Lake Anderson Sediment Characterization and Phosphorus Inactivation Study

Final Report

January 2006

Prepared For:

Professional Engineering Consultants
200 E. Robinson St., Suite 1560
Orlando, FL 32801

Prepared By:

ERD

Environmental Research & Design, Inc.
3419 Trentwood Blvd., Suite 102
Orlando, Florida 32812

TABLE OF CONTENTS

Appendices

LIST OF TABLES

LIST OF FIGURES

SECTION 1

INTRODUCTION

This report provides a summary of work efforts performed by Environmental Research and Design, Inc. (ERD) for Professional Engineering Consultants (PEC) to conduct a bathymetric survey and sediment characterization study for Lake Anderson. The primary emphasis of this study is to evaluate the significance of sediment phosphorus release and the feasibility of using alum for sediment inactivation. Lake Anderson is a 12.5-acre urban lake located south of downtown Orlando and northeast of Little Lake Conway in unincorporated Orange County. A location map for Lake Anderson is given in Figure 1-1. Lake Anderson is hydraulically connected to the Lake Conway chain-of-lakes through a pump station located on the south shore of the lake.

Field monitoring and laboratory analyses were conducted by ERD from September-November 2005 to evaluate bathymetric and sediment characteristics in Lake Anderson. Field measurements were performed for development of a water depth contour map for Lake Anderson, along with estimated depths of unconsolidated organic sediments. A sediment monitoring program was also performed to quantify the physical and chemical characteristics of existing sediments within the lake and to evaluate the potential for internal recycling of phosphorus from sediments into the overlying water column. Physical-chemical profiles of temperature, pH, conductivity, dissolved oxygen, and redox potential were also conducted to assist in evaluating the significance of internal recycling within the lake.

This report is divided into four separate sections. Section 1 contains an introduction to the report and provides a brief summary of the work efforts performed by ERD. Section 2 contains a description of the field and laboratory activities conducted by ERD. The results of the field and laboratory activities are summarized in Section 3. The feasibility of alum inactivation of sediment phosphorus release is discussed in Section 4.

Figure 1-1. Location Map for Lake Anderson.

SECTION 2

FIELD AND LABORATORY ACTIVITIES

Field and laboratory activities were performed to develop bathymetric contour maps for water depth and unconsolidated organic sediments in Lake Anderson. Sediment core samples were also collected and evaluated for a variety of physical and chemical characteristics to assist in evaluating the potential for internal recycling of phosphorus from the sediments into the overlying water column of the Lake. Field and laboratory activities used to perform these assessments are described in the following sections.

2.1 Bathymetric Surveys

Bathymetric surveys were performed in Lake Anderson on October 28 and November 4, 2005 to evaluate water column depth as well as thickness of unconsolidated sediments within the lake. Bathymetric measurements of water depth and sediment thickness were conducted at 82 individual sites in Lake Anderson. Data collection sites used for the bathymetric study are indicated on Figure 2-1. Each of the data collection sites was identified in the field by longitude and latitude coordinates which were recorded using a portable GPS device.

Water depth at each of the data collection sites was determined by lowering a 20 cm diameter Secchi Disk, attached to a graduated line, until resistance from the surficial sediment layer was encountered. The depth on the graduated line was recorded in the field and is defined as the water depth at each site. After the water depth is defined at each site, a 1.5-inch diameter graduated aluminum pole is then lowered into the water column and forced into the sediments until a firm bottom material, typically sand or clay, is encountered. This depth, measured at the water surface, is defined as the depth to the firm lake bottom. The difference between the depth to the firm lake bottom and the water depth is defined as the depth of unconsolidated sediments at each site.

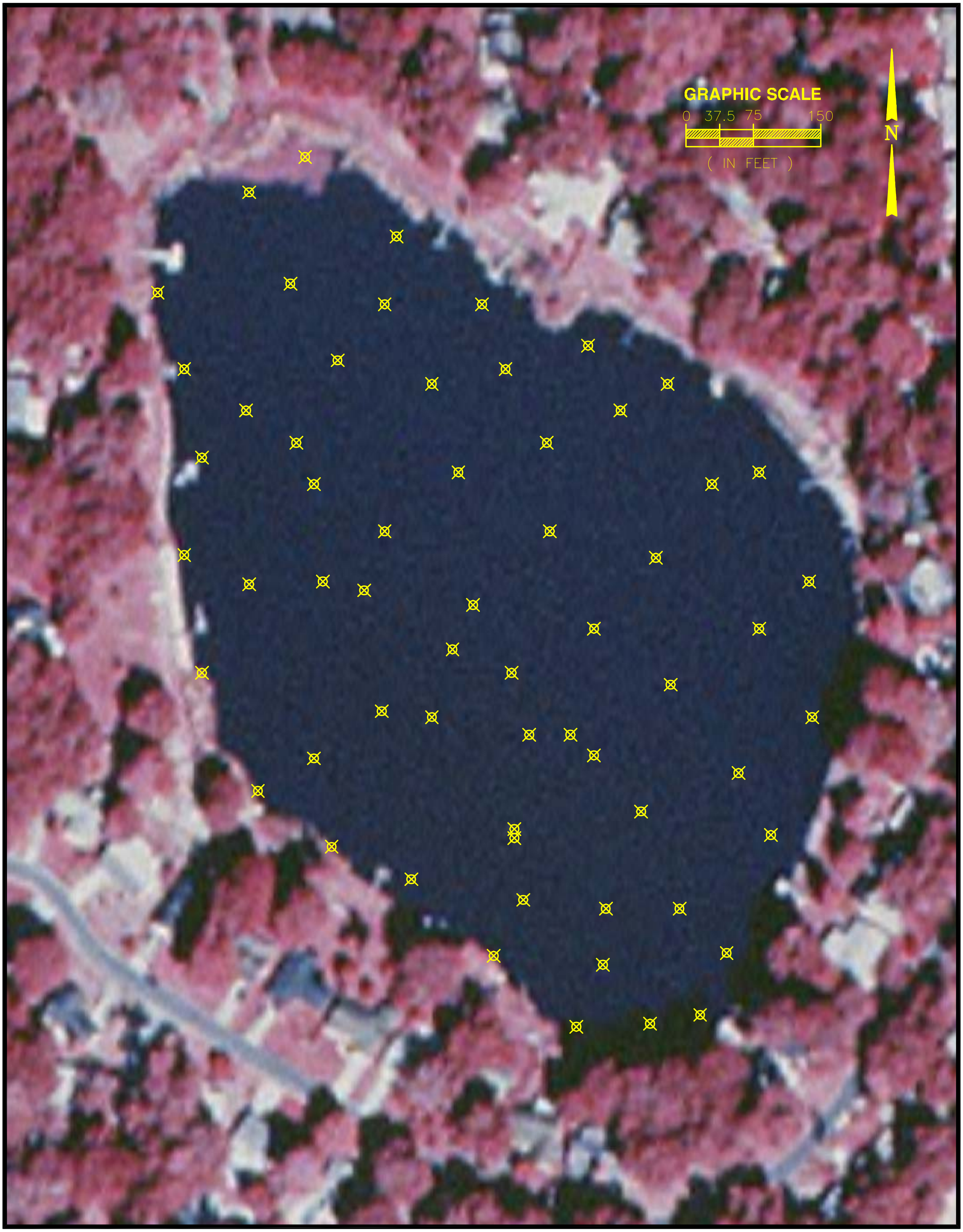

Figure 2-1. Bathymetric Data Collection Sites in Lake Anderson.

The generated field data was converted into bathymetric maps for both water depth and unconsolidated sediment depth in Lake Anderson using Autodesk Land Desktop Version 2006. Estimates of water volume and unconsolidated sediment volume within the lake were generated from the bathymetric information.

2.1 Collection of Sediment Core Samples

Sediment core samples were also collected by ERD to assist in evaluating the significance of sediments for impacting water quality in Lake Anderson. Sediment core samples were collected at 28 separate locations. Locations of sediment sampling sites in Lake Anderson are illustrated on Figure 2-2. Sediment samples at the 28 sites were collected on October 28, 2005.

Sediment samples were collected at each of the 28 monitoring sites using a stainless steel split-spoon core device, which was penetrated into the sediments at each location to a minimum distance of approximately 0.5 m. After retrieval of the sediment sample, any overlying water was carefully decanted before the split-spoon device was opened to expose the collected sample. Visual characteristics of each sediment core sample were recorded, and the 0-10 cm layer was carefully sectioned off and placed into a polyethylene container for transport to the ERD laboratory. Duplicate core samples were collected at each site, and the 0-10 cm layers were combined together to form a single composite sample for each of the 28 monitoring sites. The polyethylene containers utilized for storage of the collected samples were filled completely so no air space was present in the storage container above the composite sediment sample. Each of the collected samples was stored on ice and returned to the ERD laboratory for physical and chemical characterization.

