deposition that occurs in reservoirs. There are three main soil associations found within the VMR watershed: 1) Goss-Wilderness-Peridge association (deep, well drained and moderately well drained sloping soil); 2) Pembroke-Eldon-Creldon association (deep, well drained to moderately well drained sloping soils); and 3) Wilderness-Viraton association (deep, moderately well drained sloping soils) (Table 6). All of the soil associations within the VMR watershed are found on upland

Table 6. Main Soil Associations, Location, Parent Material, and Slope in VMR Watershed (Hughes, 1982)

Association		Location	Parent Material	Slope (%)
1	Goss	Convex sides and tops of upland ridges	Residuum weathered from cherty limestone or dolomite and in thin loess or alluvium	2 to 20
	Wilderness	Tops and sides of upland ridges		
	Peridge	Tops, sides, and slight depressions of upland ridges and terraces		
2	Pembroke	Tops, sides, and slight depressions of upland ridges and terraces	Residuum weathered from cherty limestone and in thin loess or alluvium and limestone residuum	2 to 14
	Eldon	Convex sides and tops of upland ridges		
	Creldon	Tops and sides of upland ridges		
3	Wilderness	Tops and sides of upland ridges	Residuum weathered from cherty limestone and thin loess	2 to 9
	Viraton	Tops, sides, and foot slopes of ridges on uplands and terraces		

and terraces. The topography of the VMR watershed is gently to strongly sloping with slopes ranging from 2 to 20 percent (Hughes, 1982). Steeper slopes may lead to higher erodibility especially if poor agricultural practices occurred or where large areas of bare soil exist.

HYDROLOGY OF THE WATERSHED

A karst drainage system has developed throughout this watershed. The watershed is a headwaters area with only first and second order streams. Streams within the catchment are ephemeral except the stream leading from Sanders Spring to VMR. The VMR is spring fed by Sanders Spring, just upstream of the reservoir, and Jarrett Spring, within the lake bed. Thus, the reservoir is only supplied with water and sediments from the watershed during storm events. The golf course and industrial park located within the watershed both have detention basins, which hold back water during storm events. During baseflow conditions, Sanders and Jarrett springs are the only source of water and sediment.

VMR drains into the South Dry Sac River, which has a large losing section just downstream of VMR. This losing section feeds directly into Fulbright Spring, a source of drinking water for the city of Springfield. During baseflow conditions, VMR supplies approximately 70 percent of the discharge of Fulbright Spring (A. Coulter, personal communication, 2003). Some of the water flowing into VMR is lost to groundwater through the bed of the reservoir. Some of the water in the reservoir is then discharged out of Shotgun Spring on the South Dry Sac and an unnamed spring on the Grandview Tributary.

Floods within the watershed are generally of short duration due to the karst topography and this being a headwater area. One precipitation event warrants special mention. During the summer of 2000, a 100-year rain event occurred. The golf course currently in the watershed was under construction at the time of the storm and was entirely bare soil. The detention ponds and dams built to hold back storm water were breached and large amounts of soil were eroded and deposited in VMR.

HISTORICAL AND CURRENT WATERSHED LAND USES

Prior to 1954 there are no aerial photos for VMR watershed so land use information was drawn from regional sources. Archeological evidence suggests that the area around current day Springfield was used by the Osage tribe from the 1700's to 1830 (Feraldi et al., 1999). Initial settlement by white settlers began to occur around 1830. The watershed was most likely dominated by agricultural land use from the 1850's to 1900 since the wheat grist mill could not have operated if no wheat supply was available. In addition to the grist mill, a blacksmith, a general store, a schoolhouse, and other businesses were all located close to VMR (Rayl, 2000). After the sale of the VMR to Springfield Water Company in 1899 until 1954, land use was probably dominated by agriculture. However, based upon the 1954 aerial photos land use may also have been dominated by forests. In general, this area probably had an agricultural based land use with residential areas associated with the farms, some businesses that catered to a localized group, and forests where farmland had been abandoned or where farming was not feasible. Besides the early businesses associated with the wheat mill, only one other

business has been known to operate within the watershed, which is the Springfield Underground, a limestone quarry that has been operating since 1947.

Land use within the watershed was historically dominated by agriculture from the 1954 until the 1990's (City of Springfield Planning and Zoning, 1954-2001). Mixed in with agriculture were forests, which for some periods co-dominated (Table 7). The first industrial park was platted in 1974 but remained small until the late 1980's. Between 1990 and 1995 aerial photos indicate a rapid increase in industrial land use especially in the Southeast quadrant of the watershed. Historical aerial photos indicate that limited suburban residential areas were present in 1975 and have continually increased since that time. Currently, industrial land uses completely dominate the Southeast quadrant, which contains three industrial parks. In the Northwest quadrant, a golf course currently dominates and includes an area of high density residential. In the Northeast and Southwest quadrants of the watershed, agriculture continues to dominate. However, the Southwest quadrant has seen an increase in commercial and industrial land uses. A portion of Springfield, Missouri's third largest city with a population of approximately 150,000 (U. S. Census Bureau, 2000), lies within the watershed. As indicated by the current and historical land uses, this watershed is an urbanizing watershed and is planned for continued development. Table 8 lists the important land use and disturbance dates within the VMR watershed.

Table 7. VMR Watershed Historical and Current Land Uses (City of Springfield Planning and Zoning, 1954-2001)

Year	Quarter	Land Uses	Dominant Land Use
1954	NW	Agriculture, forests	Agriculture
	SW	Agriculture	Agriculture
	NE	Agriculture, forests	Agriculture
	SE	Agriculture, quarry	Agriculture
1960	NW	Agriculture, forests	Agriculture
	SW	Agriculture	Agriculture
	NE	Agriculture, forests	Agriculture/Forests
	SE	Agriculture, quarry	Agriculture
1975	NW	Agriculture, forests, limited suburban residential	Agriculture
	SW	Agriculture, limited commercial	Agriculture
	NE	Agriculture, forests, limited suburban residential	Agriculture
	SE	Agriculture, 1 industry, trailer park, quarry	Agriculture
1980	NW	Agriculture, forests, some suburban residential	Agriculture
	SW	Agriculture, forests, commercial	Agriculture
	NE	Agriculture, forests, limited suburban residential	Agriculture/Forests
	SE	Agriculture, limited industry, trailer park, quarry	Agriculture
1985	NW	Agriculture, forests, suburban residential	Agriculture
	SW	Agriculture, forests, limited commercial	Agriculture
	NE	Agriculture, forests, limited suburban residential	Agriculture
	SE	Agriculture, limited industry, trailer park, quarry	Agriculture
1990	NW	Agriculture, forests, suburban residential	Agriculture
	SW	Agriculture, forests, commercial, limited industry	Agriculture
	NE	Agriculture, forests, limited suburban residential	Agriculture/Forests
	SE	Agriculture, industry, trailer park, quarry	Agriculture
1995	NW	Agriculture, forests, suburban residential	Agriculture
	SW	Agriculture, forests, commercial, industrial	Agriculture/Forests
	NE	Agriculture, forests, limited suburban residential	Agriculture/Forests
	SE	Agriculture, industrial, quarry	Agriculture/Industrial
2001	NW	Agriculture, forests, suburban residential, golf course	Golf course
	SW	Agriculture, forests, commercial, industrial	Agriculture
	NE	Agriculture, forests, limited suburban residential	Agriculture
	SE	Agriculture, industrial, quarry	Industrial

Road density within the area is generally low. However, Interstate 44 and U. S. Highway 65, constructed in 1958, quarter the watershed (Missouri Department of Transportation, 2003). Valley Water Mill Road runs on the north and east sides of the reservoir. Valley Mill Reservoir Road is present in the 1954 aerial photographs but construction date is unknown.

Table 8. Important Land Use and Disturbance Dates for VMR and its Watershed

Date	Land Use or Disturbance
1700-1830	Osage tribe uses land around VMR
1830	Initial settlement by white settlers
Between 1850 and 1871	Initial impoundment of VMR for use as a grist mill
1908	VMR dam raised to current height of 5.5 m
1947	Limestone quarry begins operation
1958	Interstate 44 and U.S. Highway 65 constructed
1969	VMR excavated to remove excess sediments
1975	First commercial, industrial, and urban developments
1995	Industrial land use increases dramatically in one quarter of watershed
2001	Golf course dominates one quarter of the watershed

CHAPTER FOUR – METHODOLOGY

This chapter describes the research design and methodology used for this study. Sedimentation surveys, core collection, geochemistry, ^{137}Cs dating, physical characteristics, and GIS were used to analyze bathymetry, sediment distribution, and the environmental history of the VMR.

FIELD METHODS

Collection of field data was necessary in order to complete this research. Field data included: (1) bathymetric data, (2) sediment thickness probing, (3) stratigraphic analysis of bottom sediment cores, and (4) Cesium dating. All sampling locations were recorded by a Garmin XL[®] GPS unit, which has a 1m to 5 m positional accuracy. Figure 2 shows a map with all sampling sites.

Bathymetry

Bathymetric data were measured at each site by lowering a graduated metal rod to the sediment surface or through surveying (Brenner et al., 1999; Trujillo, 1982). The two different methods were used because the reservoir was drained during the course of this study. One hundred ninety-five bathymetric data points were collected.

Sediment Thickness

Sediment thickness data were collected by the spud method from a boat and with an Oakfield probe in the drained lake bed (Brenner et al., 1999; Ritchie and McHenry, 1985). A 2 cm diameter rod was manually driven into the reservoir bed material and the bottom of the reservoir was estimated to be at refusal which was either very tight, dense material, bedrock, or gravel (Heimann, 1995). Refusal depths are the points where the probing device can no longer be driven into the sediment. Once the lake had been

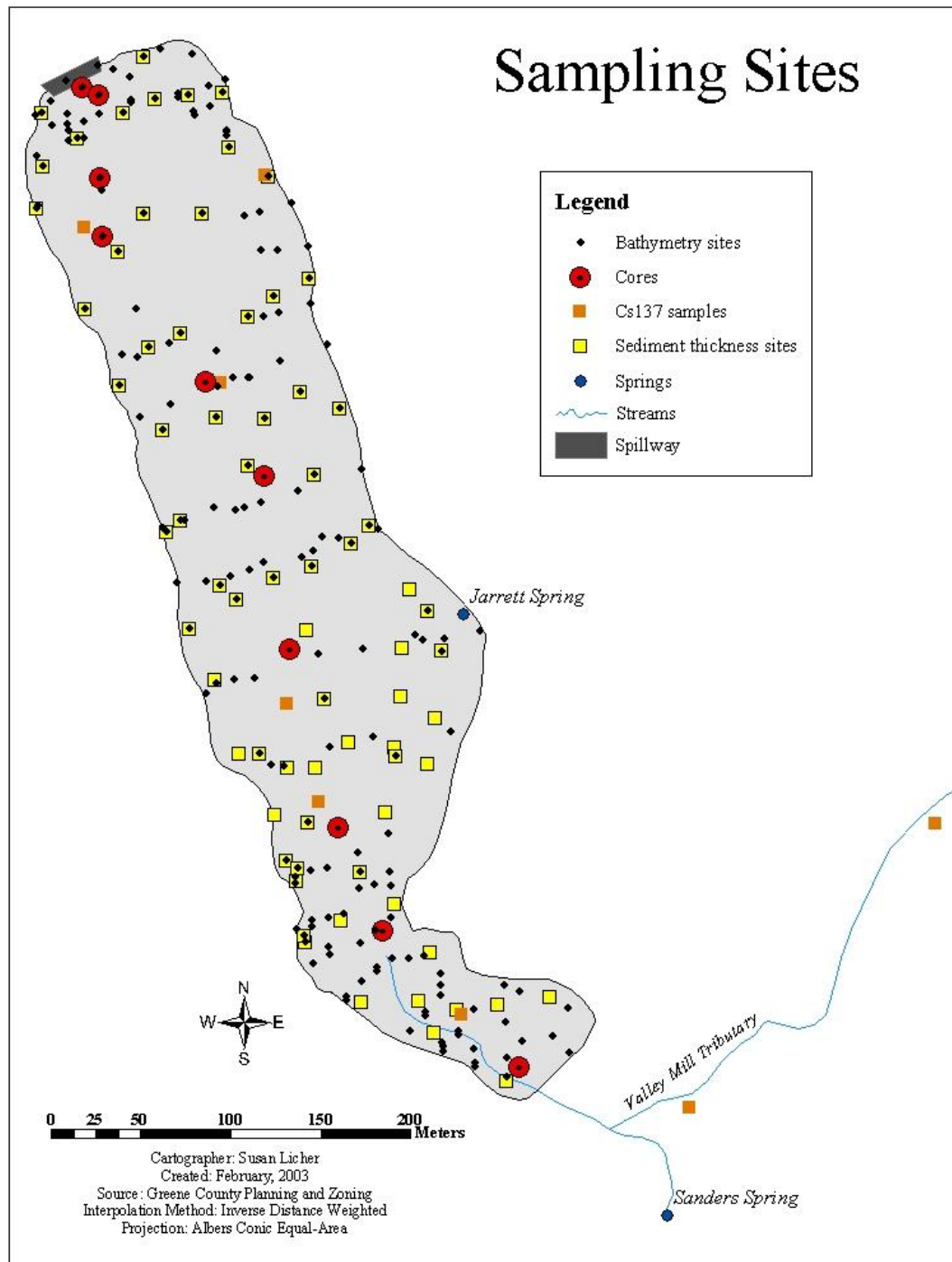


Figure 2. All sampling sites

drained, an Oakfield probe was pushed through the sediments until gravel or bedrock refusal. Eighty-two sediment thickness probes were conducted.

Sediment Cores

Sediment cores were collected after the reservoir had been drained with a 5 cm diameter coring tube. These cores were cut into differing lengths (4 – 25 cm) depending upon stratigraphy identified in the field, labeled, bagged, and sealed for transport back to the laboratory (Sanei et al., 2000). The 10 core locations were located along a transect corresponding to the longest portion of the reservoir. Ninety-five sediment samples were collected from 10 different cores.

Cesium Sampling

¹³⁷Cs sample collection was done by digging eight pits and collecting sediment samples every 5 cm after the face of the pit had been cleaned (J. Ritchie, personal communication, 2003). These samples were again labeled, bagged, and sealed for transport back to the lab. One hundred samples were sent for analysis to Dr. Jerry Ritchie, USDA Hydrology and Remote Sensing Laboratory.

LABORATORY METHODS

Once sediment samples were transported back to the Southwest Missouri State University (SMSU) Geomorphology lab, they were dried at 60°C until all ambient moisture was removed. After being dried, all sediment samples except for the ¹³⁷Cs samples were disaggregated with a mortar and pestle and passed through a 2 mm sieve. ¹³⁷Cs samples were disaggregated with a DynaCruch® electric grinder and then passed through a 2 mm sieve.

Geochemistry

All sediment samples except ^{137}Cs samples were processed for geochemical analysis. Five grams of sample were bagged and sent to ALS Chemex Laboratories (Sparks, Nevada) for analysis of 34 elements. Sediments were first digested with a 3:1 mixture of hydrochloric and nitric acids, also known as aqua regia digestion. Sediment geochemistry was analyzed through Inductively Coupled Plasma – Atomic Emissions Spectroscopy (ICP-AES) method (Lee et al., 1997; Nightingale, 1987).

Organic Matter

Organic matter content was also determined for all sediment samples, except ^{137}Cs samples, by loss on ignition. Approximately 5 grams of sample were placed in crucibles and dried at 105°C for 2 hours to remove atmospheric moisture. These samples were then placed in a muffle furnace for 6 hours at 600°C . Organic matter percentage was then calculated by the following equations:

$$\text{OM (grams)} = (s_{\text{pre}} - c) - (s_{\text{post}} - c)$$

$$\text{OM\%} = (\text{OM} / s_{\text{pre}} - c) * 100$$

where, OM = organic matter, s_{pre} = pre-burn sediment weight, c = crucible weight, and s_{post} = post-burn sediment weight.

Color

For the sediment cores additional analysis was conducted. Munsell color was determined for both dry and wet samples. Two – three grams of sample were compared to Munsell color chips either dry or wet enough to form a ball. The Munsell color, hue, and saturation were recorded along with the color word description.

pH

The pH of core sediment was also determined. Five grams of sediment were placed in a beaker and 10 mL of distilled water was added. This suspension was stirred and then allowed to sit for 10 minutes. The samples were stirred again and pH was determined using a pH meter (Thomas, 1996).

Grain-size

Sediment texture characteristics were determined for 68 core samples. A combination of hydrometer and wet sieving methods were used for texture determinations (Pavlowsky, 1995). Forty grams of dry sample and 50 mL of distilled water were placed in a beaker and digested with 5 mL of 1% acetic acid and 5 to 10 mL of 30% hydrogen peroxide to remove organic matter (Pavlowsky, 1995). After digesting overnight, samples were placed on a hot plate and heated at 90°C for 1 hour. Samples were then dried at 105°C for 3 hours and weighed to determine total sediment mass placed in the settling tubes. One hundred twenty-five mL of sodium hexametaphosphate dispersant was added to the dried samples and allowed to soak for 12 to 24 hours (Pavlowsky, 1995). Samples were blended for 15 minutes and then transferred to 1000 mL settling tubes where distilled water was added to obtain a volume of 1000 mL. Samples were then allowed to sit overnight to equilibrate with the room temperature. Finally, sediments were suspended with a stirring rod and hydrometer readings were taken for the 63 μm , 32 μm , 26 μm , 8 μm , 4 μm , 2 μm , and 1 μm fractions.

Wet sieving was completed on the same samples used for hydrometer readings. The 1000 mL solution was passed through a 63 μm sieve. The sand fraction was then dried and weighed to determine percent sand of the sample (Pavlowsky, 1995). The

hydrometer readings were then adjusted to the wet sieving sand percentages (Pavlovsky, 1995).

Cesium Dating

^{137}Cs was used as a dating method for temporal analysis of sediments. Dr. Jerry C. Ritchie conducted ^{137}Cs analysis at the USDA Hydrology and Remote Sensing Laboratory (Beltsville, MD). Samples were dried at 90°C for 48 hours and weighed in order to calculate dry bulk density of the volumetric samples. One-liter Marinelli beakers were filled with approximately 1000 g of 2mm sieved soils and sealed for gamma ray analysis (J. Ritchie, personal communication, 2003). Gamma ray analyses were conducted with a Canberra Genie – 2000 Spectroscopy System[®] with a Windows-based software/hardware package that receives input into three 8192 channel analyzers from three Canberra high purity coaxial germanium crystals (J. Ritchie, personal communication, 2003). Estimates of radionuclide concentrations were made using Canberra Genie-2000 software. The system was calibrated and efficiency determined using an analytic mixed radionuclide standard whose calibration can be traced to U.S. National Institute of Standards and Technology. Measurement precision was ± 4 to 6%.

DATA ANALYSIS

Data analysis was undertaken using a variety of different software packages that enabled the researcher to more clearly see and understand spatial and temporal trends. Data analysis included modeling bathymetry, calculating storage volume of water, estimating total volume of sediment, determining residence time, computing trap

efficiency, laying out longitudinal and cross-sectional profiles of the reservoir, and analyzing geochemical trends.

Map Projection

Albers Conic Equal-Area projection is used for all database layers in this thesis. Albers Conic Equal-Area projection is used because map area is proportional to the same area on the Earth (Environmental Systems Research Institute, 1994). Additionally, Albers Conic Equal-Area projection provides good results for regions that extend in the east-west direction and are located in the middle latitudes. For this thesis research, it is important for map area to be proportional to the Earth because water and sediment volumes are calculated. The Albers Equal Area projection was used because it provides the most accurate volume and area calculations for large-scale maps.

Bathymetry

Bathymetry was modeled using a Geographic Information System (GIS) (Heimann, 1995). Specifically, the Spatial Analyst extension found in ArcMap was used to model bathymetry. The Spatial Analyst tool used GPS points to interpolate a raster surface. Tension spline interpolation was used when modeling bathymetry because it provided the smoothest contours while keeping the integrity of the original survey data.

Water and Sediment Volume

Water and sediment volume calculations were determined. The raster surface interpolated for the bathymetric contours was used as the bottom surface for the water volume calculations and as the top surface for the sediment volume calculations. Surface was then used to calculate both water and sediment volume.

Residence Time

Residence time is the amount of time water is stored within the reservoir.

Residence time was calculated by the following equation:

$$T_r = C / I$$

where, T_r is the residence time, C = the capacity or volume of the reservoir in cubic meters, and I = the volume of annual inflow in cubic meters (Dodds, 2002).

Trap Efficiency

Trap efficiency was calculated based on two different methods, the Brune curve and the Heinemann equation (Brune, 1953; Heinemann, 1981; Neil and Mazari, 1993). These two methods were chosen because Brune curves are classically used in order to figure trap efficiency (Neil and Mazari, 1993). However, Heinemann (1981) developed a equation that was specifically designed for small reservoirs with watershed areas less than 15 mi². The Brune trap efficiency was determined by comparing the capacity-inflow ratio (C/I) to the Brune regressions curves. The Heinemann trap efficiency was calculated by the following equation:

$$TE = -22.0 + \frac{119.6 * C/I}{0.012 + 1.02 * C/I}$$

where, TE = trap efficiency and C/I is the capacity to inflow ratio.

Longitudinal and Cross-sectional Profiles

The longitudinal and cross-sectional profiles of the reservoir bottom were graphed out in Excel in order to aid in the understanding of the geomorphological units within the reservoir. For the longitudinal profiles, the distance from the dam was used in combination with the elevation relative to the top of the dam. The cross-sectional

profiles were compiled using the “zero” distance from the left or west side of the reservoir looking down stream and the elevation relative to the top of the dam.

Core Profile Analysis

The physical properties and geochemistry of core profiles were analyzed using LogPlot[®] software. This software allowed for the visualization of geochemical trends and changes in physical properties.

Enrichment Factors

Enrichment factors allow the researcher to examine if the increased element concentrations are due to increased background levels or are due to increases from anthropogenic sources. The enrichment factor is obtained by normalizing all elements to Al and then dividing the normalized concentration by the mean normalized background concentration (Thomas et al., 1984). In this study, enrichment factors ≥ 1.5 were considered enriched and this number was used to determine initial enrichment depths.

CHAPTER FIVE – RESULTS AND DISCUSSION

RESERVOIR MORPHOMETRY

This chapter describes the bathymetric and physical properties of VMR including (1) morphometric properties; (2) residence time; and (3) trap efficiency. Morphometry of a reservoir is the size and shape of the reservoir and its watershed and is one of the most basic features of reservoirs but was unknown for VMR. Residence time and trap efficiency are closely related and aid in understanding how the reservoir was acting as a sediment trap and affecting downstream water quality. Appendix A contains bathymetric data while Appendix B contains sediment thickness data.

