A Strategy for Evaluating In-lake Treatment Effectiveness and Longevity
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in cooperation with
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Executive Summary

This report presents a strategy for evaluating the effectiveness and longevity of in-lake treatment and illustrates it by using available lake management data. Specifically, this document provides:

- A strategy to develop regional criteria for evaluating lake treatment effectiveness and longevity,
- A review, evaluation, and synthesis of data for one commonly used lake treatment (nutrient inactivation) in relation to regional criteria, and
- A framework in which lake management goals can be established and effectiveness and longevity of treatment can be evaluated.

Our focus is on in-lake nutrient inactivation treatments that have been applied to a number of lakes throughout the United States. Data were insufficient to adequately address the longevity or effectiveness of dredging, water level drawdown, or aquatic macrophyte harvesting; however, these techniques are noted when they are used in conjunction with nutrient inactivation efforts.

Our findings indicate that:

- It is possible to establish initial lake management goals for lakes in a given ecoregion by using STORET data and establish treatment effectiveness criteria for phosphorus and chlorophyll concentrations and Secchi transparency;
- In-lake nutrient inactivation can significantly decrease total phosphorus concentrations in lakes while causing a rapid improvement in lake conditions by reducing in-lake chlorophyll concentrations and increasing Secchi transparency; and,
- Nutrient inactivation combined with other treatments can improve the condition of selected lakes for up to 10 years (longer-term records are unavailable).
As a result of these findings, we recommend the following:

- To evaluate the longevity and effectiveness of lake management projects, scientists and managers should collect at least three to five years of pre-treatment and post-treatment monitoring data.

- After lake restoration projects are completed, all data should be entered into the EPA data management system, STORET.

- To improve restoration efficiency, lake managers and scientists should direct greater attention to studying and understanding lake processes and moving from a technology-based approach to one based on the scientific understanding of lakes and their environments.

<table>
<thead>
<tr>
<th>CONTENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acknowledgements .......................................... III</td>
</tr>
<tr>
<td>Executive Summary ........................................... v</td>
</tr>
<tr>
<td>Chapter 1: Introduction ...................................... 1</td>
</tr>
<tr>
<td>Lake and Reservoir Management ............................ 1</td>
</tr>
<tr>
<td>Background .................................................. 1</td>
</tr>
<tr>
<td>Intended Audience .......................................... 3</td>
</tr>
<tr>
<td>Report Organization ......................................... 3</td>
</tr>
<tr>
<td>Chapter 2: Criteria Development ........................... 5</td>
</tr>
<tr>
<td>Background .................................................. 5</td>
</tr>
<tr>
<td>Information Sources ......................................... 6</td>
</tr>
<tr>
<td>Criteria Development ........................................ 7</td>
</tr>
<tr>
<td>Ecoregions ................................................... 8</td>
</tr>
<tr>
<td>Goal Setting ................................................ 9</td>
</tr>
<tr>
<td>Attainable Goals ............................................ 11</td>
</tr>
<tr>
<td>Effectiveness Criteria ...................................... 15</td>
</tr>
<tr>
<td>Longevity Criteria .......................................... 16</td>
</tr>
<tr>
<td>Chapter 3: Treatment Evaluations ......................... 21</td>
</tr>
<tr>
<td>Background .................................................. 21</td>
</tr>
<tr>
<td>Treatment Effectiveness ..................................... 25</td>
</tr>
<tr>
<td>Treatment Longevity ......................................... 34</td>
</tr>
<tr>
<td>Chapter 4: Discussion ........................................ 41</td>
</tr>
<tr>
<td>Management Goals ........................................... 41</td>
</tr>
<tr>
<td>Treatment Effectiveness and Longevity .................... 42</td>
</tr>
<tr>
<td>Lake Management—Scientific Testing and Evaluation .... 44</td>
</tr>
<tr>
<td>Chapter 5: Conclusions and Recommendations ............. 47</td>
</tr>
<tr>
<td>References .................................................. 49</td>
</tr>
<tr>
<td>Appendix: Sources of Information ......................... 53</td>
</tr>
</tbody>
</table>
CHAPTER 1

Introduction

Lake and Reservoir Management

The U.S. Environmental Protection Agency’s (EPA) Lake and Reservoir Restoration Guidance Manual (Olem and Flock, 1980) was designed to educate and assist informed lay people, consultants, and public officials in restoring, managing, and protecting lakes. By considering both lake and watershed management, this report presents a strategy for evaluating the effectiveness and longevity of in-lake treatment. Lake management cannot be effective or long-lasting unless managers implement concurrent and complementary watershed management practices. The techniques, procedures, and practices available for lake and watershed management are reasonably well known (N. Am. Lake Manage. Soc. 1985; Cooke et al. 1986) and have been the subject of several meetings and symposiums (U.S. Environ. Prot. Agency, 1979, 1983; N. Am. Lake Manage. Soc. 1988; 1989).

Watershed management practices have been applied since the 1940s; however, they were used primarily to reduce soil loss from agricultural or range lands. Only in recent years has it been demonstrated that techniques to reduce soil erosion in farmlands successfully could also be used to restore and protect lakes. When soil erosion is reduced, the input of nutrients adsorbed to soil particles and the rate at which sediments accumulate in a lake are decreased, extending the life of a lake and often reducing its trophic state.

Despite the usefulness of various in-lake and watershed management techniques in rehabilitating and managing lakes and watersheds, relatively little information is available on their effectiveness and longevity. This report presents an approach for developing criteria and then evaluating treatment to establish realistically attainable lake management goals.

Background

On November 3, 1986, a group of experts—limnologists, ecologists, economists, soil scientists, and environmental and civil engineers—convened to formulate criteria for evaluating the effectiveness and longevity of in-lake and watershed management techniques. In this workshop, participants also developed a format for presenting this information to the
public and a matrix capable of linking a lake’s problems to its causes and distinguishing symptoms from causes.

The experts recommended that the following seven criteria be used to evaluate in-lake and watershed management techniques:

- Effectiveness,
- Longevity,
- Confidence,
- Applicability,
- Potential negative impacts,
- Capital cost, and
- Operation and maintenance.

Out of the many in-lake rehabilitation techniques implemented over the years, only four have been applied in a sufficient number of lakes throughout the United States to merit evaluation of their effectiveness and longevity:

- **Sediment Removal or Dredging**—used to deepen a lake and increase its volume, reduce or eliminate the internal recycling of nutrients, and remove toxic substances and rooted aquatic plants;

- **Nutrient Inactivation**—commonly consists of applying alum (aluminum sulfate or sodium aluminate) to a lake to remove phosphorus from the water column and retard its release from the sediments;

- **Water Level Drawdown**—frequently used for fisheries management to control aquatic plants by desiccation or to allow lake dredging with conventional earth-moving equipment; and

- **Harvesting**—cuts or uproots aquatic plants and removes them from the lake. Harvesting provides only temporary relief and must be repeated from year to year and, in some instances, several times a year.

All four management techniques address the three generic, primary lake problems: sedimentation, growth of algae, and excessive growth of aquatic plants (macrophytes).

Three extensively used watershed management tools complement the four lake treatment techniques by reducing inputs of sediment, nutrients, and organic matter and by maintaining and protecting lake resources.

- **Streamside/Shoreline Management Zones or Buffer Strips** are areas where natural vegetation is maintained and, if appropriate, where livestock have limited access. If the natural vegetation has been removed, plants (grass, trees, shrubs) can be introduced between the disturbed area and the stream to act as a buffer strip.

- **Detention or Sedimentation Basins** retain runoff water laden with suspended particles and associated contaminants so that this material can settle out before entering a primary waterbody.

- **Land Use Zoning Ordinances** can protect waterbodies by regulating watershed activities that cause erosion and pollution problems or by controlling development to protect the aesthetics and integrity of a watershed.

Regional differences in climate, geology, soils, and other watershed characteristics that affect water quality also influence the effectiveness of many management techniques. Lakes in one region may be rich in nutrients because of naturally fertile watershed soils and, in another region, lakes with infertile soils may be naturally poor in nutrients. A nutrient-rich lake in a region that typically has nutrient-poor waterbodies is probably a viable candidate for management, whereas a nutrient-rich lake in a region with typically nutrient-rich waterbodies may or may not be a viable candidate. Therefore, managers must consider regional differences when evaluating treatment longevity or effectiveness.

**Intended Audience**

The primary users of this report are expected to be:

- lake managers and consultants,
- state project officers and sponsors, and
- regional EPA Clean Lakes project officers.

**Report Organization**

The remainder of this report is divided into four chapters:

- Chapter 2—Criteria Development,
- Chapter 3—Treatment Evaluation,
- Chapter 4—Discussion, and
- Chapter 5—Conclusions and Recommendations.