During the sediment monitoring on October 28, 2005, field measurements of pH, specific conductivity, dissolved oxygen and oxidation-reduction potential (ORP) were recorded at water depths of 0.25 m, 0.5 m and at 0.5 m intervals to the lake bottom at the center of the lake. This information is used to evaluate stratification regimes within the lake and to assist in identifying the significance of internal recycling.

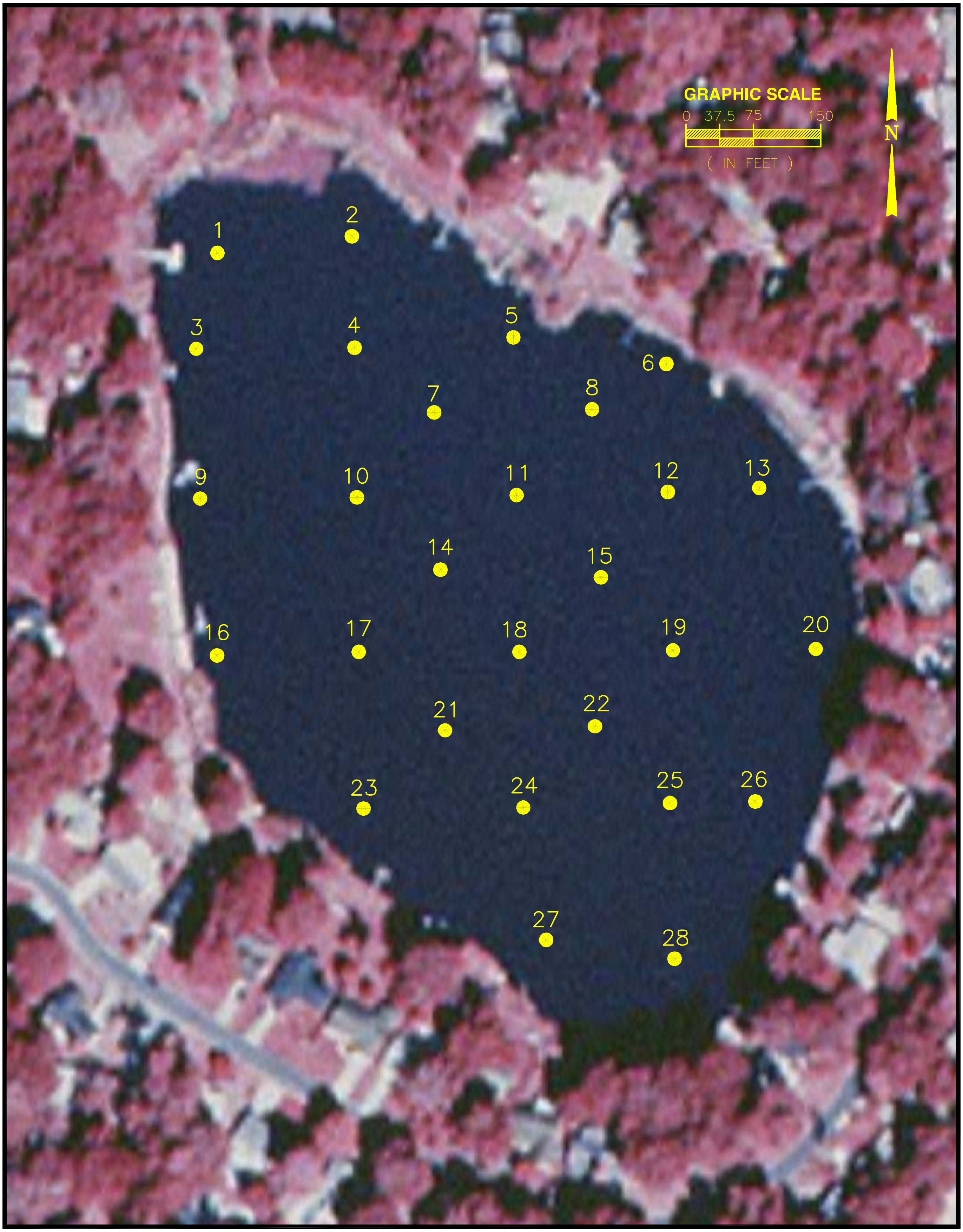

Figure 2-2. Locations of Sediment Core Collection Sites in Lake Anderson.

2.3 Sediment Characterization and Speciation Studies

Each of the 28 collected sediment core samples was analyzed for a variety of general parameters, including moisture content, organic content, sediment density, total nitrogen, and total phosphorus. Methodologies utilized for preparation and analysis of the sediment samples for these parameters are outlined in Table 2-1.

TABLE 2-1

ANALYTICAL METHODS FOR SEDIMENT ANALYSES

MEASUREMENT PARAMETER	SAMPLE PREPARATION	ANALYSIS REFERENCE	REFERENCE PREP./ANAL.	METHOD DETECTION LIMITS (MDLs)
pH	EPA 9045	EPA 9045	3 / 3	0.01 pH units
Moisture Content	p. 3-54	p. 3-58	1 / 1	0.1%
Organic Content (Volatile Solids)	p. 3-52	pp. 3-52 to 3-53	1/ 1	0.1%
Total Phosphorus	pp. 3-227 to 3-228 (Method C)	EPA 365.4	1/ 2	0.005 mg/kg
Total Nitrogen	p. 3-201	pp. 3-201 to 3-204	1/ 1	0.010 mg/kg
Specific Gravity (Density)	p. 3-61	pp. 3-61 to 3-62	1/ 1	NA

REFERENCES:

1. Procedures for Handling and Chemical Analysis of Sediments and Water Samples, EPA/Corps of Engineers, EPA/CE-81-1, 1981.

2. Methods for Chemical Analysis of Water and Wastes, EPA 600/4-79-020, Revised March 1983.

3. Test Methods for Evaluating Solid Wastes, Physical-Chemical Methods, Third Edition, EPA-SW-846, Updated November 1990.

In addition to general sediment characterization, a fractionation procedure for inorganic soil phosphorus was conducted on each of the 28 collected sediment samples. The modified Chang and Jackson Procedure, as proposed by Peterson and Corey (1966), was used for phosphorus fractionation. The Chang and Jackson Procedure allows the speciation of sediment phosphorus into saloid-bound phosphorus (defined as the sum of soluble plus easily exchangeable sediment phosphorus), iron-bound phosphorus, and aluminum-bound phosphorus. Although not used in this project, subsequent extractions of the Chang and Jackson procedure also provide calcium-bound and residual fractions.

Saloid-bound phosphorus is considered to be available under all conditions at all times. Iron-bound phosphorus is relatively stable under aerobic environments, generally characterized by redox potentials greater than 200 mv (E_h), while unstable under anoxic conditions, characterized by redox potential less than 200 mv. Aluminum-bound phosphorus is considered to be stable under all conditions of redox potential and natural pH conditions. A schematic of the Chang and Jackson Speciation Procedure for evaluating soil phosphorus bounding is given in Figure 2-3.

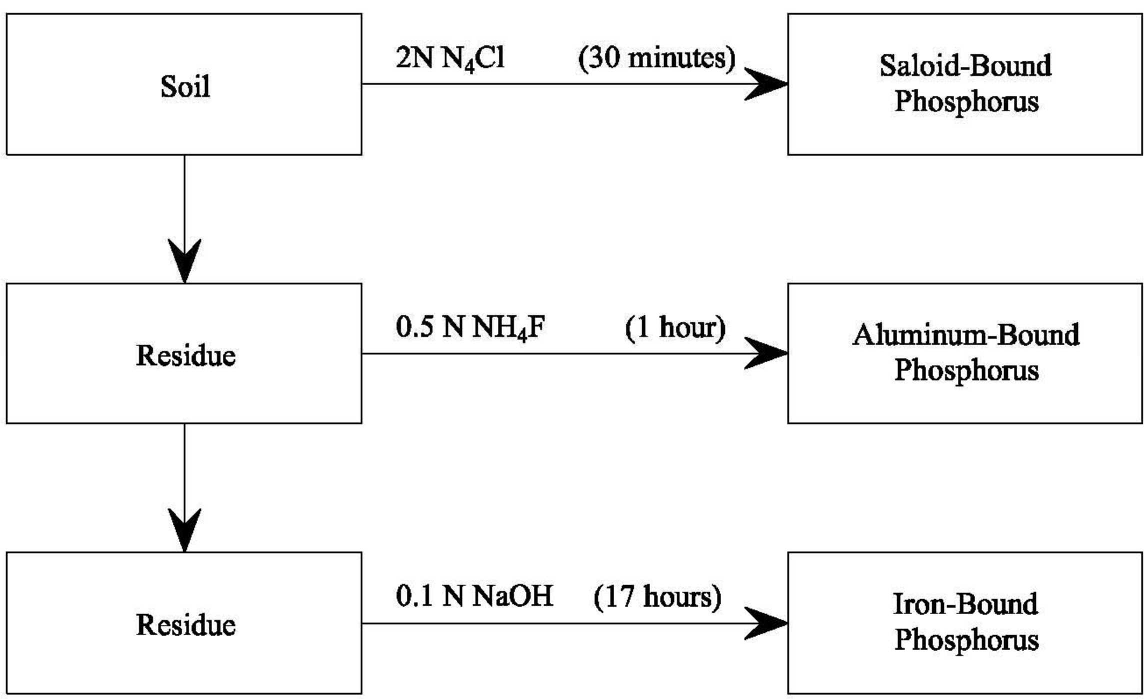

Figure 2-3. Schematic of Chang and Jackson Speciation Procedure for Evaluating Soil Phosphorus Bonding.