MORPHOMETRIC PROPERTIES

VMR is a normally ponded, surface discharged reservoir with a surface area of 5.9 ha and an average depth of 2.6 m. The current water storage volume of the reservoir is 149,536 m³. Figure 3 is a map showing the bathymetry of VMR and Table 9 shows morphometric properties. The reservoir is elongated in the north-south direction. The Valley Mill tributary enters the reservoir on the eastern edge. On the western edge of the reservoir there is a back water area which is directly across from the entrance of the stream. The upper half of the reservoir is shallow with depths less than 3 meters. Jarrett Spring is inundated during normal reservoir conditions, which may be influencing bathymetry along the eastern edge of the reservoir. The influence of Jarrett Spring is questionable because when the reservoir is full the spring may actually be a conduit for groundwater outflow rather than being a source of water for the reservoir. The deepest point in the reservoir, 6.1 m, is located approximately 85 m away from the dam. The deep point was located further away from the dam than expected but was probably due to

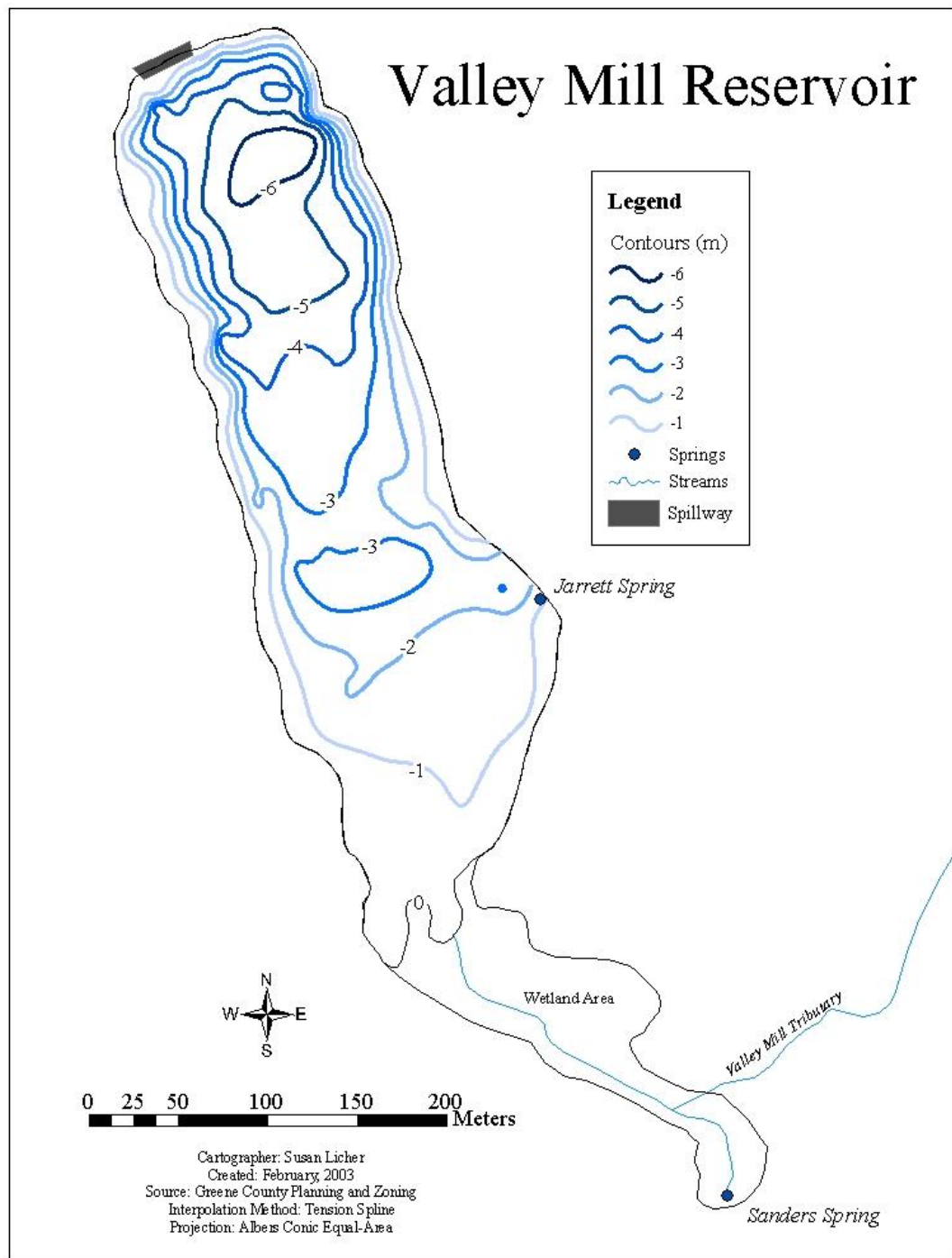


Figure 3. Bathymetry of VMR

Table 9. Morphometric Characteristics of VMR

Morphometric Characteristic	Valley Mill Reservoir
Surface drainage area (km ²)	12
Surface area (ha)	5.9
Average width (m)	105
Length (m)	505
Average depth (m)	2.6
Maximum depth (m)	6.1
Total volume (m ³)	149,536
Shoreline length (m)	1300
Watershed area/lake volume	85.5
Shoreline development index	1.5

the reservoir not being excavated all the way to the dam in 1969. The deep point was close to the dam, which is typical of reservoirs.

The shallowness of the reservoir influences the extent of the flora found in the reservoir. During sediment sampling when the reservoir was filled, vegetation mats were evident from the mouth of the reservoir to a water depth of approximately 3.5 m. When sampling in the shallow areas where vegetation was evident, sediment samples were generally obtained. This was most likely because the vegetation was still alive and upright in the water. Once we moved into deeper water, the dead vegetation was a mat covering the bottom sediments and interfered with sampling. Specifically, we were not able to obtain sediment samples at three sites and all of these samples were at a water depth of 3.4 m.

Another characteristic of morphometry, which is often investigated when studying reservoirs, is the watershed area to lake volume ratio. This ratio is an indication of how much influence the watershed will have on the reservoir. VMR's watershed area to lake volume ratio is 85.5. This ratio indicates that the watershed will have a relatively low influence on the reservoir because there is less land from which nutrients and sediments can be washed; watershed area to volume ratios in other reservoirs range from 4 to 134,000 (Dodds, 2002).

The low watershed area to volume ratio of VMR indicates that the watershed will have a relatively low influence on the reservoir's trophic state. However, the low mean depth, together with moderately high nutrient levels, indicate that the reservoir should be productive. While the trophic state was not measured directly, TP and TN in the water column were measured during the drained conditions only. Total P exhibited a mean of

207 $\mu\text{g/L}$ during runoff events and a mean of 56 $\mu\text{g/L}$ during baseflow. Total N during the same sampling period exhibited a mean of 2,180 $\mu\text{g/L}$ during runoff events and a mean of 2,250 $\mu\text{g/L}$ during baseflow (Pavlowsky et al., 2002).

Based upon the TP and TN concentrations found in the water column during drained conditions and according to Nürnberg's trophic classification system, VMR is classified as eutrophic (30-100 $\mu\text{g/L}$) using mean TP concentrations during baseflow conditions. Based upon runoff event TP concentrations and TN concentrations during both baseflow and runoff events, VMR would be classified as hypertrophic (TP >100 $\mu\text{g/L}$ and TN >1200 $\mu\text{g/L}$) (Dodds, 2002). Therefore, VMR lies along the continuum between eutrophic and hypertrophic. In addition to the TP and TN water column concentrations during drained conditions indicating eutrophy, the large amounts of vegetation found in VMR also indicate excessive nutrients and eutrophy. One problem with this assessment is it was done during drained conditions. If the reservoir were filled, TP and TN concentrations may drop due to increased residence time in the reservoir. TN and TP may be taken up biologically, settled out in particulate form, or may become chemically reactive with other elements and therefore the water column concentrations may decrease.

RESIDENCE TIME

Residence time is the amount of time water is held in a reservoir and is important in understanding residence time of pollutants and sediment and the general influence tributaries will have on a reservoir. Residence time can range from a few hours to hundreds of years (Dodds, 2002). Residence time of VMR was calculated to be 48.8

hours during baseflow conditions and only 113 minutes during a two-year run-off event. A short residence time indicates that pollutants will quickly wash from the reservoir and that tributaries will continually bring in new nutrients, pollutants, and sediments. However, during baseflow conditions water does not flow over VMR dam and relatively little water seeps through the dam. This indicates that the rest of the water is being lost through the bed of the reservoir or evaporated. Since this is the case, some of the nutrients and pollutants may be retained in the pore water or adhering to the sediments as the water flows through the reservoir sediments into the karst systems below. The very short residence time of water during a two-year storm event indicates that the pollutants and sediment associated with storm run-off are quickly washed over the dam and are not retained. Since VMR is a surface discharged reservoir, once the inflow diminishes some of the receding limb storm run-off will be retained along with nutrients and pollutants.

TRAP EFFICIENCY

Trap efficiency is the percent of incoming sediment which is deposited in the reservoir (Heinemann, 1981). Trap efficiency was calculated using two different methods: the Brune curves (1953) and the Heinemann equation (1981). The estimated Brune sediment trap efficiency of VMR ranged from a minimum of 15% to a maximum of 45% during baseflow conditions (Table 10). During the two-year storm event trap efficiency was below the Brune graph (i.e. negative trap efficiency with the reservoir being a source of sediment). Heinemann's equation, specifically developed for small reservoirs, estimated trap efficiency at 16% for baseflow conditions and -20% for the two-year storm event.

Table 10. VMR Sediment Trap Efficiency

Trap Efficiency	Brune	Heinemann
Baseflow median	29%	16%
Baseflow maximum	45%	—
Baseflow minimum	15%	—
2-year median	Below the graph	-20%

Note: Trap efficiencies are based on Brune curves (1953) and the Heinemann equation (1981).

Observations of baseflow conditions do not support the calculated trap efficiency. During baseflow conditions, the only water coming out of the reservoir was via a few small cracks in the dam itself with no water flowing over the top of the dam. The small amount of water trickling through a few cracks in the dam wall would indicate that the trap efficiency was closer to 100% than to the maximum calculated efficiency of 45%. There are other additional problems in a karst area. First, the reservoir was spring fed and the inflowing water had low sediment concentrations, which may lead to higher trap efficiencies. Secondly, some of the lake water may be lost via conduits in the bed of the reservoir. This loss of water may decrease trap efficiency if the conduits are large enough for sediment. The field observations indicated that during baseflow conditions, VMR was effectively trapping sediments and thus positively influencing downstream water quality.

During storm events, water did flow over the top of the dam. Here again, the data must be interpreted carefully because the calculated trap efficiencies indicated that the reservoir may actually be a source of sediment. When sediment deposits were examined in the field, a 1-4 cm thick flood deposit produced by a 100-year flood in the summer of 2000 was discovered. This deposit indicated that at least some portion of the sediment was trapped even during a 100-year flood event. Based upon the 100-year flood deposit, it can be assumed that during a 2-year flood event some of the sediment is also being trapped. Additionally, there was little evidence of scour or resuspension based upon: 1) ^{137}Cs profiles were consistent with deposition, 2) 2000 marker evident after two two-year events and 3) overall, textural and bedding trends indicate graded sedimentation.

During the course of this study, the deductive models do not seem to fit VMR. Therefore, the trap efficiency estimates of VMR should be verified beyond just the general modeling approach undertaken in this study. In order to fully understand the trap efficiency, it is recommended that inflowing and outflowing sediment loads be studied.

SPATIAL DISTRIBUTION OF SEDIMENT

Sediment thickness measurements were evaluated to understand the spatial distribution of sediment and to aid in understanding sedimentation patterns. Sediment thickness ranged from 0.04 to 2.87 m, with an area weighted mean of 1.00 m (Table 11). The total volume of sediment was 60,629 m³.

Sediment thickness was mapped out using GIS. The distribution of sediment found in VMR showed a delta formation with little or no sediment focusing (Figure 4). The delta formed at the mouth of the lone tributary flowing into VMR and extended almost to Jarrett Spring. The delta formation was recognized through the high sediment

Table 11. VMR Sediment Thickness

	Sediment Thickness (m)*
Mean	1.00
Minimum	0.04
Maximum	2.87
Total Volume (m ³)	60,629

* n = 90

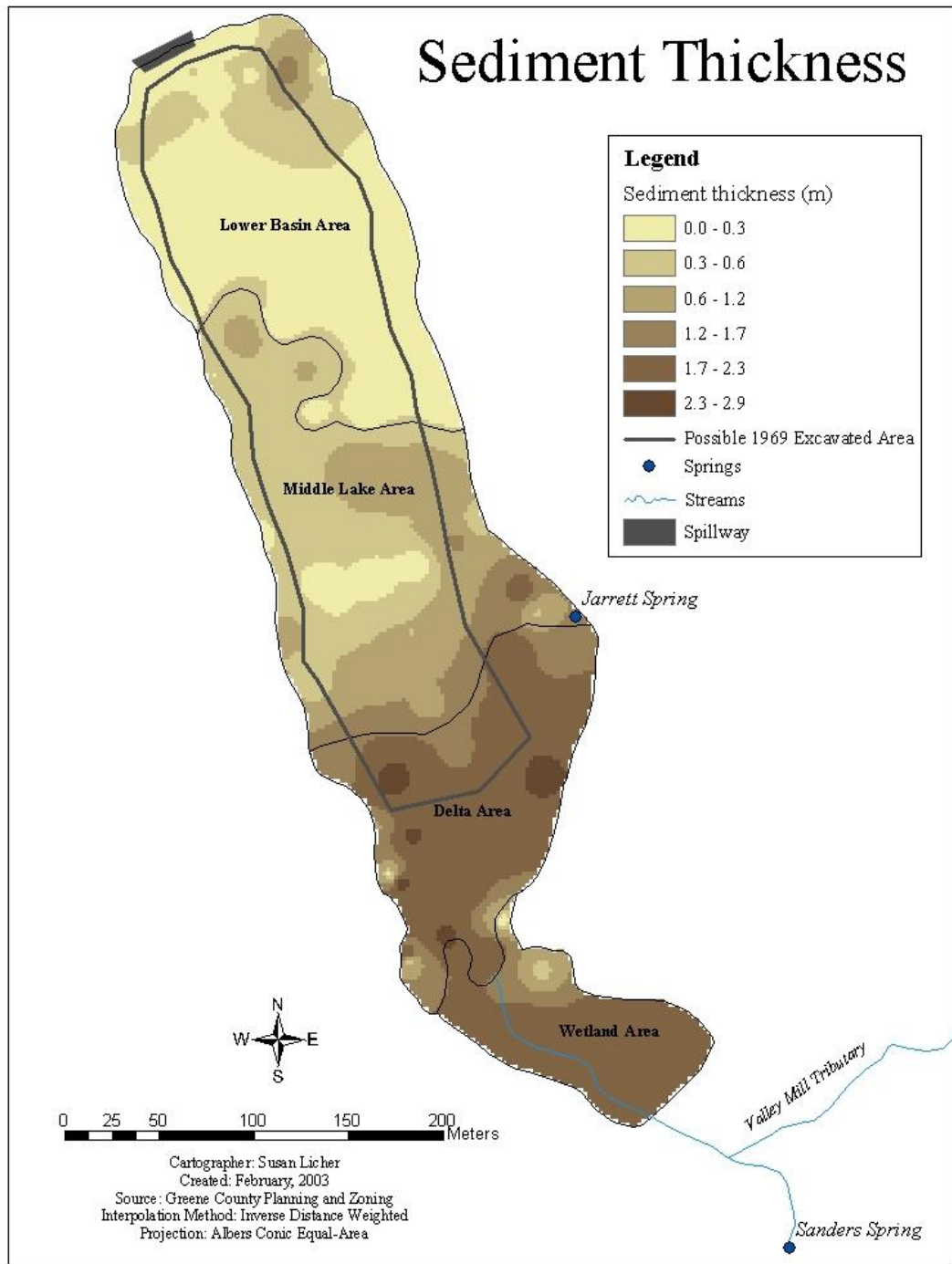


Figure 4. VMR sediment thickness

thickness values and their steep gradient from the mouth of the reservoir to just south of Jarrett Spring. The wetland area and the floodplain of the Valley Mill Tributary reflect the subaerial expression of deltaic sedimentation, trapping sediment during flood events due to vegetation filtering and backwater sedimentation. The wetland and floodplains in areas were understood to be acting as part of the delta from ^{137}Cs dating and depositional records. The ^{137}Cs dating and depositional records will be looked at further in Chapter Six. The lack of sediment focusing was evident through the relatively uniform sediment thickness values found horizontally from east to west, across the lake basin.

Delta formation is a common feature found in reservoirs because as the sediment laden water spreads out in the reservoir and velocity slows most of the coarse sediment particles will drop out of suspension (Hilton et al., 1986; Morris and Fan, 1998). In VMR, the clay-sized particles generally indicated that there was fining downlake (Table 12). Additionally, the sand-sized particles supported the down-lake fining trend with the exception of the lower basin. In the lower basin sand-sized particle percentages increased and clay-sized particle percentages decreased. The extension of relatively high sediment thickness values along the east side of the reservoir was probably due to turbid density currents and coriolis forces acting to move these currents to the right-hand (east) shore (Hilton et al., 1986).

Sediment focusing is found in some small reservoirs but was not found to be affecting sedimentation patterns in VMR. Sediment focusing was the dominate sedimentation pattern found in Eau Gall Lake and was attributed to the lake-like morphometry (Gunkel et al., 1983). VMR, in contrast, has a classic reservoir shape with an elongated basin and this may explain why sediment focusing was not found. Crusius

Table 12. Clay- and Sand-Sized Particle Percentages of Sediment Deposited either Post-1964 or Post-1969.

Core	Clay-sized particles post-1964 (%)	Sand-sized particles post-1964 (%)	Clay-sized particles post-1969 (%)	Sand-sized particles post-1969 (%)
1	36.0	1.7	—	—
3	38.2	3.1	—	—
4	—	—	40.2	0.6
6	—	—	42.4	0.6
7	—	—	40.0	1.2

and Anderson (1995) also found sediment focusing to be a dominate sedimentation pattern but attribute the focusing to peripheral wave action and mixing at turnover.

Peripheral wave action was most likely not a large influence because VMR has a short fetch relative to the prevailing west-east wind direction. Mixing regime was unknown in VMR but did not appear to be affecting sedimentation patterns based on sediment focusing evidence. Additionally, sediment focusing may not be a prevalent redistribution pattern because VMR experiences large amounts of vegetation growing on the bottom of the reservoir throughout most of the year and thus re-suspension in VMR may not be occurring to a great extent.

SUMMARY

The bathymetry of the VMR is typical of small reservoirs with shallow areas near tributaries, the deepest point being close to the dam, and a low mean depth. However, other morphometric characteristics were atypical of reservoirs with a low watershed area

to lake volume ratio of 85.5. VMR had a short residence time during both baseflow conditions (48.8 hours) and during the two-year storm event (113 minutes). The calculated trap efficiencies, which ranged from 15 to 45 % for baseflow conditions and were negative for the two-year storm event, appeared to be well below the actual trap efficiency and should be studied further.

The spatial distribution of sediments within VMR displayed a delta formation with little or no sediment focusing. Additionally, the wetland area and upstream floodplain are acting as part of the delta. The total amount of sediment found within VMR was relatively high, and if removed, would increase the total water volume storage by two and one-half times.

CHAPTER SIX – RESULTS AND DISCUSSION VERTICAL DISTRIBUTION AND CONTAMINATION OF SEDIMENTS

This chapter presents the results and discussion of the vertical distribution of the physical properties and contaminants in sediment cores collected from VMR. The three main characteristics examined include: 1) ^{137}Cs dating, 2) physical stratigraphy, and 3) geochemical stratigraphy. Appendix C contains the ^{137}Cs data and Appendix D contains the location, physical properties, and geochemical data for the cores.

^{137}Cs DATING

^{137}Cs was used to date stratigraphic units and calculate sedimentation rates. Figure 5 shows ^{137}Cs sampling locations. Sampling sites Cs-11 through Cs-14 all had complete records from 1871? to 2002. The 1871 date was questionable because the exact date of impoundment was unknown and could have occurred anywhere from 1851 to 1871. The 1871 date was used because it showed maximum sediment thickness and sedimentation rates. ^{137}Cs has a known peak at 1964 and in the VMR cores this peak occurred at depths ranging from 10-15 cm down to 45-50 cm (Figure 6). ^{137}Cs activity decreased on either side of this peak. ^{137}Cs activity decreases to zero in 1954 and this date in VMR ranged from 55-60 cm to 70-75 cm in depth. The sites Cs-15 through Cs-18 were excavated or dredged in 1969 and thus only one time period is known (1969 to 2002). At sites Cs-15 and 16 ^{137}Cs activity zeroed out indicating that there was some older sediments left after excavation and that these sediments were older than 1954, but the exact date was unknown. At sites Cs-17 and -18, all older sediment was removed so