In Chapter 2, criteria methodologies are developed to evaluate the effectiveness and longevity of in-lake treatment techniques. The effectiveness and longevity of the selected in-lake treatment techniques are evaluated in Chapter 3. Chapter 4 discusses these evaluation criteria, focusing on their relation to treatment longevity and effectiveness and some of the lessons learned in this study, and Chapter 5 presents conclusions and recommendations from the study. Lastly, the appendix documents sources of information.
CHAPTER 2

Criteria Development

Background

Any lake management project should address the following questions:

- What management techniques can be implemented? (Selection)
- How well will the techniques work? (Effectiveness)
- How long will the effects last? (Longevity)

However, these questions are difficult to answer. For example, the selection of appropriate in-lake management technique(s) depends on an understanding of the quality and quantity of water entering a lake and the ecological processes whose imbalance caused objectionable conditions (Cooke, 1990). In most instances, in-lake treatment will have limited success if managers ignore nutrient and sediment inputs. Likewise, if the interrelationships between abiotic (physical and chemical) conditions and biotic (biological) conditions are not understood, the use of inappropriate management approaches may actually exacerbate lake problems.

In this report, how well techniques work—treatment effectiveness—is based on how well the technique reduces nutrients, specifically phosphorus, and chlorophyll a (an indicator of algae mass) and increases water clarity, as measured by Secchi transparency, at the completion of treatment.

Longevity addresses how long the effects last. In this document, longevity is defined as the length of time phosphorus, chlorophyll a, and/or Secchi transparency are maintained within a desired range.

Additional factors that should be considered in assessing effectiveness and longevity or establishing criteria to evaluate effectiveness include:

- lake size,
- shape,
- flushing rate,
- geographic location,
- mean and maximum depths,
Depending on the objectives of the project, inconsistent results can complicate the selection of in-lake management treatments.

Even if a treatment works in one part of the country, there is no information available to ascertain its effectiveness elsewhere or determine whether lakes of differing trophic state in a region can be returned to some common level.

Our first step toward evaluating effectiveness and longevity was to obtain literature on and data for projects that used one or more of the following treatments: dredging, nutrient inactivation, or drawdown. Sources of information included:

- EPA Clean Lakes Clearinghouse database,
- North American Lake Management Society (NALMS) questionnaires sent to lake associations, and
- Communications with project managers and scientists working in lake management.

The EPA Clean Lakes Clearinghouse database was the primary source for Phase I and Phase II Clean Lakes studies, Clean Lakes demonstration projects, and reports presented at NALMS symposia. Project officers and scientists, contacted directly, turned out to be the best source of data.

Criteria Development

We conducted a search of the EPA Clean Lakes Clearinghouse database by using the key terms “nutrient inactivation,” “alum treatment,” “drawdown,” and “dredging.” Reports taken from the database were reviewed; those selected for further consideration met the following criteria:

1. Only one treatment was implemented;
2. The database for the project contained information on total phosphorus, chlorophyll a, and Secchi disk transparency; and
3. Pre- and post-treatment data were available.

However, very few projects were selected using this strategy. The first criterion was then revised to consider one or more treatments per lake project because most projects reviewed applied more than one management technique; for example, dredging projects were often coupled with drawdown and nutrient inactivation projects with septic tank or wastewater treatment system diversions. Therefore, evaluating effectiveness and longevity of a single treatment technique would be difficult.

The second criterion was also revised because many projects did not monitor or analyze water samples for total phosphorus, chlorophyll a, or Secchi disk transparency. Thereafter, projects with pre- and post-implementation data for at least one of the parameters were included in the set to be evaluated (Table 2.1). In addition, data were restricted to those values collected in July and August, months when lakes are heavily used for water recreation, many water quality problems (algal scums, excessive aquatic weeds, shallowness,) occur, and people are more likely to notice and complain about them.

This report focuses on evaluating nutrient inactivation either alone or in conjunction with one or more of the other techniques because our literature search and data provided insufficient information to adequately evaluate dredging, water level drawdown, or aquatic macrophyte harvesting techniques either singly or in conjunction with any other treatment.

We considered ways to aggregate or analyze data to easily transfer information from one project to another. We decided that data could be aggregated by the treatment used and by attributes such as surface area,

- watershed geology,
- soil types,
- land management/use, and
- natural vegetation around the lake.

Treatment results often differ from lake to lake, probably because of a combination of these factors.

Pastorak et al. (1982) reported an example of inconsistent treatment results from artificial circulation, which is used to reduce or eliminate chemical and thermal stratification, thereby increasing dissolved oxygen in the lower depths of the water column. Artificial circulation can

- produce an increase in acceptable habitat (depth and volume of water) for aquatic organisms,
- decrease internal phosphorus loadings from bottom sediments,
- reduce the algae population by mixing it throughout the water column, and
- increase transparency by reducing the algae population.

However, field results of artificial circulation applications were inconsistent with these predicted results. In 80 percent of the lakes evaluated, dissolved oxygen increased as expected, but in 53 percent, Secchi transparency decreased instead, and in 65 percent, total phosphorus, which should have decreased, increased or remained the same.

Depending on the objectives of the project, inconsistent results can complicate the selection of in-lake management treatments. Projects to increase dissolved oxygen have a better than average chance of succeeding, however, for projects to increase transparency, the success rate is about 50-50.

Although successes for specific in-lake treatment techniques have been documented (Dunst, 1980; Dunst et al. 1983; Domine, 1980; Gasperino et al. 1980), guidance to assist lake managers in determining the effectiveness of an in-lake treatment or its longevity is limited. Even if a treatment works in one part of the country, there is no information available to ascertain its effectiveness elsewhere or determine whether lakes of differing trophic state in a region can be returned to some common level.

To provide guidance on treatment effectiveness and longevity, we developed a protocol for evaluating existing information and a strategy for establishing criteria. This strategy provides a framework to establish specific attainable restoration goals and evaluate specific techniques for effectiveness and longevity.

Information Sources

Our first step toward evaluating effectiveness and longevity was to obtain literature on and data for projects that used one or more of the following techniques:
mean depth, watershed to surface area ratio, or other factors, using a reference site or sites representing least disturbed lakes for comparison with the treatment lake to provide a baseline for attainable water quality conditions and lake uses. This concept then was expanded to consider data on a regional or ecoregional basis, as described by Omernik (1987). This document investigates the use of ecoregions for comparisons of treatment effectiveness and longevity among lakes within similar regions. The ecoregional approach can be refined by selecting reference lakes for each region (Hughes et al. 1986; Hughes, 1988; U.S. Environ. Prot. Agency, 1990) or further subdividing the ecoregion into areas with even greater similarity among lakes (Omernik et al. 1988). Initially, however, treated lakes were evaluated within ecoregions and without direct comparison to reference lakes.

Ecoregions
The concept of the ecoregion is based on the premise that areas in the conterminous United States have relatively homogeneous geography. The factors used to determine geographic homogeneity include land surface form and use, potential natural vegetation, and soils (Omernik, 1987). To assist managers of aquatic resources in understanding regional patterns of ecosystem quality, ecoregions within the conterminous United States have been mapped and the relative importance of factors that may determine the quality of their environments examined (Omernik, 1987). Larsen et al. (1988) and Rohm et al. (1987) found ecoregional stream classification was potentially useful for evaluating and managing streams.

In this document, lake management projects are considered within the framework of ecoregions to establish initial lake restoration goals. Lakes within an ecoregion may respond similarly, and this similar response may provide a way to classify or generalize effectiveness and longevity. As the characteristics of lakes and their attributes (variability, distributions) in an ecoregion are further refined and analyzed, management goals presented in this document should be reevaluated.

Goal Setting
A community’s desired uses for its lake should be defined in a goal statement. Lake usage is a match between people’s desires and a lake’s capacity to sustain them, with lake problems being limits on desired uses that can be prevented with proper management or corrected through rehabilitation. These definitions are critical: a lake cannot be all things to all people, and desirable uses, even obtainable ones, often conflict. Aesthetic pleasure, great fishing, clean water, sandy shorelines and bottoms, and a healthy wildlife population—all without pests, insects, or weeds—are some desired uses. Unfortunately, almost no lakes can meet all of these demands.

A goal statement should specify desired uses that are attainable and quantifiable. Expectations for a management project should not exceed realistically attainable goals, and, in many cases, these goals can be quantified by using surrogate trophic criteria or water quality criteria.

Some lakes will never be crystal clear. No matter which management techniques are used, a lake will return to its former state if nutrient loads are not reduced, particularly if the drainage area is large relative to lake surface area and the soils are highly erodible and nutrient-rich. Even the most reliable management techniques are not universally appropriate. The same procedure (for example, aeration) that improves quality in one lake can diminish it in another. It is critical, therefore, to determine desired lake uses and have these goals clearly in mind as problems are delineated. For example, in Table 2.2, Wetzel’s (1983) general trophic criteria are compared to values for these criteria in Moon Lake, an oxbow lake located in the Mississippi Delta. Classified as eutrophic because it has high concentrations of total phosphorus and nitrogen, high chlorophyll a concentrations, and low Secchi transparency, Moon Lake is turbid, has excessive algal blooms, poor largemouth bass fishery, and odor problems. Swimming, aesthetics, a good bass fishery, and no odors are desirable goals for Moon Lake. Target trophic conditions or water quality criteria can be used as surrogates for desired uses following in-lake rehabilitation.

