# Development of a Guide to Lake and Reservoir Zone Determination

by

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# Development of a Guide to Lake and Reservoir Zone Determination

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(Abstract)

Reservoirs are generally created by damming rivers. The upper reaches of any reservoir is generally narrow and winding like the parent river. This is the riverine zone of the reservoir. The reservoir is deepest and widest near the dam. Here, lake-like conditions exist and the water is quiescent. This is the lacustrine zone. The transitional zone separates the lacustrine and riverine zone. It has intermediate characteristics.

There are many characteristics, both physical and chemical, that differentiate between these three zones. Based on the differences in characteristics between the three zones, a method has been developed to successfully divide any reservoir into three zones. The method developed was applied to Lake Manassas and the Occoquan Reservoir located in the Occoquan watershed in Virginia. Both are man-made impoundments.

Analysis of data, based on the method developed, was successfully in dividing both reservoirs into the three zones. This method may therefore be successfully applied to obtain zonation in reservoirs.

**Dedicated to my family**

# Acknowledgements

This journey began with an offer for assistantship from my advisor, Dr. Adil N. Godrej, for which I'm eternally grateful. Every step of the way, his guidance and valuable input have been key to successful completion of this thesis. I would like to express my gratitude to him in a very special way, for his time and advice, on numerous occasions.

I would next like to thank Dr. Thomas J. Grizzard and Mr. Harold Post for being a part of my committee. Their valuable input, encouragement and guidance have helped me tremendously, in successful development of this thesis. I've to thank Dr. Grizzard in a special way for always being there, with valuable advice. I would also like to thank Mr. Post for providing me help with the data, whenever I asked for it. Many thanks, also, to the members of the Occoquan Watershed Monitoring Laboratory, where all of the high-quality data, used in the analyses done for this thesis was collected and tested and also for making the two years I worked there so pleasant. A big thank you to my friend, Yingmei Liu for all the help.

A special note of thanks to Virginia Department of Environmental Quality for providing me with the opportunity to work on the Occoquan TMDL project. This thesis is a direct result of that work. It was a pleasure doing the project and a unique learning experience.

My family has a big role to play in what I am today. I am eternally grateful to my parents V. J. C. Peter and Leela C. Peter who taught me early on the value of education and most importantly to believe in myself. They are the ones responsible for igniting a love of learning in me.

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enormous faith in me and everything I do is humbling. I owe a lot to you. I would also like to thank Kochappan (Dr. N. A. Antony) and Aunty (Rosey Antony) for always being there with advice and a helping hand.

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# Table of Contents

# Table of Contents (continued)

# Table of Contents (continued)

# Table of Contents (continued)

# Table of Contents (continued)

# List of Figures

# List of Figures (continued)

# List of Figures (continued)

# List of Tables

# 1 INTRODUCTION

Reservoirs are generally created by damming rivers. Though most reservoirs are generally man-made, volcanic activity and any land-slip activity too can result in damming of rivers and creation of lakes or reservoirs of sufficient size. These lakes are generally called calderas (Wetzel 2001). Volcanic activity and tectonic processes, together, can cause collapse of existing landscape and form depressions, some of which can be of sufficient magnitude to form lakes and reservoirs. Very often, lava flowing into the valley, on solidifying, can form dams on rivers, in the process creating lakes, which can be similar to man-made reservoirs.

Every reservoir has three zones: riverine, transitional and lacustrine. The river-like region, in the upper reaches of the reservoir which is narrow, winding and shallow, often like the parent river, is the riverine zone. The deepest portion of the reservoir near the dam has lake-like characteristics and is called the lacustrine zone. The region in between the lacustrine and riverine zone is called the transitional zone. It has intermediate characteristics.

All the water bodies in Virginia are subject to the criteria listed in Virginia Water Quality Standards (WQS). If any of the water bodies (river, lake, etc.) are in violation of standards, then the development and implementation of a Total Maximum Daily Load (TMDL) may be required. Until recently, there were no separate WQS for lakes and reservoirs. They were evaluated based on the same criteria as streams and rivers. As the physical characteristics and chemical dynamics of lakes and reservoirs vary from that of streams and rivers, it is inappropriate to evaluate both these systems under the same set of criteria. Lakes and reservoirs generally stratify in summer. As a result of this stratification very little mixing of surface and bottom waters takes place. This phenomenon significantly alters the dynamics, interactions, nutrient and oxygen availability in lakes and reservoirs. Therefore, under the recommendation of an Academic Advisory Committee, convened by the Virginia department of Environmental Quality (VaDEQ), new standards, which took into account summer stratification, were developed for lakes and reservoirs. Changes were made to the guidelines that are followed while sampling the lakes and reservoirs, to accommodate for stratification. The new standards, as developed by the Virginia Department of Environmental Quality (DEQ) are defined and described as amendments to 9 VAC 25-260-5 and 9 VAC 25-260-50, and in the new section 9 VAC 25-260-187 (*Criteria for man-made lakes and reservoirs to protect aquatic life and recreational designated uses from the impacts of nutrients*) in the Virginia WQS. The relevant portions and the revisions made are described below.

9 VAC 25-260-50 in the standards was revised to include the following footnote:

> For a thermally stratified man-made lake or reservoir in Class III, IV, V or VI waters that are listed in 9 VAC 25-260-187, these dissolved oxygen criteria apply only to the epilimnion in the lacustrine portion of the water body. When these waters are not stratified, the dissolved oxygen criteria apply throughout the water column.

9 VAC 25-260-187 was added to the standards to define the phosphorus and chlorophyll *a* criteria to be applied to lakes and reservoirs. Portions from this section are quoted below:

> Whether or not algicide treatments are used, the chlorophyll *a* criteria apply to all waters on the list. The total phosphorus criteria apply only if a specific man-made lake or reservoir received algicide treatment during the monitoring and assessment period of April 1 through October 31,
>
> The 90th percentile of the chlorophyll *a* data collected at one meter or less within the lacustrine portion of the man-made lake or reservoir between April 1 and October 31 shall not exceed the chlorophyll *a* criterion for that water body in each of the two most recent monitoring years that chlorophyll a data are available. For a water body that received algicide treatment, the median of the total phosphorus data collected at one meter or less within the lacustrine portion of man-made lake or reservoir between April 1 and October 31 shall not exceed the total phosphorus criterion in each of the two most recent monitoring years that total phosphorus data are available.

Under the amendments mentioned above, lake and reservoir standards, in general, apply to the lacustrine portion of these water bodies. Thus, one of the first tasks when applying the new WQS to lakes and reservoirs is to identify the riverine, transitional and lacustrine zones. The definition of the lacustrine region as quoted from 9 VAC 25-260-5 of the WQS is:

> Lacustrine means the zone within a lake or reservoir that corresponds to non flowing lake-like conditions such as those near the dam. The other two zones within a reservoir are riverine (flowing, river-like conditions) and transitional (transition from river to lake conditions).

This definition, although it describes the lacustrine zone, is inadequate in identifying the lacustrine zone. It does not provide characteristics, whether physical, chemical and biological, which distinguish the lacustrine zone from the other zones, except for a general statement about flow characteristics.

The main objective of this thesis is to develop a method that will help isolate the three zones. This method developed is based on differences in physical, chemical and biological characteristics, as it is observed between the three zones. The method developed was also applied to two man-made impoundments, Lake Manassas and the Occoquan Reservoir. This was done to test the method.

**Note:** In the remainder of this document, unless otherwise specified, the terms “lake” and “reservoir” are used interchangeably. Virginia principally has reservoirs, even though there may be a “lake” in the name, and there are only two natural lakes. The term “run-of-the-river reservoir” refers only to reservoirs, and is particularly used to indicate long and narrow reservoirs.

# 2 ORGANIZATION OF THE THESIS

The three zones vary from each other in physical, chemical and biological characteristics. It is these characteristics that aid in differentiating between the three zones. While there are many characteristics that vary along the length of the reservoir, it is important to identify measurable parameters, which can be accessed with reasonable ease. The literature review attempts to identify all such parameters.

Each parameter that helps identify the different zones is an intricate part of the method developed. The utility of the method is based on whether the analysis conducted can display the variation in characteristics, along the length of the reservoir. Therefore, it is of utmost importance to determine and describe with accuracy the changes in characteristics that can be observed in the different zones in the reservoir. When comparison is made between what is obtained from the analysis conducted to what the possible results are, the necessary identification can be made.

The structure of the method developed is such that, the description of the parameters is a necessary part of the method developed. This description basically includes all the literature review done on the subject. So, instead of a traditional literature review, there is a detailed section in the next chapter, which elaborates all the parameters that are a part of the method developed. Detailed discussion regarding how these parameters vary from zone to zone will also be described there. Section 3.4, therefore, sums up all the literature review that is pertinent to this thesis.

# 3 METHOD DEVELOPED FOR IDENTIFICATION OF ZONES IN RESERVOIRS

The method developed, is based on the differences in characteristics, physical, chemical and biological, between the three zones. There are about 14 such parameters which have been identified. Each of these parameters has different characteristics in the different zones. This difference in characteristics has to be expressed in terms of a measurable quantity or in terms of differences in trends. The value or range of values or the trends expected for the measurable quantity for each parameter, in each of these three zones needs to be documented and comparison will be done based on the values or trends obtained. For effective comparison of all these parameters, it is essential that the differences and expected values of the measurable quantity of each parameter be presented side by side, for each of the three zones. Therefore, arranging these parameters in table format is the best possible solution to developing this method. Placing the parameters in table format will bring about a systematic approach and help simplify the application of the method. This will also ensure that the user can find all the necessary information to make the division of zones, within the table itself, including the method to be followed to measure the measurable quantity, associated with each parameter. For detailed information, the section containing the description that is presented after the table of parameters can be referred. These parameters have also been prioritized and they are arranged in the table in order of decreasing priority. The next section deals with the rationale involved in prioritizing the parameters.

### *3.1 Prioritizing Parameters*

There are many parameters that differentiate the three zones. Those parameters that are associated with measurable data are included in this document. Some of these data are easy to obtain, while some are not. For example, data needed to determine whether or not a system is stratified, or those related to depth, are relatively easy to obtain. Data on sediment dynamics and sediment composition are more difficult to obtain. The table is presented in order of decreasing priority. The parameters at the top of the table are the most important ones in defining the lacustrine zone. They often are also the easiest ones to obtain data on.

An example of an important and easily determined parameter would be stratification. The lacustrine zone in reservoirs is normally always stratified during summer, with a thick hypolimnion (although some large events can disrupt the stratification temporarily). As this parameter defines the lacustrine zone and is easy to measure, it has a high priority in the table. Other parameters like algal cell losses are characteristics of the lacustrine zone, although they alone cannot define the lacustrine zone and data on these are difficult to obtain. Therefore, they are relegated toward the bottom of the table. If these data are available, however, they can certainly be used to assist in or verify the identification.

## *3.2 Parameter Table and Usage*

### 3.2.1 Using the Parameter Table

The table (section 3.2.2) lists parameters, in order of decreasing priority that help in identifying the lacustrine zone. The priority has been determined subjectively, based on a combination of data-gathering ease, ease of application of the rules for a parameter, and the frequency with which the data required for that parameter are gathered. For example, DO data are gathered practically every time there is a water quality measurement made, whereas something like algal counts may only be gathered on special occasions. Consideration was also given to whether or not the particular parameter was a good indicator of zonation.

For a successful identification of the lacustrine zone to be made, it is not necessary to go through the entire set of parameters. Many parameters have been listed so that most possible scenarios required to identify the lacustrine zone have been covered. Often, the top two or three parameters are all that is necessary to perform the identification. It is only in cases (mostly exceptions) where some of the top criteria have not been met to satisfaction that one needs to go further down the table to perform the identification. Neither is it necessary to always attempt to gather information on the top parameters. If there are sufficient data available to enable identification based on two or three parameters further down the list, that is perfectly acceptable.

It is hoped that, with the help of the table, isolating the lacustrine zone from the other zones can be successfully done. Often, this process will also lead to a successful identification of the other two zones. There is no clear-cut test to determine if the boundaries of the zones thus determined are correct or not, although with practice a better sense of a good identification can be developed. It is easy enough, however, to see that the innermost sections of the zones identified using this approach (say, the deepest part of the lacustrine zone) are almost definitely in the proper zone.

Therefore, one must use some judgment about any particular lake. If, for example, sampling is being done only in the deeper sections of the lake, and that section is well within the boundaries of what has been identified as the lacustrine zone, then it is not important as to where the real lacustrine boundary lies. Note that the deepest sections of reservoirs often lie near the dam, close to what would be a zone boundary, but that is a very clear cut case of being in the lacustrine zone. It is the boundaries that are in the main body of the reservoir that are sometimes difficult to define precisely. Of course, if it is necessary to sample in the other zones, then the location of those boundaries does become more important.

While much of the identification work can be done as a paper exercise (that is, without field work), provided the appropriate data have been gathered previously and are available, it is recommended that one perform a site visit to see where the boundaries that have been determined lie. Doing so will often provide some additional support to the original determination, but sometimes may indicate that the zonation needs to be adjusted.

Here is how the process of zone identification using the table should be done:

1. Start with the first parameter listed in the table.
2. Are data available to use the determination procedure for that parameter?
3. If no, go to step 4c.
4. If yes, perform the determination for that parameter and check the following:
    a. Have determinations been done for 2 to 3 parameters? That is, do you feel comfortable that you have identified the zones correctly?
    b. If yes, stop the identification process. You might use one or more of the other parameters to check or support the zonation, but otherwise you are done. Go to step 5.
    c. If no, are more parameters available in the table?
        i. If yes, move to the next parameter in the table and go to step 2.
        ii. If no, zone determination using this process is not possible until data can be gathered. Alternatives are to either get someone familiar with lake zonation to help, or do a rough zonation based on best judgment until data can be obtained.
5. Finish the zone determination by demarcating the boundaries on a map of the water body. Establish where the current or planned monitoring locations lie.

The procedure is straightforward, and is shown schematically in the flowchart below (Figure 1). The main effort is in gathering the data needed and analyzing it appropriately. Guidelines for doing that are included in the section for each parameter in the parameter table.

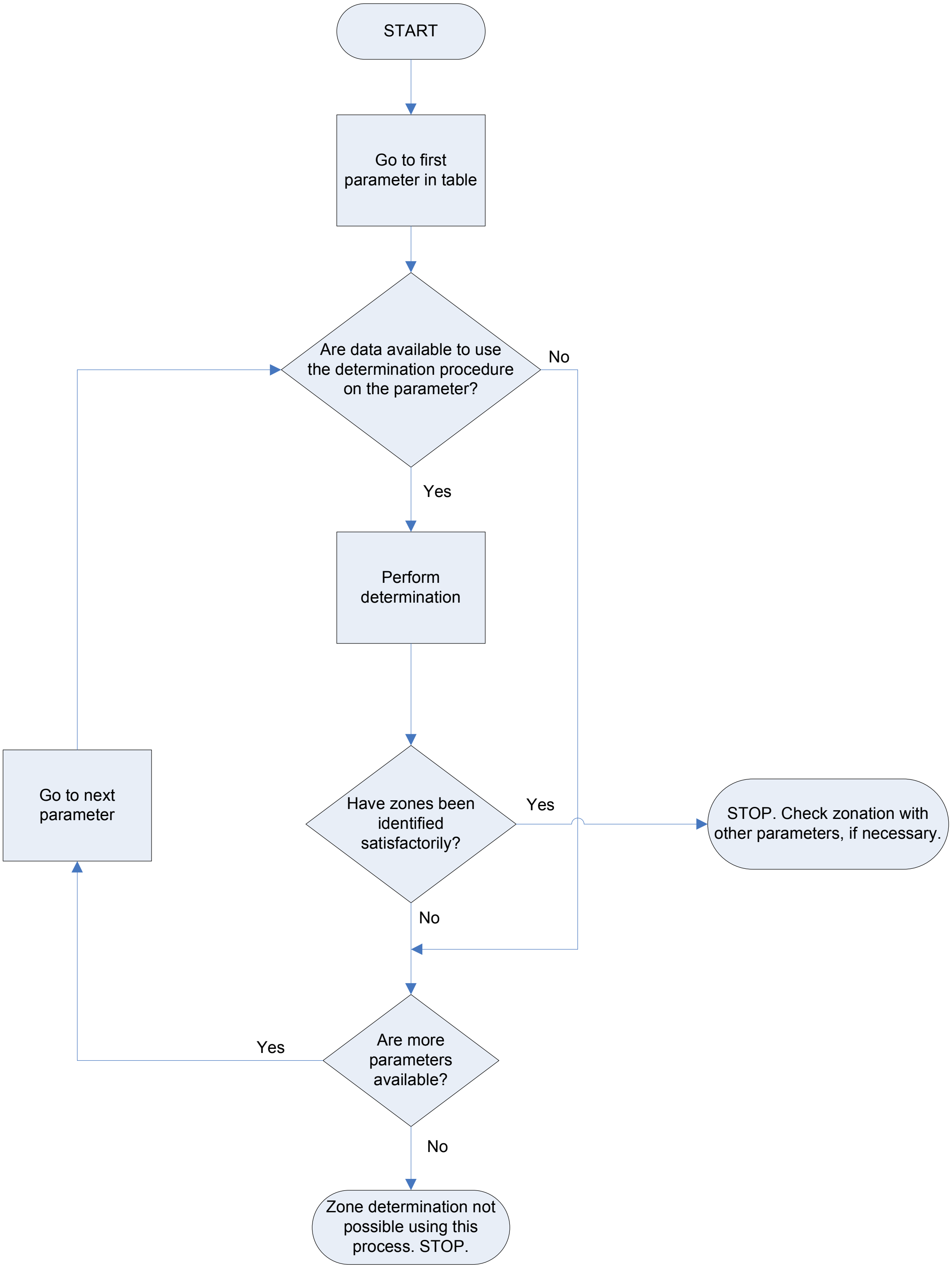

**Figure 1. Schematic representation of the method for zone identification.**

### 3.2.2 The Table of Parameters Used for Zone Determination

The parameters used for differentiating between the three zones have been arranged below in table format (Table 1) in order of decreasing priority. By analyzing the parameters in the table, a successful zone determination can be made.

The structure of the table is as follows:

1. The column labeled **Parameter** is the basic parameter or characteristic that can be used to perform a zone determination analysis.
2. The next three columns, labeled **Riverine Zone**, **Transitional Zone** and **Lacustrine Zone** provide a brief description of the characteristic or behavior in the zone with respect to the parameter.
3. The **Measured or Derived Variable** column lists the measurement that is characteristic of the parameter. This is the value that can be applied directly to zone determination. For some parameters, there may be more than one variable that can be used. If so, all such variables are listed for that parameter. Only one of the variables for that parameter should be counted toward the two or three parameters needed for satisfactory zone identification.
4. The **Difficulty in Determining Parameter** provides general insight into how difficult it might be to use that parameter and/or obtain a value for the measured or derived variable.
5. The **References** column indicates where the information used in the table for the parameter came from, and also provides a means for reading more about

the parameter. Note though, that much of the information on that parameter from those references and others is summarized in the sections below.