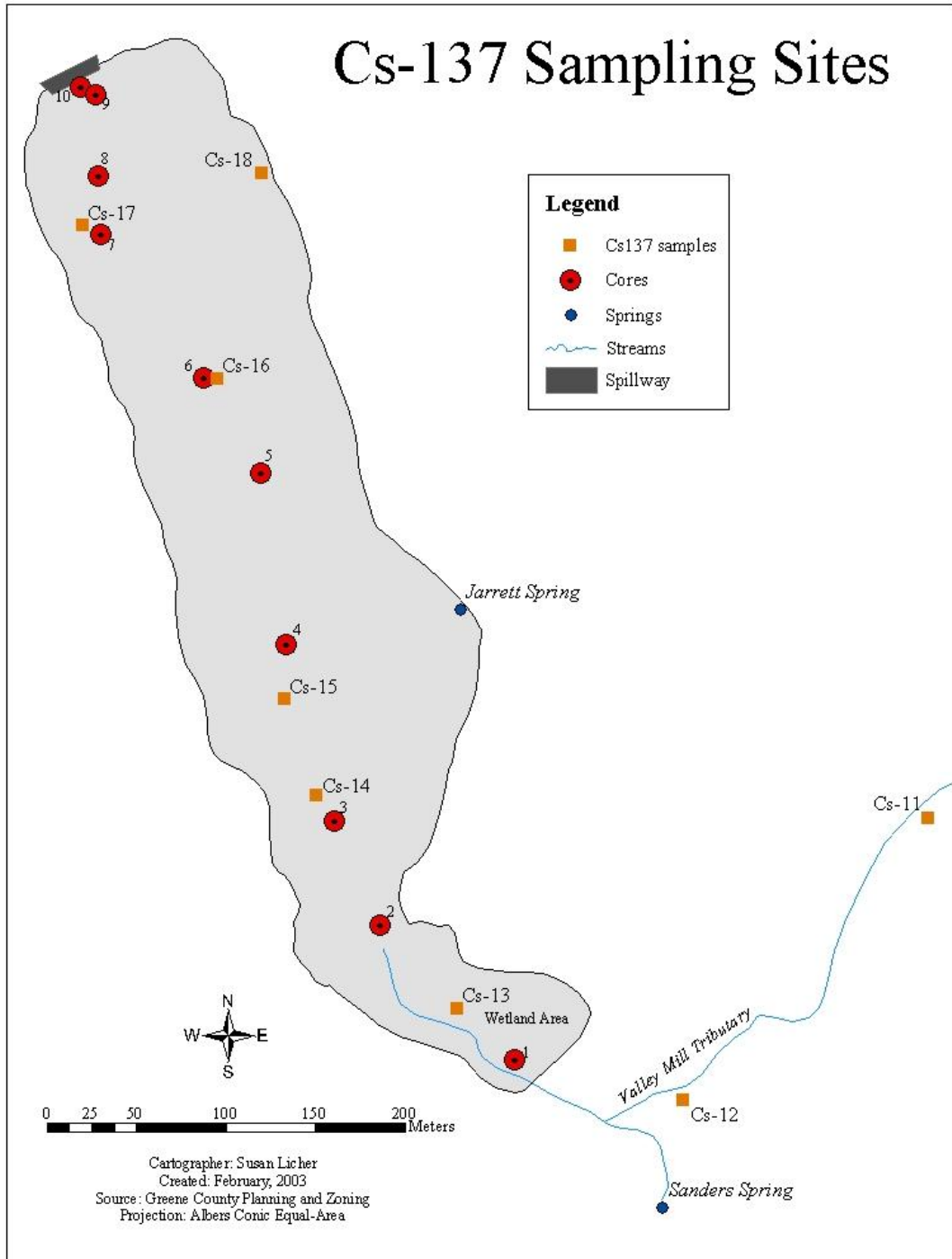


Figure 5. Locations of ^{137}Cs sampling sites and core sites

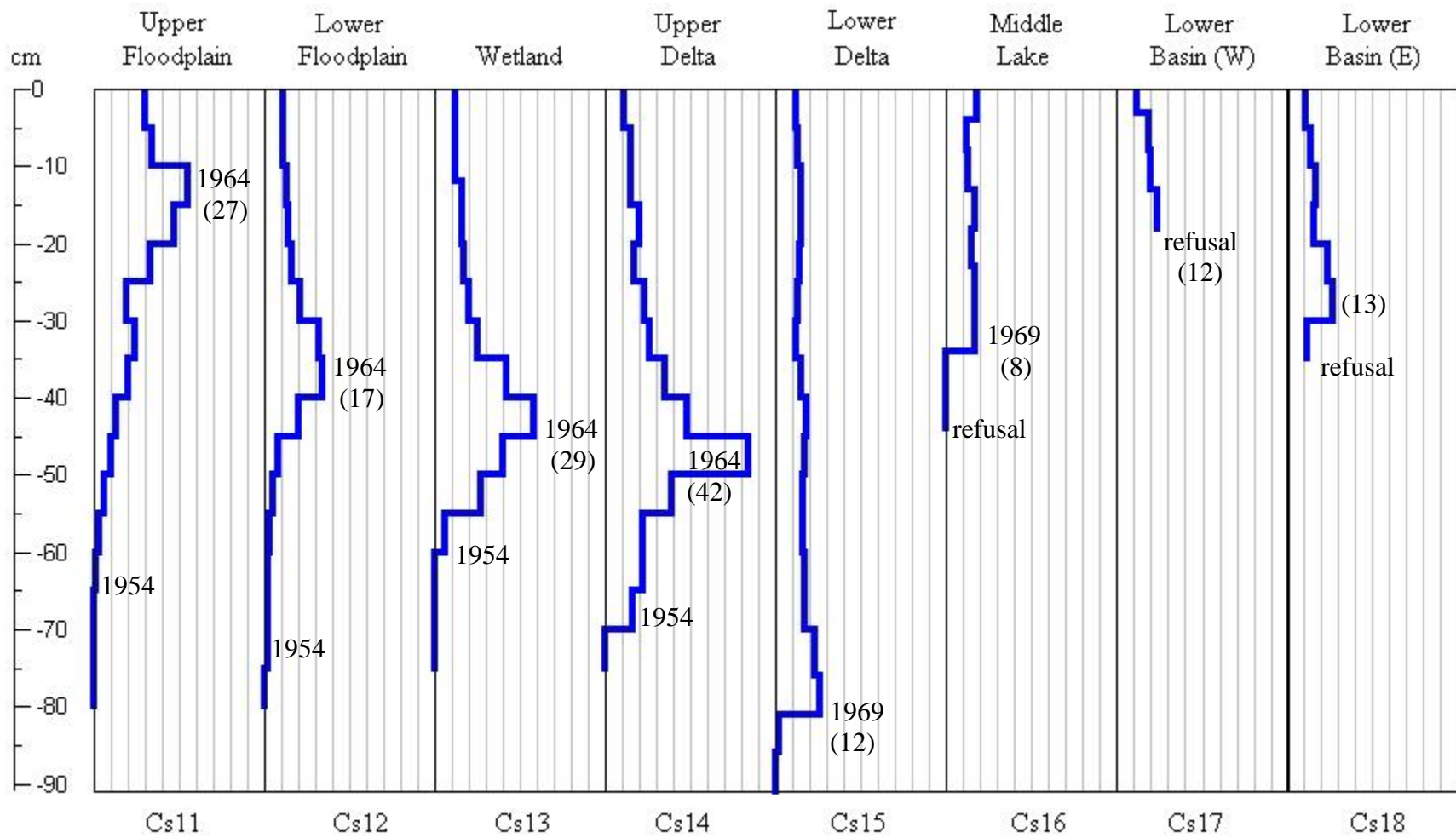


Figure 6. ¹³⁷Cs activity (Bq/kg) of Cores. Each individual graph ranges from 0-50 Bq/kg with the grid lines representing 5 Bq/kg and the numbers in parentheses indicating the peak ¹³⁷Cs activity.

the post-1969 sediment was deposited on the refusal surface and ^{137}Cs activity did not reach zero.

Based upon the distinct 1964 peak and identifiable 1954 boundary in most of the ^{137}Cs profiles, it is assumed that bioturbation and physical reworking of sediments in VMR is negligible (Faulkner and McIntyre, 1996). The 1964 peak is not as distinct in core Cs-17 as in Cs-11, -13, and -14, but is present. Additionally, in both Cs-11 and -12, the 1954 boundary is not as distinct as compared to Cs-13 and -14. However, both Cs-11 and -12 are sites that experienced higher sedimentation rates, which would stretch out the ^{137}Cs record and reduce the peak contrast. At sites Cs-15 and -16 ^{137}Cs activity dropped to zero but did not have a 1964 peak. The lack of a 1964 peak but a decrease to zero ^{137}Cs activity is attributed to the excavation of these sites, which accumulated sediments younger than 1964 but also left some old sediments (pre-1954). At site Cs-15 there appeared to be some activity within the pre-1954 sediments, which may be due to either bioturbation or physical reworking. Here, VMR is shallower and this core record is located at the leading edge of the delta.

Sedimentation thickness data for the three different time periods were utilized to understand where sedimentation was occurring within the system. Historically (1871? – 1954) the immediate lake area (the wetland and delta) showed greater sediment thickness than the upstream floodplains (Figure 7). From 1954 to 1964 the greatest sediment thicknesses were in the floodplains with Cs-11 experiencing the greatest sedimentation. In recent times, 1964 to 2002, the lake areas were again receiving more sediment and the sedimentation decreased upstream with Cs-11 receiving less than half as much as Cs-12.

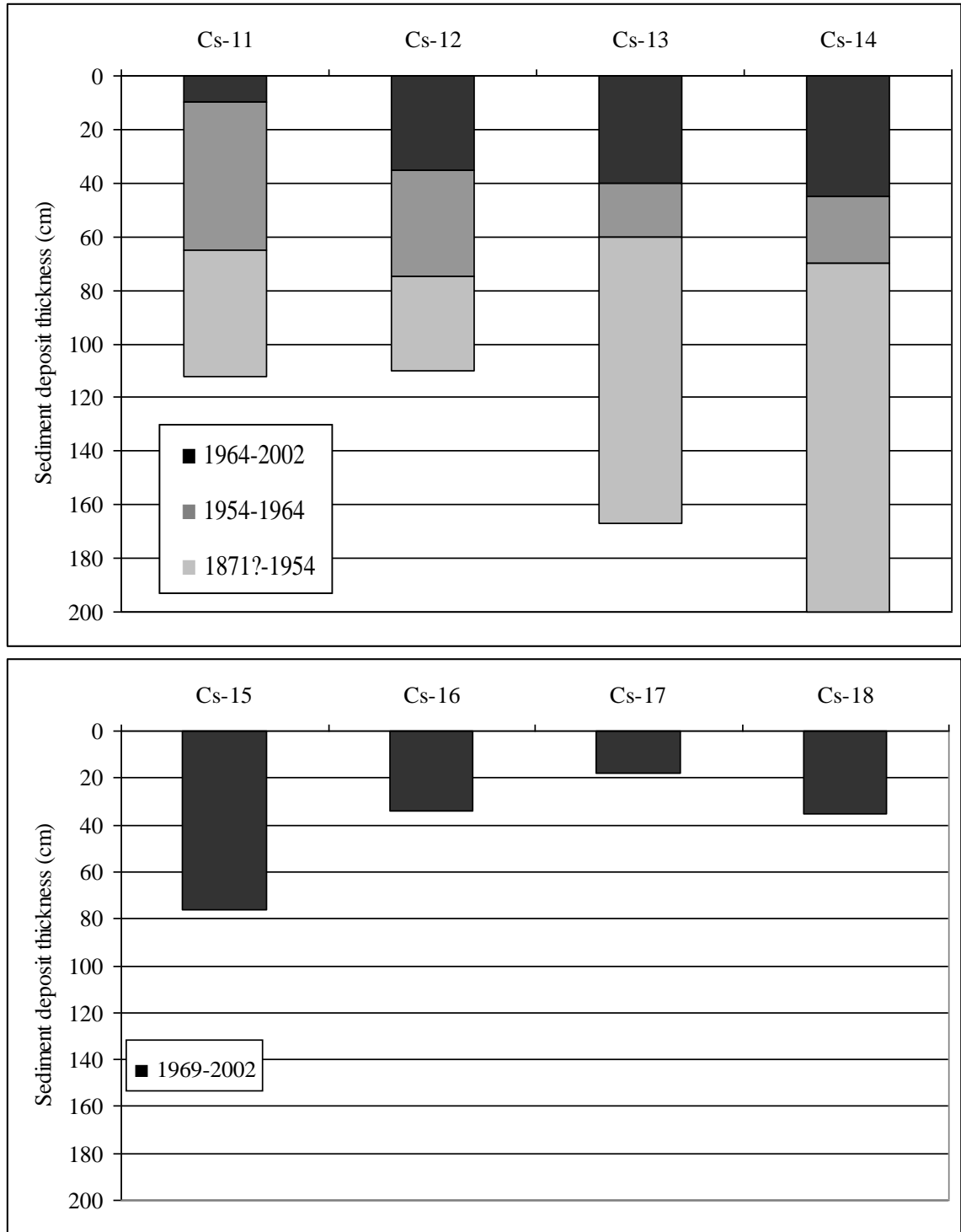


Figure 7. Sediment deposit thickness for different time periods in VMR

The middle lake and lower basin, which were excavated, have only one known time period (1969 to 2002) since they were dredged in 1969. In the reservoir, sediment thickness was very high at Cs-15 compared both to other reservoir sites and sites which correspond to the 1969 to 2002 time period (Figure 7). The dredged area in the lower delta has the highest sedimentation depths post-1969, which indicated that delta deposition has progressed to this site. Sites Cs-16 and 18 have similar sediment thicknesses, which was unexpected because Cs-18 was further down lake. However, Cs-18 was much closer to the shore and may be influenced by bank slumping or a local source of sediment from road repair. Site Cs-17 had the lowest sediment thickness, which was expected because it was deeper than Cs-18 and further down lake than all other sites.

In the lower basin, sediment thickness ranged from 4 to 50 cm with an average thickness of 19 cm. One site did have a refusal depth of 165 cm and was found along the eastern edge of the reservoir near the dam. However, upon drainage of VMR, the area that has a refusal depth of 165 cm represents an older natural or artificial channel fill related to earlier mill activities. The refusal depth of 165 cm is therefore considered an anomaly.

Figure 8 diagrams the sediment thickness of the one known time period (1964/69 to 2002) for the entire reservoir area including the floodplains. The sediment deposit thickness increases downstream from the floodplain to the last sample in the delta. Downstream of the delta sediment thickness decreases.

Sedimentation rates were determined from ^{137}Cs dating and sediment thickness. Historically (1871? to 1954) sedimentation rates were low on the floodplains and ranged

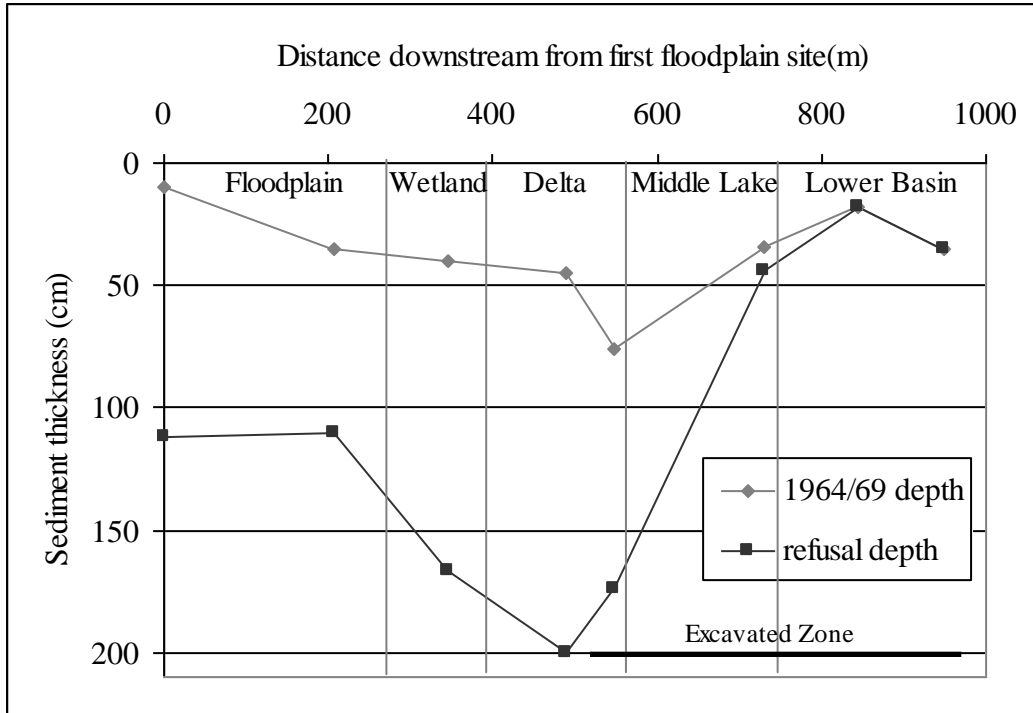


Figure 8. Diagram showing the longitudinal thickness of the 1964/69 layer as dated by ^{137}Cs (1964) or by dense unit (1969) and refusal depths

0.4 and 0.6 cm/yr (Figure 9). The reservoir area (wetland and delta) had higher sedimentation rates at 1.3 and 1.6 cm/yr. This was expected since reservoirs trap sediments more readily than do floodplains. The lake sedimentation rates were higher for this time period than those found by Bertine and Mendeck (1978). The ten years between 1954 and 1964 saw an increase in sedimentation rates throughout the floodplains and lake area, which may have been linked to major highway construction. However, the highest sedimentation rates were in the floodplains and indicated that this area was acting as part of the reservoir delta. During the 1950's and 60's alluvial backwater sedimentation increased in the floodplains. Sedimentation rates decreased downstream. From 1964 to 2002 the trend reversed and sedimentation rates increased downstream. This suggests that the locus of deposition has shifted downstream since 1964 with high post-1964 deposition downstream with the lower floodplain, wetland, and delta having greater sedimentation rates. The vegetation found in VMR may be increasing sedimentation rates in the delta and mid-lake areas of the reservoir.

In the reservoir, sedimentation rates decreased downstream from 1969 to 2002 (Figure 9). Site Cs-15 had the highest sedimentation rates and higher rates than Cs-13 and 14 suggesting this area was the front edge of the delta that has pro-graded downstream. The lower sedimentation rates found at Cs-16 indicated that this area was part of the bottomset beds and that the delta was the predominate sediment feature found in VMR. Site Cs-17 was expected to have the lowest sedimentation rates because it was close to the dam and in deeper water than Cs-16. Finally, site Cs-18 has higher sedimentation rates than Cs-17 which was unexpected. The higher rates may be due to local influences such as slumping.

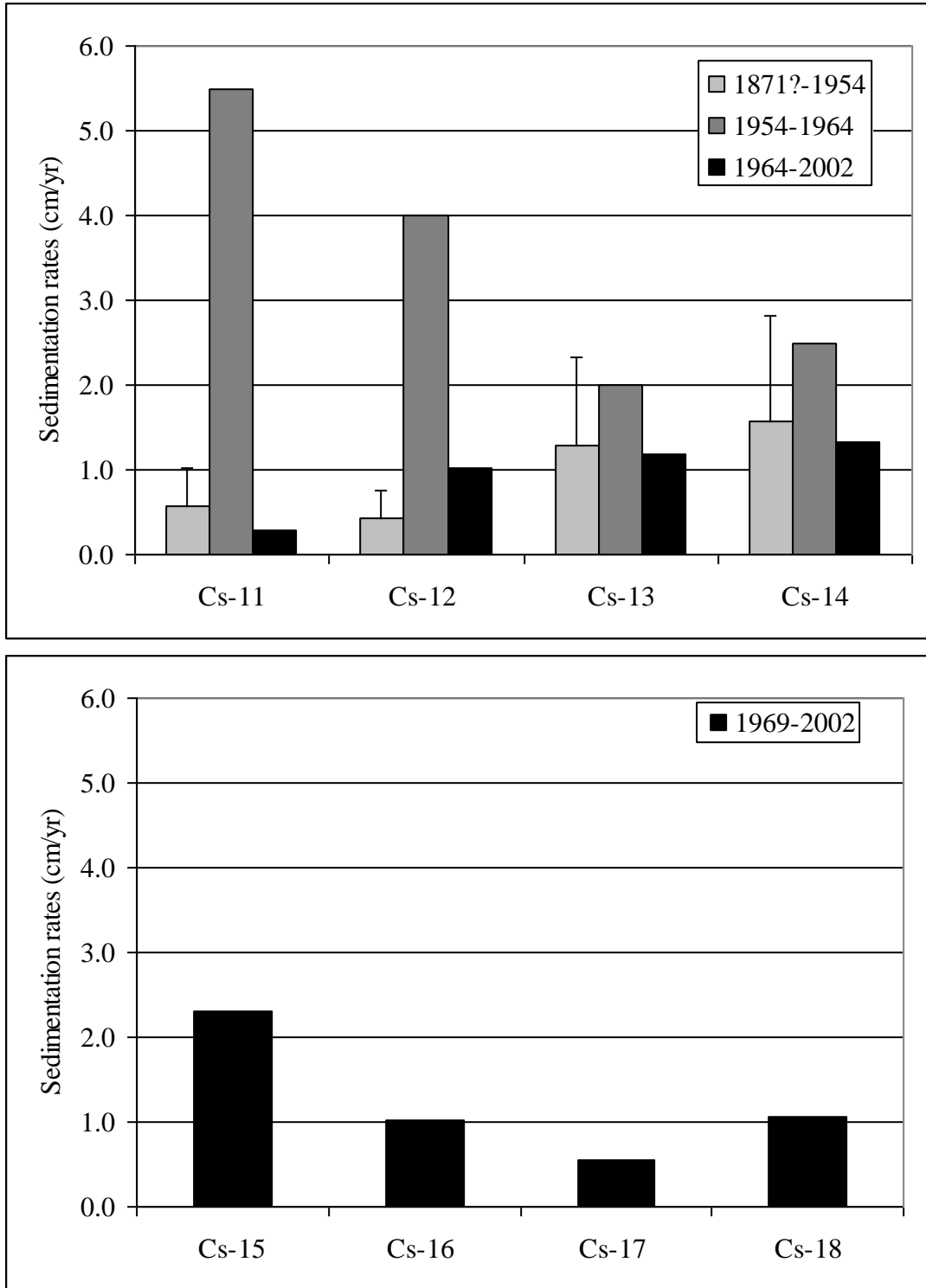


Figure 9. Sedimentation rates (cm/yr) for VMR. Sedimentation rates area based on ^{137}Cs dating. Error bars in top graph represent the sedimentation rates (cm/yr) if 1908 is used instead of 1871 (1908 is the date when the dam was raised 2 m to its current height).

PHYSICAL STRATIGRAPHY

Stratigraphic units within reservoir cores can be used to understand the environmental history of a watershed. Ten cores were taken along a longitudinal transect and sampled according to stratigraphy observed in the field (Figure 5). Figures 10 to 16 present field stratigraphy, Munsell color, particle size, organic matter, and pH for VMR cores 1 through 7.

Field logs allowed for the initial categorization of VMR sediments. In broad terms, five sedimentary units were found. The uppermost layer was one of high organic matter content mixed with brown sediment. This layer was believed to be recently deposited due to the high organic component and the color difference compared to the underlying reddish sediment. The post-2000 layer ranged in thickness from 1 to 9 cm. Throughout most of the lake a 2 cm to 4 cm thick layer at or near the top of the core consisting of a red-brown color was found. The red-brown color was indicative of the red clay residuum that was exposed during the construction of an upstream golf course. During the golf course construction, a 100-year flood event occurred and large amounts of sediment were delivered to VMR. Thus the red-brown layer is assumed to have been deposited during the 100-year flood event, which occurred in July 2000. Below the 2000 layer, a layer consisting of brown silty or clayey particles was found and corresponded to sediment deposition from 1969 to 2000. The time period from 1969 to 2000 was deduced from knowledge of the layer above and the layer below the brown silty or clayey particles. The 1969 to 2000 layer ranged in thickness from 10 cm near the dam to 57 cm in core 4. A fourth layer found was a dense gleyed unit. In 1969 VMR was excavated but the extent and depth of excavation was unknown. Upon coring in VMR and through

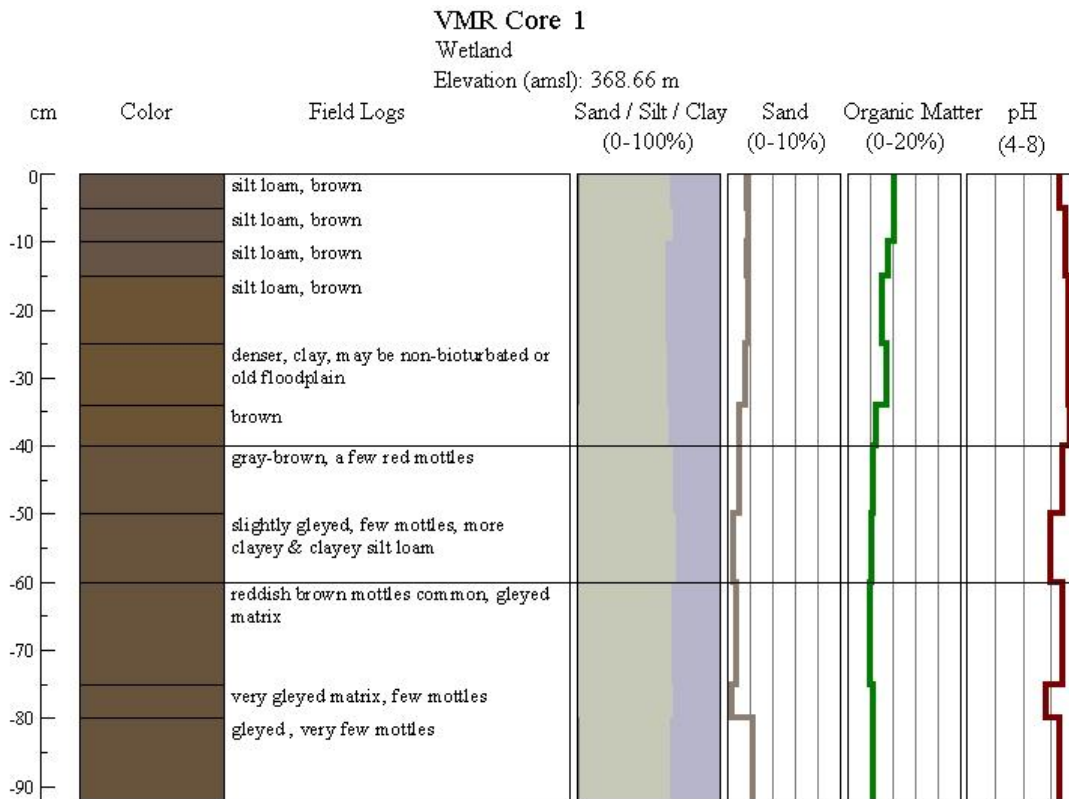


Figure 10. Core 1 stratigraphy of color, particle size, organic matter, and pH. Numbers in parentheses are the range for each category. Top horizontal line represents 1964 and bottom horizontal line represents 1954. Depth to refusal: 215 cm.