A possible goal statement for Moon Lake might be to decrease annual mean nutrient and chlorophyll a concentrations and increase the annual mean Secchi transparency to levels similar to the mean trophic criteria...
for oligotrophic lakes. Is this goal realistic? Are oligotrophic conditions attainable? To answer these questions, we must have some estimate of what is attainable in the region. One approach is to determine the water quality conditions of other similar lakes in the area that do have these desired uses.

When the Mississippi Department of Environmental Protection conducted a Clean Lakes survey in 1982, the lakes with the best water quality in the Delta were found inside the Mississippi River main levee system where near-lake human influences were at a minimum (Miss. Dep. Nat. Resour. 1983). These waterbodies, therefore, became reference lakes for the Moon Lake project. "Inside the Mississippi River levee" refers to lakes located on the side of the levee closest to the river. Lakes inside the levee are not affected by agricultural practices typically occurring in the watersheds of lakes outside the levee. Lakes on the side of the levee the farthest away from the river are said to be "outside" the levee. In Table 2.2, Moon Lake, which is outside the Mississippi River levee, is compared to lakes inside the Mississippi River levee.

In this example, the goal for Moon Lake—to become oligotrophic—is unrealistic, even if attainable, since the desired condition would require extraordinary effort and expense. A more reasonable goal for a Moon Lake management project might be to reduce in-lake nutrient concentrations to levels similar to those of other Delta lakes inside the Mississippi River levee (FTN Assoc., Ltd. 1991).

### Attainable Goals

An attainable water quality goal is defined as one that is reasonably achievable within the constraints of natural drainage area influences such as geology, size of watershed, soil types, and land use patterns. Because the soils in the Moon Lake watershed are naturally phosphorus rich and runoff from the watershed will naturally maintain relatively high phosphorus concentrations in the water, it is not practical to make Moon Lake's management goal a reduction in nutrient concentrations to oligotrophic levels because this is not realistically attainable. There are methods to reduce runoff and soil losses that will, in turn, reduce phosphorus loads from the watershed; however, the most realistic goal for a Moon Lake management program is an adjustment in nutrient concentrations to levels similar to those in oxbow lakes inside the Mississippi River levee.

There are several approaches to developing attainable goals for lakes in the United States' ecoregions. One approach would be to identify several reference lakes in an ecoregion (as was done for the Moon Lake Clean Lake project) and then use appropriate water quality indicators (total phosphorus, chlorophyll a, and Secchi transparency) as indicators for attaining lake management goals. Water quality surveys of lakes have been conducted by several States. From the initial results, lake(s) with good water quality can be identified and used as reference waterbodies if they are in a similar ecoregion.

Another approach to developing attainable goals uses storage retrieval (STORET), which is EPA's data management system for ambient water quality monitoring systems throughout the United States. Total phosphorus, chlorophyll a, and Secchi transparency data were retrieved for all lakes within selected ecoregions as defined by Omernik (1987).
Frequency distributions for each parameter were developed for each ecoregion and the 25th percentile for total phosphorus and chlorophyll a concentrations and the 75th percentile for Secchi disk transparency were designated as initial or preliminary management goals for Clean Lakes projects in each specified area.

Fulmer and Cooke (1990) selected the 25th percentile as a reasonable lake management goal for the Ohio ecoregions. For chlorophyll a and total phosphorus, the 25th percentile means that 25 percent of the lakes in an ecoregion have concentrations less than or equal to the concentration at the 25th percentile. For Secchi disk transparency, the 75th percentile means 25 percent of the Secchi disk transparency measurements were greater than the 75th percentile Secchi disk transparency measurements. These values are assumed to represent the phosphorus and chlorophyll a concentrations and the Secchi disk transparency measurements from an ecoregion’s least disturbed lakes that are at or near levels that permit achievement of desired lake uses (Fulmer and Cooke, 1990).

Least disturbed lakes are those that are minimally impacted by point and nonpoint source contributions (Hughes and Larsen, 1988).

To evaluate whether the STORET database was a reasonable approach to developing initial management goals, total phosphorus and chlorophyll a concentrations and Secchi disk transparency depth measurements were retrieved from STORET for the ecoregions within Arkansas (Table 2.3). Ecoregion descriptions from Omernik (1987) for Arkansas are presented in Table 2.4.

The STORET statistics are consistent with the characteristics of each of these ecoregions. The lowest Secchi transparency depths, the highest total phosphorus concentrations, and the highest chlorophyll a concentrations occurred in the Delta (Mississippi Alluvial Plain). The Delta is the flattest region within Arkansas and possesses a maximum relief of only a few feet per mile (Ark. Dep. Pollut. Control Ecol. 1987). The majority of the land is agricultural, and the soil is phosphorus rich. Because of these conditions, relatively high concentrations of total phosphorus are expected and, therefore, high algal productivity, which results in elevated concentrations of chlorophyll a. Waters with high algae populations can also have low Secchi depth transparencies.

Lakes in Arkansas’ Ouachita Mountains ecoregion represent the other extreme. The highest mean Secchi transparency depth measurements, the lowest mean total phosphorus concentration, and the lowest mean chlorophyll a concentration measured in the State occurred in this region. The Ouachita Mountain ecoregion is composed of severely folded and faulted sandstone, shale, and novaculite strata; local outcrops of igneous rock as well as some interbedded limestone are also found in portions of the Ouachita Mountains (Ark. Dep. Pollut. Control Ecol. 1987). Land use is predominantly forest with limited agriculture, and lakes in the Ouachita Mountains ecoregion are nutrient poor.

STORET-derived ecoregion statistics compare favorably with broad-based investigations done in Vermont (Smeltzer et al. 1988) and Wisconsin (Omernik et al. 1988). Statistics for lakes included in Vermont’s lake monitoring program are compared with data retrieved from STORET for the Northeastern Highland Ecoregion (Table 2.5), which includes most of Vermont. The spring phosphorus values and summer chlorophyll a and transparency values reported in the Vermont program are similar to the July/August values obtained for the Northeastern Highland Ecoregion from STORET.

<table>
<thead>
<tr>
<th>South Central and Ouachita Mountain Ecoregions</th>
<th>Arkansas River Valley Lakes</th>
<th>Boston Mountain Lakes</th>
<th>Mississippi Alluvial Plain</th>
<th>Ozark Highlands</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Secchi transparency (m)</td>
<td>0.86</td>
<td>0.88</td>
<td>0.90</td>
<td>1.03</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.34</td>
<td>0.37</td>
<td>0.39</td>
<td>0.47</td>
</tr>
<tr>
<td>Median</td>
<td>0.90</td>
<td>0.90</td>
<td>0.90</td>
<td>0.90</td>
</tr>
<tr>
<td>75th Percentile</td>
<td>0.95</td>
<td>0.95</td>
<td>0.95</td>
<td>0.95</td>
</tr>
<tr>
<td>Total Number of observations</td>
<td>105</td>
<td>102</td>
<td>105</td>
<td>102</td>
</tr>
<tr>
<td>Mean chlorophyll a (ug/L)</td>
<td>14.5</td>
<td>14.5</td>
<td>14.5</td>
<td>22.7</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Median</td>
<td>14.5</td>
<td>14.5</td>
<td>14.5</td>
<td>22.7</td>
</tr>
<tr>
<td>75th Percentile</td>
<td>25.6</td>
<td>25.6</td>
<td>25.6</td>
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</tr>
<tr>
<td>Total Number of observations</td>
<td>105</td>
<td>102</td>
<td>105</td>
<td>102</td>
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</tbody>
</table>

Table 2.3—Summary of selected water quality variables for lakes and reservoirs by ecoregions in Arkansas (data from STORET).
Table 2.4—General description of ecoregions within Arkansas.