6. Finally, there is a section for each parameter that spans all columns except the first and last. This section is a description of what measurements to make and how to use the measured or derived variable for that parameter to provide information that can then be used to perform the zonation based on the information contained in the columns describing the characteristics of the parameter for each zone (that is, the **Riverine**, **Transitional** and **Lacustrine Zone** columns). This section is called **Zone Determination**.
7. Measurements of length are given in meters. These are converted to feet and rounded to the nearest 5-foot number.

**Table 1. Table of Parameters Used for Reservoir Zone Determination.**

| Parameter | Riverine Zone | Transitional Zone | Lacustrine Zone | Measured or Derived Variable | Difficulty in Determining Parameter | References |
|---|---|---|---|---|---|---|
| Stratification | This zone is well mixed and is not stratified<br>Stratification does not occur if Water Retention Time (WRT) <10 days | Stable stratification does not exist. If stratified, it is weak, with a thin hypolimnion<br>Stratification does not occur if Water Retention Time (WRT) <10 days | Stable stratification with thick hypolimnion<br>Stratification does not occur if Water Retention Time (WRT) <10 days | Depth of stratification or depth of thermocline | Easy | (Thornton, Kimmel et al. 1990; Cooke, Welch et al. 1993; Kalff 2001; Wetzel 2001) |
| | | | | | | |
| | **Zone Determination:** Make measurements of temperature with depth to generate a temperature-depth profile. Perform measurements at increments of 1.5 meters (5 ft) or less. Plot temperature vs depth and examine the profile to locate the thermocline. A thermocline is typically characterized by a section of the profile which has a >1ºC/meter (>0.55ºF/ft) change. The epilimnion is the section above the thermocline (which is in the metalimnion: see the stratification descriptive section later in this document), and the hypolimnion is the section below it. Both the epilimnion and the hypolimnion typically have no, or very low, thermal gradient during the middle of summer when the stratification is strongest (Figure 3, below displays a typical temperature-depth profile in a stratified lake/reservoir.). Therefore, it is recommended that determining portions of strong vs. weak stratification be done during the summer (June-August). Stratification is usually poor if the depth of the water body is less than 5-7 meters (15-25 feet).<br>Those areas of the lake exhibiting a strong stratification in summer lie in the lacustrine zone. If the sampling point exhibits this and is in the deepest section of the lake, it can be considered to be in the | | | | | |

<table>
<tr><th>Parameter</th><th>Riverine Zone</th><th>Transitional Zone</th><th>Lacustrine Zone</th><th>Measured or Derived Variable</th><th>Difficulty in Determining Parameter</th><th>References</th></tr>
<tr><td></td><td colspan="5">lacustrine zone. If there are multiple sampling points, some of which are in water that is shallower than 7 meters (25 ft), multiple temperature-depth profiles may need to be taken to demarcate where the lacustrine zone starts. Assuming that the shallowest station that is presumed to be in the lacustrine zone is farthest upstream, it is recommended that a temperature-depth profile be taken at a distance of 50 meters (165 ft) upstream of the station. If that profile shows a reasonably clear thermocline during summer, then one can assume that the station lies in the lacustrine portion of the lake. If the lacustrine zone needs to be demarcated with more certitude, then a series of profiles, about 50-100 meters (165-330 ft) apart can be used to do so.<br><br>***Caution:*** Stratification can be disrupted, even in summer and in deeper lakes, due to a large rain event. This is more common in run-of-the-river reservoirs, rather then in true lakes. Please see the descriptive section on stratification for more details about this. Also, if the lake is not stratified, then stratification cannot be used for zone determination.</td><td></td></tr>
<tr><td>Morphometry</td><td>Follows the channelized basin of the parent river. Narrow and dendritic in shape</td><td>Broader and deeper basin</td><td>Broad deep lake-like basin, ovoid to triangular in shape</td><td>Channel width</td><td>Easy</td><td>(Thornton, Kimmel et al. 1990; Kalff 2001; Wetzel 2001)</td></tr>
<tr><td></td><td>The mean depth is shallow</td><td>Intermediate mean depth</td><td>Region of maximum depth</td><td>Depth</td><td>Easy</td><td></td></tr>
<tr><td></td><td>Depth gradient is minimum</td><td>Intermediate depth gradient</td><td>Depth gradient is maximum</td><td>Depth gradient</td><td>Easy</td><td></td></tr>
<tr><td></td><td>Shoreline erosion and substrata distribution</td><td>Shoreline erosion and substrata distribution</td><td>Shoreline erosion and substrata distribution</td><td></td><td></td><td></td></tr>
</table>

<table>
<tr><th>Parameter</th><th>Riverine Zone</th><th>Transitional Zone</th><th>Lacustrine Zone</th><th>Measured or Derived Variable</th><th>Difficulty in Determining Parameter</th><th>References</th></tr>
<tr><td rowspan="2"></td><td>extensive due to water currents</td><td>in-between riverine and lacustrine</td><td>less from wind induced currents</td><td></td><td></td><td rowspan="2"></td></tr>
<tr><td colspan="5">**Zone Determination:** If a surface map of the lake is available, then only the channel width can be used. However, channel width by itself is not a good means of identifying the zone. The riverine sections of a lake can often have a wide channel section, particularly in a reservoir where the water level is higher than the top of the channelized basin of the parent river that lies in a plain.  If a bathymetric survey of the lake is available, then all three measurements of lake morphometry that apply to zone determination can be used.<br><br>There are no firm rules on what type of channel width constitutes the lacustrine zone. Generally, if the deeper parts of the lake have a width that makes that section look ovoid to triangular in shape it would be in the lacustrine zone. On run-of-the-river reservoirs (sometimes also called channel lakes), channel width by itself can be difficult to apply for zone determination, as these reservoirs are generally long and narrow.<br><br>For depth, if the depth in a section is greater than 10 meters (35 ft), the section is likely to stratify strongly in summer. Thus, an area that lies at the downstream end (closest to the outlet or mouth of a lake, and closest to the dam of a reservoir) and has depths of 10 meters or more is likely to be in the lacustrine zone. If digital bathymetric data are available, a 10-meter contour can be used to outline this section.<br><br>Depth gradients (channel slope) can be computed when bathymetric data are available. Compute the gradient for lengths of 100 meters (330 ft) or greater, depending on the length of the water body. For long and narrow channels (width: length > 10), lengths of up to 500-1,000 meters (1,650-3,300 ft) can be used. For channel width, there are no firm numbers for what constitutes a large depth gradient. Plotting the depth gradient and depths along the length of the water body can often show the point at which the gradient and depth increase substantially. If the depth gradient for any particular lake is close to the maximum for that lake, then that section is likely in the lacustrine zone.</td></tr>
</table>

| Parameter | Riverine Zone | Transitional Zone | Lacustrine Zone | Measured or Derived Variable | Difficulty in Determining Parameter | References |
|---|---|---|---|---|---|---|
| | ***Cautions:*** When using depths for zone determination, it is possible that upper reaches of the lake have depths >10 m, or that there are multiple areas with depths >10 m. In such cases, note the relative sizes of the zones. A large zone close to the mouth of the water body is most probably lacustrine. Smaller zones of such depths that are close to the upstream boundary of the lake are probably either riverine or transitional.<br>In some cases, two or more large zones of depth >10 m may be separated by a small, shallower zone. If these are sufficiently far away from where the river enters the water body, they may together constitute the lacustrine zone, even though the small area between the deeper sections is shallower than 10 m. | | | | | |
| Dissolved oxygen (DO) concentrations | A diel DO pulse is common<br>Oxygen concentrations change with depth depending on wind mixing | An oxygen block could be a characteristic of a transition zone | Diel DO pulse is not very common except in large coves where littoral plants and phytoplankton blooms are abundant<br>Oxygen concentrations change less over a greater depth in the epilimnion | DO profile | Easy | (Thornton, Kimmel et al. 1990; Wetzel 2001) |
| | **Zone Determination:** Determination of the presence of a diel pulse requires measurements taken through the day and night. These data are rarely available for lakes, unless an automated depth profiling system has been deployed on the lake. This section will assume that diel measurements are not available in the majority of the cases. | | | | | |

<table>
<tr><th>Parameter</th><th>Riverine Zone</th><th>Transitional Zone</th><th>Lacustrine Zone</th><th>Measured or Derived Variable</th><th>Difficulty in Determining Parameter</th><th>References</th></tr>
<tr><td></td><td colspan="5">Make measurements of DO with depth (these are often done together with temperature measurements). Measurements should be performed at increments of 1.5 meters (5 feet) or less. Plot DO vs. depth and examine this profile plot. Strongly-stratified lacustrine zones in summer (June-August) often show a lack of, or very low, DO in the hypolimnion. The DO profile in the epilimnion usually shows small changes with depth. There is a thermocline-like DO gradient in the metalimnion, although this may extend into the hypolimnion. That is, it may not be as strongly demarcated as the true thermocline. If a DO profile of this type exists at the station, the station is most likely in the lacustrine zone.<br><br>For multiple stations, some in shallower water, a procedure similar to that described in the stratification section above can be followed to demarcate the zones.<br><br>***Cautions:*** A shallower section (< 5 m or <15 feet) can exhibit a DO profile similar to that seen in the lacustrine zone, especially during periods of very little inflow and when there is sufficient biological activity in the bottom waters. This is more likely to occur in the transitional zone. These factors must be taken into account when looking at DO profiles.<br><br>Stratification can be disrupted, even in summer and in deeper lakes, due to a large rain event. This is more common in run-of-the-river reservoirs, rather then in true lakes. This may result in disruption of the DO profile normally seen in the lacustrine zone due to mixing of the waters. Higher-than-expected values of DO may be measured in the hypolimnion even after stratification is restored after a disruption if the biological activity in the hypolimnion is not very high. Therefore, performing these measurements for lake zone determination should be avoided for about 7-10 days after the end of a large event.</td><td></td></tr>
<tr><td>Penetration of light (euphotic zone)</td><td>High suspended solids leading to high turbidity and low light availability;</td><td>Reduced suspended solids therefore lower turbidity and enhanced availability</td><td>Relatively clear and higher penetration of light in the water column.</td><td>Depth of mixed layer and depth of euphotic</td><td>Easy</td><td>(Kimmel, Lind et al. 1990; Kalff 2001)</td></tr>
</table>

| Parameter | Riverine Zone | Transitional Zone | Lacustrine Zone | Measured or Derived Variable | Difficulty in Determining Parameter | References |
|---|---|---|---|---|---|---|
|  | $z_{eu} < z_{mix}$<br>$z_{eu}$ = thickness of the euphotic zone (where phytoplanktonic photosynthesis > phytoplanktonic respiration)<br>$z_{mix}$ = thickness of the well-mixed layer<br>Light penetration is minimal and generally limits primary production | of light<br>Significant sedimentation occurs in transition zone with a subsequent increase in light penetration. Light penetration may increase gradually or abruptly, depending on the flow regime | $z_{eu} > z_{mix}$<br>Light penetration is sufficient to promote primary production with potential for nutrient limitation and production of organic matter exceeds processing within the mixed layer | zone |  |  |
|  | **Zone Determination:** The depth of the mixed layer is generally taken to be the depth of the epilimnion ($z_{mix}$). This can be determined from temperature-depth profiles. Use a Secchi disc to determine the Secchi depth. This is the depth of the euphotic zone ($z_{eu}$).<br>In general, if $z_{eu} > z_{mix}$ then the station is in the lacustrine zone. For greater surety, use $z_{eu} > n \times z_{mix}$, where n=1.1–1.5, with a suggested value of 1.1 for n. |  |  |  |  |  |

| Parameter | Riverine Zone | Transitional Zone | Lacustrine Zone | Measured or Derived Variable | Difficulty in Determining Parameter | References |
|---|---|---|---|---|---|---|
| | ***Cautions:*** The Secchi depth reading is sensitive to the presence of suspended matter. In eutrophied lakes, with large algal populations, the euphotic depth can be very small. In those cases, the relationship will indicate a riverine zone, even if the lake is strongly stratified and there is sufficient depth such that one can be sure that one is in the lacustrine zone. In these cases, use other parameters to make the zone determination.<br>After a storm event, the suspended matter in the surface layer of water can be high, reducing the Secchi depth, and, thus, the euphotic zone. If this parameter is to be used for zone determination, one should wait for a sufficient period after the end of the event to allow the suspended solids concentration to drop back to normal conditions. | | | | | |
| Trophic state | More nutrient enriched | Intermediate | Less nutrient enriched | Trophic state index | Moderate | (Thornton, Kimmel et al. 1990) |
| | **Zone Determination:** The trophic state of a water body can be determined from trophic state indices (TSI), Vollenweider diagrams and comparing primary productivity. The procedures are too long to include here. Information on how to determine the trophic state is available in the trophic state information section later in this document. Note that the nutrient enrichment differences between the riverine, transitional and lacustrine zones are on a comparative basis, not on an absolute scale. More eutrophied waters will have higher nutrient enrichment overall, and vice versa.<br>***Caution:*** The usefulness of this parameter for lake zone determination is compromised when the lake is eutrophied. While theoretically the riverine sections, where the nutrients enter the water body, should have a higher TSI than the lacustrine, these values are often the same in eutrophied lakes. This makes zone determination based on this parameter difficult. The trophic state parameter works well if the water body has aged naturally and has minimal anthropogenic impact. | | | | | |
| Deposition of sediments along the lake or reservoir | Deposition of sediments is high in riverine zone | Deposition of sediments highest in transition zone | Decreases exponentially in the reservoir towards the dam. | Sedimentation rate | Moderate to difficult | (Thornton 1990; Wetzel 2001) |

| Parameter | Riverine Zone | Transitional Zone | Lacustrine Zone | Measured or Derived Variable | Difficulty in Determining Parameter | References |
|---|---|---|---|---|---|---|
| | **Zone Determination:** To perform evaluation on the basis of deposition of sediments along the lake or reservoir, sediment depth measurements must be made. One method to do this is to take sediment cores and do an analysis of $^{137}$Cs concentrations for various depths. This will provide the age of the sediment at that depth and can be used to determine the sedimentation rate. If these data are available, lake zone determination is based on judgment and comparison of sedimentation rates along that particular lake. The lacustrine zone can be located where the sedimentation rate decreases rapidly along the length. In most case, however, these data are difficult to obtain and will not be available.<br>***Caution:*** In many run-of-the-river reservoirs that are narrow, a very large storm event (such as the remnants of a hurricane) can stir up the sediments and cause them to flow out of the system. This might result in negative sedimentation rates if samples are taken some years before and after the event. | | | | | |
| Properties of sediments along the lake or reservoir | Sediment samples contain coarse particulate organic matter (POM), sand and coarse silts | Sediment samples contain silts, coarse to medium clays and fine POM | Sediment samples contain fine clays and colloidal material | Sediment profile | Moderate to difficult | (Thornton 1990; Kalff 2001; Wetzel 2001) |
| | Release of Phosphorus, Mn(II), Fe(II) and sulfide from sediments to water column does not occur | Anoxic conditions during stratification can cause release of phosphorus, Mn(II), Fe(II) and sulfide from sediments to water column | Anoxic conditions during stratification can cause release of phosphorus, Mn(II), Fe(II) and sulfide from sediments to water column | Fe and Mn concentrations | | |
| | **Zone Determination:** Sediment samples may be obtained by dredging or other means. Size fractionization can be used to determine the proportion of coarse and fine matter, and that of sand, and coarse and fine silts. POM can be determined via instrumental means in a laboratory. Fe and Mn | | | | | |

| Parameter | Riverine Zone | Transitional Zone | Lacustrine Zone | Measured or Derived Variable | Difficulty in Determining Parameter | References |
|---|---|---|---|---|---|---|
| | concentrations can be determined via standard procedures.<br>The zone determination is based on judgment. Sandy sediments are characteristics of riverine zones, and silty sediments are associated with lacustrine zones.<br>***Caution:*** The retrieval of bottom sediments using a dredge, such as an Eckman dredge, is relatively straightforward. However, the retrieval of a representative bottom sediment sample is more difficult. | | | | | |
| Phytoplankton productivity | Light limited phytoplankton productivity | Phytoplankton productivity/$m^3$ relatively high | Phytoplankton productivity nutrient limited | Phytoplankton productivity, depth of photic zone, nutrient concentrations | Moderately difficult to difficult | (Thornton, Kimmel et al. 1990; Wetzel and Likens 1990) |
| | **Zone Determination:** This approach uses phytoplankton productivity, the availability of nutrients (nutrient concentrations) and depth of the photic zone. The most common approach to determine phytoplankton productivity is to take samples of the natural community and isolate them in a closed container. Measurements are then made on oxygen evolution and uptake of $CO_2$ after incubating the samples either in situ or under similar conditions of light and depth as the depth from which the samples were collected. On comparing the productivity plots to plots of depth of the photic zone along the reservoir, the areas where productivity is low as a result of low light availability can be determined. Similarly, on comparing nutrient availability (nutrient concentration) and productivity, the region where productivity is limited due to nutrient availability can be determined. If the data analysis clearly shows either light or nutrient limitation, then the riverine or lacustrine sections, respectively, may be identified. If the trends are not very clear, then judgment must be used. | | | | | |
| Organic matter | Organic matter is transported by | Transportation and part sedimentation of | Sedimentation of organic matter is high | Total Organic | Easy to moderately | (Thornton, Kimmel et |

| Parameter | Riverine Zone | Transitional Zone | Lacustrine Zone | Measured or Derived Variable | Difficulty in Determining Parameter | References |
|---|---|---|---|---|---|---|
| | advective currents but very little is deposited in this zone | organic matter occurs | | Carbon (TOC) | easy | al. 1990; Kalff 2001; Wetzel 2001) |
| | Organic matter supply primarily allochthonous (origin external to lake);<br>P<R<br>P - photosynthesis<br>R - respiration | Organic matter supply allochthonous to autochthonous. At some point within the mixed layer of the zone of transition a compensation point between production and processing of organic matter is reached. Beyond this point autochthonous production of organic matter within the mixed layer should dominate. | Organic matter supply mostly autochthonous (origin internal to lake);<br>P>R | DOC:DON Ratio | | |
| | **Zone Determination:** TOC measurements are not necessary, but, if available, they help in indicating the zone, provided the water body does not have a very large algal concentration, as then the algal-associated carbon dominates the measurement. The variation of TOC values along the length of the water body can be examined. TOC will be lower in the lacustrine zone because much of the particulate carbon will have settled.<br>To determine whether the source of nutrients is allochthonous or autochthonous the DOC: DON ratio needs to be determined once samples have been collected and the DOC and DON measurements | | | | | |

| Parameter | Riverine Zone | Transitional Zone | Lacustrine Zone | Measured or Derived Variable | Difficulty in Determining Parameter | References |
|---|---|---|---|---|---|---|
| | made. A DOC: DON ratio in the range of 12:1 or lower indicates that the source is autochthonous, thus indicating a lacustrine zone. A ratio in the range of 50:1 or higher indicates that the source is allochthonous, indicating a riverine zone. Ratios between 12:1 and 50:1 are characteristics of transitional zones. | | | | | |
| Nutrient supply | Nutrient supply is generally by advection; relatively high nutrients<br>Advective forces transport significant quantities of finer suspended particles such as silts, clays and organic particulates | Advective nutrient supply is reduced considerably<br>Advective forces reduced | Nutrient supply is generally by internal recycling, relatively low concentration of nutrients available | Phosphorous concentration in sediments | Moderate | (Kennedy and Walker 1990; Kalff 2001) |
| | **Zone Determination:** The mechanism of nutrient supply in the lake or reservoir can be determined by taking sediment samples and determining phosphorus concentrations in the sample. In regions where advective flow is predominant, phosphorus concentration is low, and in regions where advective flow is low, phosphorus concentrations in sediments is higher. Determination of the zone is based on an examination of the relative concentrations of sediment phosphorus over the length of the water body, and is judgment-based.<br>***Caution:*** In run-of-the-river reservoirs, large events, such as remnants of hurricanes, can cause some degree of resuspension of bottom sediments, even in the deeper sections, and these sediments can be carried over the dam. This may change the phosphorus concentration characteristics of sediments. | | | | | |

| Parameter | Riverine Zone | Transitional Zone | Lacustrine Zone | Measured or Derived Variable | Difficulty in Determining Parameter | References |
|---|---|---|---|---|---|---|
| Fetch | | | Wind mixing is generally greatest in the lacustrine zone where fetch and exposure to wind are greatest | Fetch | Moderate | (Cole and Hannan 1990) |
| | **Zone Determination:** Fetch is not an especially good parameter to use for zone determination, as it is dependent on the most-frequent prevalent wind direction. Typically, the widest portions of the lake or reservoir will generally have the most wind action on it, and the shore-to-shore length in the direction of the most frequent prevalent wind provides a measure of fetch. However, sometimes the most frequent prevalent wind direction is along the length of a lake or reservoir and this may occur in a straight riverine section, too, so care must be used in interpreting the data. Wind direction data on the lake or reservoir can be different from weather stations close by, so this data must be gathered either on-lake or on the shoreline. Because this type of data gathering is not frequently done, and requires at least a year's worth of data, use of this parameter for zone determination is limited. | | | | | |
| Macro-zooplankton | Very low macrozooplankton population; growth (doubling rate) < flushing (dilution) rate | Variable macrozooplankton population; growth rate varies between less than to greater than flushing rate | Intermediate macrozooplankton population; growth rate > flushing rate | Macrozooplankton counts | Moderate | (Wetzel and Likens 1990; Kalff 2001) |
| | **Zone Determination:** Sampling the water for macrozooplankton can be done using zooplankton nets and the zooplankton counts can be determined along the length of the reservoir. Macrozooplankton counts and diversity are low in the riverine zone and moderately high in the lacustrine zone.<br>***Caution:*** Eutrophied water bodies may have high algal and macrozooplankton populations even in the transitional and lower riverine zones. | | | | | |