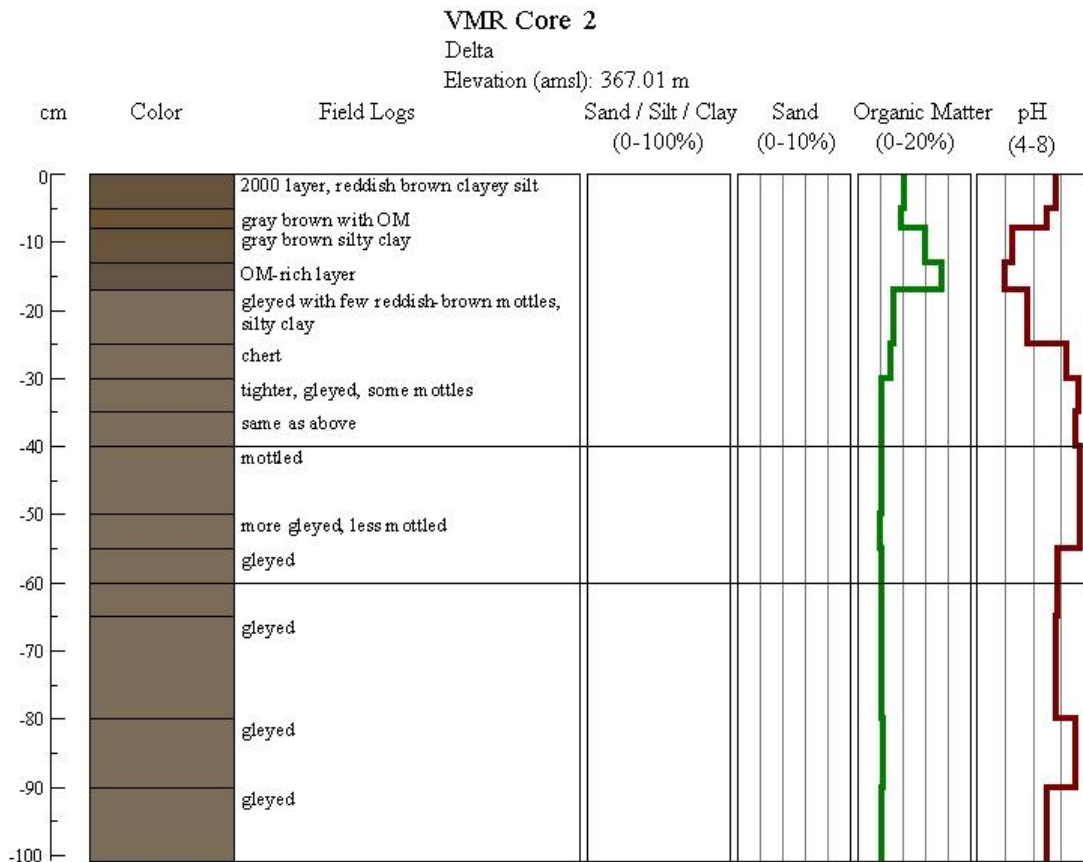


Figure 11. Core 2 stratigraphy of color, particle size, organic matter, and pH. Numbers in parentheses are the range for each category. Top horizontal line represents 1954 and bottom horizontal line represents 1964. Depth to refusal: 215 cm. Particle size analysis was not conducted on this core.

VMR Core 3

Delta

Elevation (amsl): 365.57 m

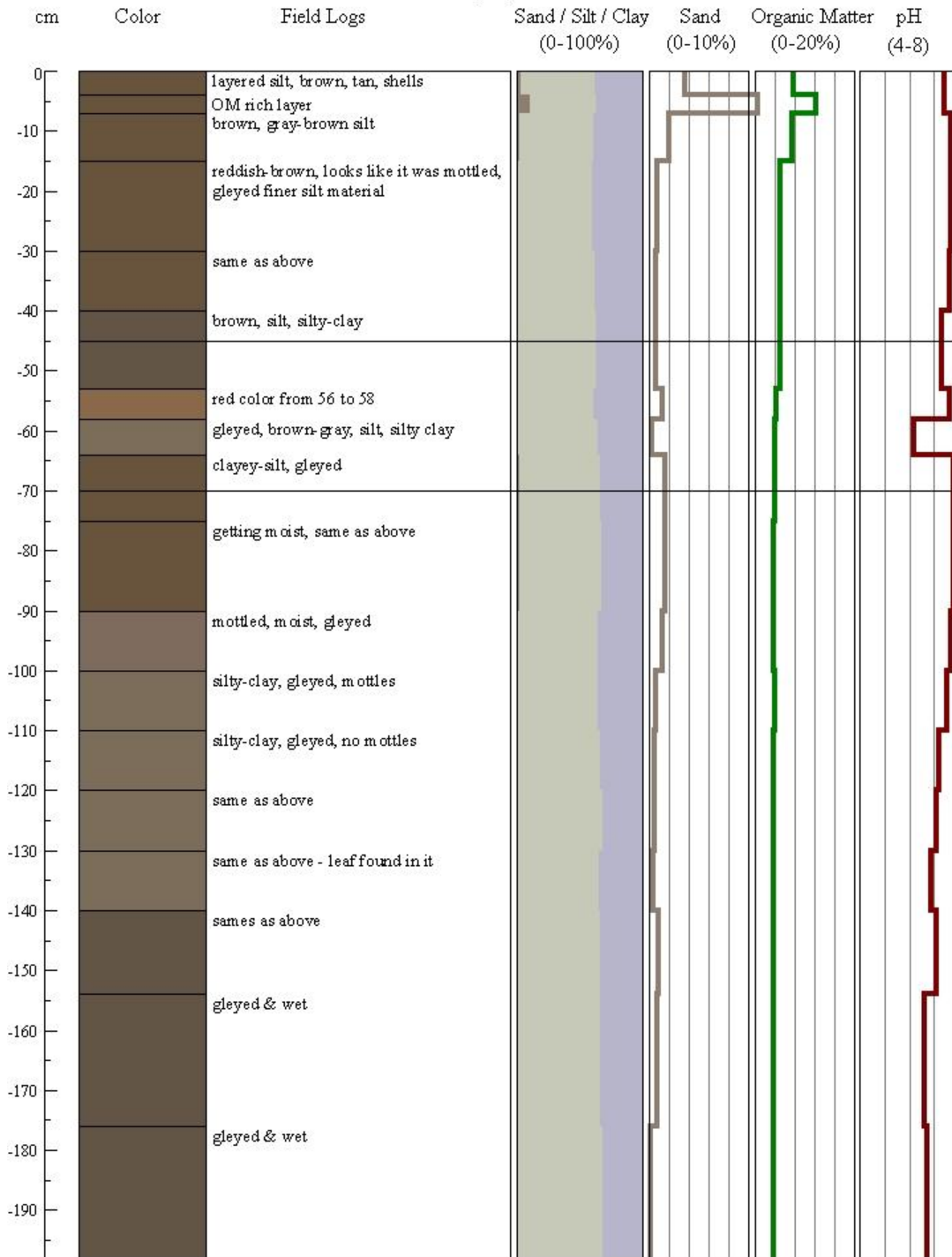


Figure 12. Core 3 stratigraphy of color, particle size, organic matter, and pH. Numbers in parentheses are the range for each category. Top horizontal line represents 1964 and bottom horizontal line represents 1954. Depth to refusal: 198 cm.

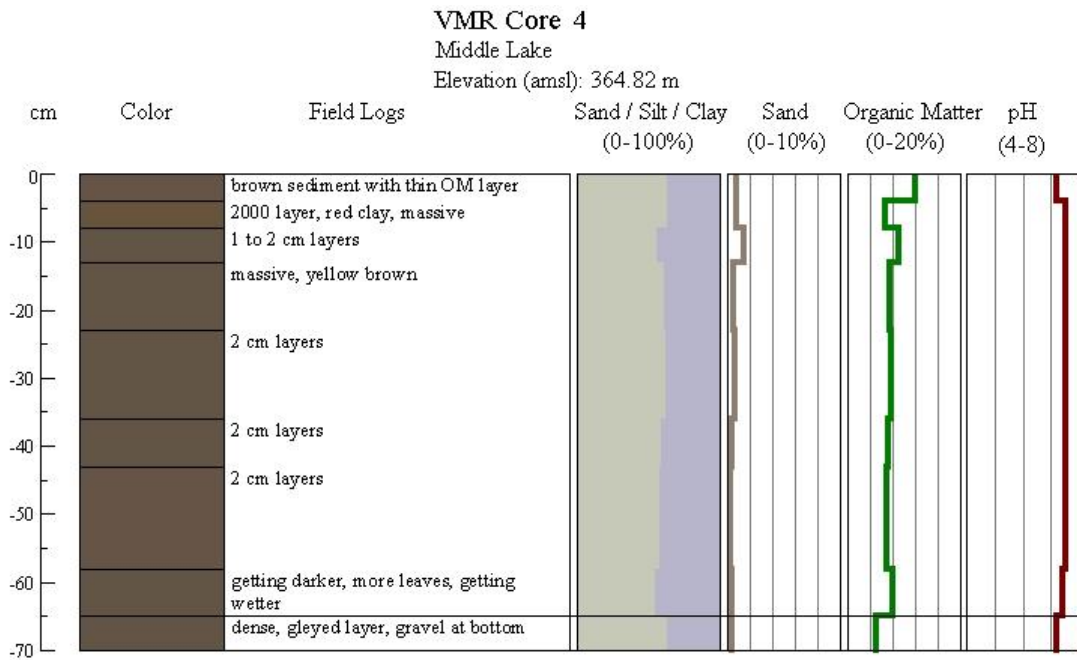


Figure 13. Core 4 stratigraphy of color, particle size, organic matter, and pH. Numbers in parentheses are the range for each category. Horizontal line represents 1969. Depth to refusal: 71 cm.

VMR Core 5
 Middle Lake
 Elevation (amsl): 364.21 m

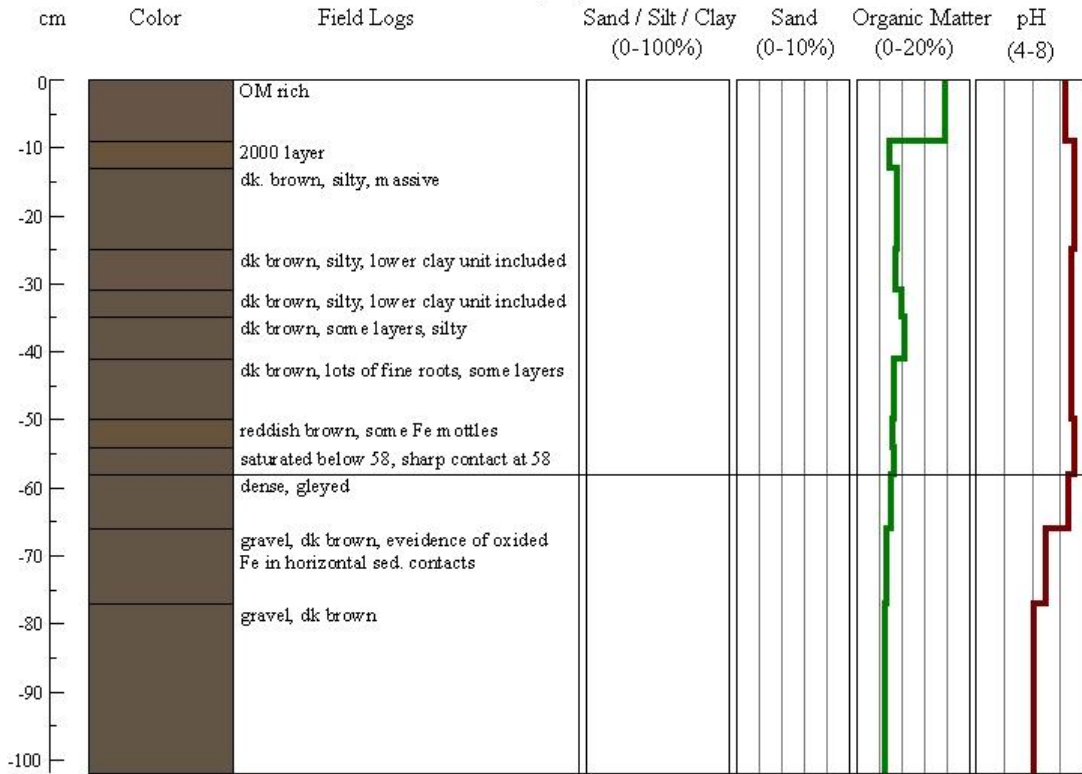


Figure 14. Core 5 stratigraphy of color, particle size, organic matter, and pH. Numbers in parentheses are the range for each category. Horizontal line represents 1969. Depth to refusal: 102 cm. Particle size analysis was not conducted on this core.

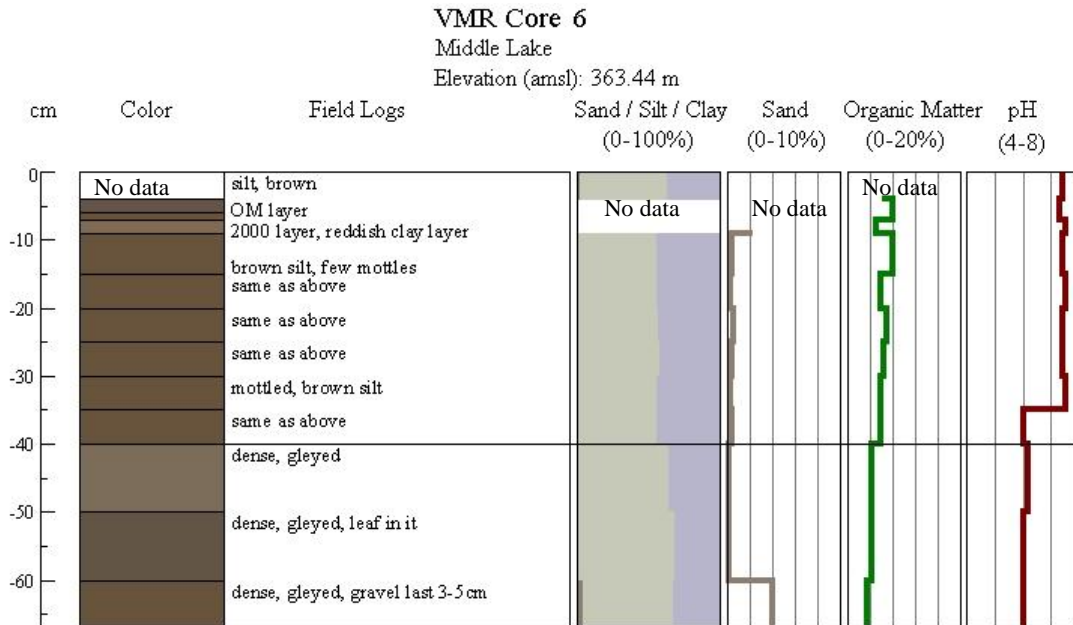


Figure 15. Core 6 stratigraphy of color, particle size, organic matter, and pH. Numbers in parentheses are the range for each category. Horizontal line represents 1969. Depth to refusal: 67 cm.

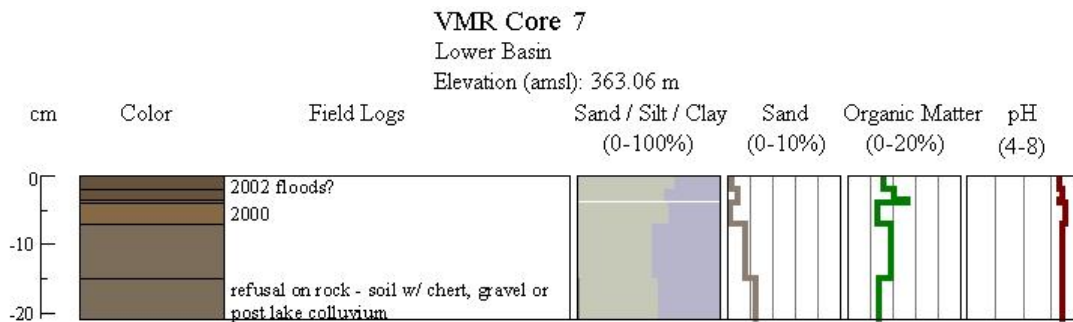


Figure 16. Core 7 stratigraphy of color, particle size, organic matter, and pH. Numbers in parentheses are the range for each category. Bottom of core represents refusal which is ≥ 1969 . Depth to refusal: 21 cm.

¹³⁷Cs dating, the dense unit was believed to be the sediment that was dewatered during the excavation but left behind. The dense unit is lake sediment based upon evidence organic matter (leaves) found to be perfectly preserved within horizontal varve-like strata in two of the cores. Additionally, similar dense units were observed to form upon the current dewatering of VMR. The dense layer was non-existent in some areas because the reservoir was excavated to bedrock (near the dam) or not excavated at all (the wetland). In other areas the dense contact corresponds to the cut-line of excavation. The dense unit ranged in thickness from 0.3 to 0.85 m. The final sedimentary layer found in VMR was pre-impoundment sediment. Pre-impoundment sediment was indicated by the presence of gravel and density changes. The pre-impoundment layer ranged in thickness from 1 cm to 25 cm, depending on refusal factors, and was sampled at the bottom of the cores. Table 13 shows eight historical dates for VMR which are based upon ¹³⁷Cs dating, physical stratigraphy, and historical references.

Munsell color was used to understand color changes within the cores and look more closely at reduced conditions in the sediments. Reduced conditions were identified through low chroma colors (chroma \leq 2). Cores 2, 3, 4, 7, 9, and 10 all exhibited low chroma in the lower portions of the core. Cores 5 and 6 also exhibited low chroma in the lower portions of the core but at the very bottom of the cores the chroma became greater than 2. Both cores 1 and 8 exhibited chromas above 2 throughout the core. However, the entire Core 1 (to refusal) was not retrieved due to a relatively high water table level, which prevented complete extraction. The saturated sediments did not stay in the coring devices used for this study. The reduced sediments were also noted in the field and generally corresponded well to the color profiles. Additionally, it should be noted that

Table 13. Key Dates and Events Recorded in VMR Sediments

Date	Event
July 2002	Cores removed from VMR
July 2000	100-year flood event occurred in watershed
1978	Peak Pb activity
1969	Sediment from VMR was excavated
1964	Peak ¹³⁷ Cs activity
1958	Interstate-44 and U.S. Highway 65 constructed
1954	Initial ¹³⁷ Cs activity
1908	Dam was raised to current height of 5.5 m
1851-1871	Initial impoundment occurred in between these two dates

cores were collected after VMR was drained and thus color may have changed due to improved drainage and more oxic conditions especially in surface sediments.

Particle size analysis was undertaken to understand sedimentation processes occurring in VMR and to understand the one of the basic characteristics of sediments. All of the sediments in VMR can be classified as silty clay or silty clay loam. The mean post-1964/69 clay-sized particle percentages increased down lake with the exception of core 7 which decreased relative to core 6 (Figure 17). The higher sand percentage in Core 3 for the post-1964/69 time-period indicates that this area is part of the delta. For the time-period of 1954 to 1964 the mean clay-sized particle percentage increased between core 1 and core 3 also (figure 18). However, during the pre-1954 time period, clay percentages were very similar in both core 1 and core 3.