For purposes of evaluating release potential, ERD typically assumes that potentially available inorganic phosphorus in soils/sediments, particularly those which exhibit a significant potential to develop highly reduced conditions below the sediment-water interface, is represented by the sum of the soluble inorganic phosphorus and easily exchangeable phosphorus fractions (collectively termed saloid-bound phosphorus), plus iron-bound phosphorus, which can become solubilized under reduced conditions. Aluminum-bound phosphorus is generally considered to be unavailable in the pH range of approximately 5.5-7.5 under a wide range of redox conditions.

SECTION 3

RESULTS

3.1 Bathymetric Surveys

A bathymetric survey was conducted in Lake Anderson on October 28, 2005 at 82 separate sites to generate water depth and unconsolidated sediment contours for the lake. A water depth contour map for Lake Anderson, based upon the field monitoring program performed by ERD, is given in Figure 3-1. The maximum water depth in Lake Anderson exceeds 30 ft in southern areas of the lake. Based on the shape of the contours in Figure 3-1, and the depth of the water column, it appears that Lake Anderson may have originated as a sinkhole.

Stage-storage relationships for Lake Anderson are summarized in Table 3-1. At the water surface elevation present on October 28, 2005, the lake surface area is approximately 12.56 acres. The lake volume at this surface area is 163.0 ac-ft which corresponds to a mean water depth of 13.0 ft. This value is relatively deep for a Central Florida lake.

A bathymetric contour map of the depth of unconsolidated organic sediments in Lake Anderson is given in Figure 3-2. In general, unconsolidated organic sediments are concentrated primarily in central and southern portions of the lake, where sediment depths exceed 12 ft.

A summary of estimated organic muck volumes in Lake Anderson is given in Table 3-2. Approximately 61% of the lake area, consisting primarily of perimeter shoreline and northern areas, has existing muck accumulations ranging from 0-1 ft in depth. An additional 22% of the lake area has organic muck accumulations ranging from 1-3 ft. Approximately 12% of the lake has muck depths ranging from 3-5 ft, with 3% of the lake covered by muck accumulations ranging from 5-7 ft, and 2% of the lake with muck accumulations greater than 7 ft. Overall, Lake Anderson contains approximately 1,131,771 ft^3 of unconsolidated organic sediments. The volume of unconsolidated sediment in Lake Anderson is sufficient to cover the entire lake area to a depth of 2.07 ft.

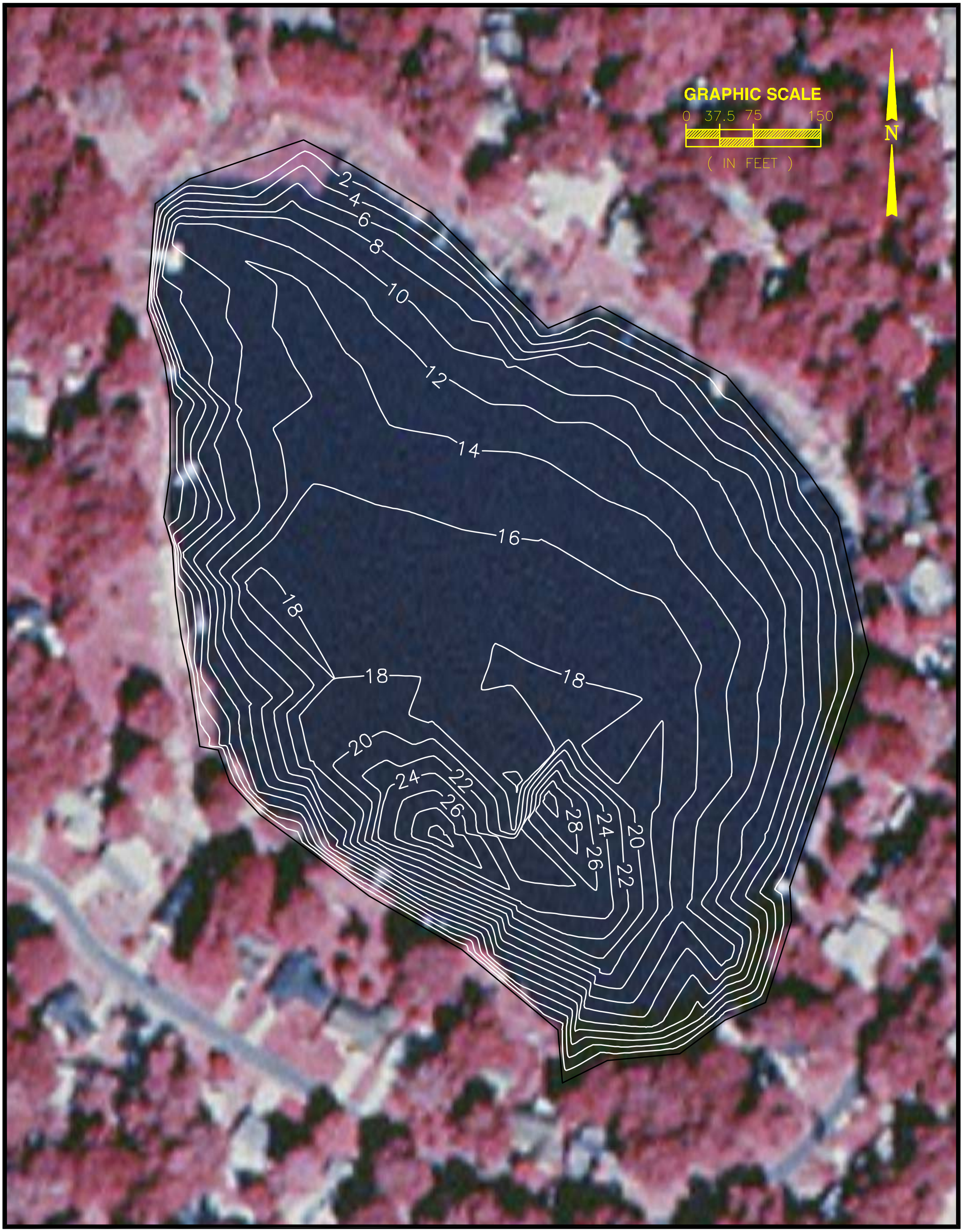

Figure 3-1. Water Depth Contours in Lake Anderson on October 28, 2005.

Figure 3-2. Isopleths of Organic Sediment (Muck) Depths in Lake Anderson.

TABLE 3-1

STAGE-STORAGE RELATIONSHIPS FOR LAKE ANDERSON

DEPTH (ft)	AREA (ac)	VOLUME (ac-ft)
0.0	12.56	163.0
2.0	11.97	138.5
4.0	11.35	115.1
6.0	10.68	93.1
8.0	9.92	72.5
10.0	8.92	53.7
12.0	7.62	37.2
14.0	5.93	23.6
16.0	4.20	13.5
18.0	1.86	7.43
20.0	1.09	4.49
22.0	0.81	2.59
24.0	0.53	1.25
26.0	0.26	0.47
28.0	0.10	0.11
30.0	0.01	0.00

TABLE 3-2

SUMMARY OF UNCONSOLIDATED ORGANIC SEDIMENT ACCUMULATIONS IN LAKE ANDERSON

MUCK DEPTH (ft)	AREA IN LAKE (ac)	PERCENTAGE OF LAKE AREA	MUCK VOLUME (ft^3)
0-1	7.64	61	488,195
1-3	2.80	22	413,593
3-5	1.49	12	158,198
5-7	0.32	3	49,611
7-9	0.25	2	17,627
9-11	0.06	< 1	4,323
> 11	< 0.01	< 1	224
TOTAL:	**12.56**	**100**	**1,131,771**

3.2 Sediment Characteristics

3.2.1 Visual Characteristics

Visual characteristics of sediment core samples were recorded for each of the 28 sediment samples collected in Lake Anderson during October-November 2005. A summary of visual characteristics of sediment core samples is given in Table 3-3. In general, shoreline areas of Lake Anderson are characterized by sandy sediments with little or no visual accumulations of unconsolidated organic muck. The base material beneath the lake bottom consists primarily of light brown fine sand.