<table>
<tr><th>Parameter</th><th>Riverine Zone</th><th>Transitional Zone</th><th>Lacustrine Zone</th><th>Measured or Derived Variable</th><th>Difficulty in Determining Parameter</th><th>References</th></tr>
<tr><td rowspan="2">Algal cell losses</td><td>Algal cell losses generally due to sedimentation and advection</td><td>Algal cell losses generally due to both sedimentation and advection</td><td>Algal cell losses often primarily as a result of grazing</td><td>Zooplankton feeding rate.</td><td>Difficult</td><td rowspan="2">(Thornton, Kimmel et al. 1990; Wetzel and Likens 1990; Kalff 2001)</td></tr>
<tr><td colspan="5"><b>Zone Determination:</b> Algal cell losses are dependent on zooplankton feeding rates, which can be determined by observing changes in the number of particles removed over time by grazing, or by measuring the rate of removal of radio-labeled food particles. The region with the highest feeding rates will correspond to the lacustrine region, if other parameters tally.</td></tr>
<tr><td rowspan="2">Flow rate</td><td>Relatively high flow rate and rapid water flushing</td><td>Reduced flow and flushing</td><td>Little flow and slowest flushing</td><td>Flow rate</td><td>Moderately difficult</td><td rowspan="2">(Thornton, Kimmel et al. 1990; Kalff 2001; Wetzel 2001)</td></tr>
<tr><td colspan="5"><b>Zone Determination:</b> Measurement of flow rate must be made along the length of the reservoir. This can be a difficult task in the deeper zones as flow rates can be very low. Care must be taken to account for water movement due to wind action. A plot of distance vs. flow rate will help determine regions of high flow and regions having low flow rate. The region with the lowest flow rate will correspond to the lacustrine zone.</td></tr>
</table>

### *3.3 Extreme Events and Conditions*

Lake and reservoir zone boundaries are not clear-cut determinations, but often a matter of judgment. Moreover, they can vary with changing conditions, such as large storm or high wind events. When such events occur, care must be taken that the lacustrine zone has not temporarily come under the influence of a non-lacustrine zone.

Large storms can generate high runoff flows. In run-of-the-river reservoirs, these flows can displace the volume of the entire reservoir multiple times in a matter of a few days. During the high flows, the riverine zone expands downstream, and the other zones get compressed. In extreme cases, in shallower reservoirs, the entire lacustrine zone may not exist for a few days. This statement is with reference to the typical characteristics of the lacustrine zone: while some of the physical aspects, such as width and depth, do not change, many of the other aspects, such as a low flow rate, water clarity, etc., become more like the transitional or even the riverine zones. After a large storm, such as the remnants of a hurricane or a >3-inch rain event, it can take days or weeks for the reservoir zones to re-establish their normal boundaries. Because the length of the disruption depends on many factors, and because such events are rare, it is hard to define how quickly the zone boundaries return to normal. In such cases, if a sampling trip is scheduled for the first 2-3 weeks following such an event, it is best to seek advice from those with a greater knowledge of the behavior of lakes and reservoirs.

Prolonged droughts can cause drawdown in lakes and reservoirs, particularly those reservoirs that are used to supply drinking water. Sometimes, a reservoir may be drawn down deliberately to perform maintenance on the dam structure, or for cleanout of accumulated sediments near the dam. In these situations, the length of the lake or reservoir pool shrinks, causing the zones to shrink, too. Generally speaking, the upstream end of the riverine zone moves downstream to where the new lake or reservoir starting point is and extends beyond the old riverine zone boundary. Similarly, the transitional zone boundaries shift downstream and the lacustrine zone shrinks. Sampling points located well within the old lacustrine zone may remain in the lacustrine zone even during the drawdown. However, care must be taken to ensure that the lacustrine zone is still exhibiting the characteristics of a lacustrine zone. In relatively shallow lakes and reservoirs, for example, the lacustrine zone may not exist, as it is defined here, if the drawdown is significant. Again, the best option when large drawdown conditions occur is to seek advice from a person with knowledge of lake and reservoir behavior.

## *3.4 Explanation of Parameters*

In this section each of the parameters listed in the parameter table will be discussed in greater detail. The aim of this section is to provide a more complete description of the parameters and discussion of the science as it pertains to the scope of this document.

### 3.4.1 Stratification

As spring progresses, the surface waters of deep lakes, usually of depth 6 m (20 ft) or greater, are heated more rapidly than heat can be distributed. Rapid surface heating occurs during a warm, calm period of several days. As the surface waters are warmed and become less dense, the relative thermal resistance of mixing increases. This is due to the fact that water has its highest density at 4ºC. A difference of a few degrees is sufficient to prevent complete circulation. From that point on, the water column is divided into three separate regions, which are exceedingly resistant to mixing with each other (Wetzel 2001). The lake thus becomes thermally stratified. The bottom layer is called the hypolimnion and the top well-mixed layer is called the epilimnion. The epilimnion and hypolimnion is separated by the metalimnion, which contains the thermocline. Figure 2 below, displays a stratified lake with three regions. In the temperate region, studies have shown that thermal stratification is weak if the basin depths are less than 5-7 m (16 – 23 ft) (Wetzel 2001).

#### 3.4.1.1 Epilimnion

The topmost layer containing more or less uniformly warm and well-mixed water is called the epilimnion. The epilimnion floats over the metalimnion followed by a cold and relatively undisturbed hypolimnion (Wetzel 2001). It is the epilimnion that is in contact with air and subject to wind action.

#### 3.4.1.2 Metalimnion

The stratum between the epilimnion and the hypolimnion is called the metalimnion. It displays marked thermal discontinuity. It is defined as the layer of water between the upper homothermal epilimnion and the lower hypolimnion, with a steep thermal gradient (Wetzel 2001).The region between the epilimnion and hypolimnion can be a single thermocline step or a series of many step-like gradations which extend over an appreciable part of the depth. This broad region that contains one or more thermoclines is called a metalimnion (Imberger 1985).

### 3.4.1.3 Hypolimnion

The layer of water near the bottom of the lake bed during stratification is called the hypolimnion. The initial temperature in the hypolimnion is determined by the final temperature during the spring isothermal condition. The temperature of the hypolimnetic waters changes very little while it is stratified, especially in deep lakes (Wetzel 2001)

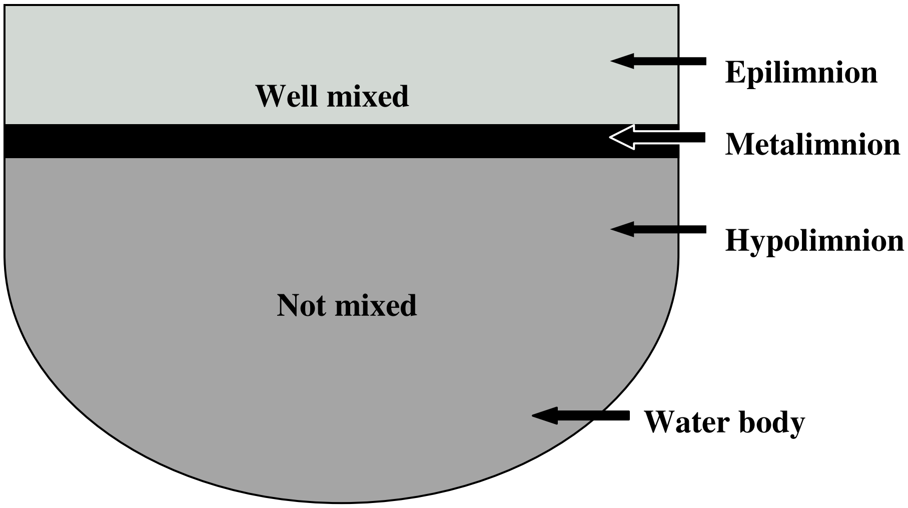

**Figure 2. Pictorial representation of thermal stratification.**

#### *3.4.1.3.1 Thermocline*

The term thermocline has many definitions but what it usually refers to is the plane of maximum rate of decrease of temperature with respect to depth (Wetzel 2001). The depth of the metalimnion varies greatly among lakes from year to year, depending on the weather conditions. The generally accepted definition of a thermocline is that it generally exhibits a temperature change of >1°C per meter. This definition was given by E.A. Birge. It is, however, inappropriate for large temperate lakes where the gradients are so long and gradual that the $> 1°C{\cdot}m^{-1}$ limit is never attained. It is also inappropriate in tropical lakes that have a temperature difference between the epilimnion and hypolimnion so small that a $>1°C{\cdot}m^{-1}$ is never reached even though the lake is under stable stratification. In these lakes, the thermocline has been defined as the depth interval over which the temperature changes more than 0.1 to 0.2 $°C{\cdot}m^{-1}$ (Cole 1983; Kalff 2001). A persistent thermocline is the most common measure of mixing depth but a thermocline may be located in a metalimnion of any thickness. Therefore, the depth of the mixed layer in relation to the location of a thermocline is uncertain (Kling 1988). Modeling of temperate lakes has established that summer thermocline depth is predictable and that it increases as a function of lake fetch or area (Table 2). This relationship is strong for temperate lakes having a fetch of up to 30 km.

**Table 2. Regression equations for lake mixing depth ($z_e$ or E) as a function of lake size.**

| Reference | Region | Regression equation for $z_e$ or E | $r^2$ | N (Number of lakes studied) |
|---|---|---|---|---|
| **Epilimnion depth, E (m)** | | | | |
| Arai (1981) | Japan | $4.6 f^{0.304}$ | – | 32 |
| Patalas (1984) | Poland, Canadian Shield | $4.6\ F^{0.41}$ | 0.85 | 88 |
| Green et al. (1987) | New Zealand | $7\ L^{0.42}$ | 0.79 | 33 |
| Davies-Colley (1988) | New Zealand | $7.69 f^{0.463}$ | 0.940 | 22 |
| Davies-Colley (1988) | New Zealand | $6.85\ F^{0.446}$ | 0.918 | 22 |
| **Thermocline depth, T(m)** | | | | |
| Ventz (1973) | East Germany | $4.72 f^{0.39}$ | – | 30 |
| Ragotskie (1978) | Wisconsin USA,<br>Canadian Shield | $4\ f^{0.45}$ | – | 18 |
| Arai (1981) | Japan | $6.22\ f^{0.304}$ | 0.53 | 32 |
| I. Smith | Scottish Highlands | $4.66\ F^{0.55}$ | 0.41 | 59 |
| Davies-Colley (1988) | New Zealand | $9.52 f^{0.425}$ | 0.954 | 22 |
| Davies-Colley (1988) | New Zealand | $8.58\ F^{0.408}$ | 0.928 | 22 |

The index of lake size is fetch, defined $f = A^{1/2}$ (where *A* is lake area in km$^2$) or F = (L + *W)/2* (where *L* and *W* are "effective" length and width, respectively, or simply "effective" lake length, L).

**Source:** Davies-Colley (1988). References listed in table are from the source, and are not listed in this document. © New Zealand Journal of Marine and Freshwater Research. Used with permission.

### *3.4.1.3.2 Planar Thermocline*

The planar thermocline, $z_t$, is defined as the depth where the temperature gradient is maximal (Hutchinson 1957). The planar thermocline lies within the metalimnion (Cole 1983). In cases where the thermal gradient is not very steep, the planar thermocline can be used. The regression equations for determination of planar thermocline depth ($z_t$) for different regions are as follows.

For worldwide lakes (Kalff 2001),

$z_t = \ln (A^{0.5}/0.043)^{2.35}$ ; $r^2 = 0.66$ and $N = 150$

A= area ($km^2$)

For Lakes in North America (Kalff 2001),

$z_t = 0.298 \ln (MEL)+1.82$ ; $r^2 = 0.66$ and $N = 73$

MEL= maximum effective length (km)

### 3.4.1.4 Profile of a Thermally Stratified Lake

Figure 3, below, displays the temperature-depth profile of a stratified lake. All lakes undergoing stratification during summer show similar profiles.

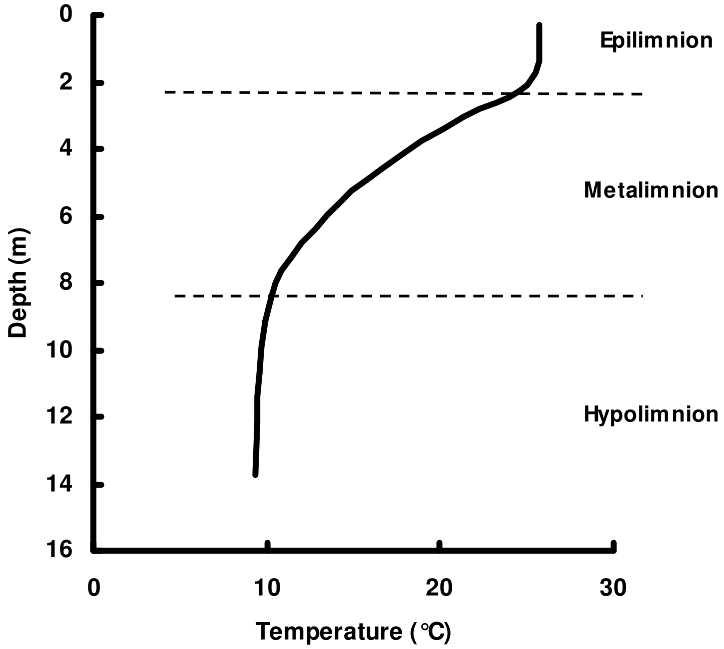

**Figure 3. Typical temperature-depth profile in a stratified lake.**

### 3.4.1.5 Stability of Stratification

The stability of stratification is defined as the amount of work needed to fully destratify a lake at any one moment, without having to consider the addition or removal of heat required over time (Kalff 2001). Stability of stratification is linked more closely to maximum or mean depth than to the surface area of lakes (Kling 1988). It is, therefore, more dependent on the volume of lake than on the surface area. This is because the energy needed to overcome inertia of the water mass to mixing rises sharply with increasing depth. The deeper a lake is, the more stable is its stratification. However, studies have shown that beyond a mean depth of about 40 m, depth plays a very minor role in the stability of stratification. Shallow lakes of a particular surface area are much less stably stratified than their deep counterparts. Lakes with small seasonal variation in water temperature tend to be less stably stratified than those showing prominent vertical change in water temperature. This is because less energy is required to destratify these less stable stratified lakes. Lakes can also be destratified due to major storm events.

A simple estimate of whether temperate lakes will exhibit summer stratification is based on the ratio of thickness of the epilimnion ($z_{e,}$ or E, as defined in Table 2) to maximum lake depth ($z_{max}$). Different values for the parameter and what they indicate are listed below (Davies-Colley 1988):

| | |
|---|---|
| $z_e / z_{max} < 0.5$ | 3-layer lake (epi-,meta-, hypolimnion). Stable and strong stratification. |
| $0.5 < z_e / z_{max} < 1.0$ | 2-layer lake (epi-, metalimnion). May be turned over by strong winds or hydrological events. |
| $1.0 < z_e / z_{max} < 2.0$ | Mixed lake. Intermittent stratification during calm periods. |
| $z_e / z_{max} > 2.0$ | Turbulent lake with much exchange between water and sediments. Rarely stratifies, usually very turbid. |

### 3.4.1.6 Relative Thermal Resistance (RTR)

Relative Thermal Resistance (RTR) is defined by the density difference at adjacent depths compared to the density difference between 4° and 5°C. The largest RTRs are found at the depth of maximum temperature change (Kalff 2001). Figure 4, displays an example of RTRs at different depths. RTRs can help identify the location of the thermocline.