Core 1, the wetland core, had clay-size particle contents of 30% to 38% while core 7 ranged from 31% to 47%. The differences in the lower range of the clay-sized percentages were within the $\pm 2\%$ of error expected for the hydrometer method (Gee and Bauder, 1986). However, the upper clay-sized percentages were well beyond the $\pm 2\%$ of error. Clay-sized particle percentages had greater ranges within the core the further down lake the core was located. Sand-sized particles were a very small percentage of the total sample and ranged from 0.08% to 10.99%. Sand-sized particle percentages were relatively constant ranging from 0.08% to 3.94% with the exception of one Core 3 sample (4-7 cm) which had 10.99% sand-sized particles. The higher sand percentage in the delta may be due to the 2000 flood bringing larger sized particles further into VMR than under other conditions. Silt-sized particles were also relatively constant throughout VMR and

Sand-silt-clay percentages post-1964/69

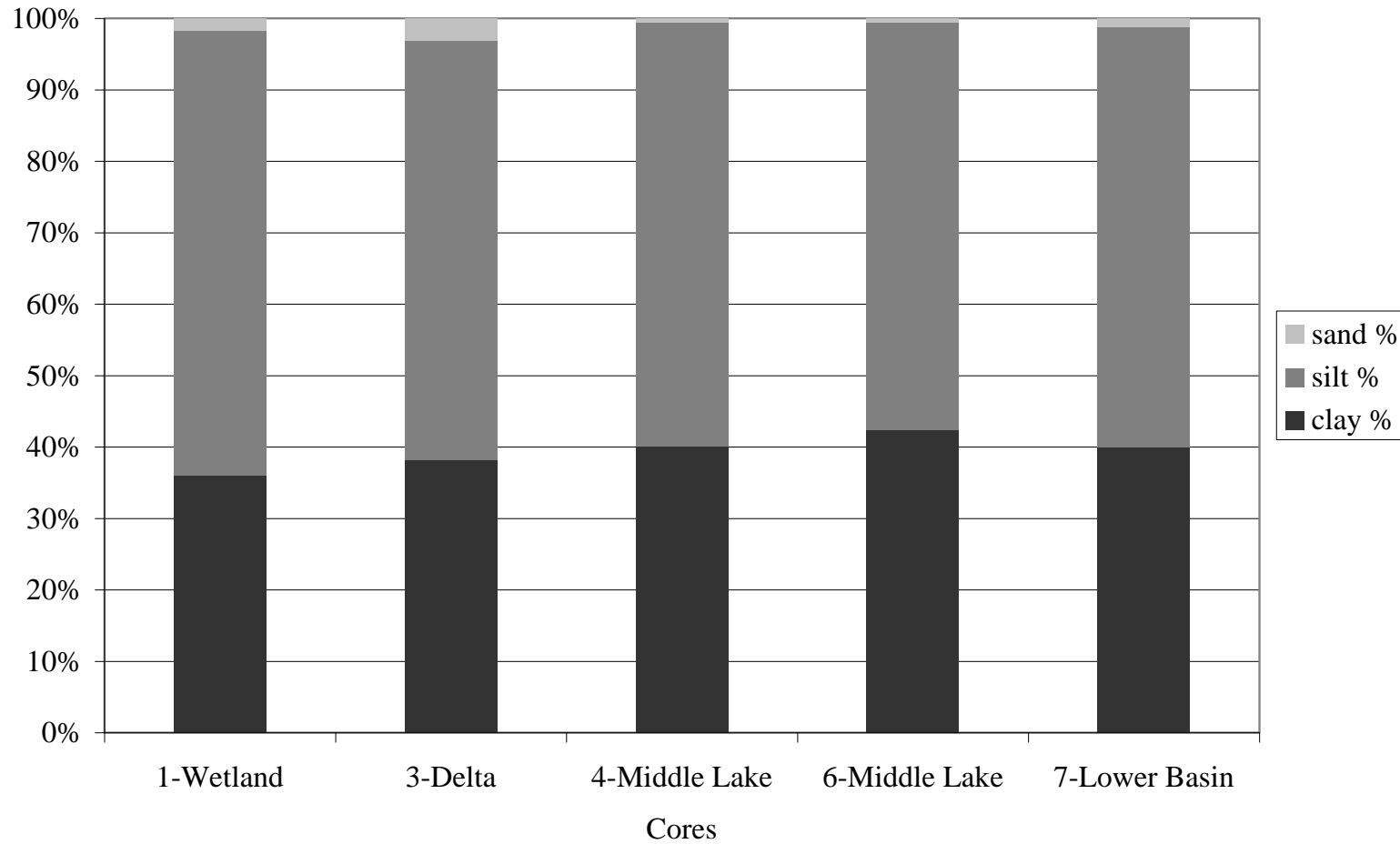
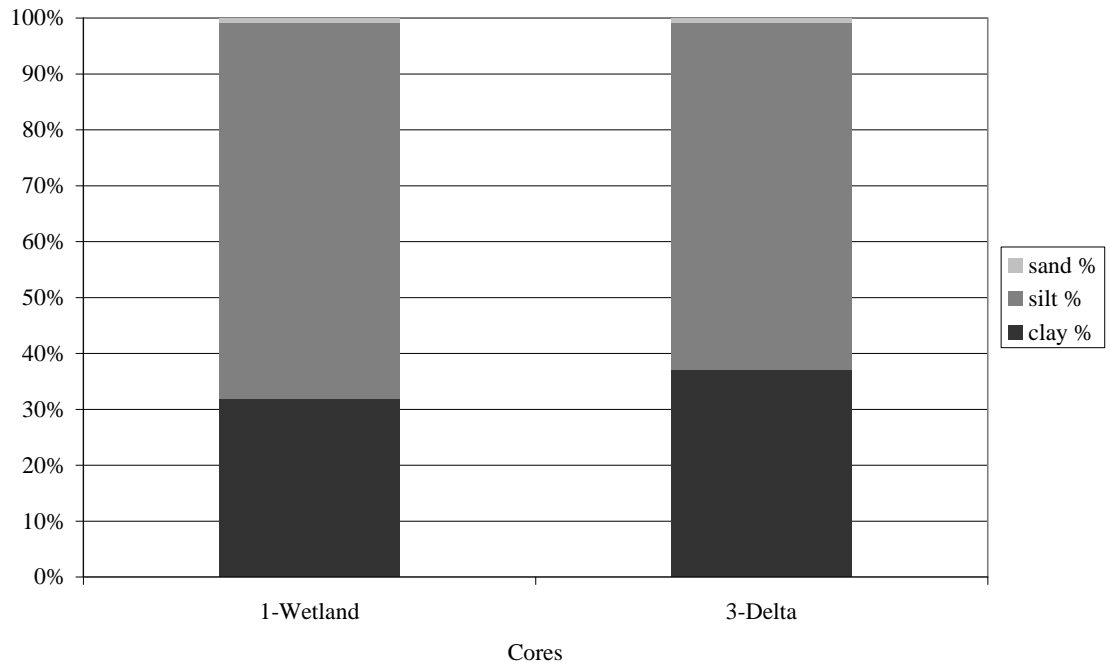


Figure 17. Down-lake sand-silt-clay percentages

Sand-silt-clay percentages 1954-1964



Sand-silt-clay percentages pre-1954

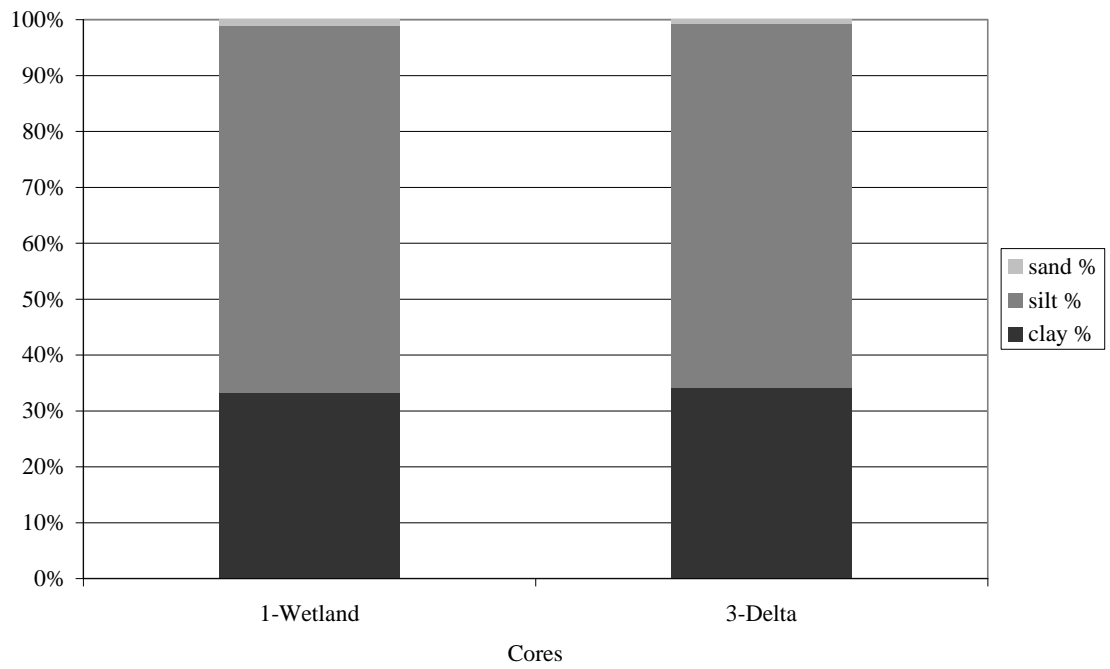


Figure 18. Sand-silt-clay percentages. Both cores 1 and 3 are shown for both 1954 to 1964 and pre-1954.

throughout the cores ranging from 50% to 69%. Core 7 had the greatest within core range with 50% to 68% silt-sized particles. For comparison, Table 14 presents the ranges of sand, silt, and clay sized particles found in the upland soils of VMR watershed.

Organic matter content can indicate the relative productivity of a lake system. The wetland (core 1) and the lower basin (core 6 and 7) both exhibited relatively constant organic matter percentages with a range of 4% to 8%. The consistency in the lower basin was probably due to light limitation while the wetland consistency was probably due to relatively consistent environmental conditions. Cores 2, 3, 4, and 5 all displayed increased organic matter percentages in the top 15 cm and then decreased to about 4% for the rest of the core. The increased organic matter content found in the top 15 cm may be due to increased nutrient loadings and a general trend toward eutrophication. Additionally, the increased organic matter may be due to less breakdown of the organic matter due to shorter time for breakdown to occur. In cores 4, 5, and 6 organic matter increased after 1969. However, the sediment below the post-1969 layer is of unknown age. Thus, the increase in organic matter may not be as sharp as indicated because some of the sedimentary

Table 14. Range of Sand-, Silt-, and Clay-sized Particles Found in Upland Soils of VMR Watershed (Hughes, 1982)

	Percent sand	Percent silt	Percent clay
A-horizon	0-50	72-88	0-28
B-horizon	0-20	60-72	28-40
Residuum	0-50	0-40	40-100

record is missing. Whenever, the 2000 layer is present, organic matter decreases. The high sedimentation rate of relatively unaltered residuum soil material may cause the reduced organic matter content seen in the 2000 layer. In core 7 organic matter was generally in the same range as other post-1969 sediment.

Soil pH was measured to see if VMR has become more or less acidic with time and to understand the availability metals to the water column. The pH values throughout all cores ranged from 5.0 to 7.8 with most ranging from 6.5 to 7.8. The two lowest values (5.0 and 5.3) were both found in core 2 from 8-17 cm. When values of pH fall below 5.5 exchangeable Al may be present (Thomas, 1996). Additionally, as pH decreases, metals are more easily released into the water column. The pH values found in VMR were generally above levels which would more easily release metals into the water column. Where pH levels would be a concern (core 2, 8-17 cm) the sediment was buried deep enough that the metals would not be readily available to the water column.

Longitudinal and Cross-Sectional Profiles

A longitudinal profile of bottom sediments in VMR was created to visualize geomorphic and sedimentary units. The longitudinal profile showed a general steady slope of the top surface from the wetland to the deepest point in VMR, which was about 85 m away from the dam (Figure 19). The exception to the slope was at the mouth of the reservoir (about 525 m away from the dam) where it appears that there was a small area of scour in channel. From the deepest point of the reservoir to the dam the slope was very steep and was presumably a function of construction and/or subsequent excavations.

Longitudinal Profile of Valley Mill Reservoir

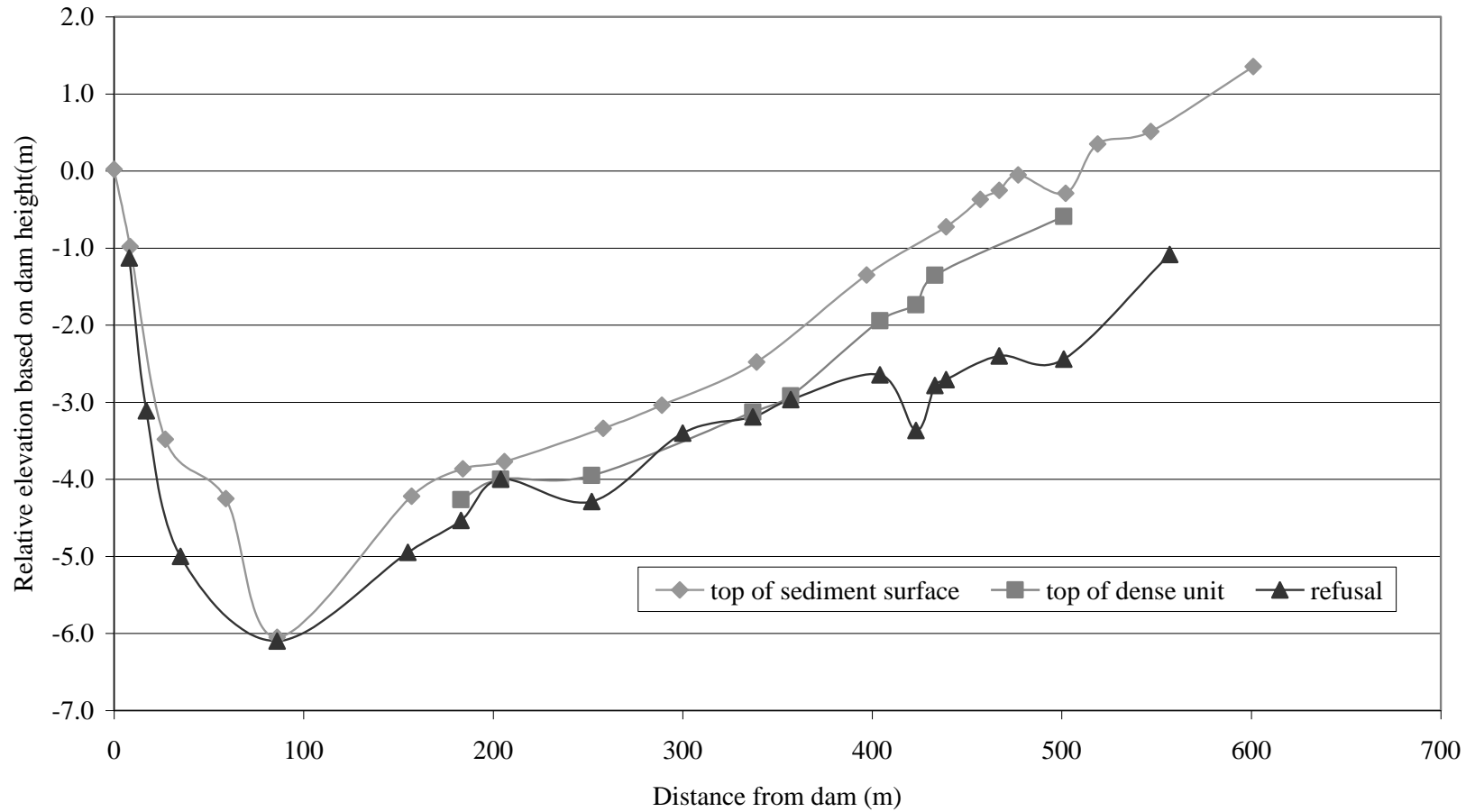


Figure 19. Longitudinal profile of bottom sediments in VMR

The dense unit while seen through much of the profile was not present throughout. The area from the dam to 85 m was most likely one area of the reservoir that was not excavated due to the fear of damaging the dam. The area from 85 m to 185 m away from the dam was most likely excavated to bedrock and therefore there was no contact record of excavation left above refusal. No dense unit was found from 275 m to 375 m and 430 m to 500 m because these data points were not data soil probes/cores but rather just elevation data. Therefore, based upon known information, that the dense unit was found throughout most of the longitudinal profile, and based upon ^{137}Cs dating, it can be assumed that the dense unit is found from 185 m to 500 m and is an indicator of the stratigraphic level of excavation and its date. Sediment thickness from the dense unit to the surface ranged from 0.3 to 0.85 m. The thickest deposits were found from 330 to 430 m away from the dam. Down lake recent deposits thinned to 0.3 m thick.

The refusal depths showed greater variation in slope and thickness. The differing refusal depths may be due to sampling methods, probing from the boat may not have allowed us to reach true refusal but rather the unit of dense fines found elsewhere in the reservoir, or to the natural topography of the original valley floor. Refusal depths may indicate a delta formation as was seen through the spatial modeling of sediment thickness. However, refusal depths may be an uneven due to uneven bedrock contact, dense clays, or buried logs.

Cross-sectional profiles were also utilized to understand geomorphic and sedimentary units (Figure 20). Cross-section A in the lower basin showed a typical lake cross-section with a general semi-circle shape (Figure 21). In the lower basin recent sedimentation was very low and ranged from 0.05 to 0.3 m. The lower basin was the area

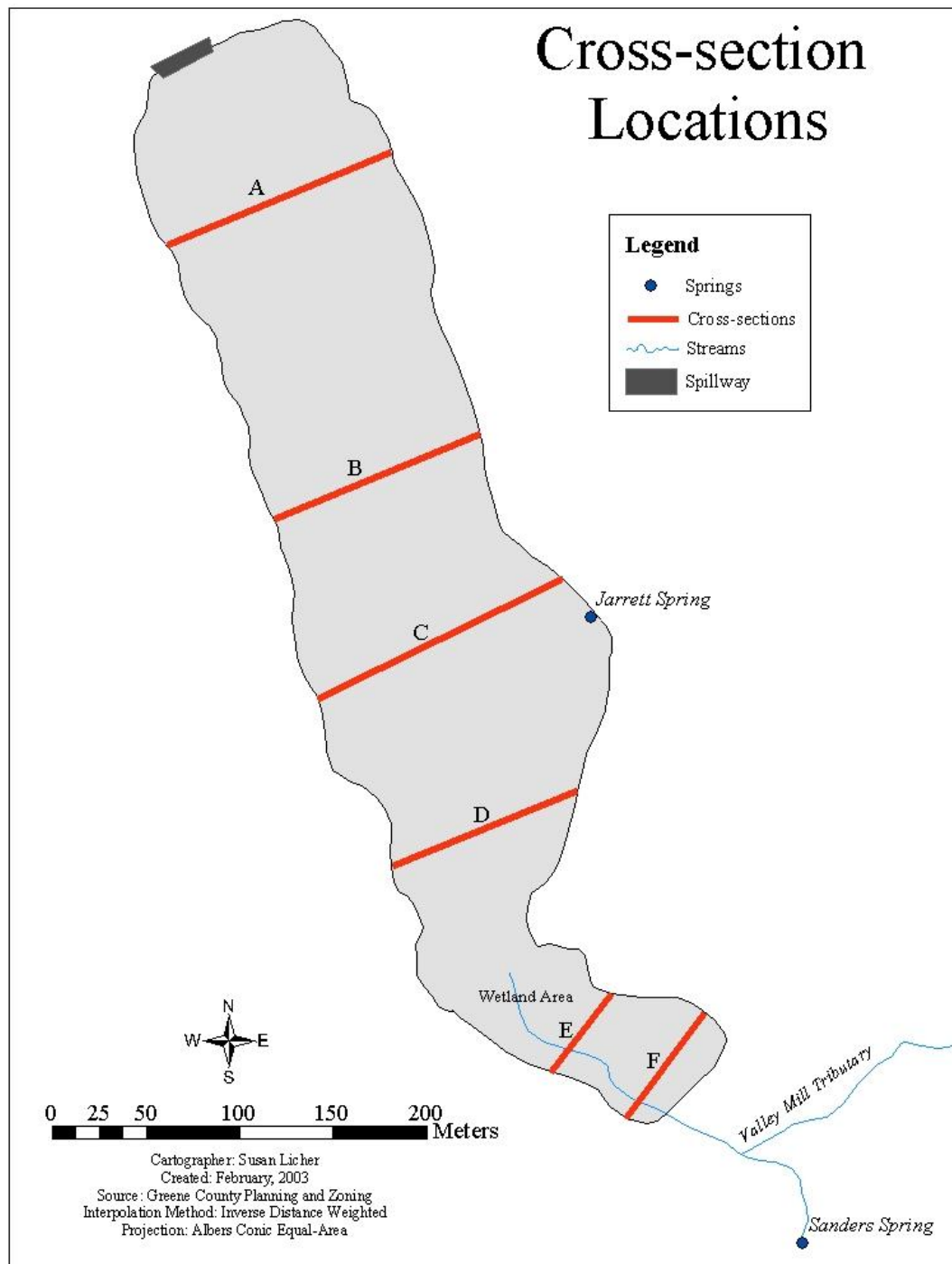


Figure 20. Location of cross-section profiles in VMR

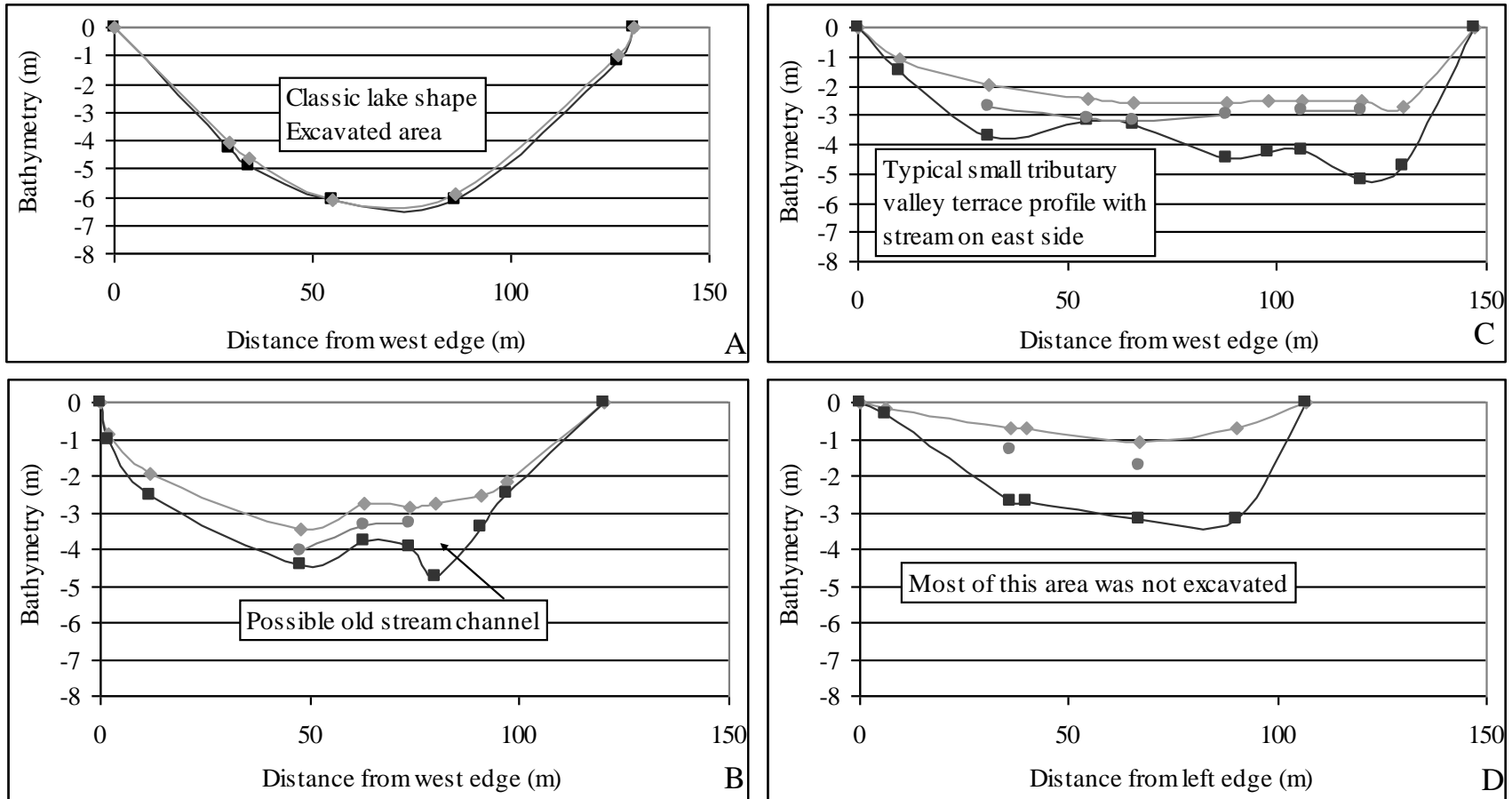


Figure 21. Cross-sectional profiles of VMR. Top elevation (◆), dense unit (●), and refusal (■) are indicated.

that was excavated to bedrock. Cross-section B moved into the middle part of the lake and here the cross-sectional profile changed. In cross-section B there was greater recent sedimentation and total sedimentation than in cross-section A. The dense unit was detected but only in the center of the cross-section. Additionally, the refusal profile varied more than in cross-section A. Cross-section C showed the reservoir becoming wider, the top elevation becoming almost uniform, the dense unit showing up again across the width of the reservoir, and varied refusal depths probably showing the original valley floor. Finally, cross-section D showed a uniform top elevation with a classic lake shape, the dense unit was only evident in two spots indicating that parts of this area were not excavated, and refusal depths again became a more classic lake shape.

The cross-sectional profiles showed thicker old deposits (late 1800's to 1969) in the upper portions of the reservoir but this is mostly a factor of excavation rather than true differences. The younger deposit (1969 to 2002) was also thicker in the upper portions of the reservoir indicating greater sedimentation. Top elevations were uniform and displayed classic lake bottom form in the upper portions of the reservoir. This uniformity was probably due to thicker sediments, which masked the valley floor topography.