As water depths increase within the lake, the accumulations of organic muck become deeper. Areas where deep deposits of organic muck have accumulated are characterized by a surface layer of unconsolidated organic muck, approximately 1-6 inches in thickness. This unconsolidated layer is comprised primarily of fresh organic material, such as dead algal cells, which have accumulated onto the bottom of the lake. This organic material is easily resuspended by wind action or boating activities which disturb the bottom. As the sediment depth increases, the organic layer becomes more consolidated with a consistency similar to pudding. These layers typically do not resuspend into the water column except during vigorous mixing action within the lake.

TABLE 3-3

VISUAL CHARACTERISTICS OF SEDIMENT CORE SAMPLES COLLECTED IN LAKE ANDERSON DURING OCTOBER-NOVEMBER 2005

SITE NO.	LAYER (cm)	VISUAL APPEARANCE
1	0->28	Brown fine sand with organics
2	0->22	Brown fine sand with organics
3	0-4	Brown fine sand with organics
	>4	Light brown fine sand
4	0-3	Dark brown unconsolidated organic muck
	3-4	Dark brown consolidated organic muck
	>4	Brown fine sand with organics
5	0-1	Dark brown unconsolidated organic muck
	>1	Brown fine sand with organics
6	0-11	Brown fine sand with organics
	11-17	Light brown fine sand
	17-20	Brown fine sand with organics
	20-21	Light brown fine sand
	21-25	Brown fine sand with organics
	25->28	Light brown fine sand
7	0-3	Dark brown unconsolidated organic muck
	3-8	Dark brown consolidated organic muck
	>8	Brown fine sand with organics
8	0->16	Brown fine sand with organics
9	0-7	Brown fine sand with organics
	7-18	Light brown fine sand
	>18	Brown fine sand with organics
10	0-3	Dark brown unconsolidated organic muck
	3-9	Dark brown consolidated organic muck
	9-47	Brown fine sand with organics
	>47	Dark brown consolidated organic muck
11	0-2	Dark brown unconsolidated organic muck
	2-8	Dark brown consolidated organic muck
	>8	Brown fine sand with organics
12	0-2	Dark brown unconsolidated organic muck
	>2	Brown fine sand with organics
13	0-0.5	Dark brown unconsolidated organic muck
	0.5-4	Light brown fine sand
	>4	Brown fine sand with organics
14	0-3	Dark brown unconsolidated organic muck
	>3	Dark brown consolidated organic muck
15	0-3	Dark brown unconsolidated organic muck
	3-9	Dark brown consolidated organic muck
	>9	Brown fine sand with organics
16	0-4	Brown fine sand with organics
	>4	Light brown fine sand

TABLE 3-3 -- CONTINUED

VISUAL CHARACTERISTICS OF SEDIMENT CORE SAMPLES COLLECTED IN LAKE ANDERSON DURING OCTOBER-NOVEMBER 2005

SITE NO.	LAYER (cm)	VISUAL APPEARANCE
17	0-5	Dark brown unconsolidated organic muck
	5-30	Dark brown consolidated organic muck
	30-44	Brown fine sand with organics
	>44	Light brown find sand
18	0-5	Dark brown unconsolidated organic muck
	5-60	Dark brown consolidated organic muck
	>60	Dark brown consolidated organic muck
19	0-3	Dark brown unconsolidated organic muck
	>3	Dark brown consolidated organic muck
20	0-1	Dark brown unconsolidated organic muck
	>1	Brown fine sand with organics
21	0-3	Dark brown unconsolidated organic muck
	3-31	Dark brown consolidated organic muck
	>31	Light brown fine sand
22	0->30	Dark brown unconsolidated organic muck
23	0->15	Light brown fine sand
24	0->29	Dark brown unconsolidated organic muck
25	0-4	Dark brown unconsolidated organic muck
	>4	Dark brown consolidated organic muck
26	0-6	Dark brown unconsolidated organic muck
	6-20	Dark brown consolidated organic muck
	>20	Brown fine sand with organics
27	0-17	Dark brown unconsolidated organic muck
	>17	Light brown fine sand
28	0-2	Dark brown unconsolidated organic muck
	2-13	Brown fine sand with organics
	13-23	Light brown fine sand
	>23	Brown fine sand with organics

3.2.2 <u>General Sediment Characteristics</u>

After return to the ERD laboratory, the collected sediment core samples were evaluated for a variety of general characteristics including pH, moisture content, organic content, sediment density, total nitrogen, and total phosphorus. A summary of general characteristics measured in each of the 28 collected sediment core samples is given in Table 3-4. In general, sediments in Lake Anderson were found to be approximately neutral in pH, with measured sediment pH values ranging from 6.49-7.47 and an overall mean of 7.05. These values are typical of pH measurements commonly observed in hypereutrophic urban lakes.

Isopleths of pH measurements in the top 10 cm of sediment collected in Lake Anderson are illustrated on Figure 3-3. The most elevated sediment pH values were observed in central portions of Lake Anderson in an area with little organic muck accumulation. The lowest sediment pH values were observed in southern central portions of the lake in areas where relatively deep organic sediment accumulations were measured.

Measurements of sediment moisture content and organic content in Lake Anderson were found to be highly variable throughout the lake. Sediment samples with relatively low moisture contents are often comprised largely of fine sand and are also characterized by a relatively low organic content. In contrast, sediments which exhibit a high moisture content are often comprised primarily of organic muck and are also associated with a high organic content.

Isopleths of sediment moisture content in Lake Anderson are summarized in Figure 3-4 based upon the information provided in Table 3-4. Areas of elevated moisture content are present in northeastern and southern central portions of the lake. Sediment moisture contents in access of 50-70% are often indicative of highly organic sediments, with moisture contents less than 50% reflecting either sand or mixtures of sand and muck.

Figure 3-3. Isopleths of pH in the Top 10 cm of Sediments in Lake Anderson.

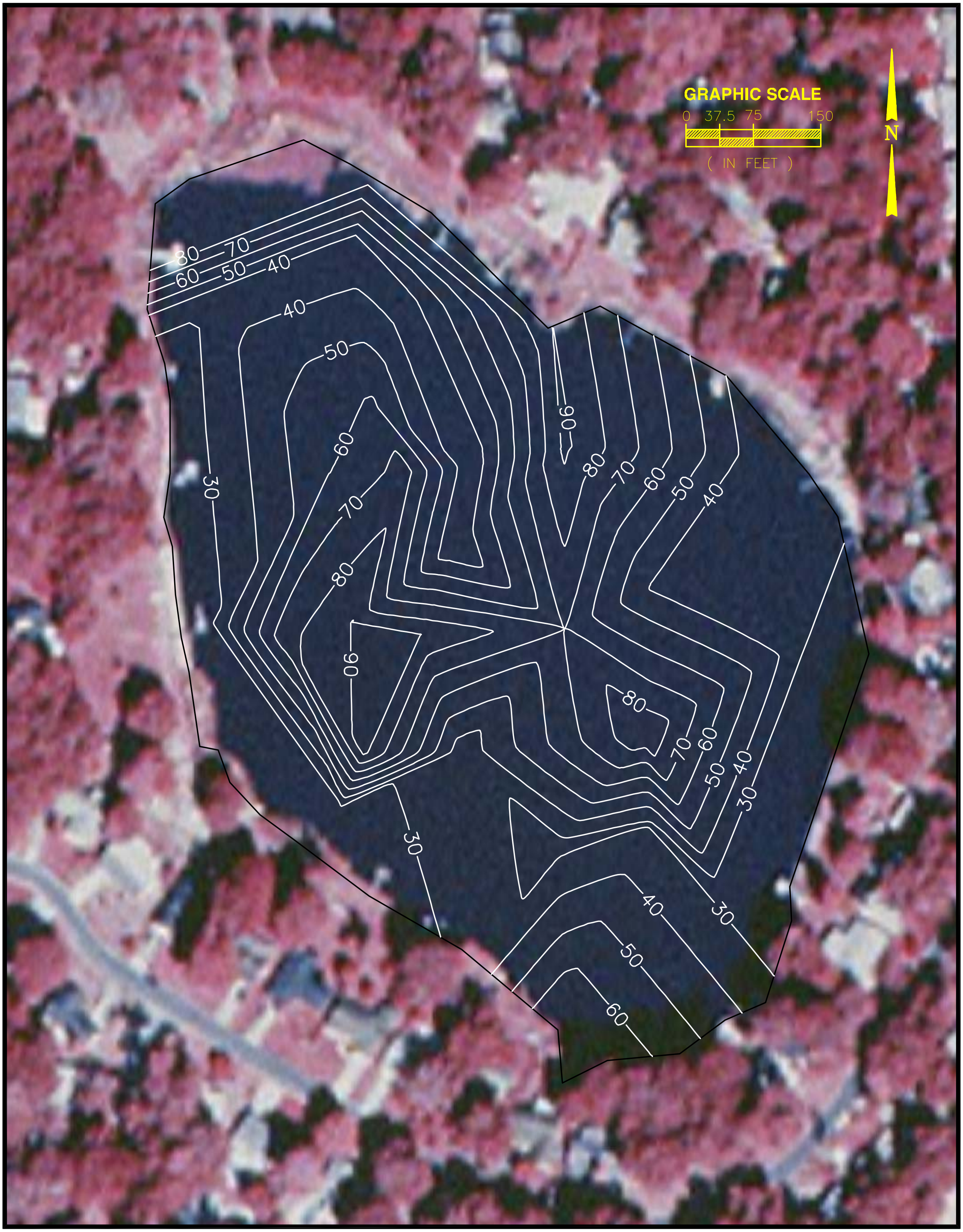

Figure 3-4. Isopleths of Moisture Content (% dry wt.) in the Top 10 cm of Sediments in Lake Anderson.