<table>
<thead>
<tr>
<th>ECOREGION</th>
<th>LAND SURFACE FORM</th>
<th>POTENTIAL NATURAL VEGETATION</th>
<th>LAND USE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ozark Highland</td>
<td>Open hills, high hills</td>
<td>Oak/hickory, woodland and forest</td>
<td>Most of cropland, pasture</td>
</tr>
<tr>
<td>Boston Mountains</td>
<td>Low mountains</td>
<td>Oak/hickory</td>
<td>Forest and woodland</td>
</tr>
<tr>
<td>Arkansas River Valley</td>
<td>Plains with hills</td>
<td>Varied forest types: oak/hickory, southern floodplain, prairie, cypress</td>
<td>Cropland, pasture, woodland, and forest</td>
</tr>
<tr>
<td>Ouachita Mountains</td>
<td>Open high hills to open low mountains</td>
<td>Oak/hickory/pine</td>
<td>Forest and woodland</td>
</tr>
<tr>
<td>South Central Plains</td>
<td>Irregular plains</td>
<td>Oak/hickory/pine</td>
<td>Woodland and forest with some cropland and pasture</td>
</tr>
<tr>
<td>Mississippi Alluvial Plain</td>
<td>Flat plains</td>
<td>Southern floodplain forest (oak, tupelo, bald cypress)</td>
<td>Cropland, cropland with grazing land; mosaics of cropland, pasture, woodland, forest, and swamp</td>
</tr>
</tbody>
</table>

Table 2.5—Comparison of STORET-derived ecoregional statistics with studies conducted within those ecoregions by Smetzer et al. (1989) and Omernik et al. (1988).

<table>
<thead>
<tr>
<th>ECOREGION</th>
<th>TOTAL PHOSPHORUS (µg/L)</th>
<th>CHLOROPHYLL a (ug/L)</th>
<th>SECCHI TRANSPARENCY (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northeastern Highland</td>
<td>10 10 7 30 20 20 24</td>
<td>2.2 2.9 3.7 4.2 4.2 4.2 4.2</td>
<td>3.7 4.1 6.2 6.3 6.3 6.3 6.3</td>
</tr>
<tr>
<td>Smetzer et al. (1989)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>North Central Hardwood</td>
<td>7 30</td>
<td>10 28</td>
<td>7 30 24 28</td>
</tr>
<tr>
<td>Forest</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Omernik et al. (1988)</td>
<td>10 20</td>
<td>20</td>
<td>10 20 24 24</td>
</tr>
<tr>
<td>Southeastern Wisconsin</td>
<td>20</td>
<td>20 24</td>
<td>20 24 24 24</td>
</tr>
<tr>
<td>7V Plain</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>STORET</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Omernik et al. (1988)</td>
<td>20 20</td>
<td>24 24</td>
<td>20 24 24 24</td>
</tr>
</tbody>
</table>

Likewise, the 25th percentile values for summer total phosphorus concentrations for Wisconsin (North Central Hardwood, Southeastern Wisconsin Till Plain) are very close to the total phosphorus initial management goal of 25th percentile for the same ecoregions based on STORET data (Table 2.5). The STORET data, however, had higher median values than the Wisconsin data for both ecoregions. Regardless of the apparent reasonableness of using the reference lakes and the ecoregional approach, there can be lakes within an ecoregion that may not be restorable to the attainable goals because of the intensity of land use, localized geological phenomena, or other reasons.

Fulmer and Cooke (1990) proposed a method to determine attainable phosphorus concentration goals for reservoirs in Ohio. The Canfield and Bachman (1981) phosphorus loading model for reservoirs was used to predict attainable in-lake phosphorus concentrations. Their loading model incorporated not only the phosphorus load to a lake but also the lake's physical and hydrological characteristics, for instance, average depth and flushing rates. The 25th percentile phosphorus concentrations, which were representative of phosphorus concentrations in least-disturbed streams within each of Ohio's five ecoregions, were incorporated into the loading model, and attainable in-lake phosphorus concentrations were predicted. If the predicted in-lake attainable phosphorus concentration was similar to the actual phosphorus concentrations in the reservoir, Fulmer and Cooke believed that a management project probably would not be effective. If the predicted in-lake attainable phosphorus concentration was less than the actual phosphorus concentration, lake restoration efforts might be effective if the phosphorus load contributed by the watershed was reduced.

As an initial starting point, we propose that the initial goals for lake projects within an ecoregion adopt the 25th percentile for total phosphorus and chlorophyll a and the 75th percentile for Secchi transparency for two reasons: (1) comparisons of ecoregion data with STORET data have indicated generally good agreement for these three trophic state indicators, and (2) information as to attainable in-lake phosphorus concentrations based on total phosphorus concentrations in least disturbed streams is not available for different ecoregions of the United States. Based on comparisons between STORET database frequency distributions and frequency distributions based on the Omernik et al. (1988) investigation, these approaches appear to be reasonable.

Effectiveness Criteria

The initial goals for in-lake management projects within an ecoregion were designated as the 25th percentile for chlorophyll a.

The initial goals for in-lake management projects within an ecoregion were designated as the 25th percentile for chlorophyll a.

The initial goals for in-lake management projects within an ecoregion were designated as the 25th percentile for chlorophyll a.

If an in-lake management technique reduces the total phosphorus and chlorophyll a concentrations from unacceptable (greater than the 50th percentile concentration) to acceptable conditions (less than or equal to the 25th per-
centile concentration), the treatment technique is considered to be effective.

- If an in-lake management technique increases Secchi transparency from unacceptable (less than the 50th percentile depth measurement) to acceptable conditions (equal to or greater than the 75th percentile depth measurement), the treatment technique is considered to be effective.
- The total phosphorus and chlorophyll a concentrations representative of the 25th percentile and Secchi transparency representative of the 75th percentile are assumed to be reasonable lake management goals. A statistically significant change from pre-treatment to post-treatment conditions also might be used to evaluate the degree of effectiveness even if these initial management goals were not achieved.

Figures 2.1 and 2.2 illustrate the concepts of effectiveness in relation to the attainable goal.

Longevity Criteria

Longevity is the duration of treatment effectiveness. In this document, longevity is defined as the period of time from when treatment is discontinued until water quality becomes unacceptable. Unacceptable water quality occurs when either the total phosphorus or chlorophyll a concentrations exceed the 50th percentile or when the Secchi depth transparency decreases to less than the 50th percentile.

To estimate longevity, examine trends in available data from lake management projects case by case to determine the rate of change in an indicator over time. By determining the rate of change, an estimate can be made of the length of time that median July and August total phosphorus and chlorophyll a concentrations remain below the 50th percentile or how long median Secchi transparency depths will remain above the 50th percentile. The rate of change in effectiveness expressed as treatment longevity is schematically presented in Figures 2.3 and 2.4. A major hindrance in determining the validity of this approach is the lack of long-term lake management data for projects in the United States; many monitoring studies end soon after treatment is completed.

There is no standard to estimate how long a treatment is expected to last. One method is to estimate treatment longevity based on anecdotal information or a few case studies. For example, Lake Trummen in Sweden was dredged to reduce internal loadings, reducing phosphorus concentrations for at least nine years (Cooke et al. 1986). Sunshine Spring, a 4-hectare lake in Wisconsin, was dredged to reduce aquatic macrophytes (Peterson, 1979). Five years after dredging, the plant biomass was still only 10 percent of what it was before the project.

Nutrient inactivation can be expected to last up to 14 years in some lakes. Garrison and Krauer (1984) reported a nutrient inactivation project in Snake Lake (Villas and Oneida Counties in Wisconsin) that was effective for nine years. Cooke et al. (1986) reported nutrient inactivation projects in Dollar and West Twin lakes (Ohio) that were still effective after six and five years, respectively. Drawdown can effectively control aquatic macrophytes, in Bussy Reservoir (northeast Louisiana), drawdown reduced them for two years (Cooke et al. 1986).

Although these examples give an idea of how long a selected treatment might last in a single lake, they do not provide quantitative insight for assessing how long a treatment can maintain concentrations within desired water quality ranges as designated by the 50th percentile for total phosphorus, chlorophyll a, and Secchi transparency.

Figure 2.1—Conceptual model for evaluating treatment effectiveness of total phosphorus or chlorophyll a reduction in a lake relative to the areacorrected distribution of values. The 25th percentile represents initial management goals.
Figure 2.2—Conceptual model for evaluating treatment effectiveness on changes in Secchi transparency in a lake relative to the ecoregional distribution of values. The 75th percentile represents initial management goals.

Figure 2.3—Conceptual model for evaluating longevity of treatment effectiveness of total phosphorus or chlorophyll a reduction relative to the ecoregional distribution of values. Treatment longevity is the period immediately following treatment until the median value exceeds the 50th percentile.
Chapter 2 discussed the use of ecoregions, initial management goals, and protocols to evaluate the effectiveness and longevity of in-lake rehabilitation projects. In Chapter 3, these concepts are applied to selected in-lake management projects that used dredging, nutrient inactivation, or drawdown. Figure 3.1 shows the seven ecoregions selected from available data by the study to evaluate lake management projects.

Background

The morphometric characteristics of the lakes varied widely (Table 3.1). Surface areas ranged in size from 2 (Dollar Lake) to 575 hectares (Annabessacook Lake), while watershed areas ranged from 13 (Mirror Lake) to 16,600 hectares (Eau Galle Reservoir). Pre-treatment mean depths ran from 1.8 (Erie Lake) to 10 meters (Medical Lake) and maximum depths...
Table 3.1—Morphometric data of lakes included in the effectiveness and longevity study.