Cross-section profiles E and F (Figure 22) are wetland profiles. The top elevation of the wetland was higher than the dam and indicated that future sedimentation here will decrease relative to the rest of the reservoir. In the wetland cross-sections, no dense unit was found which was expected since this area was not believed to be excavated and pore water pressures remained high, as the water table did not drop (J. Parker, Springfield City Utilities, personal communication).

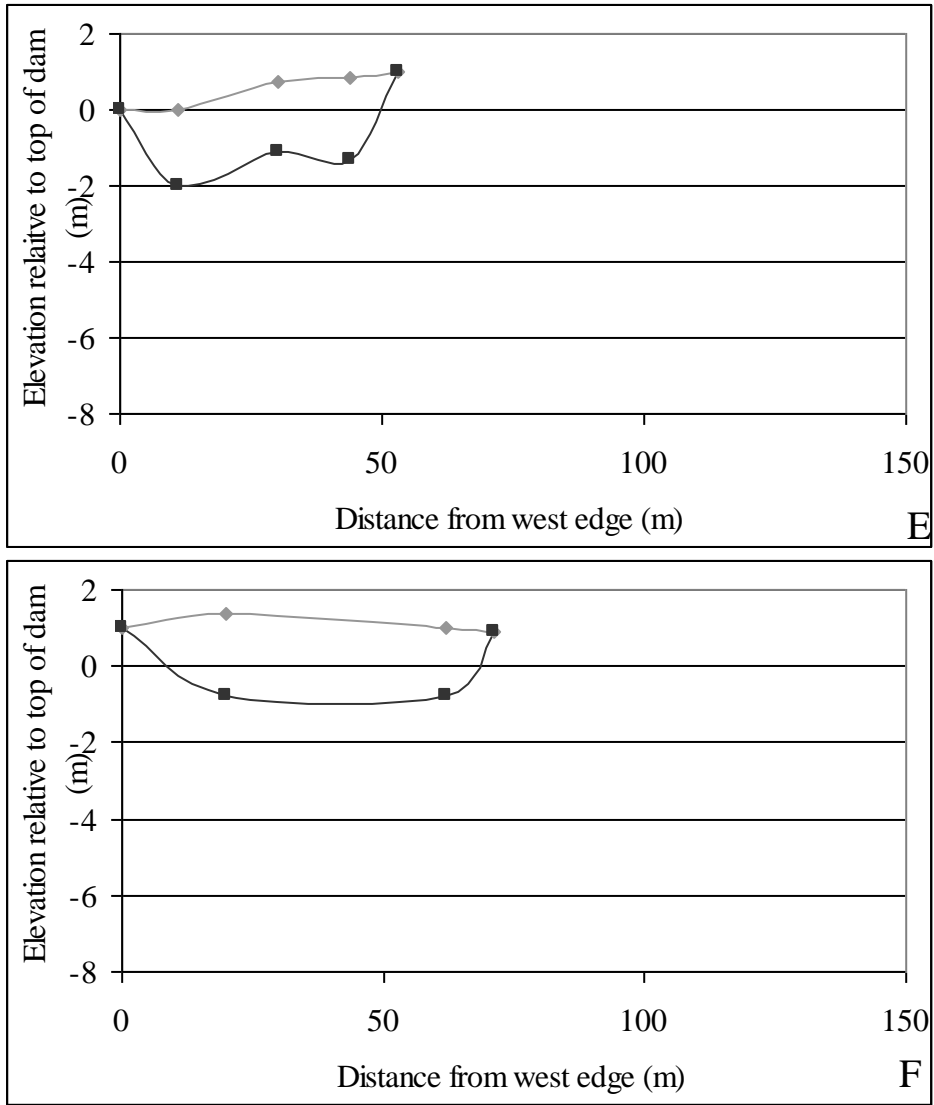


Figure 22. Cross-sectional profiles of VMR. Top elevation (◆) and refusal (■) are indicated. Note that no dense units were found in the wetland.

During the current drainage of the reservoir, the water table remained high also. Total sedimentation in the wetland area was high and closely matched cross-section D total sediment thickness.

GEOCHEMICAL STRATIGRAPHY

Geochemical stratigraphy was used to understand the pollution history and sedimentation patterns and processes in VMR sediments. Geochemical stratigraphy will be presented for each core and then compared and contrasted spatially, with other stratigraphic markers, and to source sediments.

Geochemical analysis for Core 1 did not go to refusal and was therefore an incomplete record but it did encompass the entire ^{137}Cs record. The lower portion of the wetland core was saturated to a depth of 92 cm from the surface, which limited core collection. Aluminum (1.03% to 1.28 %) and Fe (1.29 % to 1.57 %) trends closely followed one another (Figure 23). Copper was constant throughout the core with a range of 9ppm to 12 ppm. Mercury was also relatively constant with a range of 30ppm to 60 ppb. Phosphorus concentrations generally increased up-core with a peak at 25-35 cm and another peak from 0-15 cm and a range of 280 ppm to 490 ppm. Lead (18 ppm to 30 ppm) increased up-core with a large increase after 1964, peaked at 15-25 cm, and then began to decrease toward the top of the core. Zinc generally increased throughout the length of the core, again with the largest increase after 1964, and ranged from 36 ppm to 62 ppm.

Core 2 was located at the edge of the lake and wetland and again a complete record was not obtained due to water table limitations. Element concentrations were more variable in core 2 than in core 1. Aluminum concentrations stayed at or below

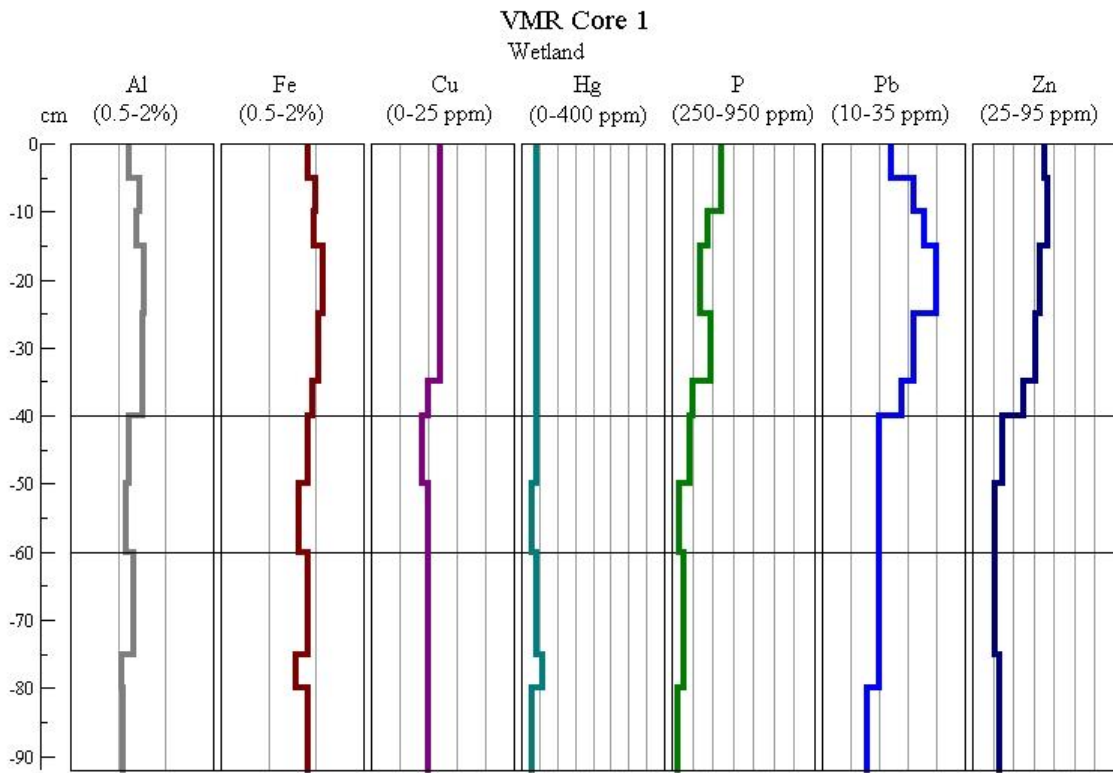


Figure 23. Element concentrations for core 1. The top horizontal line represents 1964 and the bottom horizontal line represents 1954. Depth to refusal is 215 cm.

1.00 % from 25 cm to 101 cm and then jumped up to 1.42% at 8-13 cm, decreased to 1.15% from 5-8 cm, and finally increased to 1.4 % again (Figure 24). Iron remained relatively constant from 13 cm to 101 cm (1.18% to 1.39 %) and then jumped up to 1.73 % from 8-13 cm and remained consistently higher to the top of the core. Copper ranged from 9 ppm to 15 ppm through most of the core with one high concentration of 21 ppm at 80-90 cm. Mercury was again relatively constant and ranged from 30 ppb to 60 ppb. Phosphorus concentrations were low from 101 up to 17 cm and then increased up to 680 ppm at the top of the core. Lead concentrations stayed below 20 ppm below 25 cm, then increased until a peak concentration of 28 ppm at 8-13 cm, and then decreased again. Zinc concentrations were less than 30 ppm below 30 cm, increased until 8-13 cm, where concentrations peaked at 72 ppm, then decreased for 3 cm, and finally jumped back to 70 ppm from 0-5 cm.

Sediments were collected from the entire length of core 3 and provided a complete record of sedimentation from impoundment to 2002. Aluminum concentrations stayed between 0.98% and 1.08 % from 58 to 198 cm, increased to a peak of 1.28 % at 15-30 cm, and then decreased to 1.06 % at the top of the core (Figure 25). Iron concentrations also stayed relatively consistent (1.26% to 1.37 %) from 58 to 198 cm, displayed two peaks of 1.64% with one at 53-58 cm and another at 4-7 cm, in between these two peaks concentrations ranged from 1.3% to 1.58 %, and then decreased to 1.39 % at the top of the core. Copper concentrations ranged from 10 ppm to 15 ppm throughout the core and the peak concentrations of 15 ppm occurred at 110-120 cm and again at 4-7 cm. Mercury concentrations generally ranged from 30 ppb to 40 ppb with

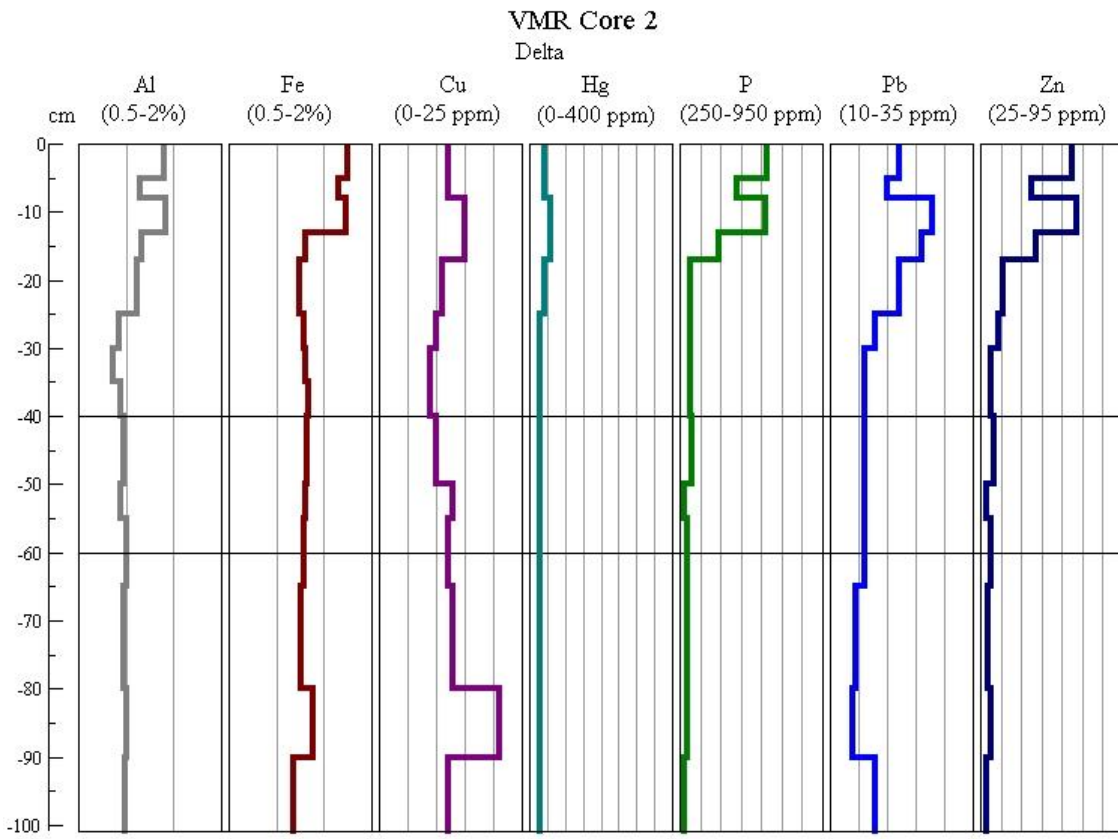


Figure 24. Element concentrations for core 2. The top horizontal line represents 1964 and the bottom horizontal line represents 1954. Depth to refusal is 215 cm.

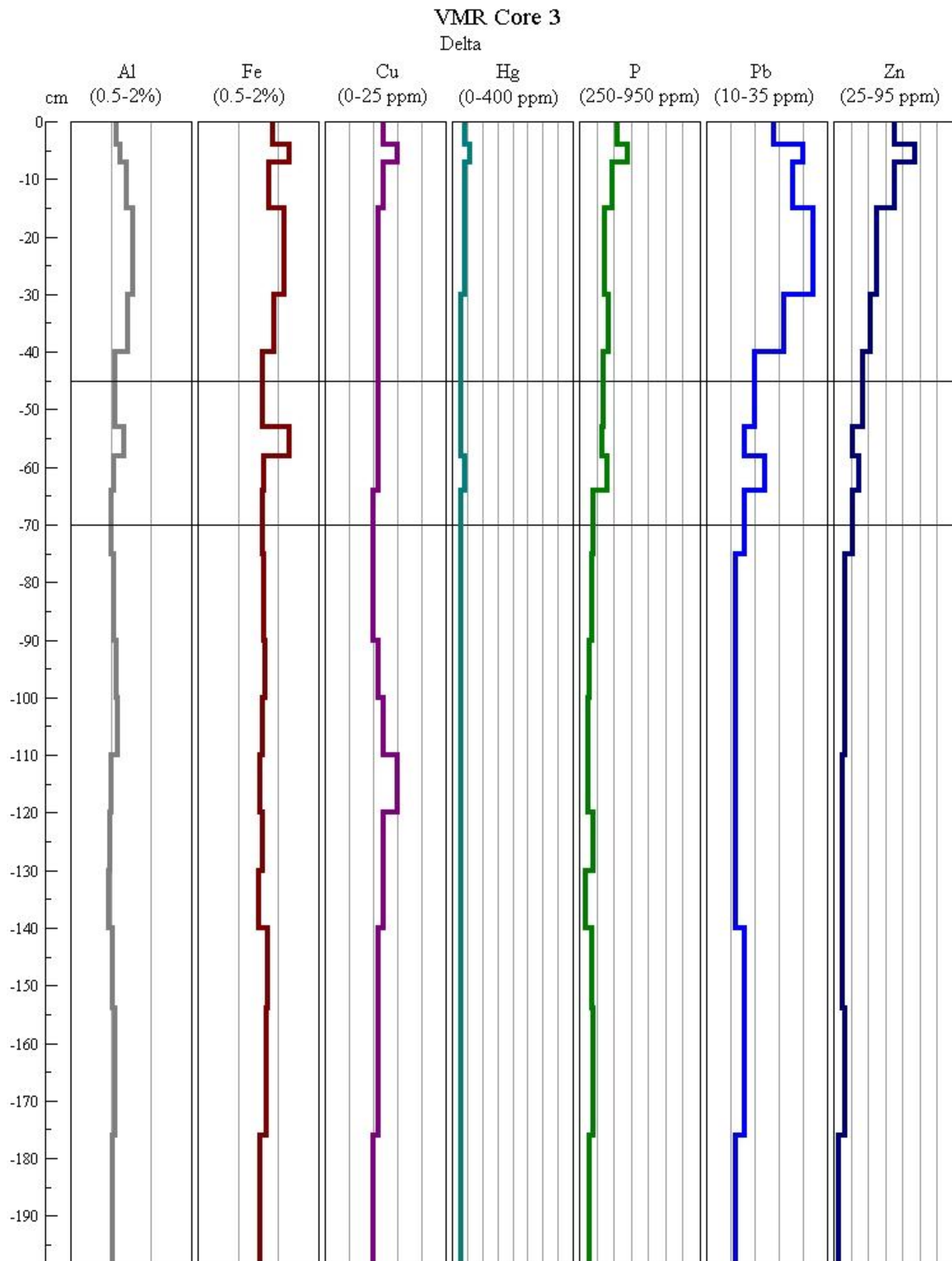


Figure 25. Element concentrations for core 3. The top horizontal line represents 1964 and the bottom horizontal line represents 1954. Depth to refusal is 198 cm.

only one 60 ppb concentration at 4-7 cm. Phosphorus concentrations were less than 350 ppm below 64 cm, then increased to a peak of 530 ppm at 4-7 cm, and then decreased in the top 4 cm. Lead concentrations were less than or equal to 18 ppm below 64 cm, then increased to a peak of 32 ppm at 15-30 cm, and then decreased toward the top of the core with a spike of 30 ppm at 4-7 cm. Zinc concentrations stayed below 35 ppm pre-1954, and then steadily increased after 1964, with a peak concentration of 62 ppm.

Core 4 was the first core where the excavation marker (65 cm) was seen and where sediment was obtained to refusal but the record was incomplete due to the excavation of the site. Aluminum concentrations ranged from 1.17% to 1.75 % with the lowest value occurring at 65-70 cm, which was below the excavation marker and the highest value occurring at the top of the core (Figure 26). Iron concentrations ranged from 1.29% to 1.76 % with the highest value occurring at the top of the core. Copper concentrations ranged from 11 ppm to 17 ppm and remained relatively consistent between 8 and 65 cm. The highest Cu concentration was found from 65-70 cm with another high value (16 ppm) found at the top of the core and the lowest value occurring from 4-8 cm. Mercury concentrations were 40 ppb from 0 cm to 65 cm while 65-70 cm had a concentration of 30 ppb. Phosphorus concentrations ranged from 320 ppm to 770 ppm with the lowest occurring at 65-70 cm and the highest occurring in the top 4 cm. In between 8 and 58 cm, P concentrations fluctuated around 500 ppm. Two other low P concentrations occurred from 4-8 cm and again at 58-65 cm. Lead concentrations ranged from 18 ppm to 30 ppm with the lowest occurring from 65-70 cm. The Pb concentrations immediately jumped to the highest concentration from 58-65 cm, then steadily decreased from 58 up to 4 cm, and then increased again in the top 4 cm. Zinc concentrations ranged

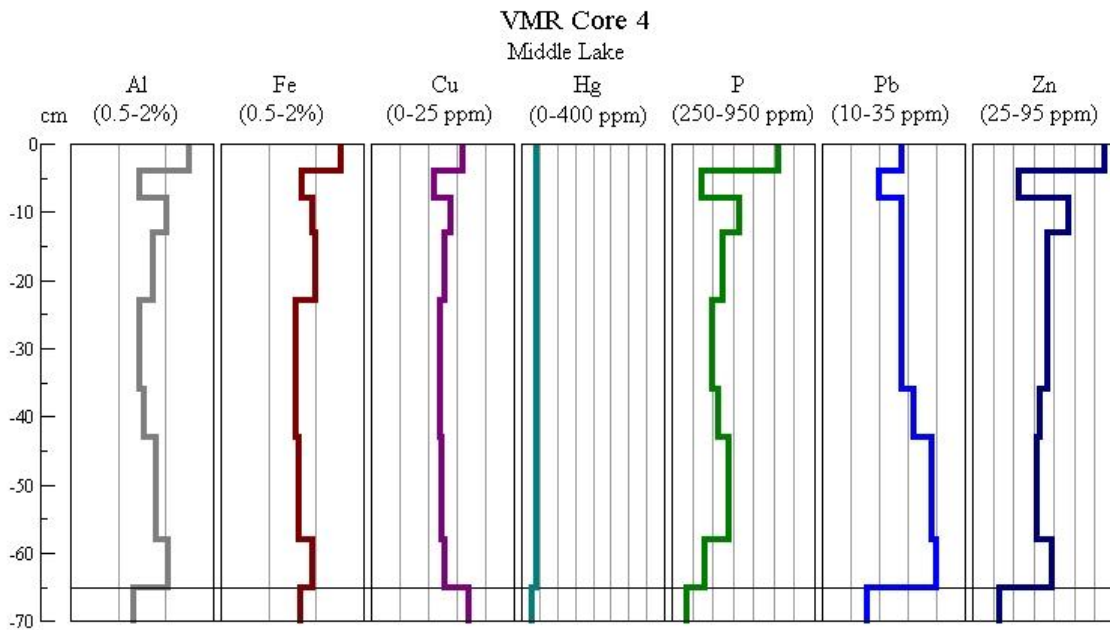


Figure 26. Element concentrations for Core 4. The horizontal line represents 1969. Depth to refusal is 71 cm.

from 38 ppm to 90 ppm with the highest occurring at the top of the core and the lowest occurring at the bottom of the core. In between the two end points the 4-8 cm depth showed markedly lower concentrations, and then concentrations decreased down core until 58-65 cm, where there was a slight increase.