TABLE 3-4

GENERAL CHARACTERISTICS OF SEDIMENT CORE SAMPLES COLLECTED IN LAKE ANDERSON DURING OCTOBER-NOVEMBER 2005

SITE	pH	MOISTURE CONTENT (%)	ORGANIC CONTENT (%)	DENSITY (g/cm^3)	TOTAL NITROGEN ($\mu g/cm^3$)	TOTAL PHOSPHORUS ($\mu g/cm^3$)
1	6.62	89.1	37.6	1.10	1493	925
2	7.31	32.0	1.5	2.00	715	447
3	7.11	32.6	1.4	2.00	616	193
4	7.04	59.7	4.3	1.58	900	551
5	7.21	33.4	0.8	1.99	667	285
6	6.99	90.2	46.3	1.08	1267	186
7	6.95	61.5	5.6	1.54	1365	1061
8	6.85	92.2	38.2	1.07	1192	402
9	7.18	26.2	0.5	2.10	348	725
10	7.22	76.5	14.6	1.30	1683	1233
11	6.91	73.9	10.8	1.35	1188	703
12	6.96	38.6	2.5	1.90	997	495
13	7.03	38.2	1.7	1.91	641	140
14	6.76	90.3	45.4	1.08	1449	1059
15	6.89	70.0	7.1	1.42	1070	633
16	7.10	31.7	1.3	2.01	726	3658
17	7.47	30.1	1.2	2.04	563	888
18	6.83	90.2	48.1	1.08	1585	980
19	6.57	88.8	41.1	1.10	1518	692
20	7.27	32.2	1.1	2.01	467	162
21	6.49	92.3	48.3	1.06	1581	667
22	7.32	26.5	1.3	2.09	528	479
23	7.43	27.3	0.7	2.08	370	622
24	7.27	33.5	1.8	1.98	906	588
25	7.11	29.1	1.2	2.05	562	545
26	7.46	26.7	0.6	2.09	874	1441
27	7.39	32.5	2.4	1.99	394	1124
28	6.61	65.5	8.5	1.47	3003	2406
Mean	**7.05**	**54.0**	**13.4**	**1.66**	**1024**	**832**
Maximum	**7.47**	**92.3**	**48.3**	**2.10**	**3003**	**3658**
Minimum	**6.49**	**26.2**	**0.5**	**1.06**	**348**	**140**

Isopleths of sediment organic content in Lake Anderson are illustrated on Figure 3-5 based upon the information provided in Table 3-4. In general, sediment organic content in excess of 30% are often indicative of organic muck-type sediments, with values less than 30% representing mixtures of muck and sand. Based upon this criterion, areas of concentrated organic muck are apparent in south central portions of Lake Anderson. This area corresponds well with the area of accumulated organic muck deposits indicated on Figure 3-2. Measured organic sediment content within the lake ranges from 0.5-48.3%, with an overall mean of 13.4%.

Values of sediment density are also useful in evaluating the general characteristics of sediments within a lake. Sediments with calculated densities between 1.0-1.5 are often indicative of highly organic muck-type sediments, while sediment densities of approximately 2.0 or greater are often indicative of sandy sediment conditions. Measured sediment densities in Lake Anderson range from 1.06-2.10 g/cm^3, with an overall mean of 1.66 g/cm^3.

Measured concentrations of total phosphorus in Lake Anderson sediments were found to highly variable throughout the lake. Sediment total phosphorus concentrations range from 140-3658 μg/cm^3, with an overall mean of 1024 μg/cm^3. In general, sandy sediments are often characterized by low total phosphorus concentrations, while highly organic muck-type sediments are characterized by elevated total phosphorus concentrations.

Isopleths of sediment phosphorus concentrations in Lake Anderson are presented on Figure 3-6 based on information contained in Table 3-4. Areas of elevated sediment phosphorus concentrations are present in the northern central, western, and southern portions of the lake. The areas of elevated total phosphorus concentrations within the lake are similar to the areas of elevated moisture content and organic content summarized in Figures 3-4 and 3-5, respectively. In general, the overall total phosphorus concentrations observed in Lake Anderson appear to be elevated compared with phosphorus sediment concentrations normally observed by ERD in urban lakes.

Figure 3-5. Isopleths of Organic Content (% dry wt.) in the Top 10 cm of Sediments in Lake Anderson.

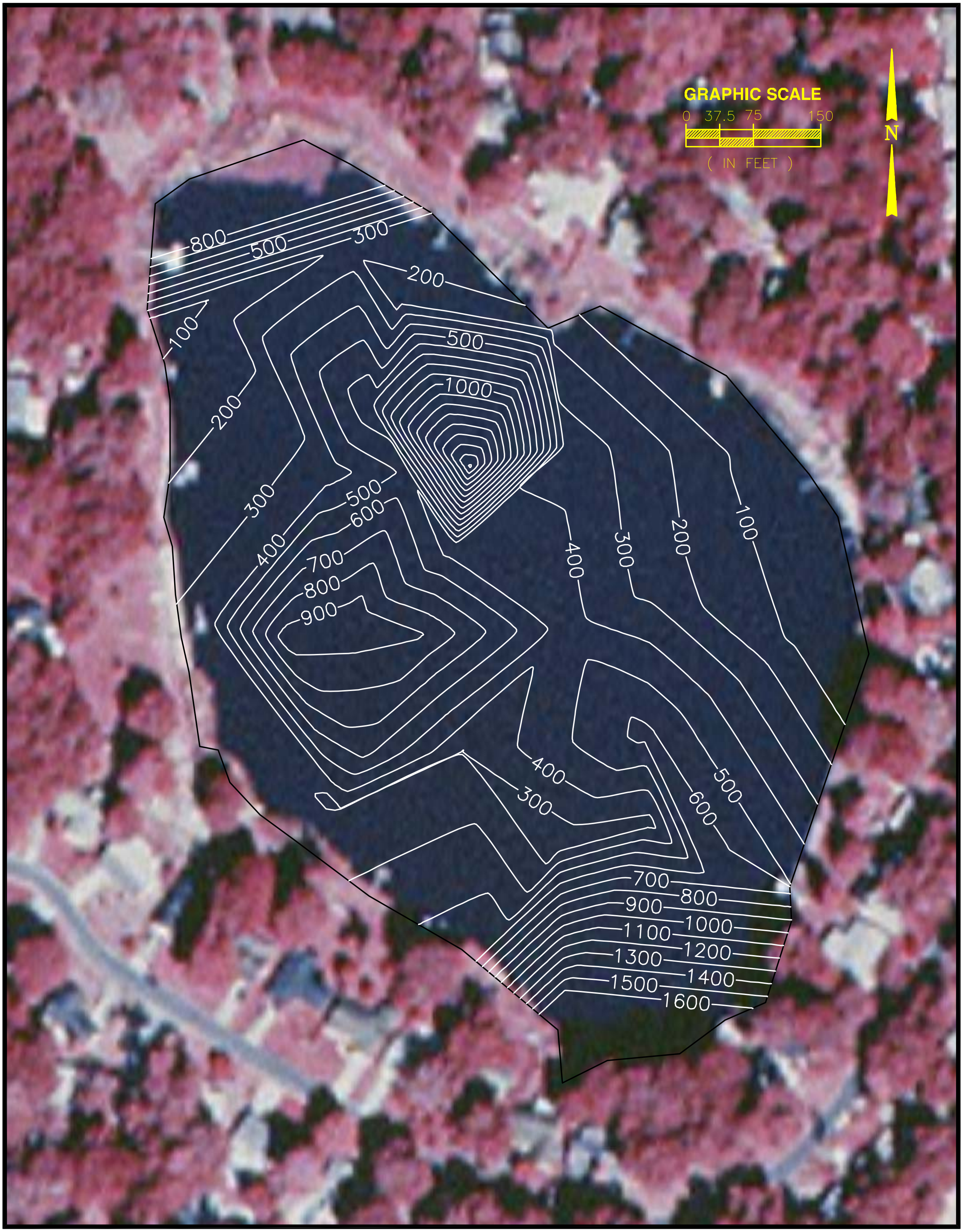

Figure 3-6. Isopleths of Total Phosphorus (µg/cm^3 wet wt.) in the Top 10 cm of Sediments in Lake Anderson.