<table>
<thead>
<tr>
<th>Ecoregion/Lake</th>
<th>Surface Area (ha)</th>
<th>Watershed Area (ha)</th>
<th>Mean Depth (m)</th>
<th>Max Depth (m)</th>
<th>Residence Time (yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Puget Lowland</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Campbell Lake</td>
<td>150</td>
<td>1,471</td>
<td>2.4</td>
<td>6.0</td>
<td>0.5</td>
</tr>
<tr>
<td>Erle Lake</td>
<td>45</td>
<td>420</td>
<td>1.8</td>
<td>3.7</td>
<td>0.6</td>
</tr>
<tr>
<td>Long Lake 1</td>
<td>137</td>
<td>2,430</td>
<td>2.0</td>
<td>3.8</td>
<td>0.3</td>
</tr>
<tr>
<td>Long Lake 2</td>
<td>130</td>
<td>2,137</td>
<td>3.8</td>
<td>6.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Pattison Lake</td>
<td>110</td>
<td>751</td>
<td>4</td>
<td>6.7</td>
<td>0.4</td>
</tr>
<tr>
<td>Columbia Basin</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liberty Lake</td>
<td>288</td>
<td>3,446</td>
<td>6</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>Medical Lake</td>
<td>64</td>
<td>closed basin</td>
<td>10</td>
<td>18</td>
<td>---</td>
</tr>
<tr>
<td>Southeastern Wisconsin</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Till Plains</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horsehoe Lake</td>
<td>9</td>
<td>700</td>
<td>4</td>
<td>16.7</td>
<td>0.7</td>
</tr>
<tr>
<td>Lilly Lake</td>
<td>37</td>
<td>105</td>
<td>1.4</td>
<td>1.8</td>
<td>1.4</td>
</tr>
<tr>
<td>North Central Hardwood Forests</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eau Galle Reservoir</td>
<td>60</td>
<td>16,600</td>
<td>3.2</td>
<td>9</td>
<td>0.07</td>
</tr>
<tr>
<td>Mirror Lake</td>
<td>5</td>
<td>13</td>
<td>7.8</td>
<td>13.1</td>
<td>4</td>
</tr>
<tr>
<td>Shadow Lake</td>
<td>17</td>
<td>27</td>
<td>3.3</td>
<td>11.6</td>
<td>---</td>
</tr>
<tr>
<td>Northeastern Highlands</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kean Lake</td>
<td>74</td>
<td>2,771</td>
<td>2.7</td>
<td>8.2</td>
<td>0.1</td>
</tr>
<tr>
<td>Money Lake</td>
<td>220</td>
<td>1,900</td>
<td>8.4</td>
<td>13</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Table 3.2—Ecoregions with management projects on lakes to be evaluated.

<table>
<thead>
<tr>
<th>Ecoregion</th>
<th>Land Surface Form</th>
<th>Potential Natural vegetation</th>
<th>Land Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Puget Lowland</td>
<td></td>
<td></td>
<td>Field crop, deciduous forest, natural grasslands</td>
</tr>
<tr>
<td>Columbia Basin</td>
<td></td>
<td></td>
<td>Field crop, deciduous forest, natural grasslands</td>
</tr>
<tr>
<td>Northeastern Highlands</td>
<td></td>
<td></td>
<td>Field crop, deciduous forest, natural grasslands</td>
</tr>
<tr>
<td>Northeastern Coastal Zone</td>
<td></td>
<td></td>
<td>Field crop, deciduous forest, natural grasslands</td>
</tr>
</tbody>
</table>

Table 3.3—Phosphorus, chlorophyll a, and Secchi transparency data for the Puget Lowland and the Northeastern Highlands.

from 3.7 (Erie Lake) to 18.0 meters (Medical Lake). In addition, morphometric parameters varied widely not only between but also within ecoregions.

Table 3.2 describes the general characteristics—land surface form, vegetation, land use, and soils—of the seven ecoregions. Descriptive statistics for each ecoregion (Table 3.3) were computed for total phosphorus, chlorophyll a, and Secchi transparency using STORET data. Differences in water quality variables among ecoregions were consistent with those in physiography and land use.

Based on the median values for total phosphorus, chlorophyll a, and Secchi transparency, for example, the Puget Lowland and the Northeastern Highlands ecoregions had similar forested land use, relatively low concentrations of phosphorus and chlorophyll a, and reasonably good transparency. In the intermediate range, the Columbia Basin, the Northeastern Coastal Zone, and the Erie/Ontario Lake Plain ecoregions with pasture, woodlands, and croplands had higher median total phosphorus and chlorophyll a concentrations and lower Secchi transparency depth measurements than the Puget Lowland and Northeastern Highlands ecoregions. The highest median total phosphorus and chlorophyll a concentrations and the lowest median Secchi transparency depths occurred in the North Central Hardwood Forests and the Southeastern Wisconsin Till Plains, where cropland is a dominant land use.
Median values were used for comparisons among ecoregions because mean values are influenced by extremely high values in the tails of the distributions. For example, in the Northeastern Highlands ecoregion, the mean total phosphorus concentration is 24µg/L. This mean value is influenced by the extremely high concentration of a single sample of 6,800µg/L. The median value (10µg/L), on the other hand, is not as sensitive to occasional extreme measures.

As discussed in Chapter 2, the initial restoration goals within an ecoregion for total phosphorus and chlorophyll a were defined as the 25th percentile concentration and the initial management goal for Secchi transparency as the 75th percentile. These estimated goals are summarized in Table 3.4, and the median concentrations for total phosphorus and chlorophyll a and median depth for Secchi transparency are included for reference. Chlorophyll a and total phosphorus concentrations greater than the median, or Secchi values less than the median, have been arbitrarily defined as unacceptable for supporting many desired lake uses.

**Treatment Effectiveness**

To evaluate treatment effectiveness on a comparative basis, median concentrations for total phosphorus and chlorophyll a concentrations and median depth for Secchi transparency were computed based on up to a maximum of three years of pre-treatment and three years of post-treatment data for each of the lake management projects. These median values were compared with the 25th and 50th percentile values for the appropriate ecoregion to determine which projects were above the ecoregional median value before treatment and which achieved the 25th percentile initial management goal following treatment (Table 3.5). In addition, the constituent change from pre- to post-treatment conditions was determined for each lake.

The changes in water quality constituents for each of the lakes in the ecoregion are shown in Figures 3.2 through 3.8. The Mann-Whitney U statistic (a nonparametric analog of the two-sample students t-test; Zar, 1974) was computed to determine if the expected improvements in constituent values were statistically significant even if the change did not meet the initial management goal established for the ecoregion (Table 3.5).

Nutrient inactivation was generally used in combination with other techniques (Table 2.1). About one-quarter of the lakes (4 out of 17) achieved at least one of the initial management goals selected for this study (25th percentile for total phosphorus or chlorophyll a, 75th percentile for Secchi transparency) following treatment; but there were no lakes in which all three management goals were achieved (Table 3.5). Initial goals for total phosphorus were achieved in three lakes, while goals for chlorophyll a were not achieved in any of the lakes and the initial goal for Secchi transparency was achieved in one. However, no consistent pattern emerged, either by treatment or ecoregion, as to which constituent achieved the targeted goal.

A statistically significant change (p < 0.1) took place in at least one constituent following treatment in about three-fourths of the lakes (12 of 17, Table 3.5), and a reduction in total phosphorus in all lakes that was statistically significant in about half (11 of 17 lakes). In general,
### Table 3.4—Attainable goals and medians for select ecoregions.

<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th>PUGET LOWLAND</th>
<th>COLUMBIA BASIN</th>
<th>SOUTHWESTERN WISCONSIN PLAINS</th>
<th>NORTH CENTRAL HARDWOOD FORESTS</th>
<th>NORTHEASTERN HIGHLANDS</th>
<th>NORTHEASTERN COASTAL ZONE</th>
<th>ERIE/ONTARIO LAKE PLAIN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total phosphorus (µg/L)</td>
<td>25th percentile</td>
<td>12.0</td>
<td>20.0</td>
<td>30.0</td>
<td>10.0</td>
<td>10.3</td>
<td>12.1</td>
</tr>
<tr>
<td>Median</td>
<td>13.0</td>
<td>20.0</td>
<td>60.0</td>
<td>60.0</td>
<td>10</td>
<td>20.0</td>
<td>18.0</td>
</tr>
<tr>
<td>Chlorophyll a (µg/L)</td>
<td>25th percentile</td>
<td>4.7</td>
<td>7.9</td>
<td>7.4</td>
<td>0.2</td>
<td>33.8</td>
<td>2.0</td>
</tr>
<tr>
<td>Median</td>
<td>12.0</td>
<td>9.0</td>
<td>36.0</td>
<td>19.0</td>
<td>1.0</td>
<td>47.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Secchi transparency (m)</td>
<td>75th percentile</td>
<td>4.7</td>
<td>5.2</td>
<td>1.8</td>
<td>2.4</td>
<td>6.2</td>
<td>2.2</td>
</tr>
<tr>
<td>Median</td>
<td>3.8</td>
<td>5.0</td>
<td>1.1</td>
<td>1.5</td>
<td>4.1</td>
<td>0.9</td>
<td>3.0</td>
</tr>
</tbody>
</table>

### Table 3.5—Change (A) between three-year median lake condition indicators prior to (PRE) and after (POST) In-lake treatment. Statistical significance of the change (Mann Whitney U, P < 0.1) is designated by an asterisk. The 25th and 50th percentile values for Secchi transparency for each ecoregion are provided to compare treatment results to initial treatment goals.