In core 5 the excavation marker occurred at 58 cm and sediment to refusal was collected. Aluminum concentrations ranged from 1.04% to 1.60 % (Figure 27). The top 35 cm displayed increasing Al concentrations down core, then concentrations decreased between 35 and 50 cm, a peak concentration occurred at 50-54 cm, then concentrations decreased again from 54-77 cm, and finally concentrations showed a slight increase between 77 and 102 cm. Iron concentrations ranged from 1.22% to 1.5% with the highest concentration at the bottom of the core. Another high Fe concentration (1.47 %) was found at the top of the core and in between the two end points concentrations oscillated between increasing and decreasing concentrations. Copper concentrations ranged from 11 ppm to 15 ppm with an increasing trend from the bottom up to the peak at 31-35 cm. After the peak concentration, Cu concentrations again decrease to the top of the core with a notable decrease from 9-13 cm. Mercury concentrations ranged from 30 ppb to 80 ppb. Mercury concentrations increased from the bottom up to the peak at 35-41 cm, then decreased from 35-9 cm, and finally increased again in the upper 9 cm. Phosphorus concentrations ranged from 300 ppm to 850 ppm with the highest concentration occurring in the upper 9 cm. The P concentration at the bottom of the core began at 360 ppm, then decrease down to 300 ppm at 58-66 cm, concentrations then increased steadily to 480 ppm at 13-25 cm, decreased sharply from 9-13 cm to 390 ppm, and finally increased very sharply to 850 ppm from 0-9 cm. Lead concentrations ranged from 20 ppm to 34 ppm

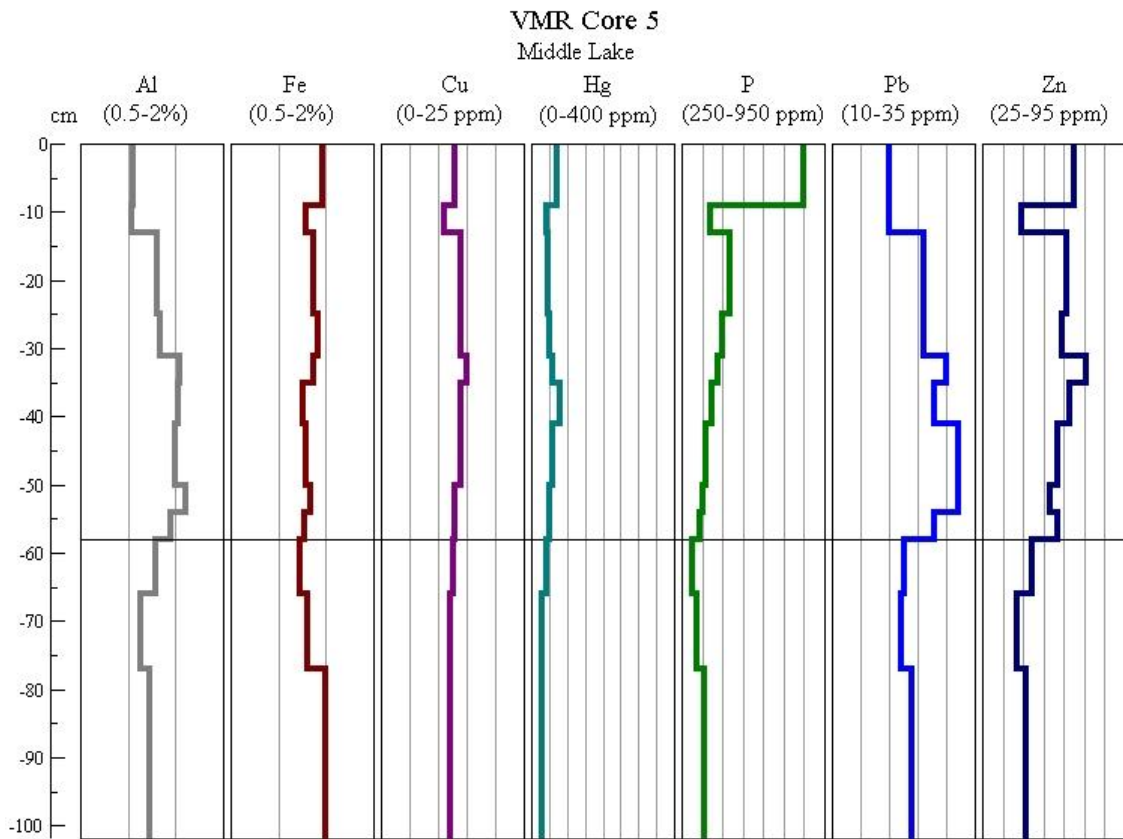


Figure 27. Element concentrations for core 5. The horizontal line represents 1969. Depth to refusal is 102 cm.

with the lowest concentrations found at the top of the core. Lead concentrations began increasing after 1969. The peak Pb concentration (32 ppm) was found at 41-54 cm, then concentrations decreased on either side of the peak, another small peak was found at 31-35 cm, and there was a slight increase at the bottom of the core. Finally, Zn concentrations ranged from 42 ppm to 76 ppm with the peak found at 31-35 cm. Zinc concentrations were also high at the top of the core with the exception of 9-13 cm where they dropped to 44 ppm. Below the peak Zn concentration, the concentrations decreased down to 54 cm, then increased slightly from 54-58 cm, and finally decreased sharply with only a slight increase in the bottom sample.

Core 6 had an excavation marker at 40 cm and a refusal depth at 67 cm.

Aluminum concentrations ranged from 1.03% to 1.64 % (Figure 28). From 40-67 cm Al concentrations were much lower than most of the rest of the core, with only depths 7-9 cm and 0-4 cm having similar concentrations (1.25 %). The rest of the core had similar concentrations (1.46% to 1.53 %) with the exception of 9-15 cm, which had a concentration of 1.64 %. Iron concentrations ranged from 1.27% to 1.77 % with the peak occurring from 4-6 cm and the lowest concentration from 40-50 cm. Copper concentrations ranged from 11 ppm to 15 ppm with two peaks occurring at 4-6 cm and 9-15 cm and the low concentration occurring at 7-9 cm. Mercury concentrations ranged from 20 ppb to 50 ppb with two peaks at 9-15 cm and at 20-25 cm. The lowest Hg concentration was at the bottom of the core with the rest of the core oscillating between 30 and 40 ppb Hg. Phosphorus concentrations ranged from 340 ppm to 930 ppm with the peak occurring just below the surface at 4-6 cm. The lowest P concentrations were found at the bottom of the core (40-67 cm) and from 7-9 cm with the rest of the core having

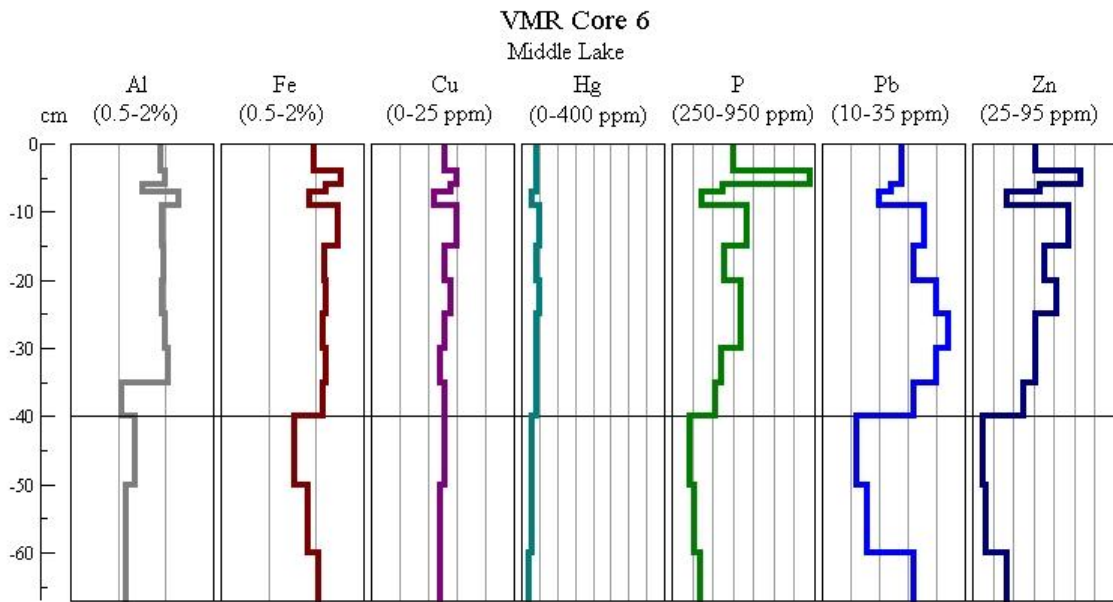


Figure 28. Element concentrations for core 6. The horizontal line represents 1969. Depth to refusal is 67 cm.

values between 460 and 620 ppm. Lead concentrations ranged from 16 ppm to 32 ppm with concentrations peaking at 25-30 cm. Lead concentrations decreased below 30 cm until 50 cm where concentrations began to increase again to the bottom of the core. Above 30 cm, Pb concentrations decreased to 20 ppm at 7-9 cm where Pb concentrations then began to increase again. Zinc concentrations ranged from 30 ppm to 78 ppm. The lowest Zn concentration was found from 40-50 cm and slightly increased concentrations were found from 50 to 67 cm. Above 40 cm Zn concentrations increased to 72 ppm at 9-15 cm, then dropped sharply from 7-9 cm (42 ppm), increased to the peak of 78 ppm at 4-6 cm, and then decreased sharply again in the top 4 cm.

Core 7 had no excavation marker and a refusal depth of 21 cm. Aluminum concentrations ranged from 1.02 % to 1.46 % with a peak of 1.46 % at 7-15 cm (Figure 29). Aluminum concentrations decreased up-core after the peak to a low concentration of 1.02 %. Below the peak there was a slight decrease in Al concentrations. Iron concentrations did not vary a lot with a range of 1.35 % to 1.50 %. Copper concentrations ranged from 11 ppm to 24 ppm and increased down-core until 4-7 cm where concentrations decreased to 11 ppm. Increased Cu concentrations were seen below 4-7 cm with the largest concentration occurring at the bottom of the core. Mercury concentrations ranged from 50 ppb to 90 ppb and increased largely from 7-21 cm. Phosphorus concentrations ranged from 290 to 850 ppm with the lowest concentration occurring at the bottom of the core and the highest concentration occurring at 3.5-4 cm. Lead concentrations ranged from 20 ppm to 26 ppm with the highest concentration occurring from 7-21 cm and again from 3.5-4 cm. Zinc concentrations ranged from 48 to

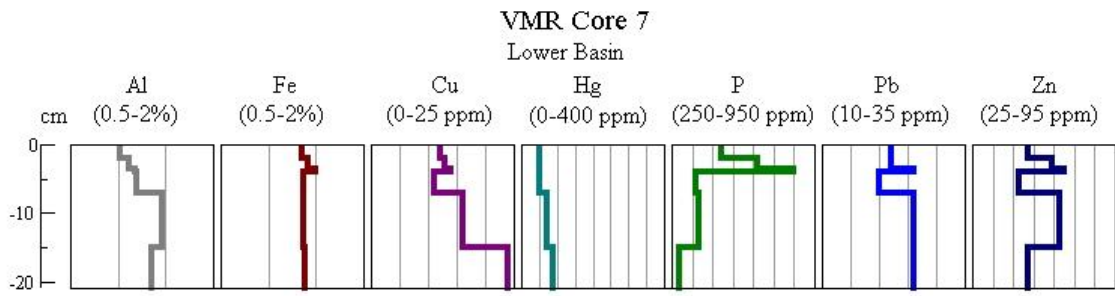


Figure 29. Element concentrations for core 7. Bottom of core represents refusal, which is ≥ 1969 . Depth to refusal is 21 cm.

70 ppm with a peak concentration at 3.5 -4 cm. Zinc concentrations oscillated back and forth between high and low concentrations.

Core 8 had only a 10 cm refusal depth and only two samples were taken from the core. For all elements the 3-10 cm sample had higher concentrations than the 0-3 cm sample (Figure 30). Aluminum concentrations were 0.99 and 1.24 %. Iron concentrations were 1.32 and 1.51 %. Copper concentrations were 12 and 13 ppm, while Hg concentrations were 50 and 60 ppb. Phosphorus concentrations were 480 and 510 ppm. Pb concentrations were 22 and 26 ppm. Finally, Zn concentrations were 52 and 60 ppm.

Core 9 had no excavation marker and a refusal depth of 32 cm. Aluminum concentrations ranged from 1.05 to 1.31 % with the highest concentration at the bottom of the core (Figure 31). The lowest concentration was found at 15-17 cm with Al concentrations increasing down-core from 17 cm. Up-core Al concentrations increased from 15 cm up to 5 cm and then from 0-5 cm decreased slightly. Iron concentrations ranged from 1.00 to 1.43 % with again the highest concentration found at the bottom of the core and the lowest concentration found at 15-17 cm. The same up- and down-core trends that were seen relative to the lowest concentration in Al were also seen in Fe concentrations relative to the lowest concentration. Copper concentrations ranged from 12 to 14 ppm. Mercury concentrations ranged from 60 to 390 ppb. The highest concentration of Hg was found at 15-17 cm. The rest of the core exhibited similar concentrations (60 ppb to 90 ppb) with a slight increase (110 ppb) in the upper 5 cm. Phosphorus concentrations ranged from 380 to 480 ppm. The upper 10 cm exhibited the highest concentrations and the lowest concentration was found at 13-15 cm. Lead concentrations ranged from 24 ppm to 32 ppm with the peak occurring at 18-25 cm.

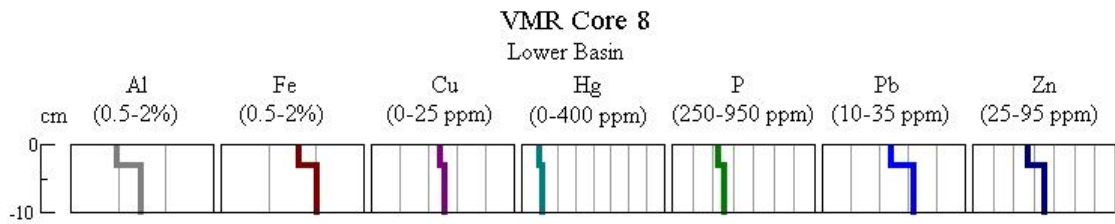


Figure 30. Element concentrations for core 8. Bottom of core represents refusal, which is ≥ 1969 . Depth to refusal is 10 cm.

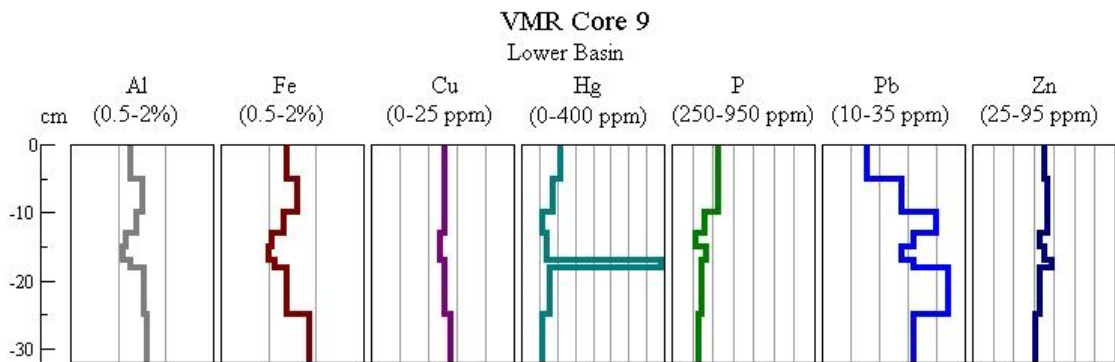


Figure 31. Element concentrations for core 9. Bottom of core represents refusal, which is ≥ 1969 . Depth to refusal is 32 cm.

Below the Pb peak, concentrations decreased. Above the Pb peak, concentrations decreased until 10-13 cm where there was another spike in concentrations and then decreased toward the top of the core. Zinc concentrations showed little variation with a range of 56 ppm to 64 ppm.

Core 10 had a refusal depth of 15 cm and only two samples were taken from the core. All concentrations are listed from the bottom of the core up. Aluminum concentrations were 1.21 and 1.06 % while Fe concentrations were 1.00 and 0.98 % (Figure 32). Copper concentrations were 15 and 14 ppm. Mercury (150 and 190 ppb) and P (290 and 400 ppm) concentrations both displayed higher concentrations on the surface. Lead concentrations were 34 and 24 ppm. Zinc concentrations were 66 and 62 ppm.

Major Disturbances as Recorded by VMR Sediments

A known 2000 layer is found in cores 4, 5, 6, and 7. All elements looked at in these cores decreased in the 2000 layer. The decrease in element concentrations is most likely due to dilution. Additionally, organic matter decreased in the 2000 layer and may be due to the erosion of residuum from the golf course construction site rather than the erosion of the A-horizon which occurs during other run-off events (Kashiwaya et al., 1997). In addition, the color of the 2000 layer was redder than the surrounding sediments. The red color also indicates erosion of residuum rather than the A-horizon.

Using the 2000 flood layer, sedimentation rates can be calculated, which are in addition to the ¹³⁷Cs sedimentation rates. The thickness of the 2000 flood layer ranged from 2 cm to 4 cm and thus a very short-term sedimentation rate would be 2 cm to 4 cm/month. This high sedimentation rate is considered a worse case scenario (a 100-

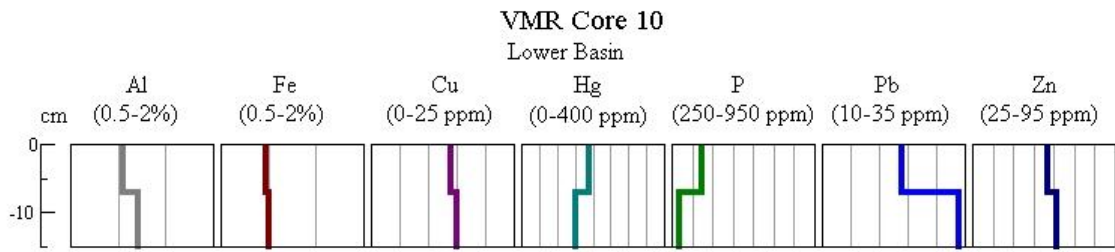


Figure 32. Element concentrations for core 10. Bottom of core represents refusal, which is ≥ 1969 . Depth to refusal: 15 cm.

year flood event occurring when approximately $\frac{1}{4}$ of the watershed is barren land) and is expected to occur rarely.

Another short-term sedimentation rate that can be calculated is the two-year sedimentation rate, which is based upon the post-2000 deposition. The post-2000 deposition ranged in thickness from 4 cm to 9 cm with an average thickness of 6 cm. Thus, an average two-year sedimentation rate is 3 cm/year. Over the short-term sedimentation rates appear to have increased. However, these sedimentation rates may just indicate an episode of increased sedimentation and if in the future these rates were averaged into a 30 year average, the sedimentation rates may appear to be closer to the past 30 year average of 1.4 cm/yr.

Lead concentrations generally peaked in the late 1970's due to the ban of leaded gasoline (Callender and Rice, 2000; Christensen and Chien, 1981; Van Metre et al., 1996). Using the assumption that VMR sediment Pb concentrations peak in 1978, sedimentation rates from 1978 to 2002 can be calculated (Table 15). An additional assumption made when looking at the Pb concentrations is that 1978 occurred in the middle of the sample in which peak Pb concentrations were measured. In 1958 two major highways were constructed in the watershed and in 1975 the first industrial and commercial land uses were seen. Thus, it is expected that Pb concentrations will increase due to increased traffic and leaded gasoline. Leaded gasoline began being phased out in 1973, although it was not completely banned until 1995 (Environmental Protection Agency, 1996). However, by 1990 regulations were in place which greatly decreased lead in the environment (Schlenker, 1996). Thus, the peak around 1978 and the decreasing Pb concentrations after 1978 are also expected.

Table 15. Depth of Peak Pb Concentrations and 1978 to 2002 Sedimentation Rate

Core	Depth of peak Pb concentration (cm)	1978 depth (cm)	1978 to 2002 Sedimentation Rate (cm/yr)
1	15-25	20	0.83
2	8-13	10.5	0.44
3	15-30	22.5	0.94
4	43-65	54	2.25
5	41-54	47.5	1.98
6	25-30	27.5	1.15
7	7-21	14	0.58
8	3-10	6.5	0.27
9	18-25	21.5	0.90
10	7-15	11	0.46

In 1969, a major portion (including the area where cores 4 through 10 were taken) of VMR was excavated. This disturbance in the reservoir is evidenced in several different ways. The most striking evidence is the sediment that was not excavated is noticeably denser than the sediment that was deposited post-1969. Additionally, in cores four, five, and six, the geochemistry changes when the first post-1969 sample is encountered. Generally, P, Pb, and Zn increase in the post-1969 sediments. Copper, Hg, and Fe generally increase also but not as markedly as P, Pb, and Zn. Aluminum increased in all but one core (core 6). Physically, the 1969 excavation line is noticed in increased organic matter and pH as compared to older sediments.

Geochemical Results Compared to Other Stratigraphic Markers

One challenge with comparing geochemical results with other stratigraphic markers was that ^{137}Cs samples were not sub-sampled in the same manner as the core samples (i.e. ^{137}Cs were sub-sampled every 5 cm while cores were sub-sampled based on field stratigraphy). Additionally, ^{137}Cs were not taken at exactly the same sites as the cores. So the assumption was made that the ^{137}Cs profiles were the same at the cores as the nearest ^{137}Cs site.

Cores 1, 2, and 3 were the samples which included a complete sedimentation record from 1954 to present and core 3 had a complete record from impoundment to present. In general, Al and Fe percentages stayed the same throughout these cores with no noticeable increase or decrease in concentrations before or after 1954 or 1964. Copper concentrations also remained constant throughout the length of the sedimentation history. Mercury concentrations did not show a change in concentration until after 1964 with concentrations changing in the upper portions of the core. Phosphorus

concentrations did not exhibit consistent patterns between core 1, 2, and 3. Core 1 P concentrations increase after 1964, core 2 P concentrations did not increase until 17 cm which was much later than 1964, and core 3 P concentrations began increasing after 1954. Generally speaking, Pb and Zn concentrations increased after 1964. Although, core 2 Pb and Zn concentrations did not increase until 30 cm which was 10 cm above the 1964 layer. Sand, silt, and clay percentages were consistent throughout cores 1, 2, and 3. The pH values were also constant throughout the core lengths with the exception of core 2 where pH values decreased above 30 cm. Organic matter increased above 1964 in both core 1 and 3 but only increased in core 2 above 30 cm. Color did change in the cores but there was no consistent pattern.

Cores 4, 5, and 6 were all located in the area of the reservoir that was excavated and where there was a definite excavation marker. In these three cores, Al and Fe percentages stayed the same both in the older sediments and after 1969. Copper concentrations also did not vary across the excavation marker. Post-1969 Hg concentrations increased relative to the older sediments. Phosphorus and Zn concentrations also increased after 1969 relative to the older sediments. In all three cores Pb concentrations exhibited similar trends with levels increasing above the 1969 marker, peaking, and then decreasing towards the top of the core again. Organic matter content and clay-sized particles also increased after 1969 relative to older sediments. The pH values remained constant throughout most of the core with only core 6 exhibiting increased pH values in the upper portions of the core.

Finally, cores 7, 8, 9, and 10 were located in the excavated area of the reservoir also but no excavation marker was present. In this area of the reservoir, Al

concentrations generally decreased near the top of the core. Iron, Cu, Hg, and P concentrations generally remained the same throughout the cores. However, Hg concentrations were higher in this area of the reservoir when compared to other reservoir areas. Lead and Zn concentrations were generally higher in the bottom of the core than in the upper portions. Organic matter generally increased up-core while pH generally decreased up-core. Texture analysis was only conducted on core 7 and clay-sized and sand-sized particle percentages were higher in the bottom of the core than in the upper core.

Core Geochemistry Compared to Source Sediments

Core geochemistry was compared to source sediment geochemistry throughout the watershed. Table 16 shows the mean sediment concentrations for different sediment units in VMR and source sediments. The sediments dated from 1871? To 1954 and 1954 to 1964 showed similar mean concentrations for all elements. The post-1969 sediments showed an increase in all element mean concentrations relative to the 1871? To 1954 and 1954 to 1964 sediments. The 1964 to 2002 also showed an increase for all elements when compared to the 1871? to 1954 and 1954 to 1964 sediments but it was not as large of an increase. The pre-1969 sediment mean concentrations were generally similar to the 1871? to 1954 and 1954 to 1964 sediments but in the case of Al and Fe were closer to the post-1969 and 1964 to 2002 sediments.

Channel sediment mean concentrations were the most similar to the post-1969 and 1964 to 2002 sediments, which was expected. The cut-bank sediments were similar in Al, P, and Zn concentrations to the 1871? to 1954 and 1954 to 1964 sediments. The roadside and shale source sediments were not similar to any of the lake sediments.