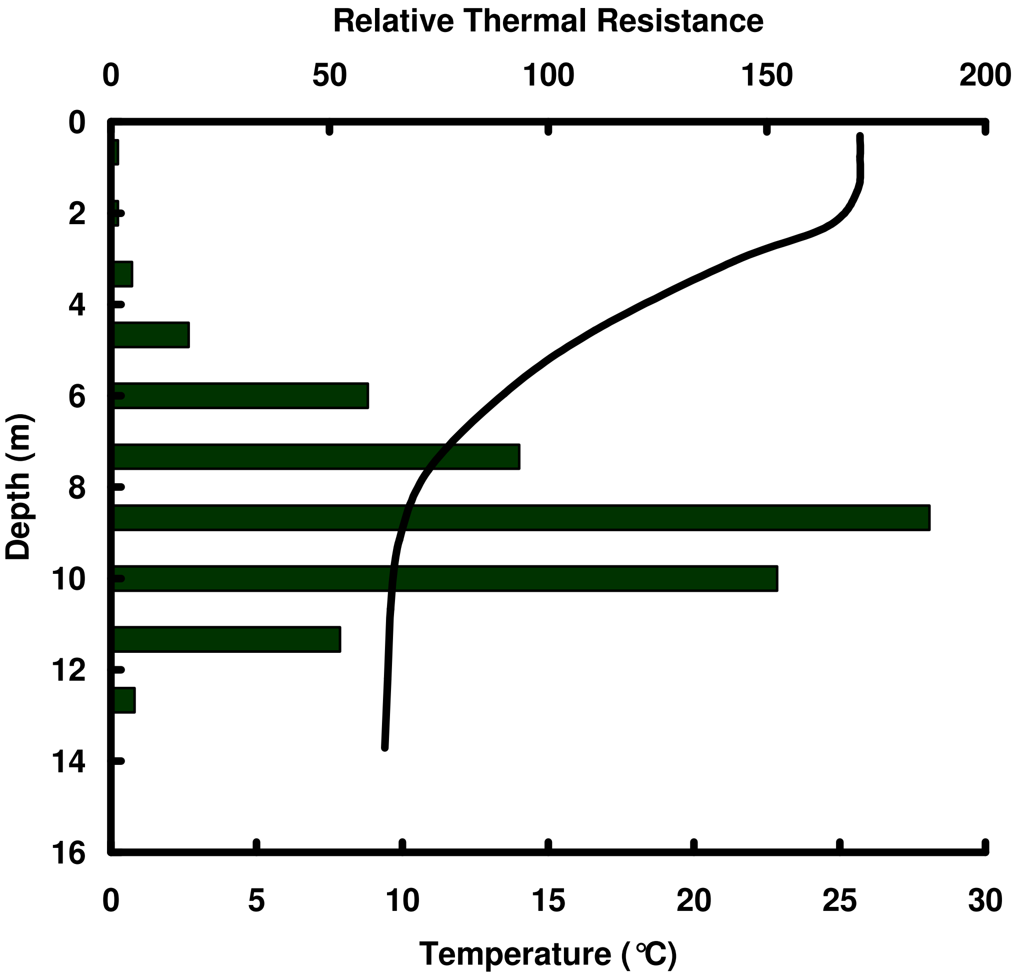

**Figure 4. Summer profile (single line) and Relative Thermal Resistance (RTR) to mixing (bars)** (After Wetzel 2001). © Elsevier Science (USA). Used with permission.

### 3.4.1.7 Dependence of the Degree of Stratification on Retention Time

Retention Time (RT) has a direct effect on the period and depth of stratification. If expressed as the difference between surface and bottom temperature during the period of maximum stratification, it has been found that stratification is asymptotic to increasing RT. Models have successfully demonstrated that an RT of over 1 yr (300 – 400 days) has little or no influence on the stability of stratification. Stratification varies interannually, depending on flow and water level conditions (Sullivan and Reynolds 2005).

### 3.4.1.8 Shallow Reservoirs

The limnological definition of a shallow lake is not just dependant on its depth, but also on whether wind-induced turbulence affects the bottom (i.e., whether the water column is well-mixed). The depth of wind-induced mixing is related to the size of the lake. A shallow lake can be defined as one in which, approximately, $z_{max} \leq z_{mix}$ ($z_{mix}$ = mixing depth, m).

For temperate lakes (Straskraba 1990),

$$z_{max} = 4.5 \sqrt{L}$$

L = Maximum length of the lake (km)

$z_{max}$ = Maximum depth (m)

In temperate regions, deep lakes are stratified and shallow ones are not.

### 3.4.2 Morphometry

The morphometry of a reservoir deals with the physical form and physical characteristics of the reservoir. Even though reservoirs are functionally similar to natural lakes, they differ from them significantly in physical characteristics. Understanding these physical differences is essential to proper management of these impounded systems.

#### 3.4.2.1 Determining Depth Gradient

If the contour map of the water body is available and the length of the isobaths (the line joining points of equal depth) is known, then the slope of the bed (depth gradient) can be determined. Figure 5, displays an example of a contour map with a contour interval of 5 units.

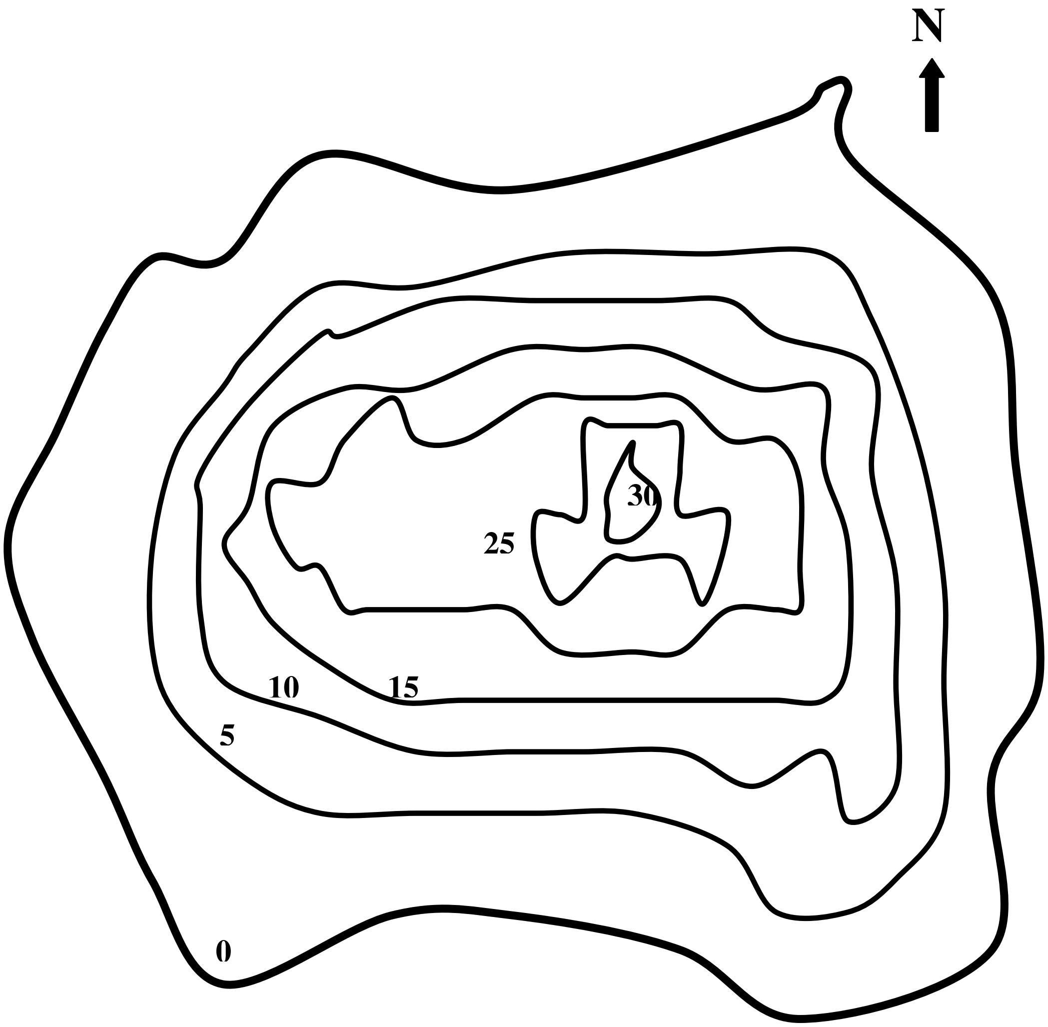

**Figure 5. Example of a water body contour map (numbers indicate depth).**

The slope is defined as the tangent between two contours. Figure 6, below, displays the slope between two contours as the tangent angle.

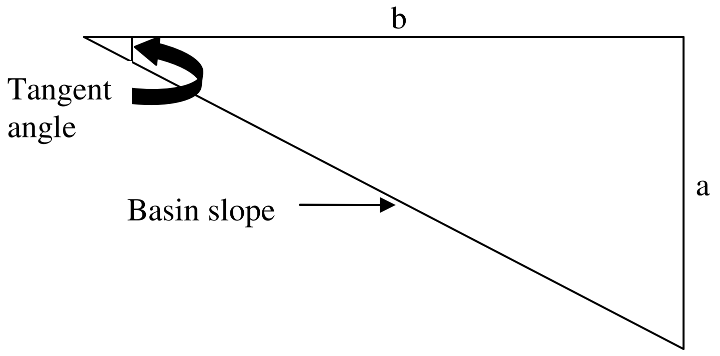

**Figure 6.** **Slope between two contours.**

The slope gradient is calculated from the contour lines using the formula below (Cole 1983):

Slope (depth gradient) = $\frac{(L_{z1} + L_{z2})(z_2 - z_1)}{2(A_{z1} - A_{z2})}$

$L_{z1}$ = Length of upper contour

$L_{z2}$ = Length of lower contour

$(A_{z1} - A_{z2})$ = Area enclosed between the two contours

$(z_2 - z_1)$ = Depth difference between the two isobaths, or the contour interval

The resultant value from the calculation is obtained in decimal format. By multiplying it with 100 it can be converted to percentage format.

### 3.4.2.2 Variation of Physical Characteristics Along the Reservoir

As we move down the reservoir, physical characteristics change from river-like to lake-like. Figure 7, below, is a pictorial representation of this change and the zonation that results in a reservoir as a result of it.

#### *3.4.2.2.1 Morphometry of the Riverine Zone*

The riverine zone receives water from the parent river. It is generally an extension of the parent river. Like the parent river it is narrow and follows the old river channel. The depth of this portion of the reservoir is generally shallow (< 6m) (Wetzel 2001). The depth gradient, which is a measure of the bed slope, is generally minimal. The entire riverine zone is shallow and therefore, there is not a big variation of the bed slope (Figure 7). Water flows through this region with comparatively high flow rates because of the narrow structure of the channel. This higher flow rate is responsible for the significantly higher shoreline erosion in this zone when compared to the other zones in a reservoir.

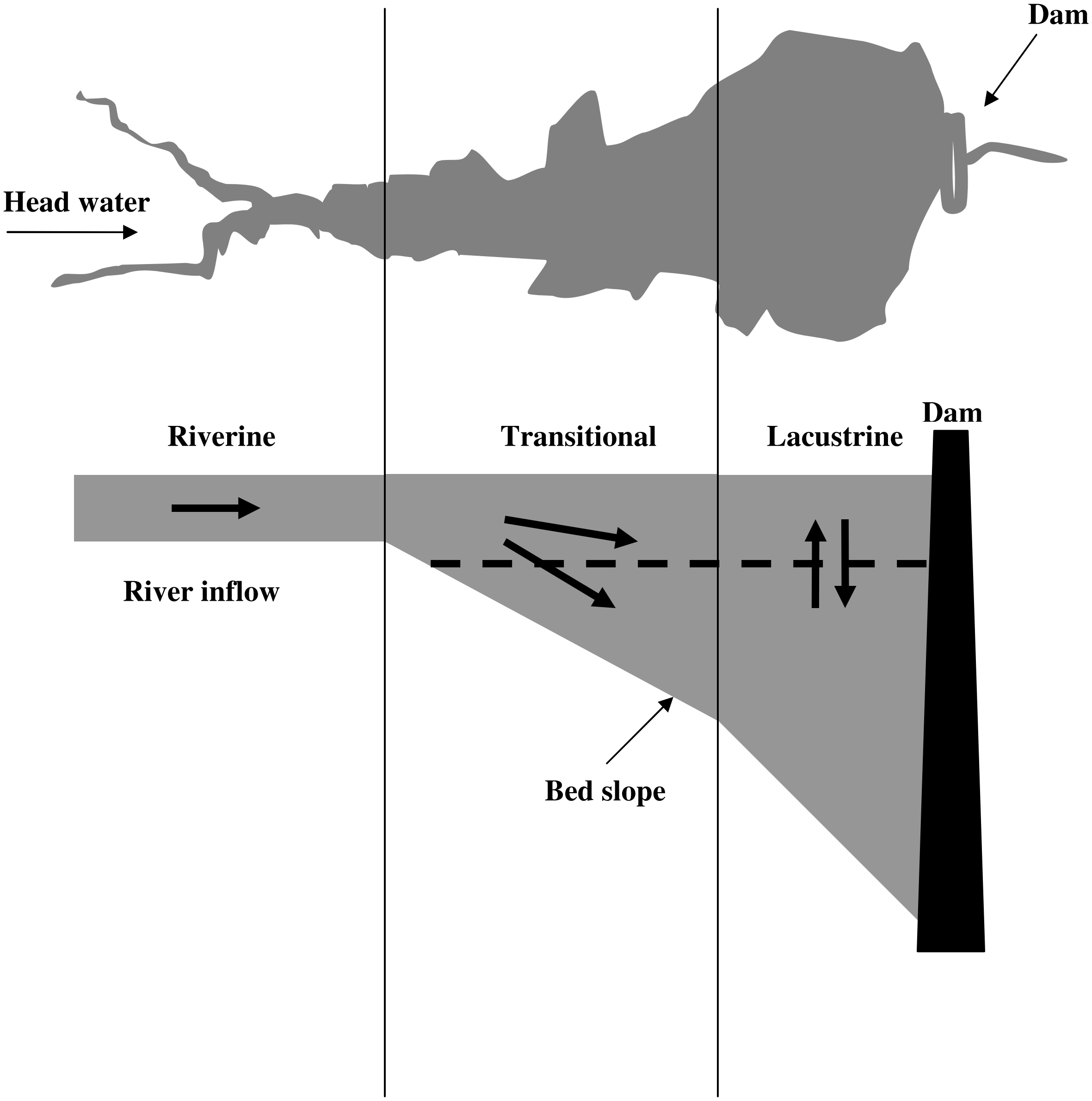

**Figure 7.** **Zonation in a Reservoir** (Modified from Wetzel 2001). © Elsevier Science (USA). Used with permission.

#### *3.4.2.2.2 Morphometry of the Transitional Zone*

In this zone, the river channel widens and it increases in depth, too, resulting in a reduction in flow rates. Stratification may or may not exist, suggesting that this region can begin in the shallow portion of the reservoir but gets deeper on moving towards the dam. This deepening results in an increase in the bed slope. The depth gradient in this zone is higher than that in the riverine zone (Figure 7). Reduced flow in this region also results in a much more stable shoreline.

#### *3.4.2.2.3 Morphometry of the Lacustrine Zone*

The lacustrine zone of the reservoir is the deepest portion of the reservoir, with characteristics similar to those of a natural lake. It is deep, wide and quiescent. The depth in this region increases progressively towards the dam. The change in depth and the depth gradient is highest in this zone (Figure 7).

### 3.4.3 Dissolved Oxygen

Dissolved oxygen (DO) is a very important parameter in limnology. It affects the metabolism and survival of aquatic species and also determines the capacity of the water to receive organic matter without undergoing adverse degrading effects. The sources of dissolved oxygen are the atmosphere, photosynthetic activity and hydro-mechanical distribution in the water column. The amount of dissolved oxygen available in water regulates the type and variety of organisms present in that environment. It is this dissolved oxygen that is available to the organisms for their metabolic activities and also for other non-biotic chemical reactions. The resulting distribution of oxygen due to all these interactions is responsible for the availability and solubility of many nutrients in the water column. In turn, this can significantly change the dynamics of the water column. Changes in oxygen content, therefore, play a key role in the environment of reservoirs and lakes.

### 3.4.3.1 Factors Affecting Dissolved Oxygen in Reservoirs

Many factors affect the dissolved oxygen concentrations in lakes. Much of the discussion of these parameters in this section (3.4.3.1) and its subsections is derived from Hutchinson (1957), Cole and Hannan (1990) and Wetzel (2001).

#### *3.4.3.1.1 Temperature*

The relationship between solubility of oxygen in water and temperature is non-linear. The solubility of oxygen is higher in cold water. If temperature was the only factor in play, then deep hypolimnetic waters would have high dissolved oxygen. This is depicted by the orthograde curve, where the DO concentration goes up with decreasing temperature, is common to oligotrophic lakes (Figure 8). In reality, most lakes and reservoirs are not oligotrophic in nature. Many studies on reservoirs have shown that an increase in temperature in the deep waters, often results in increased metabolic activity by organisms. This causes an oxygen demand, which often results in anoxia. Over a span of many years, anoxia can bring about eutrophication of the water body due to releases of bound phosphorus from sediments.

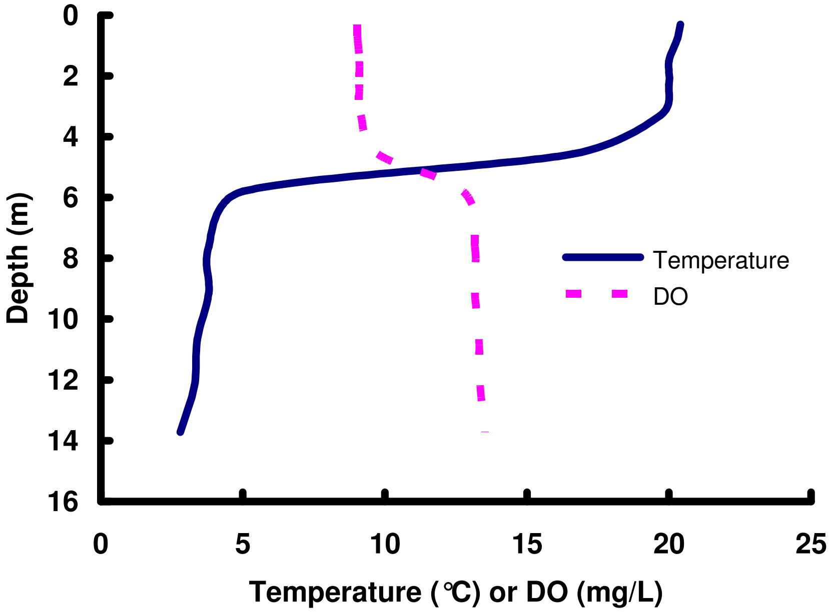

**Figure 8. Typical orthograde DO curve in an oligotrophic lake.**

### *3.4.3.1.2 Pressure*

The concentration of dissolved oxygen depends on atmospheric pressure, meteorological conditions and the hydrostatic pressure exerted by the overlying stratum of water. The actual pressure at any given depth is given by,

$$P_z = P_o + 0.0967z$$

$P_z$ = the actual pressure in atmospheres (atm.)

$P_o$ = the pressure at the surface (atm.)

$z$ = depth (m)

The importance of this relationship lies in the fact that we can determine the quantity of gas (oxygen in this case) that can remain dissolved in water at that pressure. If the quantity of gas is increased beyond that equilibrium concentration, it will result in formation of bubbles that will rise to the surface and escape. The degree of supersaturation for a particular temperature required for formation of bubbles increases with depth and hydrostatic depth. Presence of turbulence or internal waves can prevent the formation of bubbles. Formation of bubbles can result in decrease in concentration of dissolved oxygen in the water column.