<table>
<thead>
<tr>
<th>Ecoregion</th>
<th>PRE</th>
<th>POST</th>
<th>△</th>
<th>25%</th>
<th>50%</th>
<th>PRE</th>
<th>POST</th>
<th>△</th>
<th>25%</th>
<th>50%</th>
<th>PRE</th>
<th>POST</th>
<th>△</th>
<th>75%</th>
<th>50%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Puget Lowland</td>
<td>Campbell</td>
<td>45.5</td>
<td>21.5</td>
<td>24.0*</td>
<td>9.0</td>
<td>9.0</td>
<td>12.0</td>
<td>12.4</td>
<td>1.4</td>
<td>1.3</td>
<td>1.6</td>
<td>0.3</td>
<td>4.7</td>
<td>3.8</td>
<td></td>
</tr>
<tr>
<td>Elbe</td>
<td>120</td>
<td>30.5</td>
<td>89.5*</td>
<td>63</td>
<td>7.2</td>
<td>8.3</td>
<td>1.6</td>
<td>1.3</td>
<td>1.6</td>
<td>0.3</td>
<td>4.7</td>
<td>3.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Long Lake 1</td>
<td>24.5</td>
<td>35.2</td>
<td>39.3*</td>
<td>19</td>
<td>16.9</td>
<td>2.1</td>
<td>2.4</td>
<td>2.5</td>
<td>0.2*</td>
<td>1.8</td>
<td>2.3</td>
<td>0.5*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Long Lake 2</td>
<td>24.5</td>
<td>13.0</td>
<td>11.5*</td>
<td>5.7</td>
<td>1.6</td>
<td>4.1*</td>
<td>2.4</td>
<td>2.4</td>
<td>1.9*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pattison</td>
<td>21.5</td>
<td>24.5</td>
<td>3.0</td>
<td>5.3</td>
<td>3.1</td>
<td>2.2</td>
<td>4.0</td>
<td>3.1</td>
<td>0.9</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Columbia Basin</td>
<td>Liberty</td>
<td>24.0</td>
<td>18.0</td>
<td>6.0</td>
<td>7.4</td>
<td>9.5</td>
<td>-2.1</td>
<td>3.3</td>
<td>3.4</td>
<td>0.1</td>
<td>5.2</td>
<td>3.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medford</td>
<td>134</td>
<td>33.0</td>
<td>101.0*</td>
<td>30</td>
<td>3.0</td>
<td>0</td>
<td>6.6</td>
<td>2.2</td>
<td>-4.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Southeastern Wisconsin Till Plains</td>
<td>Honshuh</td>
<td>130</td>
<td>50</td>
<td>80</td>
<td>7.9</td>
<td>36.0</td>
<td>1.8</td>
<td>3.0</td>
<td>1.2</td>
<td>1.8</td>
<td>1.1</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>North Central Hardwood Forests</td>
<td>Eau Galle</td>
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<td>60.5</td>
<td>26.0</td>
<td>65.9</td>
<td>62.8</td>
<td>3.1</td>
<td>3.3</td>
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<tr>
<td>Mirror</td>
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<td>10.8*</td>
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<td>3.7</td>
<td>0.7*</td>
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<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Shadow</td>
<td>56.5</td>
<td>22.3</td>
<td>34.0*</td>
<td>14.1</td>
<td>6.0</td>
<td>8.1*</td>
<td>1.8</td>
<td>3.3</td>
<td>1.5*</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Northeastern Highlands</td>
<td>Kesar</td>
<td>16.5</td>
<td>13.5</td>
<td>3.0</td>
<td>13.7</td>
<td>2.9</td>
<td>10.8*</td>
<td>3.3</td>
<td>6.5</td>
<td>3.2*</td>
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<tr>
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<td>43.0*</td>
<td>14.1</td>
<td>6.0</td>
<td>8.1*</td>
<td>1.8</td>
<td>3.3</td>
<td>1.5*</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Northeastern Coastal Zone</td>
<td>Alvenessé</td>
<td>62.3</td>
<td>30.6</td>
<td>21.7*</td>
<td>19.5</td>
<td>12.2</td>
<td>7.3*</td>
<td>2.2</td>
<td>2.8</td>
<td>0.6</td>
<td></td>
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<td>Cochenwagon</td>
<td>16.8</td>
<td>7.0</td>
<td>7.8*</td>
<td>6.1</td>
<td>1.9</td>
<td>4.2*</td>
<td>5.7</td>
<td>8.2</td>
<td>2.5*</td>
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<tr>
<td>Erie/Ontario Lake Plain</td>
<td>Dollar</td>
<td>206.9</td>
<td>37.4</td>
<td>169.5</td>
<td>40.6</td>
<td>9.2</td>
<td>31.4</td>
<td>0.7</td>
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<tr>
<td>West Twin</td>
<td>48.7</td>
<td>17.7</td>
<td>31.0*</td>
<td>22.4</td>
<td>7.4</td>
<td>15.0*</td>
<td>2.2</td>
<td>2.4</td>
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<tr>
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<td>25.0</td>
<td>35.8</td>
<td>24.6</td>
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<td>0.3*</td>
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* Mann-Whitney U statistic significant at p < 0.1
chlorophyll a decreases and transparency increases were associated with phosphorus decreases. Seven lakes had significant decreases in chlorophyll a concentrations and seven lakes had significant increases in Secchi transparency. About a quarter of the lakes had concomitant statistically significant changes in total phosphorus and chlorophyll a (سب) or total phosphorus and Secchi transparency (five).

There was a statistically significant change in total phosphorus, chlorophyll a, and Secchi transparency after treatment in three lakes. However, some lakes where there was a significant change in constituent concentrations initially had concentrations below the 25th percentile management goals. Northeastern Coastal Zone lakes, for example, all had chlorophyll a concentrations below the 25th percentile goal before treatment. Some, such as Sebastiscok Lake, had higher chlorophyll a concentrations after treatment than before. Post-treatment total phosphorus values in each lake typically converged toward values less than about 35 µg/L regardless of treatment or ecoregion (Figs. 3.2 through 3.4). Similar changes in chlorophyll a or Secchi transparency, however, were not apparent.

No consistent pattern emerged between improved lake trophic status and the level of treatment in the lake and watershed.
lakes, for example, had significant decreases in total phosphorus associated with nutrient inactivation and watershed diversions of stormwater, while Eric and Morey lakes had equally significant reductions in total phosphorus following nutrient inactivation only, with no changes in watershed management practices. Unfortunately, it was not possible to partition the effectiveness of combined in-lake and watershed management practices into the relative contributions from in-lake versus watershed practices with the existing data. In general, watershed management practices used in conjunction with in-lake management techniques should improve both the effectiveness and the longevity of lake rehabilitation.

Evaluating treatment effectiveness and detecting differences between pre- and post-treatment conditions are significantly influenced by sampling variability (measurement, seasonal, and inter-annual and in-lake spatial variability). Summer lake survey measurements of total phosphorus and chlorophyll a in 188 lakes and reservoirs were analyzed by Knowlton et al. (1984) to determine the variability in these trophic state estimators. These scientists found that the median seasonal variability in total phosphorus and chlorophyll a was about 27 and 45 percent of the mean, respectively. The median inter-annual or year-to-year variability in total phosphorus and chlorophyll a was about 22 and 31 percent of the mean, respectively.
In a comparison of long-term trends in trophic state among 15 Indiana lakes, Spacie and Loeb (1990) found that changes smaller than about 35 percent in total phosphorus, chlorophyll a, or Secchi transparency were masked by natural lake variability. Of these three variables, Secchi transparency had the lowest natural variability. Spacie and Loeb (1990) also determined that inter-annual variance estimates for total phosphorus and chlorophyll a in individual lakes ranged over two orders of magnitude, which decreased their ability to detect statistically significant trends or differences among years in these two variables. As a result, small changes in lake trophic state that would be expected through lake management might not be apparent. This, however, does not mean these management practices are ineffective but rather that long-term monitoring data sets are necessary to evaluate the effectiveness of management practices (Spacie and Loeb, 1990). These variance estimates also are consistent with ones from a study on Vermont lakes by Smeltzer et al. (1989) who found that about five years of before and after data were needed to detect a 40 percent change at the 95 percent confidence level. Moreover, in a recent evaluation of lake management experiences in western Europe, Sas (1990) also found that about five years of pre- and post-treatment data were required to detect a significant change in trophic state following lake treatment. However, out of 21 lakes, nutrient inactivation, either individually or in
post-treatment conditions is required. Spacie and Loch (1990), Sas (1990), and Smeltzer et al. (1989) indicate that at least five years of before and after data are needed to detect differences and about 10 years of monitoring data to detect trends.