Table 16. VMR and Source Sediment Mean Concentrations

Location	n	Al (%)	Cu (ppm)	Fe (%)	Hg (ppb)	P (ppm)	Pb (ppm)	Zn (ppm)	Fe/Al (ratio)
post-1969	27	1.41	13	1.46	46	512	26	62	0.97
pre-1969	7	1.16	13	1.37	30	342	21	40	0.85
1964-2002	19	1.16	12	1.46	41	437	24	53	0.79
1954-1964	7	1.05	11	1.38	33	333	19	35	0.76
1871?-1954	16	1.03	12	1.32	33	303	17	32	0.78
A horizon	3	0.75	11	1.25	63	337	54	58	0.60
shale	1	0.21	37	0.38	10	40	9	21	0.55
resdium	2	2.67	13	4.23	90	155	26	36	0.63
channel	4	1.36	15	1.93	30	773	47	64	0.71
cut-bank	2	1.05	17	1.63	20	310	35	36	0.64
floodplain	3	1.06	15	1.88	30	567	49	64	0.57
road side	2	0.16	14	0.67	10	150	119	160	0.24

Residuum mean concentrations were similar to lake sediments except that Al, Fe, and Hg concentrations were all higher than lake sediments and P concentration was lower. A-horizon sediments were similar to lake sediments when considering Cu, P, and Zn concentrations but dissimilar in all other element concentrations.

SUMMARY

^{137}Cs dating was used to date reservoir sediments and establish sedimentation rates for the reservoir. ^{137}Cs dating helped support the theory that the dense unit found in the reservoir was sediment left after excavation because ^{137}Cs activity did not reach the same levels as other cores, which were dated to 1964, and immediately decreased to zero when the dense unit was reached in areas where excavation was known to occur. In cores where excavation did not occur, ^{137}Cs allowed the dating of three units including 1871? to 1954, 1954 to 1964, and 1964 to 2002.

Physical stratigraphy, ^{137}Cs dating, and geochemistry were used to understand the sedimentary units found in VMR. The five main stratigraphic units found in VMR were: (1) post-2000 deposition (2) 2000 flood event; (3) a brown silt- and clay-sized particle layer which corresponded to deposition from 1969 to 2000; (4) a gleyed, dense unit which was the sediment left after the reservoir was excavated in 1969; and (5) pre-impoundment soil. The upper delta area of VMR and the wetland area were not excavated and thus a complete sediment record was found. In these areas six main sedimentary units were found: (1) the post-2000 deposition; (2) the 2000 flood event; (3) a contaminant enriched layer which corresponds to the dates of 1964 to 2000; (4) a layer which corresponds to the time period of 1954 to 1964; (5) a brown silt- and clay-sized

particle layer which corresponds to deposition from date of impoundment to 1954; and (6) a pre-impoundment soil layer. Figure 33 is a diagram of the typical core found in each reservoir area.

Historically (1871? to 1954) sedimentation rates were low in the floodplains and higher in the reservoir which was expected since reservoirs trap sediments more readily than floodplains (Figure 34). During the time period from 1954 to 1964 sedimentation rates increased dramatically in the floodplains and increased some in the reservoir. From 1964 to 2002, the floodplain sedimentation rates decreased relative to the 1954 to 1964 time period but increased slightly over historical rates. In the wetland, the sedimentation rate calculated from 1964 to 1978 decreased to historical levels while the time period from 1978 to 2002 saw sedimentation rates fall below historical levels. In the delta region of VMR, the sedimentation trends are similar to the wetland trends. However, the 2000 flood layer is evident in the delta region. During the 2000 flood event, sedimentation rates dramatically increased over historical levels.

In the portion of the reservoir that was excavated, sedimentation rates during the decreased down lake in all time periods (Figure 35). In the middle lake area, sedimentation rates have increased through time. The increased sedimentation rates indicate that sediment is being delivered further into the lake as the wetland and delta areas are filled in with sediments. The lower basin experiences generally low sedimentation rates from 1969 to 2000. In both the middle lake and the lower basin sedimentation rates increased dramatically in the 2000 flood event and from 2000 to 2002.

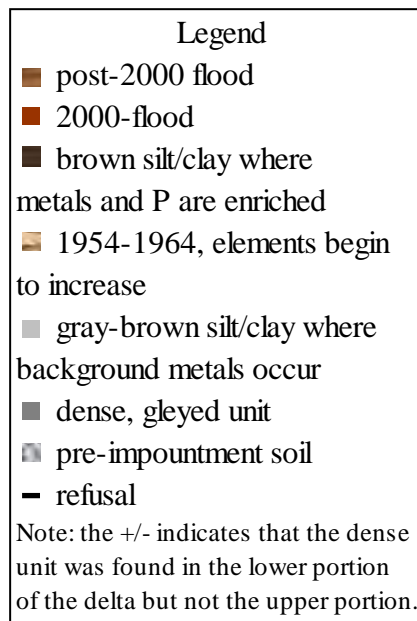
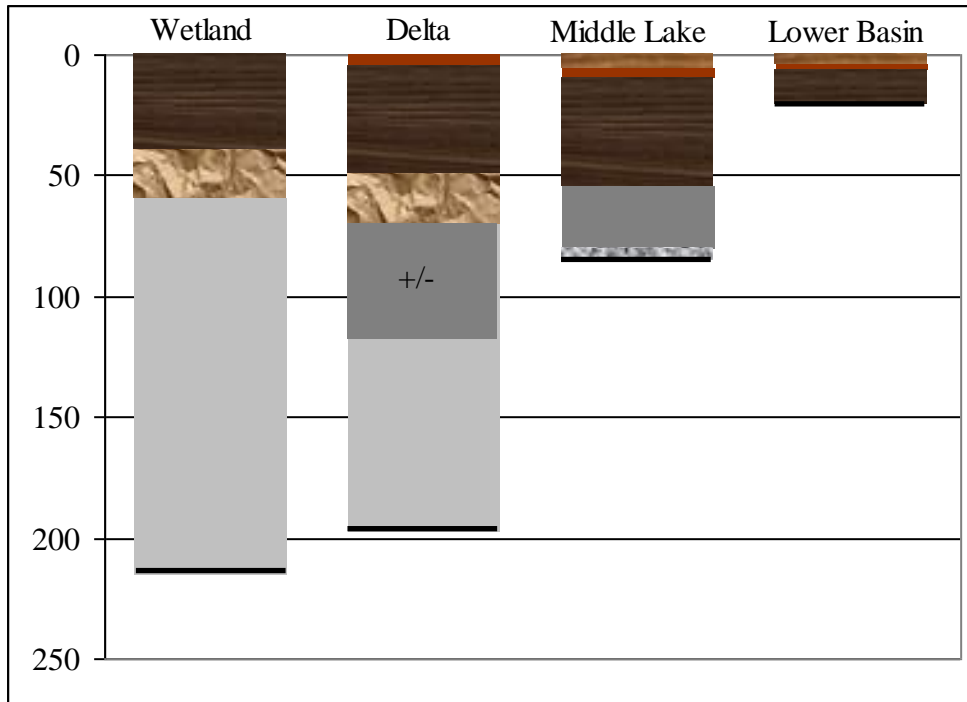


Figure 33. Typical core for each area of VMR

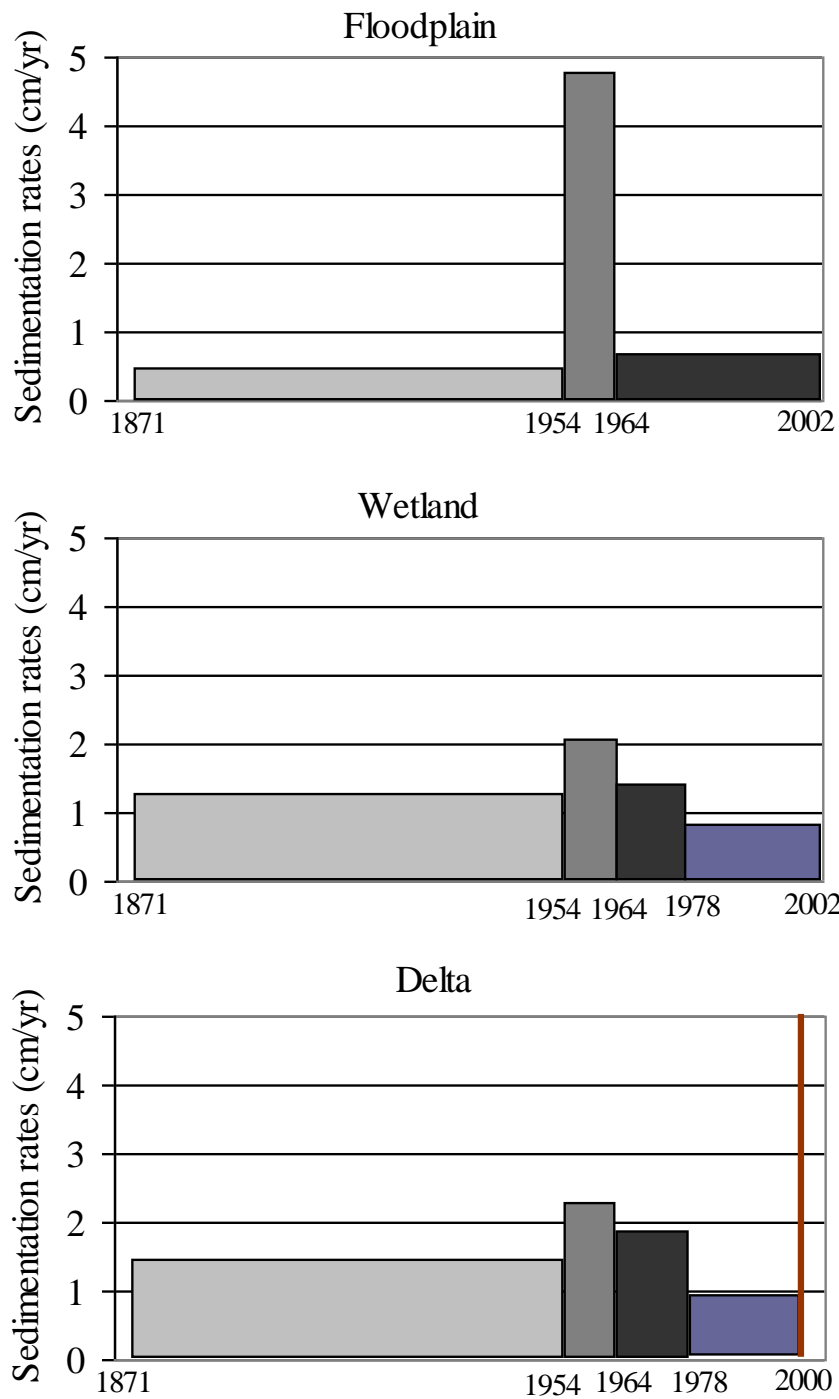


Figure 34. Average sedimentation rates for the floodplain, wetland, and delta

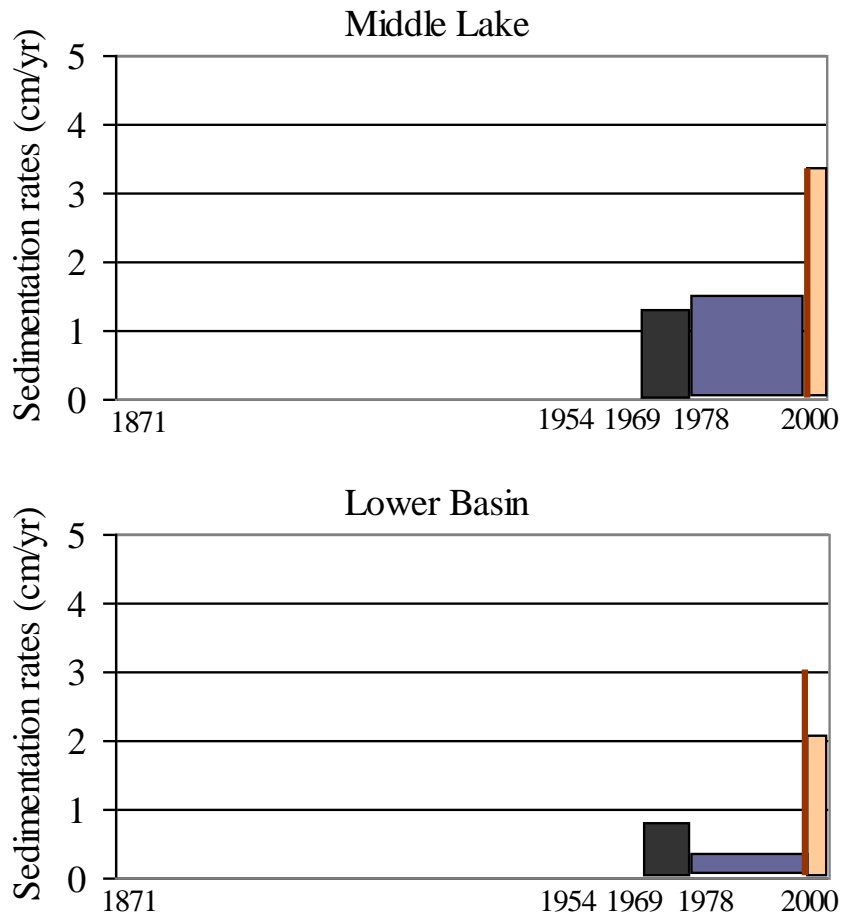


Figure 35. Average sedimentation rates for the middle lake and lower basin

Delta formation was indicated based upon longitudinal profiles. The cross-sectional data indicated that an old stream channel was detected on the east side of the reservoir. In the middle lake area the refusal depths more clearly showed a typical small tributary valley terrace profile with a stream on the east side. In the cross-sections there was little evidence of sediment focusing.

The core sediment element concentrations found in VMR are below OME guidelines for disposing of dredged sediments. In general, recent sediments (1964 to 2002 and post-1969) exhibited increased contaminant concentrations for Hg, P, Pb, and Zn as compared to older sediments. Meanwhile, Al, Fe, and Cu exhibited similar concentrations regardless of age. Table 17 lists the maximum enrichment factor, depth of initial enrichment, and the approximate date of initial enrichment. These enrichment factors indicate that VMR sediments are enriched (enrichment factor ≥ 1.5) over background levels in most areas of the reservoir.

Based on aerial photos taken in 1960 and 1975 (the land use data that was available) the watershed began seeing changes during this time period from agriculture and forests to urbanization and the addition of I-44 and U.S. Highway 65. The dating method used spanned this time also and this was the time period in which some element concentrations and enrichment factors increased. The increased concentrations and enrichment factors of Hg, P, Pb, and Zn suggests that the increase of industrial, commercial, and residential land use in the watershed negatively impacted sediment quality through increased element concentrations. The increase of Hg concentrations within the sediments after 1964/69 may also indicate an increase in soil erosion of the A-

Table 17. Enrichment Factors, Depth, and Approximate Date of Initial Enrichment

	Pollutant Enrichment in Core								
	Cu			Hg			P		
	Initial Depth of Enrichment (cm)	Approximate Date	Maximum Enrichment Factor	Initial Depth of Enrichment (cm)	Approximate Date	Maximum Enrichment Factor	Initial Depth of Enrichment (cm)	Approximate Date	Maximum Enrichment Factor
Wetland	N/A	N/A	1.3	80	1938	2.7	35	1972	2.0
Delta	140	1894	2.6	75	1950	2.5	64	1961	2.2
Middle Lake	50	pre-1969	1.8	36	1985	3.1	58	1974	3.6
Lower Basin	21	1977	2.2	32	1970	15.8	18	1978	3.2

Table 17 (continued). Enrichment Factors, Depth, and Approximate Date of Initial Enrichment

	Pollutant Enrichment in Core					
	Pb			Zn		
	Initial Depth of Enrichment (cm)	Approximate Date	Maximum Enrichment Factor	Initial Depth of Enrichment (cm)	Approximate Date	Maximum Enrichment Factor
Wetland	35	1972	1.7	30	1975	1.9
Delta	40	1971	1.9	18	1991	2.3
Middle Lake	58	1974	1.7	50	1975	2.4
Lower Basin	25	1974	2.0	32	1970	2.1

horizon and/or residuum based upon the high mean concentrations of Hg found in both the A-horizon and residuum soils of VMR watershed soils.

CHAPTER SEVEN – CONCLUSIONS

The purpose of this study was to determine reservoir bathymetry, estimate trap efficiencies, understand the spatial distribution and contamination of surface sediments, assess the environmental history of the watershed through core analyses, and determine sedimentation rates in VMR. These objectives were addressed through the use of GIS, empirical equations, geochemistry, and ^{137}Cs analysis. Based upon this study the following five conclusions were drawn.

1. Reservoir morphometry generally was typical of reservoirs.

The bathymetry of VMR was unknown and so the first step was to determine bathymetric and morphometric properties. VMR is elongated in the north-south direction and displayed typical bathymetry of reservoirs with shallows near the mouth, the deepest point being near the dam, and a low mean depth of 2.6 m. The mean width is 105 m, the length is 505 m and VMR has a current water storage capacity of 149,536 m³. VMR has a low watershed area to lake volume ratio of 85.5.

2. Estimated trap efficiencies were lower than expected and should be studied further with direct measurement rather than empirical equations.

Currently, 60,629 m³ of sediment is stored within VMR. Estimated trap efficiency for baseflow conditions ranged from 15 to 29 %. However, during baseflow incoming suspended sediment concentrations are low and no water flows over the dam. Therefore, trap efficiency is expected to be closer to 100 %. During the two-year storm event, trap efficiency is estimated to be negative with VMR acting as a source of sediment rather than a trap for sediments. Again, this estimate is questionable because sedimentation records indicated that sediment from a 100-year flood event was trapped in

the reservoir. Based on the above observations, it is recommended that trap efficiency rates of VMR be directly measured through inflowing and outflowing suspended sediment monitoring. This would allow managers to better understand how VMR is currently acting as a sediment and pollutant trap.

3. The spatial distribution of sediments displayed a delta formation but sediment focusing did not occur.

Delta formation was the main geomorphic form found in VMR. The upstream floodplain and wetland area are acting as part of the delta as indicated by sediment thickness and sedimentation rates. Additionally, down-lake clay-sized particles increase with 36.0 % clay-sized particles in the wetland and 42.4 % clay-sized particles in the lower middle lake. Sand-sized particles decrease down-lake with 3.1 % sand in the delta and 0.6 % sand in the lower middle lake. Thus, both sand- and clay-sized particles indicate a fining of sediment down-lake. There is little or no sediment focusing found in the reservoir as indicated by uniform sediment thickness found horizontally across the reservoir.

4. Sedimentation rates have varied over time with the periods from 1954 to 1964 and 2000 to 2002 both being times of high sedimentation rates.

Historically, sedimentation rates were 0.4 to 0.6 cm/yr in the upper floodplains of the inflowing tributary with rates of 1.3 and 1.4 cm/yr in the wetland and delta area respectively, which was expected since reservoirs are more efficient at trapping sediments than floodplains. The time period from 1954 to 1964 saw a large increase in sedimentation rates (5.5 and 4.0 cm/yr) in the floodplains. The sediment source for the high sedimentation rates was most likely the construction of I-44 and U.S. Highway 65 or channel bed and bank erosion due to runoff from agricultural lands or urban areas. These

high sedimentation rates indicated that this area was acting as part of the reservoir delta and currently the channel elevation is <1 m above the dam spillway. From 1954 to 1964 reservoir sedimentation rates also increased, to 2.25 cm/yr, but these increased rates are not as dramatic as the floodplain rates. From 1964 to 2002, the upstream floodplain sedimentation rates decreased back to 0.29 cm/yr, while the downstream floodplain site also decreased. However, the downstream floodplain only decreased to 1.03 cm/yr, which was not to historical levels.

Using geochemistry, the wetland and delta areas had additional sedimentation rates calculated. From 1964 to 1969 sedimentation rates were higher in the delta area than the wetland with 1.9 cm/yr and 1.4 cm/yr respectively. From 1978 to 2000, sedimentation rates were generally similar except that the 2000 flood event record was found in the delta area with a rate of 5 cm/yr.

In the reservoir where excavation occurred, sedimentation rates decreased down lake during the time period of 1969 to 2002. Sedimentation rates in the delta area were 1.9 cm/yr from 1969 to 1978 while down-lake the lower basin sedimentation rates were 0.8 cm/yr. From 1978 to 2000, sedimentation rates in the middle basin were highest with an average of 1.5 cm/yr. These high sedimentation rates suggest that the delta formation is beginning to push into the middle lake. The 2000 flood event left a layer of sediment ranging from 2 to 5 cm in VMR. After the 2000 flood, recent short-term sedimentation rates were also high in the middle lake and lower basin with an average rate of 3 cm/yr. The recent high sedimentation rates are probably due to redistribution of sediments during drawdown.

5. Contaminant concentrations increased over time.

In general, with only a few exceptions, sediment element concentrations were below the OME guidelines for disposing of dredged sediments. Recent sediments exhibited increased concentrations of Hg, P, Pb, and Zn as compared to older sediments. However, Al, Fe, and Cu exhibited similar concentrations regardless of age. Copper was the only contaminant element that generally did not increase with time. However, enrichment factors indicate that Cu was enriched over background levels but the enrichment occurred in older sediments. Enrichment factors also show that Hg, P, Pb, and Zn are enriched over background levels and enrichment factors ranged from 1.7 to 15.8.

The Pb concentration increase and subsequent decrease generally follows the use of leaded gasoline with peak Pb concentrations occurring around 1978. Generally, enrichment of Hg, P, Pb, and Zn began around 1970. The increased levels of Hg, P, Pb, and Zn indicate that increased urbanization has negatively influenced sediment quality in VMR. The construction of I-44 and U.S. Highway 65 in 1958 allowed this watershed to become more accessible. The dates of initial enrichment are around the same time that land uses within the watershed began changing from agricultural and forests to urban land use. Additionally, channel incision and channelization allows pollutants to be conveyed more quickly and directly into streams and VMR. This more direct route provides less chance for buffering or storing contaminants in soils and upper watershed sediments.

Reservoir sedimentation and contamination of bottom sediments are presently two areas of concern in the U.S because many reservoirs are reaching the end of their useful

life. Additionally, small, shallow reservoirs have not been studied as extensively as larger reservoirs even though the actual number of small reservoirs is much greater than large reservoirs. VMR is one such small reservoir that was the focus of this study. Little was known about VMR sediment and pollutant storage characteristics. The results of this thesis research provide an understanding of how geochemistry and sedimentation rates and patterns have changed over time. In a broad scientific aspect, this research will aid in the understanding of small reservoir sedimentation and contaminant levels. Locally the VMR study will also provide local managers with background information on VMR, aid in the future management of VMR, and provide sedimentation rates and patterns, which are needed in order to proceed with plans for VMR as an outdoor water quality classroom. Additionally, the level of contamination is generally under the guidelines currently in place for the disposal of dredged sediments. However, VMR is susceptible to urban and agricultural non-point contaminants during run-off events and this evidence is found in the bottom sediments of VMR.

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APPENDIX A - BATHYMETRIC DATA

APPENDIX B - SEDIMENT THICKNESS DATA

APPENDIX C - ¹³⁷CS DATA

APPENDIX D - CORE DATA