#### *3.4.3.1.3 Flow*

The riverine zone of the reservoir receives water directly from the parent river. The amount of DO in the parent river has a significant role to play. The DO concentration in the riverine zone will be similar to that in the parent river. Incoming currents from the riverine zone, if there is a difference in density, can progress forward as a separate layer. The plunge point, where the incoming current starts progressing forward as a separate layer, occurs in the transition zone. The plunge point is discussed in great detail in section 3.4.8.2.1. Depending on whether the density of the incoming current allows it to progress forward in the upper, mid or bottom layers of the reservoir, it will be an overflow, interflow or underflow. Figure 20 (section 3.4.8.2.1), displays these density currents. Interflows having low DO are often the cause of metalimnetic oxygen minima (see section 3.4.3.7). If the incoming current has sufficient density, it will lie along the bottom of the reservoir as an underflow. These underflows can be rich in DO and can increase the oxygen content in the hypolimnion. Overflows have little impact on the DO of reservoirs as the epilimnion is usually well mixed and saturated with oxygen.

Outlet location in reservoirs is an important factor in determining the amount of DO present. Bottom release reservoirs may have some DO in the hypolimnion, depending on the location of the release point, as the well-aerated top waters move toward the hypolimnion upon release of water from the bottom. In the release of hypolimnetic waters, nutrients are also removed along with the outflow. This loss of nutrients, which occurs in the lacustrine zone where release-points are typically located, can result in a decrease in primary production, which in turn decreases the oxygen demand. For surface-level outlets, the residence time of the hypolimnetic waters increases. Moreover, stratification in the reservoir prevents mixing of waters. As a result, the hypolimnetic waters are often anoxic. Midlevel withdrawals, depending on the location of the withdrawal, can have the same effect as bottom withdrawals.

##### *3.4.3.1.4 Allochthonous Inputs*

The parent river feeds the allochthonous materials into the reservoir. Allochthonous materials originate from the watershed, runoff and subsurface seepage. An increased presence of nutrients can cause an increase in the primary production. Organic matter also exerts an oxygen demand. The region where the organic load is deposited is the zone where anoxia begins to form. The anoxic zone keeps spreading if there is no mixing event.

### *3.4.3.1.5 Photosynthesis and Respiration*

Photosynthesis and respiration are two opposing mechanisms in autotrophic organisms, which take place at the same time in the presence of light. Photosynthesis results in production of oxygen, and respiration results in consumption of oxygen. These two mechanisms together influence the DO present in water. Photosynthesis occurs in the presence of sunlight. During the daytime, DO in the water increases because the rate of production of oxygen due to photosynthesis is generally greater than the rate at which oxygen is lost due to respiration. At night, in the absence of light, only respiration takes place. Therefore, the net oxygen demand is high and results in depletion of DO. This diurnal increase and decrease in DO is called a diel DO pulse (see section 3.4.3.2).

### *3.4.3.1.6 Wind*

Wind-induced mixing is responsible for the well-mixed and highly-oxygenated epilimnion. At the onset of fall, when the waters begin to cool and the temperature in the epilimnion approaches that of the hypolimnion, it is wind that initiates lake mixing (called the overturn), breaking the stratification. During the fall overturn there is almost uniform oxygen concentration throughout the depth of the reservoir.

Wind is also responsible for dispersing phytoplankton communities along the reservoir. This can have an effect on the oxygen concentration in water as a result of change in the photosynthesis rates due to changes in phytoplankton population. Thus, wind plays an important role in maintaining DO concentrations in the reservoir.

### 3.4.3.2 Diel DO Pulse

As discussed in section 3.4.3.1.5, diel DO pulse is a result of photosynthesis and respiration by phytoplankton, which are the major primary producers in reservoirs. In the riverine reach of the reservoir, phytoplankton productivity is often light-limited because of turbidity. The limited productivity, along with respiration, may result in a diel DO pulse. Figure 9 displays an example of a diel DO pulse. The transition zone is the most fertile zone with very high productivity. High productivity, combined with respiration, results in the diel DO pulse. In the lacustrine zone, however, phytoplankton productivity in oligotrophic reservoirs is nutrient-limited and low when compared to the other two zones, and a diel DO pulse rarely exists in this zone. Eutrophic reservoirs may, however, display a diel DO pulse in the lacustrine zone.

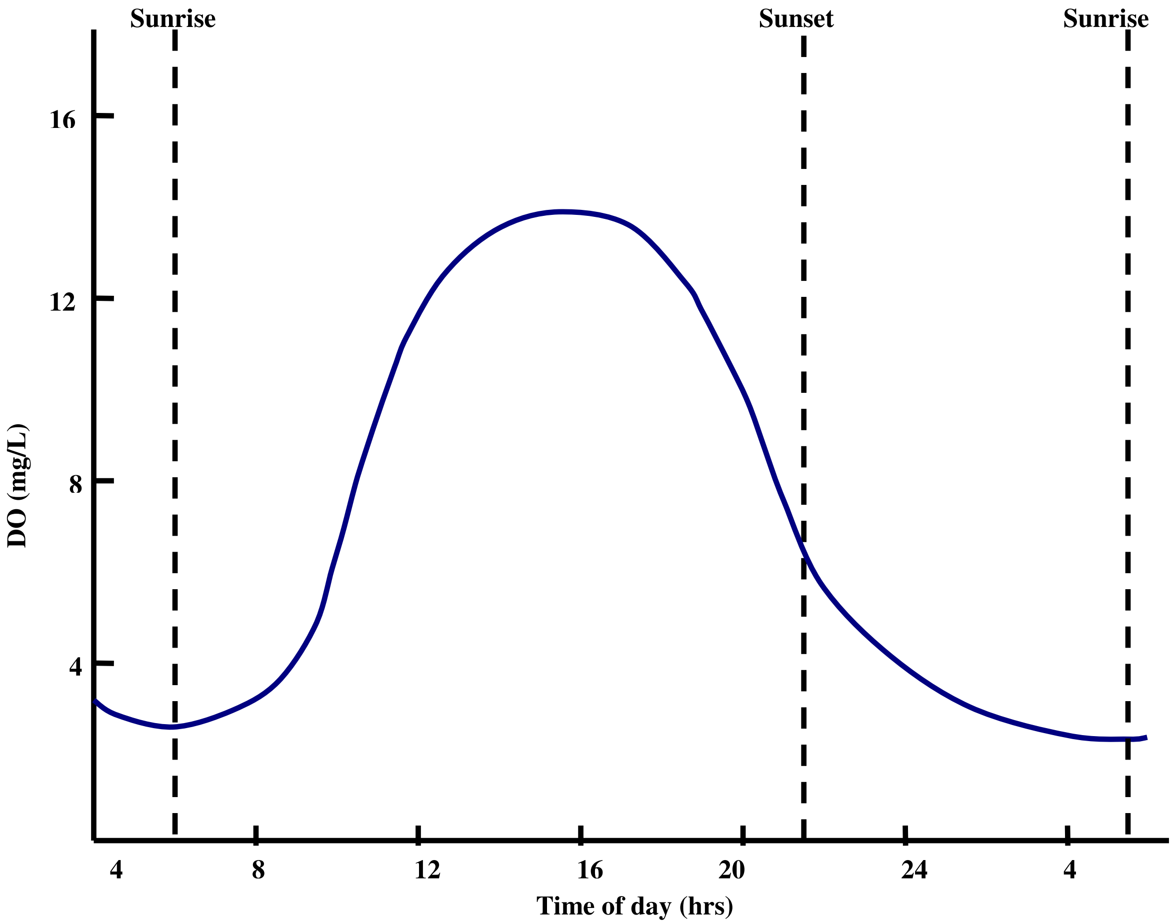

**Figure 9. Typical Diel DO variation (pulse).** The difference between the maximum and minimum DO will depend on various factors, including phytoplankton productivity, and nutrient or light limitations.

### 3.4.3.3 DO in the Riverine Zone

The riverine zone is generally shallow, relatively more turbulent, and well-mixed. Moreover, no stratification occurs in this zone. As a result, DO is usually high in this zone.

#### 3.4.3.4 DO in the Transitional Zone

The transitional zone is very dynamic with high sedimentation rates, high productivity and high decompositional activities by organisms. During summer, the transitional zone experiences some stratification, typically weak and generally with a thin hypolimnion and unstable thermocline. The high sedimentation rates and decomposition by organisms exerts an oxygen demand on the water column. While stratification exists no mixing of water takes place, and the oxygen utilized for decomposition of sediments is not replenished. Anoxia, therefore, develops in the hypolimnion of the transitional zone. Because the transitional zone has a thin hypolimnion, the volume of oxygen available for decomposition is also less, and it is here that anoxia first develops during summer stratification.

The region where anoxia first forms in the reservoir can vary from year to year, depending on flow. For years of high flow, the sedimentation zone moves further downstream and the riverine zone with well-mixed waters extends further downstream. Under these conditions, the anoxic zone is developed further downstream. In years of low flow, the sedimentation and the transitional zones move upstream. Under these conditions the anoxic zone develops further upstream. Therefore, flow conditions prevailing in the reservoir play an important role in determining where anoxia first develops in the reservoir. The variation in zonation (zone length) under different flow conditions is illustrated in Figure 10, and the development of anoxia under different flow conditions is shown in Figure 11 and Figure 12. Once anoxia is formed, it extends upstream and downstream gradually as summer progresses.

### 3.4.3.5 DO in the Lacustrine Zone

The lacustrine zone exhibits stable stratification during summer, with a thick hypolimnion. As summer progresses, decomposition in the sediments creates an oxygen demand and the DO in the water column is soon utilized. Due to stratification, the hypolimnion does not mix with the upper layers. Oxygen utilized by the microbes for decomposition is not replenished and anoxic conditions begin to develop.

Anoxia is believed to first form in the hypolimnion of the transitional zone. This anoxic condition can extend downstream faster in reservoirs with a hypolimnetic outlet than one with an epilimnetic outlet. Withdrawal of water accelerates the formation of anoxia for a bottom withdrawal and also causes an increase of temperature in the hypolimnion, as water from above moves downwards. Increased temperature leads to increased biological decompositional activities, and also results in decreased solubility of oxygen. These two factors, combined accelerate the formation of the anoxic zone.

Anoxia in the hypolimnion of the lacustrine zone can be a result of any of the following conditions (Cole and Hannan 1990):

i) Anoxia developing in the hypolimnion as described above,

ii) Anoxic zone extending from the transition zone upstream,

iii) Anoxia formed as a result of metalimnetic oxygen minima, and,

iv) Anoxia forming first in coves with high epilimnetic-hypolimnetic ratio before it develops in the “thalweg” (the main channel of the reservoir). In this case, anoxia extends from the coves into the main body of the reservoir.

#### 3.4.3.6 Development of Anoxic Conditions in the Hypolimnion Under Different Flow Conditions

Anoxic conditions develop in the lake or reservoir differently under different flow conditions, which lead to variations in the zones of a lake or reservoir. Due to the variation in zonation, there is also variation in the development of anoxia in the hypolimnion of the lake or reservoir. Figure 10-12 display a schematic representation of the changes in zonation and the development of anoxia under these changed conditions, under different flow conditions.

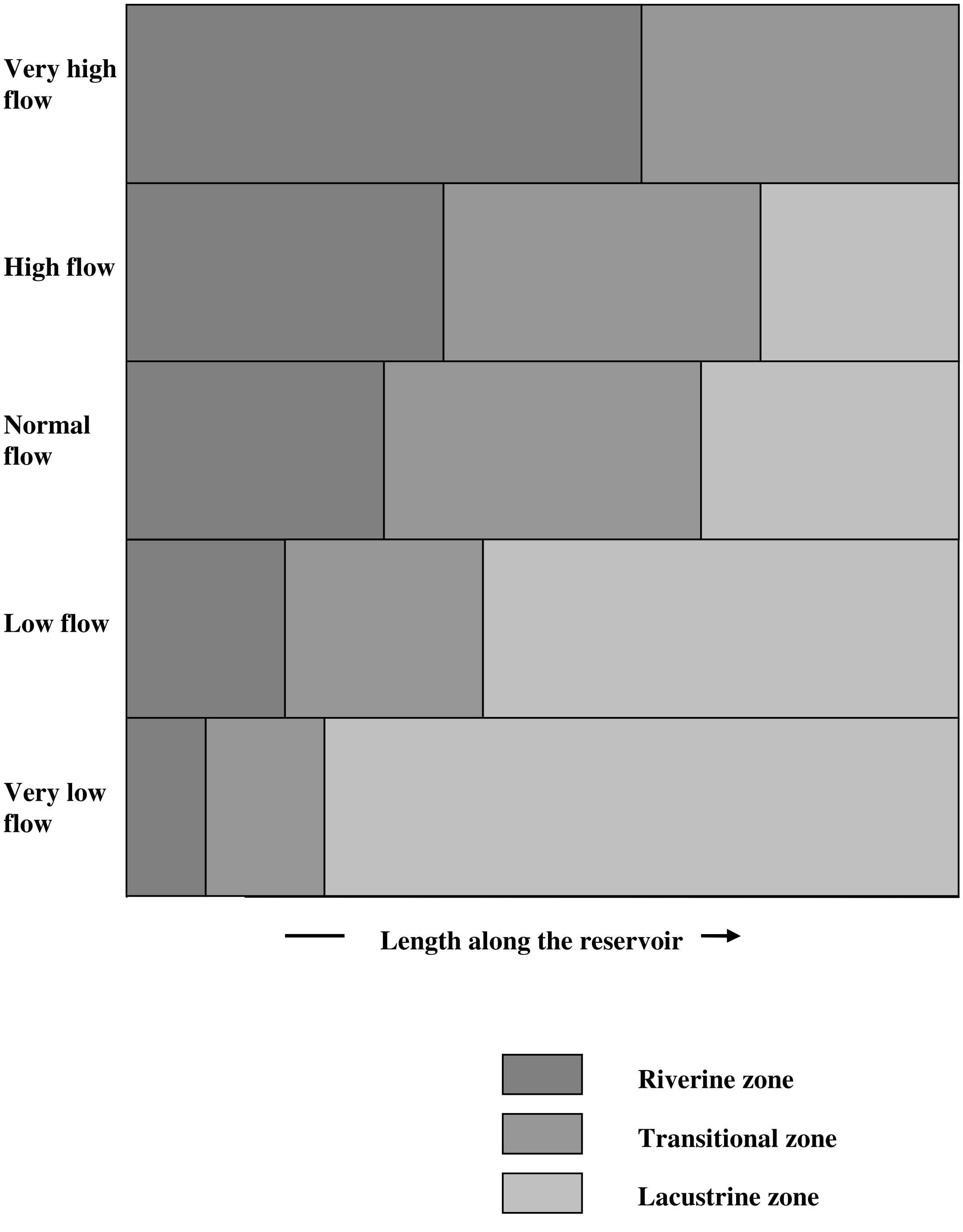

**Figure 10. Lake or reservoir zonation under different flow conditions.** Under very high flow conditions, the lacustrine zone may disappear entirely in run-of-the-river reservoirs.

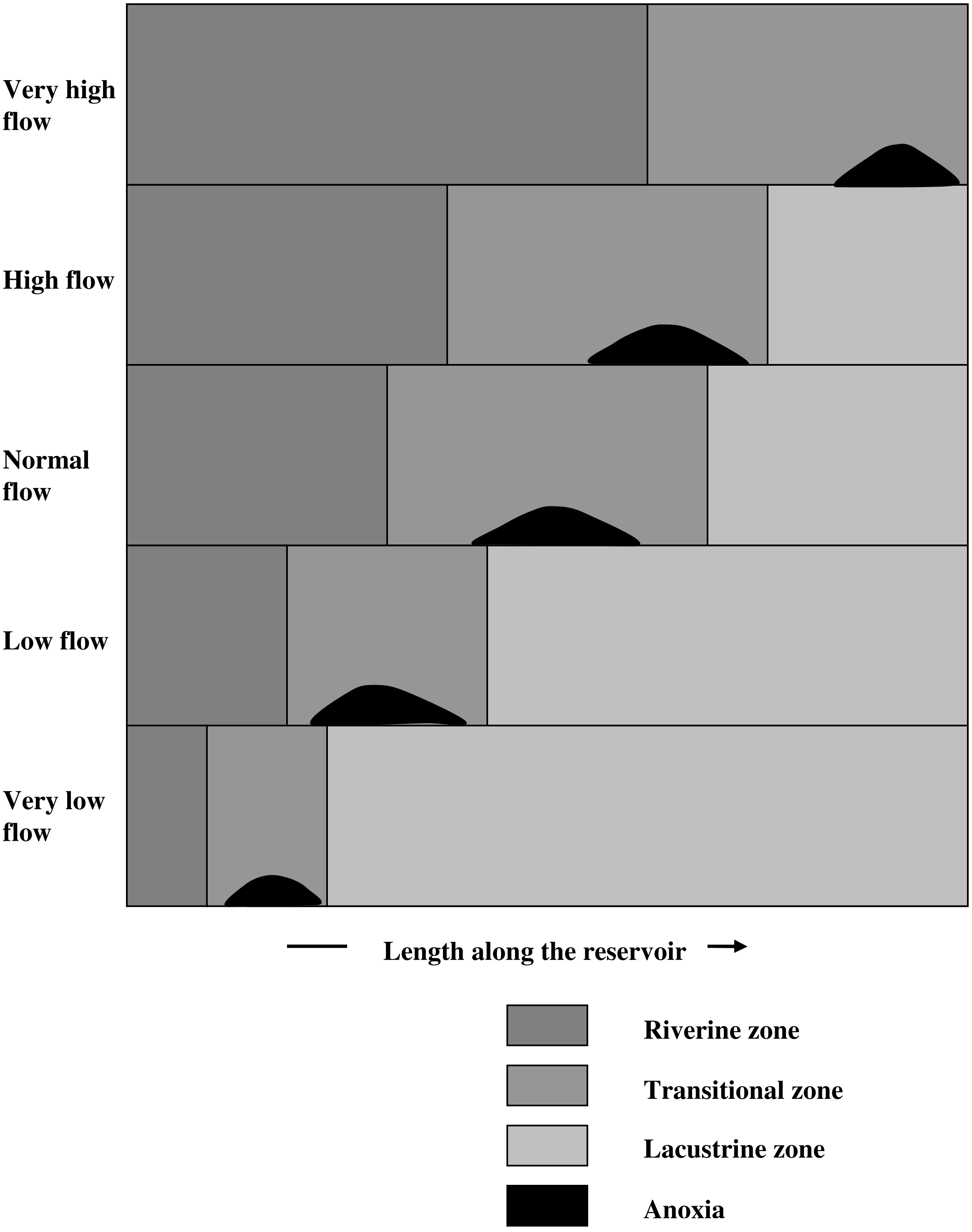

Figure 11. Anoxia in early to mid-summer in the hypolimnion of a lake or reservoir under different flow conditions.