About half of the lakes in this study (13 of 21) had less than five years of post-treatment data and only three had a sufficient period of record of both pre- and post-treatment monitoring to evaluate treatment longevity. These three lakes, Long Lake 1, Medical Lake, and Annabessacook Lake, will be discussed individually to describe the process that might be used to evaluate treatment longevity. A statistically significant decrease in total phosphorus occurred after treatment in all three lakes.

**Long Lake 1**

Long Lake 1, in the Puget Lowland ecoregion, was treated by drawdown and nutrient inactivation. Mean total phosphorus concentrations increased during the three years prior to lake management (Fig. 3.9). During drawdown (June to October), total phosphorus concentrations increased but then substantially decreased afterward and again following nutrient inactivation in September 1980. It appears there has been a slowly increasing trend in total phosphorus since about 1987, and seasonal variability in phosphorus concentrations also seems to be increasing through time.

**Treatment Longevity**

For this study, longevity is defined as the length of time a treatment maintains concentrations of phosphorus and chlorophyll a, and/or Secchi disk transparency. Combination with other techniques did result in statistically significant changes in total phosphorus (12 lakes), chlorophyll a (8), and Secchi disk transparency (8).

**Figure 3.8**—Comparison of changes in total phosphorus, chlorophyll a, and Secchi disk transparency before and after lake treatment for lakes in the Erie/Ontario Lake Plain ecoregion. The initial management goals (25th, 75th percentiles) are shown by the solid line, while the dashed line represents the 50th percentile.

**Figure 3.9**—Changes in Long Lake 1 (Kitsap Co.) total phosphorus concentrations for three years before and for nine years following treatment.

Chlorophyll a concentrations were not significantly different before and after lake treatment (Fig. 3.10) and, with the exception of the response following a significant storm and extensive and unexplained macrophyte dieoff (Welch and Kelly, 1990) in 1985, there was no apparent trend in chlorophyll a concentration over time. Secchi transparency level was significantly deeper after treatment and exhibited a gradual trend toward increased transparency until 1984 (Fig. 3.11). After 1985, transparency appears to be relatively constant from year to year.
which may explain why chlorophyll concentrations did not decrease following phosphorus reductions. Annual median chlorophyll μ concentrations remained relatively constant following treatment, but the seasonal variance in chlorophyll appeared to increase through time. Secchi transparency exhibited a decreasing trend after the first year, with increasing variability in succeeding years. This gradual increase in seasonal variability following lake treatment also occurred in total phosphorus concentrations. In general, however, median total phosphorus remained similar to that of the year immediately following treatment.

**Medical Lake**

Medical Lake is located in the Columbia Basin ecoregion. Lake management included installation of a sewer system in the watershed and nutrient inactivation (alum treatment) in the lake. Rainbow trout were stocked subsequent to treatment. Total phosphorus decreased significantly after treatment, but changes in chlorophyll a concentrations and Secchi transparency were not statistically meaningful (Figs. 3.12 through 3.14). Mires et al. (1981) indicated that predation of Daphnia by rainbow trout might have decreased grazing pressure on phytoplankton.
Figure 3.15—Changes in Annabessacook Lake total phosphorus concentrations for the 3 years before and the 10 years following lake treatment.

Figure 3.16—Changes in Annabessacook Lake chlorophyll a concentrations for the 3 years before and the 10 years following lake treatment.

Figure 3.17—Changes in Annabessacook Lake Secchi disk transparency for the 3 years before and the 10 years following lake treatment.

Annabessacook Lake is located in the Northeastern Coastal Zone ecoregion. Watershed management practices included diversion of point source discharges away from the lake as well as construction and management of manure storage facilities. In-lake treatment practices included nutrient inactivation. Total phosphorus and chlorophyll a concentrations decreased significantly, but Secchi transparency did not change noticeably following lake treatment (Figs. 3.15 through 3.17). Total phosphorus, chlorophyll a concentrations, and variability from year to year remained relatively constant through time following treatment, but Secchi transparency varied significantly seasonally and annually (Fig. 3.16).

In western Europe, an evaluation of reductions in external nutrient loadings identified two phases in lake management: an initial transient phase and a subsequent phase when the lake reached a new trophic state. The transient phase ranged from one season up to about five years because of net annual phosphorus release from the sediments (Sas, 1990). This net sediment phosphorus release, in general, did not occur before lake treatment was initiated because the sediment and overlying water column phosphorus concentrations were in dynamic equilibrium. In shallow lakes (those that did not thermally stratify), it appeared that if the phosphorus content of the upper 15 centimeters of sediment exceeded 1 mg P/g dry weight sediment, the net annual sediment phos-
Phosphorus release might be expected for up to five years following nutrient load reduction to the lake (Sas, 1990). Seasonal release of phosphorus occurred from the sediments in all western European lakes after treatment, regardless of their depth.

In the lakes evaluated as part of the current study, those with nutrient inactivation showed an immediate decrease in total phosphorus. Internal loading or release of sediment phosphorus following reduction of external nutrient loading was not apparent in lakes receiving nutrient inactivation. The most common in-lake treatment in the current study, nutrient inactivation, would be expected to reduce significantly net annual sediment phosphorus release during the transient period following lake or watershed treatment. Inactivation is the likely cause of the rapid decrease in phosphorus observed in all lakes following the use of this lake treatment technique.

Corresponding decreases in chlorophyll along with decreased phosphorus concentrations were observed in western European lakes only when the soluble reactive phosphorus (SRP) concentration in the mixed layer (trophogenic zone) decreased below an average of 10 µg P/L over the growing season. For deeper lakes that stratified, decreases in chlorophyll were associated with increased transparency (Sas, 1990). In shallow lakes, however, decreased chlorophyll concentrations did not always result in increased transparency. For some lakes, transparency decreased because of higher background extinction caused by decay of previously accumulated organic matter (Sas, 1990).

SRP concentrations were not measured for all the lakes in the current study, but median chlorophyll a concentrations decreased in 15 of 21, and this change was statistically significant in 8 of 21 lakes. Secchi transparency also increased in 16 of 21 lakes; this increase was statistically significant in 8 lakes. Although total phosphorus, chlorophyll a, and transparency were increasingly available over time, the longevity of nutrient inactivation combined with drawdown (Long Lake 1), collection and biomanipulation (Medical Lake), and point source discharge diversion and manure storage (Annabessacook Lake) was apparently effective for at least 10 years.

**CHAPTER 4**

**Discussion**

**Management Goals**

Many lake management projects do not establish goals, performance standards, or data quality objectives before lake treatment. In some instances, desired lake uses might be specified, but they are generally not related to measurable endpoints. The establishment of management goals and objectives must be based on realistically attainable lake uses and measurable lake conditions. The use of ecoregions and the population distribution of lake attributes proposed in this report represent one initial approach for establishing management goals and setting measurable lake condition endpoints.

Omernik (1987) developed a map of the ecoregions in the conterminous United States to assist those managing aquatic resources to understand their regional patterns. In January 1991, EPA's Science Advisory Board endorsed this and subsequent ecoregion-based efforts that had been reviewed as scientifically sound approaches to water quality management. The 25th and 50th percentile values for total phosphorus and chlorophyll a and the 50th and 75th percentile values for Secchi transparency were selected as initial trophic state indicator goals by using available information from STORET. Some lakes might not achieve desired uses even at the 25th percentile because

- user expectations are unrealistic for conditions that can be reasonably achieved in the lake,
- user conflicts will prevent some uses from being achieved even if the lake condition is good relative to other regional lakes, or
- the 25th percentile based on population statistics is not representative of the region.

Comparisons of descriptive population statistics between STORET-derived and independently derived data within selected ecoregions indicated, however, that the statistical attributes were similar. This approach is intended to provide a point of initiation—not termination—in selecting initial management goals. These goals were achieved in approximately one-third of the lakes and appear to be reasonable as an initial starting point.
However, as lake management improves conditions, regional lake trophic state distributions will change and the 25th and 50th percentile values will decrease, which will require reevaluation of initial target goals. While it is unlikely in the near future that regional lake conditions will reach these conditions within an ecoregion, improved lake conditions gradually will shift the distribution of lake trophic state toward the desired goal. Therefore, these regional statistical population distributions should be associated with lake user perceptions of desired water quality and various lake problems. Heiskary and Walker (1988) describe a method for associating phosphorus, chlorophyll, and transparency values with subjective user classification of lake quality or nuisance conditions. Associating similar user perceptions with phosphorus, chlorophyll, and transparency values ecoregionally can provide one approach for establishing management goals and objectives.