Similar to the trends observed for sediment phosphorus concentrations, sediment nitrogen concentrations are also highly variable in Lake Anderson. Sediment nitrogen concentrations range from 348-3003 $\mu g/cm^3$, with an overall mean of 1024 $\mu g/cm^3$. However, in contrast to the trends observed for total phosphorus, the nitrogen concentrations measured in Lake Anderson do not appear to be elevated compared with values normally observed in urban lakes.

Isopleths of sediment nitrogen concentrations in Lake Anderson are illustrated on Figure 3-7. Areas of elevated nitrogen concentrations is apparent in the western central and southern portions of the lake similar to the area of elevated moisture content indicated in Figure 3-4. Sediment concentrations of total nitrogen appear to be more uniform throughout the lake than observed for total phosphorus, organic content, or moisture content.

3.2.3 Phosphorus Speciation

As discussed in Section 2, each of the collected sediment core samples was evaluated for phosphorus speciation based upon the Chang and Jackson Speciation Procedure. This procedure allows phosphorus within the sediments to be speciated with respect to bonding mechanisms within the sediments. This information is useful in evaluating the potential for release of phosphorus from the sediments under anoxic or other conditions.

A summary of phosphorus speciation in sediment core samples collected in Lake Anderson during October-November 2005 is given in Table 3-5. Saloid-bound phosphorus represents sediment phosphorus which is either soluble or easily exchangeable and is typically considered to be readily available for release from the sediments into the overlying water column. As seen in Table 3-5, a moderate degree of variability is apparent in saloid-bound phosphorus within the sediments of Lake Anderson. Measured values for saloid-bound phosphorus range from 3-35 $\mu g/cm^3$, with an overall mean value of 20 $\mu g/cm^3$. In general, low levels of saloid-bound phosphorus are associated with sandy sediments within the lake, while elevated levels of saloid-bound phosphorus are associated with highly organic sediments.

Figure 3-7. Isopleths of Total Nitrogen (μg/cm^3 wet wt.) in the Top 10 cm of Sediments in Lake Anderson.

TABLE 3-5

PHOSPHORUS SPECIATION IN SEDIMENT CORE SAMPLES COLLECTED IN LAKE ANDERSON DURING OCTOBER-NOVEMBER 2005

SITE	SALOID-BOUND P (µg/cm^3)	Fe-BOUND P (µg/cm^3)	TOTAL AVAILABLE P (µg/cm^3)	PERCENT AVAILABLE P
1	23	137	161	17
2	14	258	272	61
3	13	42	56	29
4	29	57	86	16
5	18	72	90	32
6	15	152	167	90
7	35	199	234	22
8	22	88	110	27
9	20	354	374	52
10	17	207	224	18
11	29	113	142	20
12	3	120	123	25
13	17	83	100	72
14	15	215	230	22
15	28	120	148	23
16	28	499	526	14
17	15	145	160	18
18	20	49	69	7
19	23	98	121	17
20	13	80	93	57
21	23	142	165	25
22	16	120	136	28
23	22	269	291	47
24	25	121	146	25
25	24	354	378	69
26	17	654	670	47
27	16	1040	1056	94
28	15	267	282	12
Mean	**20**	**216**	**236**	**36**
Maximum	**35**	**1040**	**1056**	**94**
Minimum	**3**	**42**	**69**	**7**

Isopleths of saloid-bound phosphorus in Lake Anderson sediments are illustrated on Figure 3-8. Areas of elevated saloid-bound phosphorus are apparent in both the north central and south central portions of the lake. The saloid-bound phosphorus concentrations summarized in Figure 3-8 are elevated values compared with saloid-bound phosphorus concentrations commonly observed in urban lake systems. This suggests that the sediments in Lake Anderson contain a large pool of readily available phosphorus which can be released from the sediments on virtually a continuous basis.

In general, iron-bound phosphorus sediment associations appear to follow a pattern similar to that exhibited by saloid-bound phosphorus. Areas of the lake with relatively sandy sediments are characterized by low levels of iron-bound phosphorus, while highly organic sediment areas appear to have higher values of iron-bound phosphorus. Iron-bound phosphorus is relatively stable under oxidized conditions, but becomes unstable under a reduced environment, causing the iron-phosphorus bounds to separate, releasing the oxygen bound phosphorus directly into the water column. When anoxic conditions occur near the water-sediment interface in Lake Anderson, large portions of the lake appear to have conditions favorable for release of iron-bound sediment phosphorus into the overlying water column. The iron-bound phosphorus concentrations summarized in Table 3-5 appear to be relatively elevated compared with values commonly observed in urban lake systems.

Isopleths of iron-bound phosphorus in Lake Anderson sediments are illustrated in Figure 3-9. Areas of elevated iron-bound phosphorus associations are apparent in the north central and southern portions of the lake. Observed patterns for iron-bound phosphorus in the sediments appear to be somewhat similar to the patterns exhibited for saloid-bound phosphorus in Figure 3-8.

Total available phosphorus represents the sum of the saloid-bound phosphorus and iron-bound phosphorus associations in each sediment core sample. Since the saloid-bound phosphorus is immediately available, and the iron-bound phosphorus is available under reduced conditions, the sum of these speciations represents the total phosphorus which is potentially available within the sediments. This information can be utilized as a guide for future sediment inactivation procedures.

Figure 3-8. Isopleths of Saloid-Bound Phosphorus ($\mu g/cm^3$ wet wt.) in the Top 10 cm of Sediments in Lake Anderson.

Figure 3-9. Isopleths of Iron-Bound Phosphorus (µg/cm^3 wet wt.) in the Top 10 cm of Sediments in Lake Anderson.

A summary of total available phosphorus in each of the 28 collected sediment core samples is given in Table 3-5. Total available sediment phosphorus concentrations range from 69-1056 µg/cm^3, with an overall mean of 236 µg/cm^3. The mean total available phosphorus in Lake Anderson appears to be elevated in value compared with typical urban lake systems.

Isopleths of total available phosphorus in Lake Anderson sediments are illustrated on Figure 3-10. Similar to the trends observed with previous sediment parameters, areas of elevated total available phosphorus are apparent in the north central and southern portions of the lake. The isopleths presented in Figure 3-10 can be utilized as an application guide for future sediment inactivation activities.

Estimates of the percentage of available phosphorus within the sediments in Lake Anderson are also provided in Table 3-5. These values represent the percentage of the total sediment phosphorus concentration, summarized in Table 3-4, which is potentially available for sediment release, based upon the total available phosphorus values summarized in Table 3-5. Based upon this comparison, the percentage of available sediment phosphorus within the lake ranges from 7-94%, with an overall mean of 36%. Therefore, on an average basis, more than one-third of the total sediment phosphorus within the lake is potentially available for release into the overlying water column.

3.4 Physical-Chemical Profiles

Physical-chemical profiles of temperature, pH, specific conductivity, dissolved oxygen, and redox potential were performed near the center of Lake Anderson by ERD field personnel on October 28, 2004 and October 28, 2005. The monitoring event performed on October 28, 2004 was conducted at the request of the Homeowners Association to evaluate ongoing water quality problems within the lake. The field monitoring event performed on October 28, 2005 was conducted as part of the evaluation summarized in this report. Measurements of Secchi disk depth were also performed on the two monitoring dates, with a Secchi disk depth of 0.69 m during October 2004 and 0.61 m during October 2005. Each of these values reflects extremely poor water column clarity. A complete listing of physical-chemical profiles collected during October 2004 and October 2005 is given in Appendix A.

Figure 3-10. Isopleths of Total Available P (μg/cm^3 wet wt.) in the Top 10 cm of Sediments in Lake Anderson.

A graphical comparison of vertical profiles for temperature, pH, dissolved oxygen, and specific conductivity in Lake Anderson during October 2004 and October 2005 is given in Figure 3-11. Significant thermal stratification was not observed in Lake Anderson during either of the two October monitoring events. Temperature differences of less than 1^{o}C were observed between top and bottom portions of the lake during the two monitoring events, reflecting relatively well mixed water column conditions.

However, in spite of the relatively well mixed condition of the water column, a continuous decline in pH was observed with increasing water depth within the lake. Surface pH values were moderately alkaline on each of the two monitoring dates, with surface values ranging from 8.06-8.87. A steady decrease in pH was observed with increasing water depth, decreasing to 6.91 near the bottom sediments during October 2004 and 6.96 near the bottom sediments during October 2005. Rapid decreases in pH near the sediment-water interface are often associated with anoxic conditions in this portion of the lake.