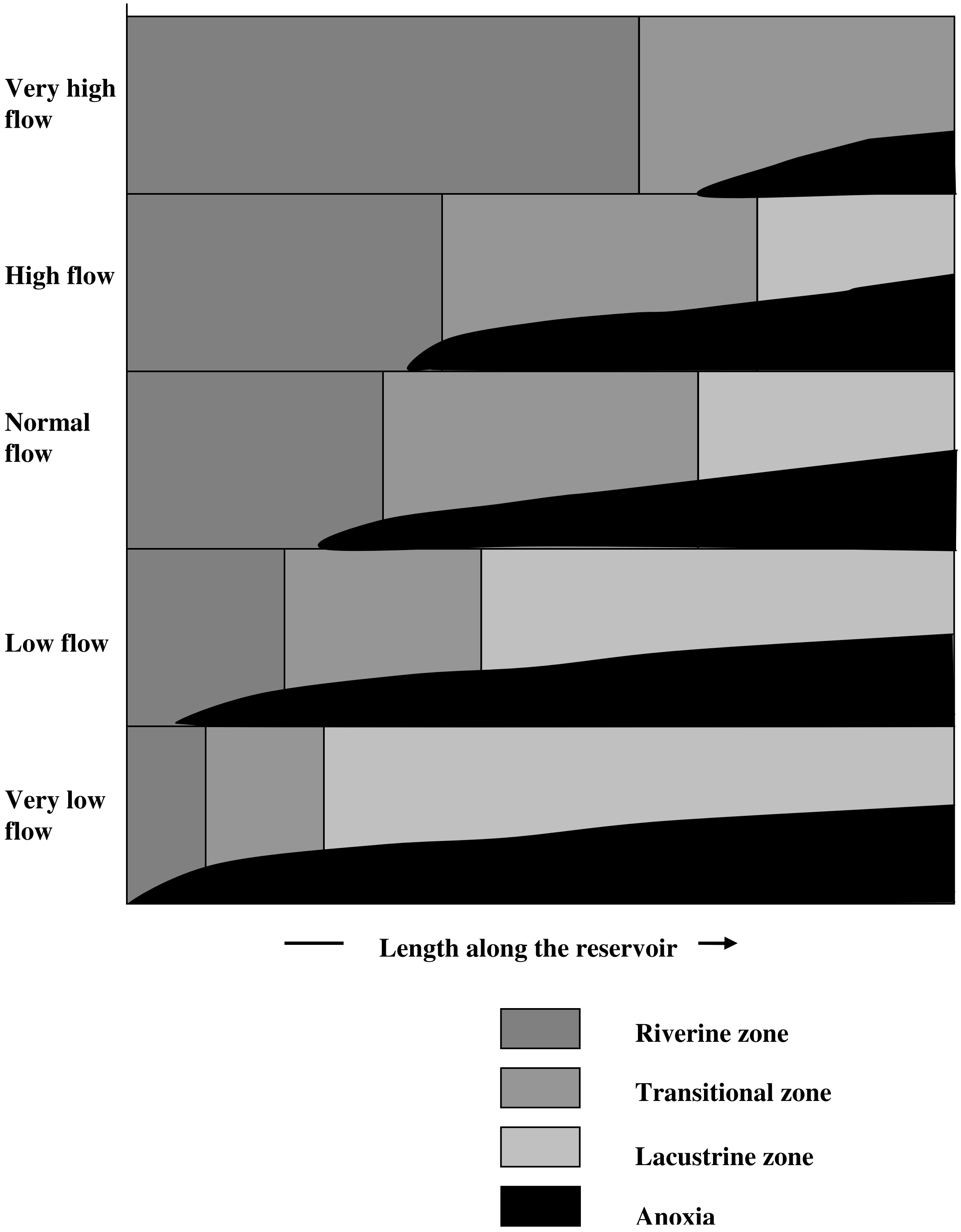

**Figure 12.** Anoxia in mid- to late summer in the hypolimnion of a lake or reservoir under different flow conditions.

### 3.4.3.7 Metalimnetic Oxygen Minima

Metalimnetic oxygen minima occur in most reservoirs. Sometimes there is a higher uptake of oxygen in the metalimnion as compared to the upper layers of the hypolimnetic waters, giving rise to a negative heterograde curve. This is referred to as the metalimnetic oxygen minima and it occurs generally in the lacustrine zone of deep storage reservoirs. The DO-depth profile to be expected in conditions of oxygen minima are shown in Figure 13. There are many possible explanations as to why oxygen minima occur.

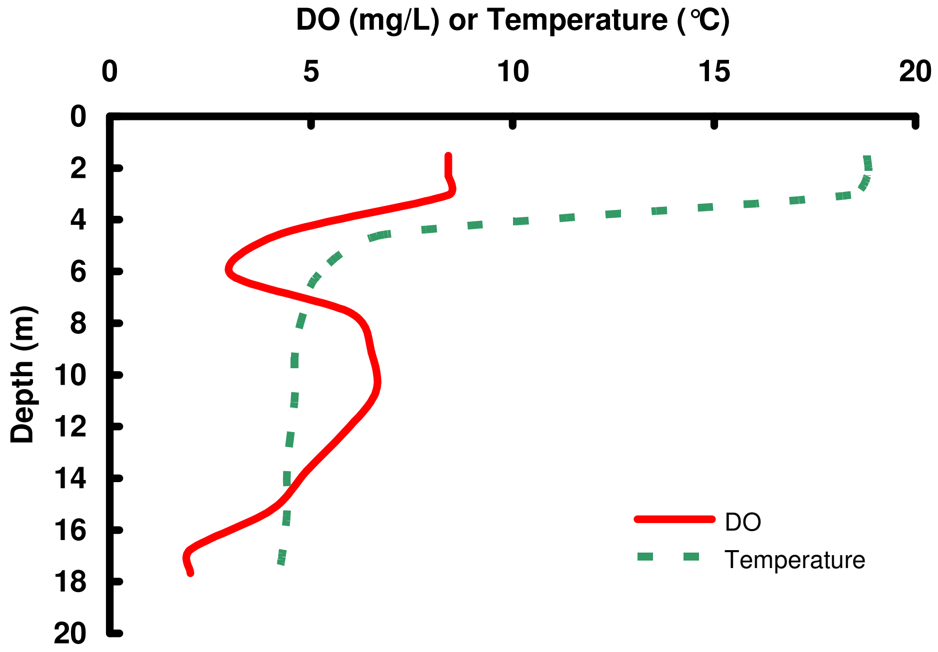

**Figure 13. Negative heterograde curve showing DO minima in the metalimnion.**

Depending on the existing conditions in the reservoir under consideration, one or more of the causes discussed below can be responsible for metalimnetic oxygen minima.

### *3.4.3.7.1 Decomposition of Seston*

Seston represents all particulate matter present in water, both biotic and non-biotic in origin. The presence of this material in water will make the layer more viscous. When seston drops out of the epilimnion, it often gets trapped in the metalimnion, making it more viscous. The easily-oxidizable materials are then oxidized by organisms, primarily phytoplankton and bacteria. Because the metalimnion is in the aphotic zone, photosynthesis does not occur, and the decomposition of organic matter depletes the layer of dissolved oxygen, creating metalimnetic oxygen minima (Hutchinson 1957; Shapiro 1960; Cole and Hannan 1990; Wetzel 2001).

### *3.4.3.7.2 Shelf Effect*

If the metalimnion comes in contact with the bottom of a reservoir having minimal slope, then a large volume of the metalimnetic water will be exposed to the sediments. The oxygen demand exerted by the sediments can cause metalimnetic oxygen minima. This is called the shelf effect (Hutchinson 1957; Shapiro 1960; Cole and Hannan 1990).

### *3.4.3.7.3 Interflow*

Interflows are density currents from the riverine reach of the reservoir. Interflows bring the allochthonous material into the reservoir and are often rich in organic matter and nutrients. When an interflow enters the metalimnion, the oxygen available may be expected to be utilized to decompose the organic matter, leading to DO depletion because oxygen is not replenished in the metalimnion as it is in the epilimnion. Despite the presence of nutrients in the interflow, however, the metalimnion is light-limited and does not support primary production. All these factors combined result in metalimnetic oxygen minima (Lyman 1944; Cole and Hannan 1990; Ford 1990).

#### *3.4.3.7.4 Withdrawal Currents*

Metalimnetic oxygen minima can also result from withdrawal currents resulting from outflow through a midlevel outlet. The currents generated from a midlevel outlet can force the hypolimnetic anoxic waters to enter the metalimnion, causing metalimnetic oxygen minima (Cole and Hannan 1990).

#### *3.4.3.7.5 Cove Effects*

As discussed earlier, anoxia can form in coves and bays. This anoxia from the coves and bays can extend into the metalimnion in the main body of the reservoir resulting in metalimnetic oxygen minima (Cole and Hannan 1990).

#### *3.4.3.7.6 Temperature Effect*

Photosynthesis, respiration and solubility of oxygen (which is temperature dependent) are key factors which play a major role in creating metalimnetic oxygen minima. In the epilimnion, photosynthesis makes up for the oxygen lost by respiration. As depth increases, photosynthesis decreases while respiration still continues. Below the metalimnion, respiration rates decrease due to decreased temperatures. Therefore, at the metalimnion, respiration can occur at a greater rate than photosynthesis. Also, the comparatively warmer waters mean less dissolved oxygen. All these factors together lead to the negative heterograde curve (metalimnetic oxygen minima) (Cole and Hannan 1990).

#### *3.4.3.7.7 Circulation Pattern*

Many studies have indicated that an oval circulation pattern is common in the epilimnion. It is by this circulation pattern that oxygen rich surface waters are transported to the bottom layers and the oxygen-depleted waters from the bottom are transported to the surface. This results in oxygenated waters surrounding a stagnant layer. Over a period of time, the stagnant cell of water can have very low DO (Cole and Hannan 1990).

### 3.4.3.8 Epilimnetic Oxygen Maxima

Epilimnetic oxygen maxima are a direct result of photosynthesis by rooted macrophytes in the littoral zone and phytoplankton blooms and are often a part of the diel DO pulse. The fluctuations in DO as a result of this pulse can vary from zero to over 200%. In the riverine zone of a reservoir both rooted macrophytes and phytoplankton are responsible for the epilimnetic oxygen maxima, though it is only during low flow conditions that stratification extends into the riverine reach of the reservoir. The phytoplankton productivity is at a maximum in the transition zone, and so are the values of epilimnetic oxygen maxima. In the lacustrine zone, phytoplankton productivity is nutrient-limited. Therefore, the epilimnetic oxygen maxima, too, vary accordingly and may be much less, except in the case of eutrophied reservoirs. Wind also plays a major role, as dispersing the phytoplankton blooms can affect the epilimnetic oxygen maxima (Cole and Hannan 1990).

#### 3.4.3.9 Metalimnetic Oxygen Maxima

Metalimnetic oxygen maxima are not observed in reservoirs as often as metalimnetic oxygen minima. Metalimnetic oxygen maxima are often referred to as the positive heterograde curve. A positive heterograde curve is shown in Figure 14. The causes of the metalimnetic oxygen maxima are listed below:

i) Lower temperatures in the metalimnion mean increased solubility of oxygen. The euphotic zone also can sometimes extend into the metalimnion. These two factors coupled together can result in metalimnetic oxygen maxima.
ii) Oxygen rich interflows can also cause metalimnetic oxygen maxima.

It is believed that the metalimnetic oxygen maxima precede the metalimnetic oxygen minima, which occur later in summer. During early spring, at the onset of stratification, when nutrient-rich interflows enter the metalimnion, the turbidity may be less as phytoplankton productivity and phytoplankton blooms may not be abundant. This can cause extension of the euphotic zone into the metalimnion. The presence of nutrients can trigger a phytoplankton bloom which can lead to the metalimnetic oxygen maxima. As summer progresses and the metalimnion becomes light-limited, this, combined with oxidation of the organic matter present there, results in oxygen depletion and the formation of metalimnetic oxygen minima (Cole and Hannan 1990; Wetzel 2001).

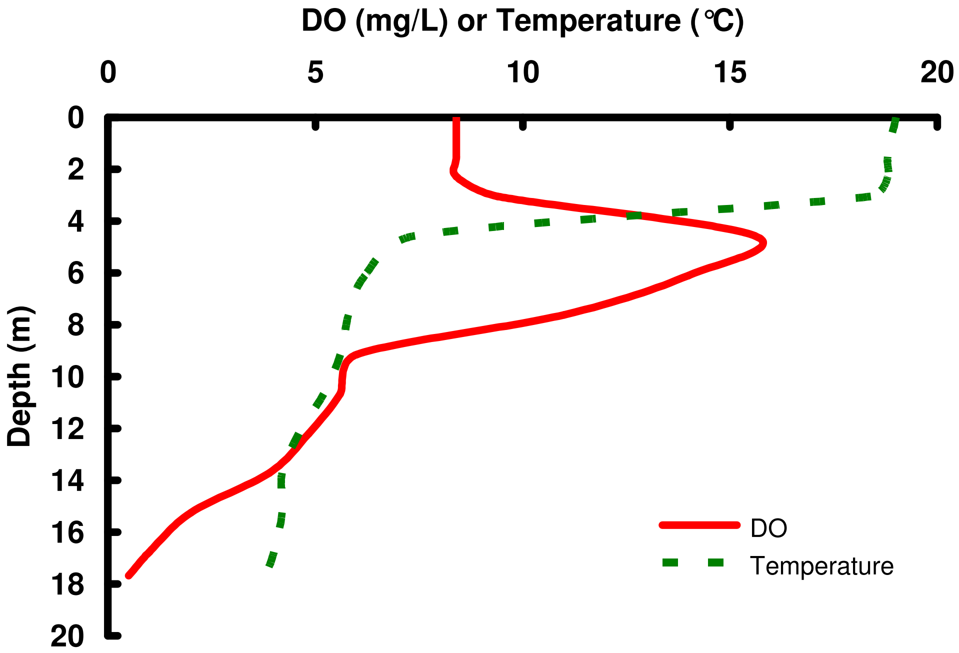

**Figure 14.** **Positive heterograde curve showing DO maxima in the metalimnion.**

### 3.4.3.10 Oxygen Block

An oxygen block could be the characteristic separating the lacustrine zone from the transition zone. An oxygen block in a reservoir is identified in Figure 15. The oxygen block refers to a column of water extending from the surface to the bottom surrounded on all sides with water having higher DO. Dye studies (Lawrence 1967 as cited in Cole and Hannan 1990) indicate that an oxygen block may be attributed to reverse density currents that on encountering inflowing water move upward, thereby carrying water low in oxygen to the surface. However, in most reservoirs, oxygen blocks can be missed if comprehensive sampling is not undertaken.

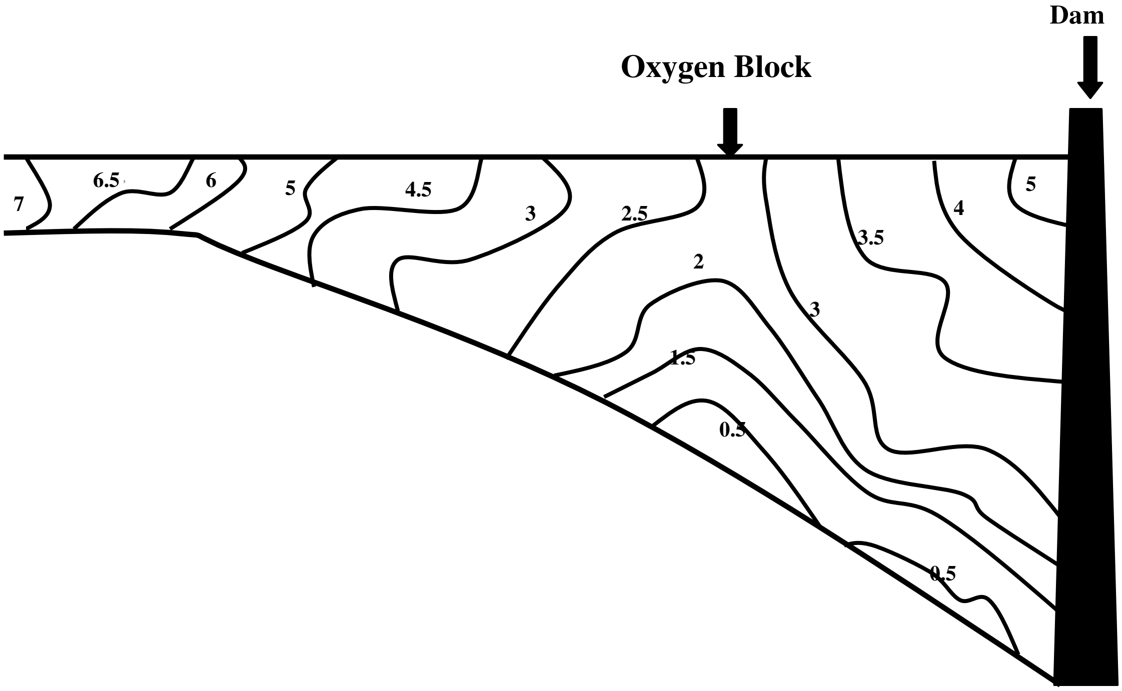

Figure 15. Isopleths of dissolved oxygen concentration (mg/L) showing oxygen block in the transition zone.

### 3.4.4 Penetration of Light (Euphotic Zone)

Light penetration plays an important role in lakes and reservoirs. Photosynthesis of phytoplankton in the water depends on availability of light. Hence, productivity in the reservoir is influenced by this parameter. Depending on the availability of light, there are two zones in the reservoir, namely, the photic and aphotic zones. These two zones are separated by the compensation depth.

#### 3.4.4.1 Euphotic Zone

The portion of the water column where phytoplankton photosynthesis is greater than phytoplankton respiration is known as the euphotic or photic or trophogenic zone (Kalff 2001). It is in this zone that primary production by phytoplankton takes place. The phytoplankton community, therefore, usually circulates within this zone.

#### 3.4.4.2 Compensation Depth

The bottom of the euphotic zone, where the phytoplankton photosynthesis just balances the respiration on a daily basis, is called the compensation depth. It is general practice to consider the compensation depth of the phytoplankton community to be the depth where one percent of the surface or immediate subsurface incident radiation remains (Kalff 2001).

#### 3.4.4.3 Aphotic Zone

Below the compensation depth is the aphotic or tropholytic zone (Kalff 2001). In this zone, there is none or very little light available. Therefore, productivity in this zone is almost non-existent.

#### 3.4.4.4 Factors Affecting Light Penetration

The factors that affect penetration of light in lakes and reservoirs are discussed below.

###### *3.4.4.4.1 Turbidity*

Turbidity results from suspended solids in water. It decreases the penetration of light in water. When light traveling through water is incident on these particles, they do not allow light to pass through, thereby reducing the depth of the photic zone greatly.

###### *3.4.4.4.2 Presence of Dissolved Organic Compounds*

The presence of dissolved organic compounds in water has a marked effect on the absorption of light. Lake waters which are rich in organic matter, especially humic substances (see section 3.4.9.4), reduce the transmission of light and shift absorption selectivity. Generally, most waters absorb infrared and red wavelengths, which can result in significant heating in the first meter depth. Presence of dissolved solids, even in small concentrations, increases UV absorbance greatly (Wetzel 2001). The effect of increased concentration of dissolved solids on light penetration is shown in Figure 16.