The ecoregional concept can assist by providing a perspective on what is realistically attainable within the area. For example, total phosphorus and chlorophyll concentrations were typically higher in lakes in the Southeastern Wisconsin Till Plains than in the Puget Lowland ecoregions (Table 3.3). Desired uses for southeastern Wisconsin lakes based on criteria for Puget Lowland lakes, therefore, would be realistically unattainable.

The ecoregional concept is robust and suited to a number of different approaches for assessing realistically attainable goals and endpoints. For example, another approach—the use of reference systems within an ecoregion—has been used to establish attainable water quality conditions; it has also been used to establish stream water quality standards and criteria for ecoregions in Arkansas (Rohm et al. 1987), Ohio (Larsen et al. 1988), and Oregon (Hughes et al. 1987).

Fulmer and Cooke (1990) presented a method for screening candidate lakes for lake management, using the reference stream concept. They computed nutrient loads from these least disturbed or reference streams within an ecoregion and, using nutrient loading models, computed trophic state conditions for selected reservoirs in Ohio’s different ecoregions. The predicted lake conditions based on least disturbed stream loadings (25th percentile total phosphorus concentrations) were then compared with actual lake conditions in candidate lakes. Those lakes with actual summer phosphorus concentrations that exceeded predicted attainable concentrations by the greatest amounts were considered to have the greatest potential for rehabilitation and management.

Lakes with the greatest restoration potential were not always those that had the worst measured trophic state. This method could be applied to provide a rational approach for setting priorities for selecting lakes for rehabilitation and for developing lake improvement and management goals. Hughes et al. (1986) have provided guidance on selecting regional reference sites for streams. A similar concept should be formulated and tested for selecting regional reference lakes.

Treatment Effectiveness and Longevity

Nutrient inactivation was the primary lake treatment technique used in about 75 percent of the lakes included in this study. Nutrient inactivation was used not only in conjunction with other lake treatment techniques but also with watershed management practices. Any technique that reduces the limiting nutrient in the system offers the potential for improving lake trophic condition and, subsequently, achieving desired lake uses.

Dredging and nutrient inactivation are the two primary long-term, in-lake treatment techniques that are used to reduce phosphorus. Dredging removes the phosphorus rich sediments from the lake while nutrient inactivation reduces the availability of phosphorus to planktonic producers. The western European experiences (Sus, 1990) provide an indication of a critical phosphorus sediment concentration that can be evaluated as part of diagnostic and feasibility studies before lake treatment to determine either the depth of dredging to achieve phosphorus concentrations below this criteria value or alum or other chemical treatment levels required to maintain sediment phosphorus releases below these levels. The release of phosphorus from sediments after implementation of external nutrient load reductions further emphasizes the necessity of long-term monitoring information to evaluate treatment effectiveness and longevity.

Watershed best management practices are effective both in theory and in practice, but the lag time associated with the lake response must be considered when evaluating effectiveness. Nutrient inactivation, used in conjunction with external source controls and other in-lake treatment techniques, can reduce or eliminate this lag time and, therefore, might be recommended as a general treatment technique for evaluation with most lake management projects that have nutrient problems. However, alum treatments can have serious, non-ecological, negative effects if not properly implemented, and they are not appropriate for all lakes (Cooke, 1990).

During our assessment of treatment longevity and effectiveness, we uncovered two interesting issues relating to variability that should be addressed in future research efforts.

1. Increased variability in phosphorus, chlorophyll a, and Secchi transparency over time might prove to be an indicator of decreasing treatment effectiveness. Because of intrinsic seasonal and interannual variability, detecting statistically significant changes in mean or median constituent concentrations can require a relatively long period of time. However, increased variance per se in these constituents might provide a better indicator or early warning of decreasing treatment effectiveness and longevity and, therefore, diminished lake uses. For most managed systems, it is both environmentally and economically cost effective if treatment can be applied before lake uses become severely impacted.

2. The second issue is the use of an index period or specific limnological seasons to compare trophic state indicators among years. Several authors (Knowlton et al. 1984; Spacie and Loeb, 1990; and Smeltzer et al. 1986) stated that at least five years of before and after data were required to detect changes because of natural lake variability. These scientists, however, averaged data over the entire growing season.

In this study, we focused on the data during a July and August index period and were able to detect significant changes with three years of before and after data. Constituent concentrations during a specific index
period of strong stratification, late summer period, or fall overturn might be expected to be less variable than conditions averaged over the entire growing season. The use of specific hydrologic periods, rather than the entire annual hydrologic cycle, is relatively common in hydrologic studies to detect changes or trends in discharge (Hirsch and Slack, 1984; Hirsch et al. 1991). The index period concept should be evaluated and tested for making comparisons among different lake attributes or treatments.

Three problems associated with evaluating in-lake treatment effectiveness and longevity also were identified in this study. The first was the confounding of in-lake and watershed management practices. Relatively few lakes have applied only one treatment technique, and, in general, multiple in-lake and watershed management techniques have been applied during lake management and restoration. While it is possible to use a factorial design to evaluate these different combinations, the sample size and number of missing cells in this a posteriori study did not permit an evaluation of either the main treatment effects or interactions among treatment techniques. It was fortuitous that nutrient inactivation was a common technique applied among the evaluated lakes.

The second problem is the lack of long-term monitoring data. Not surprisingly, most of the effort in lake management is associated with the actual lake treatment, with limited collection of pre-treatment and post-treatment data. Most of the funds associated with EPA Phase II Clean Lakes projects are expended during the treatment phase. Only one year of post-treatment monitoring is required. Most rehabilitation projects screened during the initiation of this study had little or no pre- and post-treatment monitoring information; therefore, those lakes were not considered. Monitoring Lake and Reservoir Restoration, the technical supplement to the Lake and Reservoir Restoration Guidance Manual, is useful for designing pre- and post-treatment monitoring programs as it is information on citizens monitoring programs (Wedepohl et al. 1990). There is no substitute for monitoring data in evaluating either treatment effectiveness or longevity.

The third problem encountered in this study was the availability of monitoring or lake treatment data and records. In most instances, the data have not been entered in STORET or other data management systems and are not readily available. Information might be stored in record files but requires significant time and effort to retrieve, copy, and distribute. Although there are many legitimate reasons why these data are not entered, this oversight severely restricts availability and analyses of data.

While the Clean Lakes reports provide summaries of the information, actual data are required for many additional and ancillary analyses. The States should be required to ensure that data from Clean Lakes studies are entered into STORET.

Lake Management—Scientific Testing and Evaluation

Establishing lake management goals, performance standards, and evaluation criteria also will assist in moving lake management from a technology-based to a scientifically-based discipline. Many lake management projects are and have been technology driven to improve lake

trophic state; that is, demonstrating a feasible technique rather than formulating hypotheses, testing, and determining why a particular treatment technique or practice works. Greater scientific rigor is needed when formulating specific treatment performance standards, hypotheses, data quality objectives, and evaluation criteria and then rigorously testing these hypotheses to evaluate treatment longevity and effectiveness.

This situation is not unique to lake management, however. Watershed best management practices have been known and implemented since the 1930s and yet their quantitative effectiveness in improving water quality is unknown. We have a significant opportunity to improve lake management in the future if we begin now to think of it as a scientific and not just a technological discipline.

We have a significant opportunity to improve lake management in the future if we begin now to think of it as a scientific and not just a technological discipline.
As a result of this study, the workgroup came to the following conclusions:

- Nutrient inactivation can produce statistically significant changes within total phosphorus concentrations in lakes and might be considered as a general treatment technique to accompany watershed management practices and other treatment techniques. Alum treatment, however, can have significant negative effects in some lakes. Nutrient inactivation can reduce the transient period following reduction of external nutrient loads and result in more rapid improvement in lake conditions through decreased chlorophyll concentrations and increased Secchi transparency. Long-term effectiveness, however, can be obtained only with reductions in external nutrient loads.

- Preliminary evaluations indicate that nutrient inactivation for selected lakes, when used in conjunction with a significant reduction in external nutrient loads, can be effective for 10 years or more (longer term records are unavailable).

- At least three to five years of pre-treatment and post-treatment monitoring data should be required for lake management projects. It is not possible to evaluate treatment longevity or effectiveness without monitoring information.

- All data collected as part of the EPA Clean Lakes projects should be entered into the EPA data management system, STORET. A rigorous quality assurance program is necessary to ensure data integrity from its submission to STORET to its transfer to users.

- More scientific rigor should be directed toward understanding lake processes relative to lake management; we must move from a technology-based approach to one that is science-based.
References


Additional References


Sources of Information

The information reviewed in the course of preparing this document was provided through many cooperative efforts. Contributors to this project included:

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