Supersaturated dissolved oxygen conditions were observed in Lake Anderson within the top 4-4.5 m of the lake during each of the two monitoring events. These supersaturated dissolved oxygen conditions are a result of the visible algal blooms which were occurring within the lake during the two monitoring events. However, near the sediment-water interface, dissolved oxygen concentrations were observed to decrease rapidly, reaching 2.6 mg/l during October 2004 and 0.1 mg/l during October 2005. In addition, highly reduced conditions, as indicated by redox potential values less than 200 mv, were observed near the sediment-water interface during October 2005. These reduced conditions create an environment which maximizes the potential for release of phosphorus into the overlying water column.

Specific conductivity values in Lake Anderson were relatively uniform within the top 4.5-5 m of the lake on each of the two monitoring dates. However, rapid increases in specific conductivity were observed near the sediment-water interface. A conductivity increase of approximately 5% was observed near the sediment-water interface during October 2004, with an increase of approximately 28% observed during October 2005. Each of these observed increases in conductivity are a reflection of sediment release of ions, including phosphorus near the sediment-water interface.

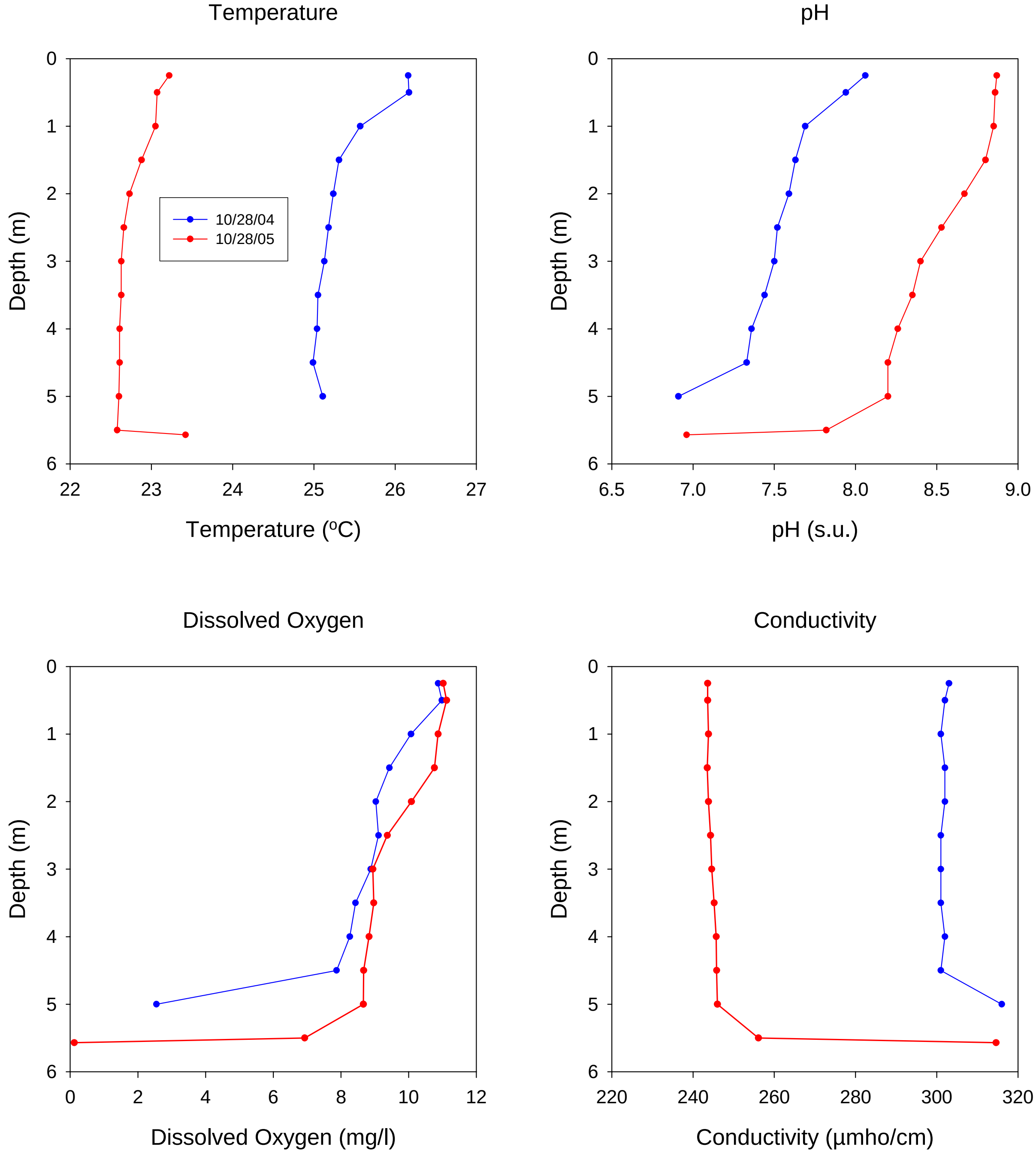

Figure 3-11. Vertical Profiles of Temperature, pH, Dissolved Oxygen, and Conductivity in Lake Anderson During October 2004 and October 2005.

In summary, the vertical profiles presented in Figure 3-11 provide compelling evidence that conditions of low dissolved oxygen are present near the sediment-water interface in Lake Anderson even during periods of relatively uniform water column circulation. Substantially reduced conditions were observed in this zone during October 2005, with rapid decreases in dissolved oxygen and pH and a substantial increase in specific conductivity. This information strongly suggests that internal recycling of ions is an ongoing occurrence in Lake Anderson under existing conditions.

SECTION 4

EVALUATION OF ALUM INACTIVATION REQUIREMENTS

4.1 Significance of Internal Recycling

Based upon the sediment characterization and field monitoring performed by ERD, it appears that internal recycling of ions, including phosphorus, from anoxic bottom sediments is an ongoing occurrence within Lake Anderson. Vertical profiles collected within the lake suggest that portions of the lake sediments in deeper portions of the lake exhibit anoxic conditions during portions of the year. In addition, increases in specific conductivity are observed in lower layers of the lake, suggesting release of ions from the sediments into the overlying water column. As a result, internal recycling appears to be a significant occurrence in Lake Anderson, which could be reduced by a properly designed application of aluminum sulfate to the lake sediments.

4.2 Sediment Inactivation Requirements and Costs

Estimates of the mass of total available phosphorus within the top 0-10 cm layer of the sediments in Lake Anderson were generated by graphically integrating the total available phosphorus isopleths presented on Figure 3-10. Areas contained within each isopleth contour were calculated using AutoCAD Release 12.0. The top 0-10 cm layer of the sediments in the lake is considered to be an active layer with respect to exchange of phosphorus between the sediments and the overlying water column. Inactivation of phosphorus within the 0-10 cm layer is typically sufficient to inactivate sediment release of phosphorus within a lake.

A summary of estimated total available phosphorus in the sediments of Lake Anderson is given in Table 4-1. On a mass basis, the sediments of Lake Anderson contain approximately 1254 kg of available phosphorus in the top 10 cm. On a molar basis, this equates to approximately 40,453 moles of available phosphorus to be inactivated as part of the sediment inactivation process.

TABLE 4-1

ESTIMATES OF AVAILABLE SEDIMENT PHOSPHORUS AND INACTIVATION REQUIREMENTS FOR LAKE ANDERSON

AVAILABLE P CONTOUR INTERVAL (μg/cm^3)	INTERVAL MID-POINT (μg/cm^3)	AREA (ac)	AVAILABLE P (kg)		INACTIVANT REQUIREMENT	
			kg	moles	moles Al[1]	gallons of alum
0-100	50	1.56	3	102	1,018	124
100-200	150	5.15	313	10.085	100,845	12,280
200-300	250	2.40	243	7,833	78,326	9,538
300-400	350	1.40	198	6,397	63,966	7,789
400-500	450	0.62	113	3,642	36,422	4,435
500-600	550	0.44	98	3,159	31,592	3,847
600-700	650	0.70	184	5,940	59,397	7,233
700-800	750	0.10	30	979	9,791	1,192
800-900	850	0.08	28	888	8,877	1,081
900-1000	950	0.06	23	744	7,441	906
1000-1100	1050	0.05	21	685	6,854	835
Total:		**12.56**	**1,254**	**40,453**	**404,529**	**49,259**

1. Based on an Al:P molar ratio of 10:1

Estimated inactivation requirements were calculated for Lake Anderson based upon a molar Al:P ratio of 10:1, as utilized by ERD in previous inactivation evaluations. Prior research involving sediment inactivation has indicated that an excess of aluminum is required within the sediments to cause phosphorus to preferentially bind with aluminum rather than other available complexing agents. A 10:1 molar ratio of Al:P has been shown to be adequate to create this driving force. Based upon this ratio, inactivation of phosphorus release from sediments in Lake Anderson will require approximately 404,529 moles of aluminum which equates to approximately 49,259 gallons of alum. Based on an average tanker volume of 4500 gallons, the required alum addition is equivalent to approximately 11 tanker loads (49,500 gallons).