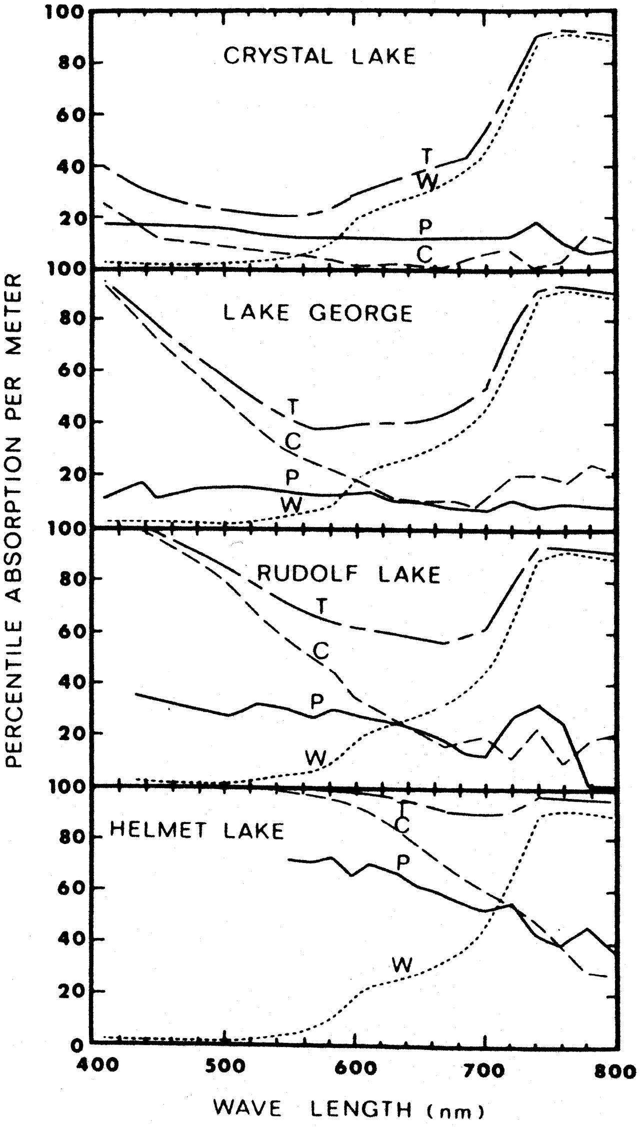

**Figure 16. Percentile absorption of light at different wavelengths in one meter of water in four lakes in Wisconsin arranged in order of increasing concentration of dissolved organic matter. T = total absorption; C = absorption by dissolved organic color; P = absorption by suspended particulate matter; W = absorption by pure water (Wetzel 2001).**
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### *3.4.4.4.3 Thickness of the Euphotic Zone ($z_{eu}$)*

The thickness of the euphotic zone is easily computed by setting $I_o = 100\%$ and $I_c = 1\%$ in the sequence of formulae given below: (Kalff 2001)

$z_{eu} = \ln 100 / k_d$

$= 4.6 / k_d$

Where,

$k_d$ = Vertical extinction or attenuation coefficient of incident light.

Now,

$I_z = I_0 e^{-k_d z}$

and,

$k_d = (\ln I_o - \ln I_z)/z$

or,

$k_d = 2.303(\log I_o - \log I_z)/z$

where,

$I_c$ = Compensation intensity.

$I_o$ = The light intensity over a specific wavelength interval just below the surface.

$I_z$ = The light intensity over a specific wavelength interval at a depth z below the surface.

z = Depth below the surface of water.

In the absence of underwater photocell or spectrophotometer measurements, $k_d$ is often estimated from the Secchi disc depth.

The most widely used equation is (Kalff 2001):

$k_d \times Z_{SD} = 1.7$

$Z_{SD}$ = Secchi depth.

Koenings and Edmundson (1991) observed that there is no fixed conversion factor but that values vary between 0.5 and 3.8. The long-used conversion factor of 1.7 is very near the median value of 1.9. It was developed for transparent lakes low in color ($<10$ mgPt·l$^{-1}$) and turbidity ($\leq 5$ NTU) (Kalff 2001). Table 3, below, shows comparative values for these parameters.

**Table 3. Comparison of euphotic zone parameters.**

| **Parameter** | **Median conversion factor** | | |
|---|---|---|---|
| | **Humic** | **Clear** | **Turbid** |
| $k_d \times Z_{SD}$ | 3.0 | 1.9 | 1.3 |
| $z_{eu} / Z_{SD}$ | 1.3 | 2.4 | 3.3 |

**Source:** (Koenings and Edmundson 1991). © (2008) by The American Society of Limnology and Oceanography, Inc. Used with permission.

The relationship between the transparency ($Z_{SD}$, in meters) and $k_d$ and $z_{eu}$, computed based on the equation $z_{eu} = 4.6/ k_d$ for non-humic mesotrophic lake, is as follows (Wetzel 2001):

$\text{Log } k_d = 0.058 - 0.61 \log Z_{SD}$ ( $r^2 = 0.87$; $n = 142$).

### 3.4.4.5 Definition of Color Units

Color units are widely used in defining the color in water bodies. Color is caused mostly by the presence of humic substances. The Platinum unit (Pt) is the most widely used comparative scale for color in the United States. It is defined as follows:

“1000 Pt units is the color from 2.492 g potassium hexachloroplatinate ($K_2PtCl_6$), 2 g cobaltic hexahydrate ($CoCl_2.6H_2O$), 200 ml of concentrated hydrochloric acid (HCl), and 800 ml water. The Color units are best examined spectroscopically at 410 nm, calibrated against Pt-Co reference solutions” (Wetzel 2001).

### 3.4.4.6 Light Penetration in the Riverine Zone

The riverine zone receives water directly from the parent river and is narrow and shallow. This zone, therefore, gets all the materials washed away from the watershed and has a relatively high concentration of suspended solids, when compared to the other zones. The velocity of flow is higher here. Therefore, though the larger particles settle out, the finer particles remain suspended. Although this zone is completely mixed, penetration of light is reduced due to the presence of suspended particles, resulting in limited productivity.

### 3.4.4.7 Light Penetration in the Transitional Zone

In the transitional zone, the river channel widens out and becomes deeper. This causes a reduction in the velocity of flow. As a result of this reduction, sedimentation of silts and coarser clays is high is this zone. The greater clarity created by sedimentation results in higher light penetration, which supports increased productivity of phytoplankton.

#### 3.4.4.8 Light Penetration in the Lacustrine Zone

The lacustrine zone is deep and wide. The flow rate of water is lowest in this zone. All the fine particles like fine silts and clays settle out here. The water is, therefore, free of suspended solids and penetration of light is highest in this zone. Light conditions in this zone are optimal for phytoplankton productivity but other factors such as availability of nutrients might limit it (Kimmel et al. 1990). In eutrophic lakes, there can be high phytoplankton productivity in this zone also, and light penetration will be reduced because of this.

### 3.4.5 Trophic State

The trophic state of a water body is an indicator of how healthy and balanced a water body is. Very often, as a result of increased human activity, there is increased loading of nutrients and other pollutants from the watershed into the water body. This can result in increased productivity, decrease in the diversity of the existing communities, inability of organisms to adapt their metabolism to increased loadings, and, in general, an imbalance in the ecosystem. All these together degrade a stable environment. Different terms are used to define the trophic state of a water body. These terms are defined below.

**Trophy** of a lake refers to “the rate at which organic matter is supplied by or to the lake per unit time” (Wetzel 2001).

**Eutrophication** indicates increased productivity and nutrient content in a lake or reservoir (Thornton et al. 1990; Wetzel 2001).

**Oligotrophic** means “poorly nourished”. Oligotrophic lakes therefore have low productivity and nutrient content (Thornton et al. 1990; Wetzel 2001).

**Mesotrophic** lakes have higher productivity than oligotrophic lakes but lesser productivity than eutrophic lakes (Wetzel 2001).

### 3.4.5.1 Trophic State Index (TSI)

Phytoplankton biomass is used as a basis for determining the trophic state of lakes and reservoirs under both nutrient-limiting and non-nutrient-limiting conditions. Algal biomass can be estimated in one of three ways, namely, chlorophyll pigment concentrations, Secchi depth, and total phosphorus concentrations. The studies carried out by Carlson (1977) indicate that total phosphorus may be better than chlorophyll at predicting summer trophic states from winter samples, and transparency should be used only if no better data are available. According to Carlson (1977):

$$\text{TSI (SD)} = 60 - 14.41 \ln (\text{SD})$$

TSI (CHL) = 9.81 ln (CHL) + 30.6

TSI (TP) = 14.42 ln (TP) + 4.15

where,

SD = Secchi depth transparency (m)

CHL = Chlorophyll pigment concentrations ($mg{\cdot}m^{-3}$)

TP = Total phosphorus concentrations ($mg{\cdot}m^{-3}$)

Each model predicts the trophic state based on a different parameter. Therefore, these values should not be averaged. TSI values associated with the different parameters are listed in Table 4.

**Table 4. Completed trophic state index and its associated parameters.**

| TSI | Secchi depth (m) | Surface phosphorus ($mg/m^3$) | Surface chlorophyll *a* ($mg/m^3$) |
|---|---|---|---|
| 0 | 64 | 0.75 | 0.04 |
| 10 | 32 | 1.5 | 0.12 |
| 20 | 16 | 3 | 0.34 |
| 30 | 8 | 6 | 0.94 |
| 40 | 4 | 12 | 2.6 |
| 50 | 2 | 24 | 6.4 |
| 60 | 1 | 48 | 20 |
| 70 | 0.5 | 96 | 56 |
| 80 | 0.25 | 192 | 154 |
| 90 | 0.12 | 384 | 427 |
| 100 | 0.062 | 768 | 1,183 |

**Source:** Carlson (1977). © (2007) by American Society of Limnology and Oceanography, Inc. Used with permission.

TSI values indicate the following (Carlson 1977; Carlson 1980; Wetzel 2001):

$TSI < 30$ – Classical oligotrophy
$30 \leq TSI < 50$ – Classical mesotrophy
$50 \leq TSI < 70$ – Classical eutrophy
$TSI \geq 70$ – Hypereutrophic conditions

### 3.4.5.2 Secchi Depth

A Secchi disc is a white or black and white disc, which is generally 20 cm in diameter. It is attached to a marked line and lowered. The depth where it just disappears or reappears provides a measure of the transparency of a lake or reservoir. Larger discs (75 – 100 cm) are used on deep lakes and in oceans (Kalff 2001).

Secchi disc depth is measured by observing the depth at which the disc, when lowered from the surface, just disappears from view. These observations must also be made in a shaded area of the water surface to account for any discrepancies that can occur due to change in light conditions. Once the point of disappearance is determined, the disc is allowed to drop further and then it is pulled upwards and the depth of reappearance of the disc is determined. The mean of the two readings is taken as the Secchi depth. These observations should preferably not be made early in the morning or late in the afternoon as light conditions can be poor at those times, and might affect the Secchi depth measured (Hutchinson 1957).

Secchi depths are indirect measurements of the productivity and, hence, the trophic status, of a lake. Table 5, contains the relationship of Secchi depths in lakes and the trophic state.

**Table 5. Secchi disc transparency and trophic classification of non-humic lakes (lakes which are not high in organic content) and lowland rivers low in inorganic suspended matter.**

| **Trophic state** | **Transparency (m)** | |
|---|---|---|
| | **Mean** | **Minimum** |
| Ultra-oligotrophic | ≥12 | ≥6 |
| Oligotrophic | ≥6 | ≥3 |
| Mesotrophic | 6 – 3 | 3 – 1.5 |
| Eutrophic | 3 – 1.5 | 1.5 – 0.7 |
| Hypertrophic | ≤1.5 | ≤0.7 |

**Source:** OECD (1982). ©OECD. Used with permission.

### 3.4.5.3 Review of Distinctions Between Oligotrophic and Eutrophic States

Table 6 contains a listing of the differences between oligotrophic and eutrophic states, and serves as a summary of the differences for various characteristics. The table is derived from Rast and Lee (1978).

**Table 6. Differences between oligotrophic and eutrophic states for various parameters.**

| **Characteristic** | **Oligotrophic** | **Eutrophic** |
|---|---|---|
| Aquatic Plant production | Low | High |
| Diversity of algal species | Many species but generally in small numbers | Few species but generally in large numbers |
| Characteristic of algae groups | Varied | Summer blue- green algae dominance |
| Rooted aquatic plants | Sparse | Abundant |
| Oxygen in hypolimnion | Present | Absent during part of summer |
| Fish species | Deep dwelling, cold water types (trout, salmon, cisco) | Surface dwelling warm water fish (pike, perch bass) and bottom dwelling fish (carp, catfish) |
| Water quality for domestic use | Good | Poor (especially in summer) |

**Source:** Adapted from Rast and Lee (1978).

### 3.4.5.4 Primary Productivity and Trophic State Indices

Phytoplankton are the major primary producers in reservoirs. Their productivity can be used as a measure of the trophic state of the reservoir. Eutrophic environments are often associated with high productivity, which is a direct result of increased nutrient loading. Primary productivity and other related characteristics of lakes as related to different trophic states are given in Table 7.

**Table 7. Trophic state based on phytoplankton productivity and other related parameters.**

| **Trophic condition** | **Mean primary productivity (mg C $m^{-2}$ $day^{-1}$)** | **Phytoplankton density ($cm^3$ $m^{-3}$)** | **Phytoplankton biomass (mg C $m^{-3}$)** | **Chlorophyll *a* (mg $m^{-3}$)** | **Dominant phytoplankton** | **Light extinction coefficients ($nm^{-1}$)** | **Total organic carbon (mg $liter^{-1}$)** | **Total P (µg $liter^{-1}$)** | **Total N (µg $liter^{-1}$)** | **Total inorganic solids (mg $liter^{-1}$)** |
|---|---|---|---|---|---|---|---|---|---|---|
| Ultraoligotrophic | < 50 | <1 | <50 | 0.01 – 0.5 | | 0.03 – 0.8 | | < 1 – 5 | < 1- 250 | 2 – 15 |
| Oligotrophic | 50 – 300 | | 20 – 100 | 0.3 – 3 | Chrysophyceae, Crytophyceae, | 0.05 – 1.0 | < 1- 3 | | | |
| Oligomesotrophic | | 1 -3 | | | Dinophyceae, Bacillariophyceae | | | 5 – 10 | 250 – 600 | 10 – 200 |
| Mesotrophic | 250 – 1000 | | 100 – 300 | 2 – 15 | | 0.1 – 2.0 | < 1-5 | | | |
| Mesoeutrophic | | 3 - 5 | | | | | | 10 – 30 | 500 - 1100 | 100 - 500 |
| Eutrophic | >1000 | | >300 | 10 – 500 | Bacillariophyceae, Cynobacteria | 0.5 – 4.0 | 5 – 30 | | | |
| Hypereutrophic | | >10 | | | Chlorophyceae | | | 30 - >5000 | 500 - >5000 | 400 – 60,000 |
| Dystrophic | <50 – 500 | | <50 – 200 | 0.1 – 10 | | 1.0 – 4.0 | 3 – 30 | <1 – 10 | <1 – 500 | 5 - 200 |

**Source:** (Likens 1975) © Likens, G. E.. Used with permission.

### 3.4.5.5 Vollenweider’s Diagram

Vollenweider’s diagram can be used to determine the trophic state of reservoirs. Vollenweider’s diagram was developed based on data from north-temperate-zone natural lakes and 18 Tennessee Valley Authority (TVA) tributary storage and mainstream reservoirs (Kimmel et al. 1990). It relates phosphorus loading to the ratio of mean depth/residence time. Based on these two parameters, it can be determined from Figure 17, whether the condition existing in the lake is eutrophic, mesotrophic or oligotrophic.

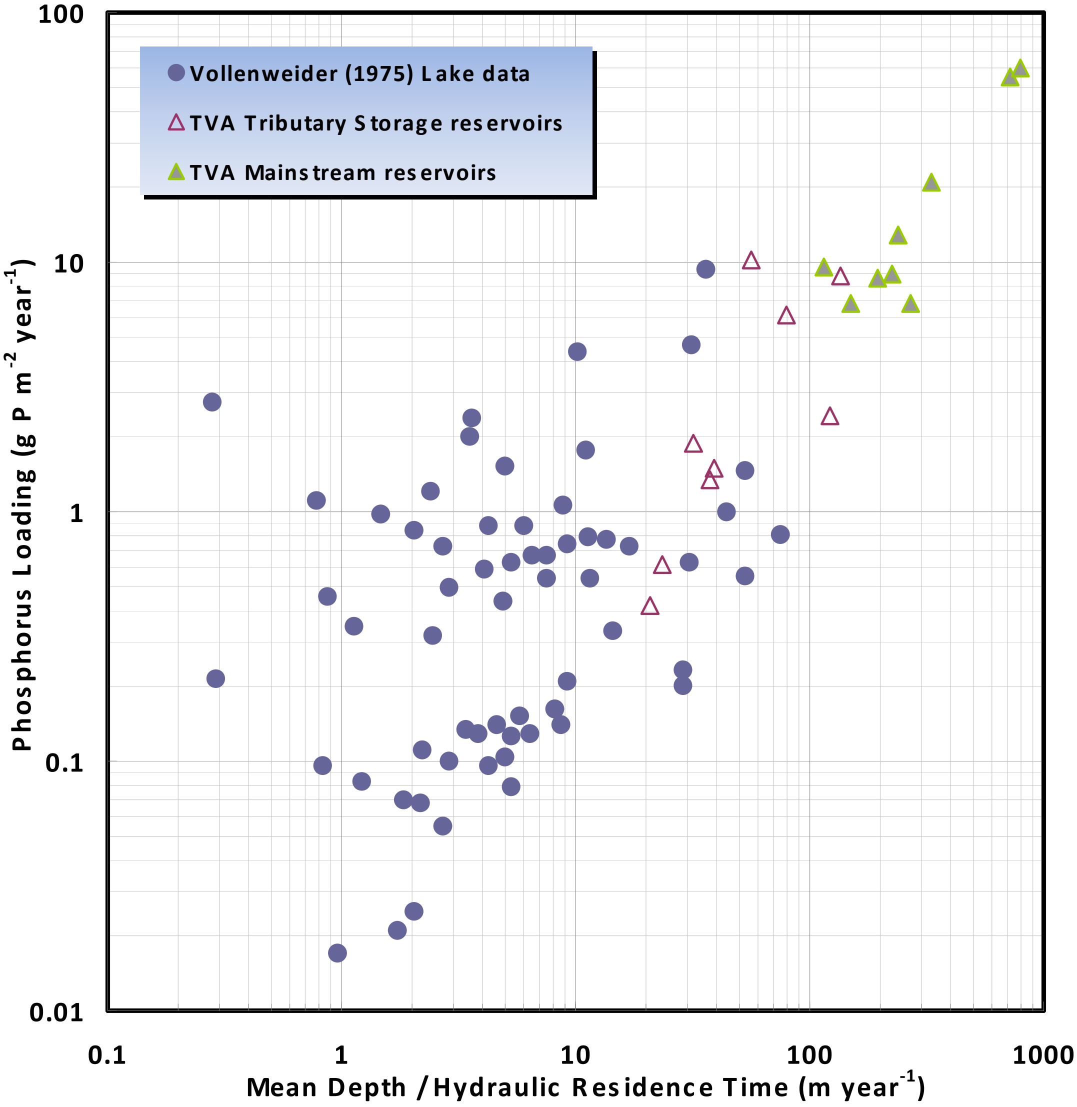


**Figure 17. Vollenweider's diagram** (Redrawn with data from Kimmel et al. 1990).

### 3.4.6 Deposition of Sediments Along the Lake or Reservoir

Reservoirs are generally built by damming rivers. When compared with natural lakes, reservoirs have a larger drainage area. A larger drainage area increases the potential for interception and/or deposition of transported particulate matter within the drainage area.