An average water column dose of alum resulting from the sediment inactivation was calculated by dividing the alum requirement of 49,259 gallons by the overall volume of the lake (163 ac-ft). Since the alum application would occur at the surface, the overall whole-lake alum dose must be considered to evaluate potential water column impacts during the application. Application of approximately 49,259 gallons of alum to Lake Anderson into a water column volume of approximately 163 ac-ft would result in an applied alum dose of 54.3 mg Al/liter.

The calculated water column alum dose of 54.3 mg Al/liter is an extremely elevated dose which will far exceed the normal buffering capacity of the lake to resist undesirable reductions in pH values during the application. An alum application of this dose to Lake Anderson would likely reduce the water column pH level to less than 4.0. In general, water column doses of approximately 5-7.5 mg Al/liter are the maximum doses which can be safely added to a lake during a single application without supplemental buffering compounds. Although multiple applications are generally recommended by ERD to minimize overall system impacts, application of the required water column dose of 54.3 mg Al/liter would require approximately 8-10 individual applications to Lake Anderson, spaced approximately 2-3 months apart. In some lakes, multiple applications of this magnitude may be an acceptable alternative. However, access into Lake Anderson is extremely limited and difficult, and a significant additional cost would be incurred in the mobilizations required to enter and exit the lake for each of the individual applications.

It appears that the best alternative for sediment inactivation in Lake Anderson is to use a buffering compound in addition to the alum to neutralize the anticipated undesirable pH impacts. Sodium aluminate, an alkaline form of alum, is commonly used in these applications as the buffering agent. Sodium aluminate provides a high level of buffering, as well as supplemental aluminum ions, which reduces the total amount of alum required during the application process. If alum and sodium aluminate are used in combination, changes in pH within the lake during the application process can be minimized.

Previous alum surface applications performed for inactivation of sediment phosphorus release by ERD have indicated that the greatest degree of improvement in surface water characteristics and the highest degree of inactivation of sediment phosphorus release are achieved through multiple applications of alum to the waterbody over a period of approximately 6-12 months. Each subsequent application results in additional improvements in water column quality and additional alum floc added to the sediments for long-term inactivation of sediment phosphorus release. The additional aluminum provided to the sediments also creates an active absorption mechanism for other phosphorus inputs into the water column as a result of groundwater seepage. Inputs of phosphorus from groundwater seepage into a lake can easily exceed inputs from internal recycling in only a few annual cycles. Multiple applications of alum provide an abundance of aluminum which can intercept groundwater inputs of phosphorus over a period of many years. As a result, multiple inputs can eliminate phosphorus from the combined inputs resulting from internal recycling as well as groundwater seepage. Therefore, the required aluminum addition for Lake Anderson, summarized in Table 4-1, should be divided into a minimum of two separate surface treatments.

Previous alum surface treatments performed by ERD have indicated that the simultaneous addition of 1 gallon of sodium aluminate for every 6.5 gallons of alum is sufficient to create neutral pH conditions during the application process. One gallon of alum provides approximately 8.21 moles of available aluminum for sediment inactivation, while one gallon of sodium aluminate provides 21.46 moles of aluminum. Therefore, as indicated previously, the use of sodium aluminate can substantially reduce the amount of alum required for the inactivation project. As seen in Table 4-1, the total estimated alum volume, without the use of supplemental buffering agents, is approximately 49,259 gallons. If sodium aluminate is used as a buffering agent, the total chemical requirements necessary to generate an equivalent total mass of available aluminum are 35,141 gallons of alum combined with 5406 gallons of sodium aluminate. As recommended previously, this application should be divided into a minimum of two separate applications, with approximately half of the required chemical volume for alum and sodium aluminate applied during each application.

A summary of estimated application costs for sediment inactivation in Lake Anderson is given in Table 4-2. This estimate assumes an alum volume of 35,141 gallons and a sodium aluminate volume of 5406 gallons will be applied. Planning and mobilization costs are estimated to be approximately $1000 per application, which includes initial planning, mobilization of equipment to the site, demobilization at the completion of the application process, and clean-up. Estimates of man-hour requirements for the application are provided based upon experience with similar previous applications by ERD. A labor rate of $100/hour is assumed which includes labor costs, water quality monitoring, expenses, equipment rental, insurance, mileage, and application equipment fees. The estimated cost for sediment inactivation in Lake Anderson is $48,479 or approximately $24,240 per application.

TABLE 4-2

ESTIMATED APPLICATION COSTS FOR SEDIMENT INACTIVATION IN LAKE ANDERSON

PARAMETER	AMOUNT REQUIRED	UNIT COST	TOTAL COST
1. Chemicals			
A. Alum	35,141 gallons	$0.50/gallon[1]	$ 22,842
B. Sodium Aluminate	5,406 gallons	$2.80/gallon	$ 15,137
2. Labor			
A. Planning and Mobilization	2 applications	$1000/application	$ 2,000
B. Chemical Application	80 man-hours	$100/hour[2]	$ 8,000
3. Lab Testing	Pre-/Post-samples x 2 events	$250/event	$ 500
		TOTAL:	**$ 48,479**

1. Approximate Orange County contract cost
2. Includes raw labor, water quality monitoring, insurance, expenses, application equipment, mileage, and rentals

4.3 Longevity of Treatment

After initial application, the alum precipitate will form a visible floc layer on the surface of the sediments within the lake. This floc layer will continue to consolidate for approximately 30 days, reaching maximum consolidation at that time. Due to the unconsolidated nature of the sediments in much of the lake, it is anticipated that a large portion of the floc will migrate into the existing sediments rather than accumulate on the surface as a distinct layer. This process is beneficial since it allows the floc to sorb soluble phosphorus during migration through the surficial sediments. Any floc remaining on the surface will provide a chemical barrier for adsorption of phosphorus which may be released from the sediments.

Based on previous experiences by ERD, as well as research by others, it appears that a properly applied chemical treatment will be successful in inactivation of the available phosphorus in the sediments of Lake Anderson. However, several factors can serve to reduce the effectiveness and longevity of this treatment process. First, wind action may cause the floc to become prematurely mixed into deeper sediments, reducing the opportunity for maximum phosphorus adsorption. Significant wind resuspension has been implicated in several alum applications in shallow lakes which exhibited reduced longevity. However, in the absence of wind resuspension, alum inactivation in lake sediments has resulted in long-term benefits ranging from 3 to more than 10 years. However, due to the depth and small surface area of Lake Anderson, it is not anticipated that wind-induced resuspension will be a problem.

Another factor which can affect the perceived longevity and success of the application process is recycling of nutrients by macrophytes from the sediments into the water column. This recycling will bypass the inactivated sediments since phosphorus will cross the sediment-water interface using vegetation rather than through the floc layer. Although this process will not affect the inactivation of phosphorus within the sediments, it may result in increases in dissolved phosphorus concentrations which are unrelated to sediment-water column processes. However, the degree of macrophyte growth in Lake Anderson appears to be limited, and recycling of phosphorus by macrophytes does not appear to be a significant concern.

A final factor affecting the longevity of an alum treatment is significant upward migration of groundwater seepage through the bottom sediments. This seepage would almost certainly contain elevated phosphorus levels which would be adsorbed onto the aluminum floc, reducing the floc which is available for interception of sediment phosphorus release. At the recommended application dose, an additional available pool of aluminum may be present within the sediments which can be used to adsorb phosphorus migrating upward as a result of groundwater seepage. The recommended repeat alum application will further reduce the impacts of groundwater seepage on phosphorus loadings to the lake. Therefore, groundwater inflow through the sediments is not anticipated to substantially reduce the longevity of a sediment inactivation process in Lake Anderson.

4.4 Summary and Recommendations

Based upon the results presented in the previous sections, it appears that sediment recycling of phosphorus is significant in Lake Anderson. Since Lake Anderson appears to be predominantly a phosphorus-limited ecosystem, reduction of phosphorus released from internal recycling will result in improved water quality characteristics within the lake. Therefore, a surface alum application for inactivation of sediment phosphorus in Lake Anderson is recommended. The application should be performed using a water column dose of 54.3 mg Al/liter which equates to approximately 35,141 gallons of alum and 5406 gallons of sodium aluminate. Application of this dose could be safely achieved while maintaining an equilibrium pH value in excess of 6.0. Dividing the required dose into multiple applications will further improve water column clarity and provide additional aluminum to the sediments to inactivate sediment phosphorus release and absorb phosphorus loadings from groundwater seepage.

APPENDIX A

PHYSICAL-CHEMICAL PROFILES COLLECTED IN LAKE ANDERSON DURING OCTOBER 2004 AND OCTOBER 2005