Thornton (1990) in his studies on reservoirs found the relationship between sediment delivery ratio and watershed area to be logarithmic, not linear, so the amount of sediments delivered to the reservoir increases considerably with increase in size of the watershed. Sediment is not only the major pollutant in reservoirs, but also a carrier of pesticides, fertilizers, organic residues, nutrients and pathogenic organisms from the drainage basin. Sediment influx into a reservoir varies seasonally and is at a maximum during a storm event.

#### 3.4.6.1 Deposition of Sediments in the Riverine Zone

When compared with the parent river, water velocity and turbulence begins to decrease in the riverine zone of a reservoir. Reduced velocities lead to reduced sediment carrying capacity. These high rates of deposition, combined with shallow depth, often lead to formation of deltas in the upper portion of reservoirs. An example given by Thornton (1990) is that of Lake Mead where the delta advanced 42 miles into the reservoir over a 13 year period from 1935 to 1948. The riverine zone of a reservoir is long and narrow and confined mostly to the old river channel (often referred to as the thalweg). The lateral dimensions remain largely the same throughout this zone. So the rate of delta propagation and deposition of sediments is often in the longitudinal direction.

#### 3.4.6.2 Deposition of Sediments in the Transitional Zone

In the transitional zone the width of the channel increases. With increase in width and depth, there is a decrease in the velocity of flow. Reduced flow rates and higher residence times result in more of the finer sediments being deposited in this zone. The primary productivity is highest in this zone, resulting in higher sedimentation due to increased presence of biomass (Thornton 1990; Wetzel 2001). Increased primary production and higher residence times lead to the highest deposition of sediments. A schematic comparison of the sedimentation rate in the transition zone to that in the riverine and lacustrine zones is shown in Figure 18.

### 3.4.6.3 Deposition of Sediments in the Lacustrine Zone

The deposition of sediments decreases exponentially down the reservoir to the dam. There is very little deposition of sediments in the lacustrine zone. Thornton (1990) reinforces this with the example of a sedimentation study conducted on Lake Red Rock, Iowa, seven years after impoundment. It was observed that, over the seven year period, about 8 m of sediments had been deposited in the upper or riverine portion of the reservoir, as compared with less than 1 m of sediments in the lower or lacustrine portion of the reservoir. Thornton also mentions several other examples which demonstrate an order of magnitude difference between the sedimentation rates in the riverine zone and the lacustrine zone. In the study at Lake Red Rock, the sedimentation rate in the headwater or riverine zone was 19.1 cm/yr, and 1.4 cm/yr near the dam or in the lacustrine zone (Thornton 1990). Thornton also mentions findings where the sedimentation rates in the riverine zone were 8 cm/yr in the riverine zone and 0.34 cm/yr in the lacustrine zone. A schematic comparison of the sedimentation rates in the different zones is shown in Figure 18.

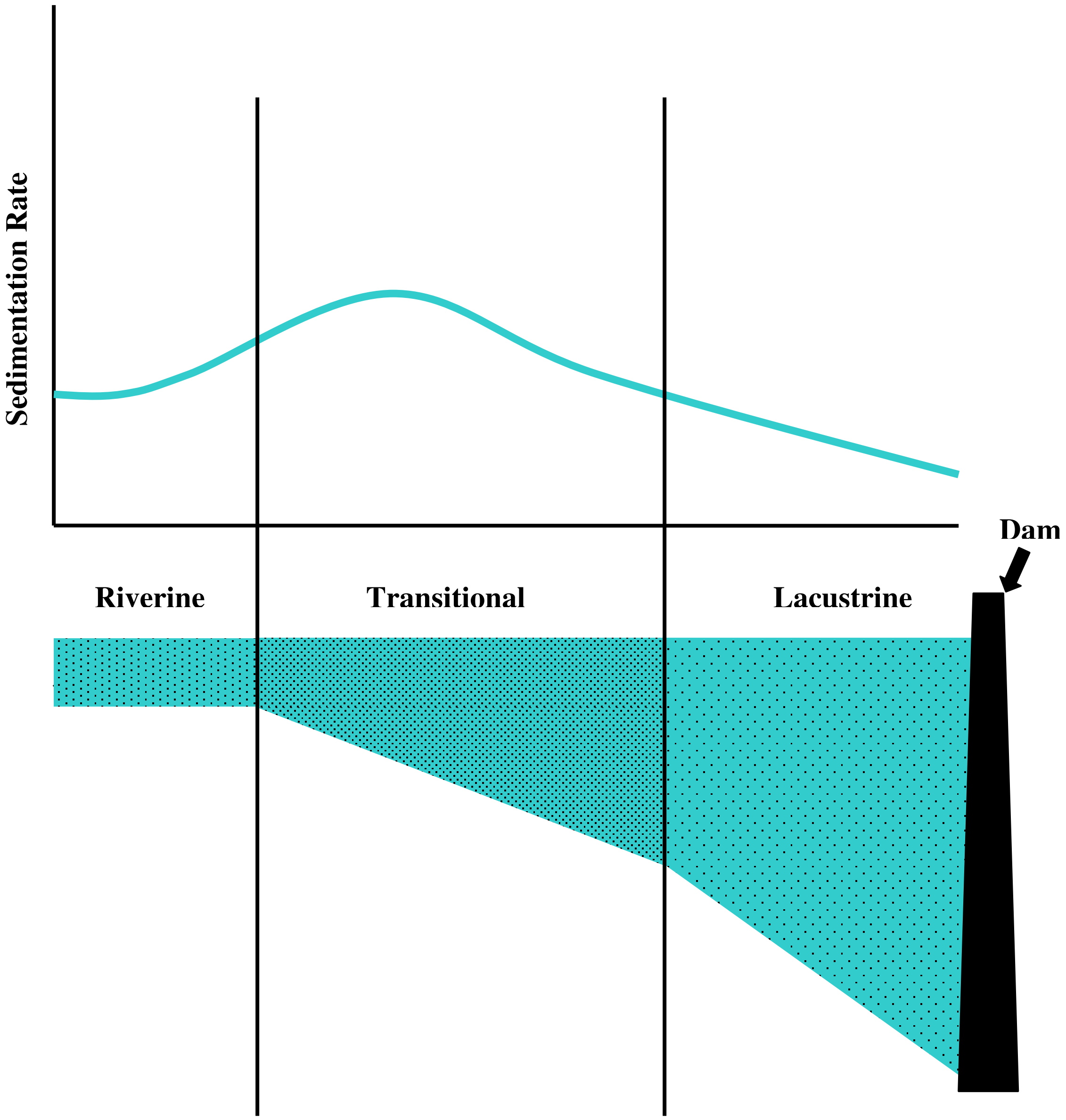


**Figure 18.** **Variation of sedimentation rates along a reservoir.**

### 3.4.6.4 Settling Rates of Different Particles

Particles which are larger in size have higher settling rates and settle out first. A list of the settling rates of different particles is given in Table 8. The values given there reinforce the concept of a decrease in settling rates with a decrease in the size of particles.

**Table 8. Settling rate of inorganic particles of the same density and different diameters under laminar-flow conditions.**

| Particle type | Particle diameter (µm) | Settling rate(m.d$^{-1}$) |
|---|---|---|
| Fine sand | 125 – 250 | 950 – 2,246 |
| Very fine sand | 62 – 125 | 225 – 950 |
| Coarse silt | 31 – 62 | 57 -225 |
| Medium silt | 16 – 31 | 16 – 57 |
| Fine silt | 8 – 16 | 4 – 16 |
| Very fine silt | 4 – 8 | 1 – 4 |
| Coarse clay | 1 – 4 | 0.1 – 1 |
| Fine clay | 0.1 | 0.001 |

**Source:** NVPDC (1980).

From the settling rates given in Table 8, it can be determined, which particles settle out first and which particles settle out last. This in turn explains the decrease of sedimentation rates along the reservoir from the headwaters to the dam. The riverine zone is shallow and the flow rate there is high, an indication of low residence time. Under these conditions, particles with high settling rates settle out. In the transitional zone, finer particles settle out. As the depth of a reservoir increases, the particles have to travel a longer distance to reach the bottom bed. The longer settling distance, combined with lower settling rates due to the finer sizes of the particles, results in a lower sedimentation rate for abiogenic particulate matter. However, productivity is often highest in this zone and contributes significantly to sediments deposited in the lake bed in the form of biomass. As a result, the total deposition of sediments is highest in the transitional zone. The lacustrine portion is the deepest and furthest away from the headwaters. Most of the coarser sediments will have settled out before reaching this zone. What remains are the fine silts and clay particles which have very low settling rates. These very low settling rates, combined with deep waters, result in significantly lower deposition of sediments in this zone. Eutrophied water bodies, however, may have high productivity even in the lacustrine zone, and, thus, may have higher sediment deposition in the zone.

The Stokes law equation, named for George Gabriel Stokes, is used to calculate the settling velocity of particles. The modified Stokes equation for algae (using terms r and D as applied to algae) is (Hutchinson 1967):

$$V=\left(\frac{2}{9}\right)\frac{g\times r\times r(D-D')}{n\times\Phi}$$

where,

V = Settling velocity

g = Acceleration due to gravity (980 $cm\cdot s^{-2}$)

r = Radius of a sphere of identical volume as algae

D = Density of algae

D′ = Density of water

n = Coefficient of viscosity of water

Φ = Coefficient of form resistance (a measure of the deviation of a particle from a sphere of the same volume).

The Stokes law equation for algal settling assumes laminar flow, with a Reynolds number (see below) of less than 0.5. Also, with r replaced by d, the particle diameter, and D replaced by the particle density, the above equation is used to compute the sedimentation rates of particles.

The Reynolds number (Re), named for Osborne Reynolds, is a dimensionless quantity which determines whether the flow is laminar or turbulent. It is defined as the ratio of inertial forces to viscous forces.

$$\begin{aligned} Re &= (\rho\, v_s\, L) / \mu \\ &= (v_s\, L) / \upsilon \end{aligned}$$

where,

$v_s$ = Mean fluid velocity

$\rho$ = Fluid density

$L$ = Characteristic length

$\mu$ = Dynamic fluid viscosity

$\upsilon$ = Kinematic viscosity ($\mu/\rho$).

### 3.4.7 Properties of Sediments Along the Lake or Reservoir

The deposition of sediments decreases exponentially along the length of a reservoir, with the maximum deposition taking place in the upper portions of the reservoir (riverine and transitional zones), and the least occurring near the dam, or the lacustrine zone, of the reservoir. As the deposition of sediments occurs longitudinally across the reservoir, sorting of the sediments based on size of particulate matter, too, takes place longitudinally. Diminishing velocities and decreasing turbulence contribute to this particle size sorting. The heavier sands and the coarser silts are the first to settle out, followed by the silts and coarse clay, and finally the fine clays and colloidal matter. Thornton (1990) provides an example of sorting of sediments according to particle size along the longitudinal axis of the reservoir. In the Callahan reservoir (Thornton 1990), it was found that in the upper portion or the riverine zone the sediment size distribution was as follows: 5% sand, 76% silt and 19% clay. In the middle of the reservoir (the transitional zone) the composition of the sediments was <1% sand, 61% silt and 38% clay. The composition of sediments near the outlet or in the lacustrine region of the reservoir was found to be 0% sand, 51% silt and 49% clay. This is in agreement with the settling of sediments according to particle size along the longitudinal axis of the reservoir.

#### 3.4.7.1 Composition of Sediments in the Riverine Zone

The heavier sands and the coarser silts are the first to settle out. Coarse Particulate Organic Matter (POM), too, settles out in the riverine zone. POM basically consists of potamoplankton (i.e., plankton of the rivers) or exported periphyton. Reduced velocities, even when combined with high turbulence, can no longer maintain the algal cells in suspension. Due to high turbidity, there is reduced penetration of light, hence low photosynthesis. The algal cells settle out. Apart from this, there are also terrestrial detrital inputs to a reservoir from streams further up. Upstream conditions and land use both influence the quantity and quality of the sediment and organic matter loads into the reservoir. Thornton (1990) provides an example of the composition of a sediment sample from the riverine zone of Watt Bar Lake, Tennessee, where the sediment sample contained leaves, stem and twigs, interlaid and mixed with clastic sedimentary layers.

### 3.4.7.2 Composition of Sediments in the Transitional Zone

In the transitional zone, silts, coarse to medium clays and fine POM settle. These particles, although not having as high a sorptive capacity as fine clay, are still responsible for adsorbing particulate phosphorus, organic carbon, iron (III), manganese (IV), calcium carbonate and other elements, and transporting them to the sediments. During summer, when the reservoir is stratified, the transition zone often develops a thin hypolimnion which might be anoxic. Anoxia in the hypolimnion has several implications. It can cause release of phosphorus, manganese (II), iron (II) and sulfide from the sediments into the water column above. This results in an increased concentration of dissolved constituents and higher ionic strength, which, in turn, results in increased flocculation of sediments (Thornton 1990). Stream sediments also have a higher capacity to adsorb particulate matter than the associated watershed soil. This has been attributed to the enrichment of clay with iron, and, then their chemical alteration during anoxic conditions, followed by resuspension, oxidation and hydration of iron-clay particles. Clay particles also absorb dissolved organic compounds.

All these factors together make the transition zone very dynamic. A continuous cycle is in play here, starting with adsorption of particulate matter by clay, deposition into the sediments, developing of anoxia, release of phosphorus, manganese (II), iron (II) and sulfide back into the water column, which increases the ionic strength, which further increases the rate of sedimentation. Besides this mechanism, high productivity in this zone also contributes to the sediment load.

### 3.4.7.3 Composition of Sediments in the Lacustrine Zone

Sediments in the lacustrine zone contain fine clay, colloidal particles and autochthonous organic matter (Thornton 1990). During the summer months, anoxia develops in the hypolimnion. Anoxia in the hypolimnion can cause the release of phosphorus, manganese (II), iron (II), and other elements adsorbed to the clay particles, back into the water column. Although this increases the ionic strength in the water column, it does not significantly increase deposition of sediments, because, before reaching this zone, most of the sediments have settled out and what remains are the very fine sediments which have low settling rates. Low settling rates, combined with deeper water, result in very little deposition.

### 3.4.7.4 Dissolved Oxygen Over Sediments in the Riverine Zone

Sediments in the riverine zone contain sand, coarse silts, POM and allochthonous organic matter. This organic matter is readily processed by microbial organisms at the sediment bed and supports a food web of benthic shredders, grazers and omnivorous fishery. Even though community respiration is high, the riverine zone is aerobic because it is shallow and well-mixed (Thornton 1990).

#### 3.4.7.5 Dissolved Oxygen Over Sediments in the Transitional Zone

When the reservoir stratifies in summer, the hypolimnion in the transitional zone is generally thin. Microbial activity in the sediments quickly depletes the oxygen in the hypolimnion, and anoxia results. The anoxic condition initially starts developing in the upstream portion of the reservoir, and then gradually spreads downstream as stratification progresses throughout summer (Thornton 1990). As the water in the hypolimnion does not mix with the well-aerated waters above, dissolved oxygen is not replenished. Dissolved oxygen concentrations are, therefore, very low over the sediments during the period of summer stratification.

#### 3.4.7.6 Dissolved Oxygen Over Sediments in the Lacustrine Zone

The organic matter in the sediment exerts an oxygen demand on the hypolimnetic waters, resulting in anoxia. For deep reservoirs with strong stratification, anoxic conditions prevail throughout summer, as long as stratification exists. In shallow reservoirs, or moderately deep reservoirs with bottom withdrawal and weak stratification, there may be some mixing in the hypolimnion, and, consequently, there is some limitation to the development of anoxic conditions (Thornton 1990). Once anoxic conditions develop, there is very little dissolved oxygen in the water column above the sediments.

### 3.4.7.7 Depository Boundary Depth

The deposition of sediments in lakes can be divided into three zones, namely, the zone of sediment erosion (ZSE), the zone of discontinuous sediment accumulation (ZDA, also known as the zone of transportation), and the zone of sediment accumulation (ZSA). The ZSE is characterized by high turbulence and coarse-grained sediments, which is the sediment characteristic in the riverine zone. The ZSA is characterized by low turbulence and fine particulate matter (typically fine silt of 2 – 32 μm diameter and clays < 2 μm diameter), which is similar to the composition of sediments in the lacustrine zone. The ZDA is a transitional zone between the ZSE and ZSA, similar to the transitional zone in a reservoir. The ZSE and the ZDA are separated by a narrow band called the depository boundary depth (DBD). The equation to locate DBD as given by Kalff (2001) is a function of maximum fetch (F, km) and underwater slope (%):

$$\text{DBD (m)} = -0.107 + 0.742 \log(F) + 0.0653 \times \text{slope}$$

In small, shallow, wind protected lakes (F< 1 km), DBD can be < 3 m. In such lakes, the thermocline can be below the DBD. However, in large temperate lakes (fetch>200 km), DBD is located at about 40 m, much below the thermocline (Kalff 2001).

## 3.4.8 Phytoplankton Productivity

There are four possible categories of primary producers in lakes and rivers, namely, planktonic algae, planktonic phototrophic bacteria, attached algae, and rooted macrophytes. However, fluctuations in water level and abiogenic turbidity in the reservoirs prevent the development of algal and macrophytic communities. Hence, primary production in reservoirs is principally due to phytoplankton (Kimmel et al. 1990; Wetzel 2001).

### 3.4.8.1 Phytoplankton Productivity in the Riverine Zone

The riverine zone is characterized by relatively high flow velocities, higher amounts of nutrients, higher turbidity, and shorter water residence times. The riverine zone is generally shallow and thoroughly mixed. However, due to high turbidity, penetration of light is limited. Without light, photosynthesis cannot take place. This, in turn, limits the productivity of phytoplankton. Therefore, in the riverine zone there is light-limited phytoplankton productivity (Kimmel et al. 1990).

### 3.4.8.2 Phytoplankton Productivity in the Transitional Zone

The transitional zone is characterized by a broader basin, decreased velocity of flow, and lower turbidity. The plunge point (see below), if it exists, is often associated with the transitional zone. The plunge point brings about a turbulent interface between the epilimnion, the hypolimnion, and an interflowing riverine layer. This results in exchange of materials from the riverine layer to the epilimnion and from the hypolimnion to the riverine zone. The plunge point and the exchange that takes place between the interflow and the hypolimnion and epilimnion are shown in Figure 19. This exchange makes available nutrients for phytoplankton productivity. As there is not much turbidity in this zone, photosynthesis is not light-limited. This zone, therefore, is the most fertile zone in a reservoir, with high planktonic productivity (Kimmel et al. 1990).

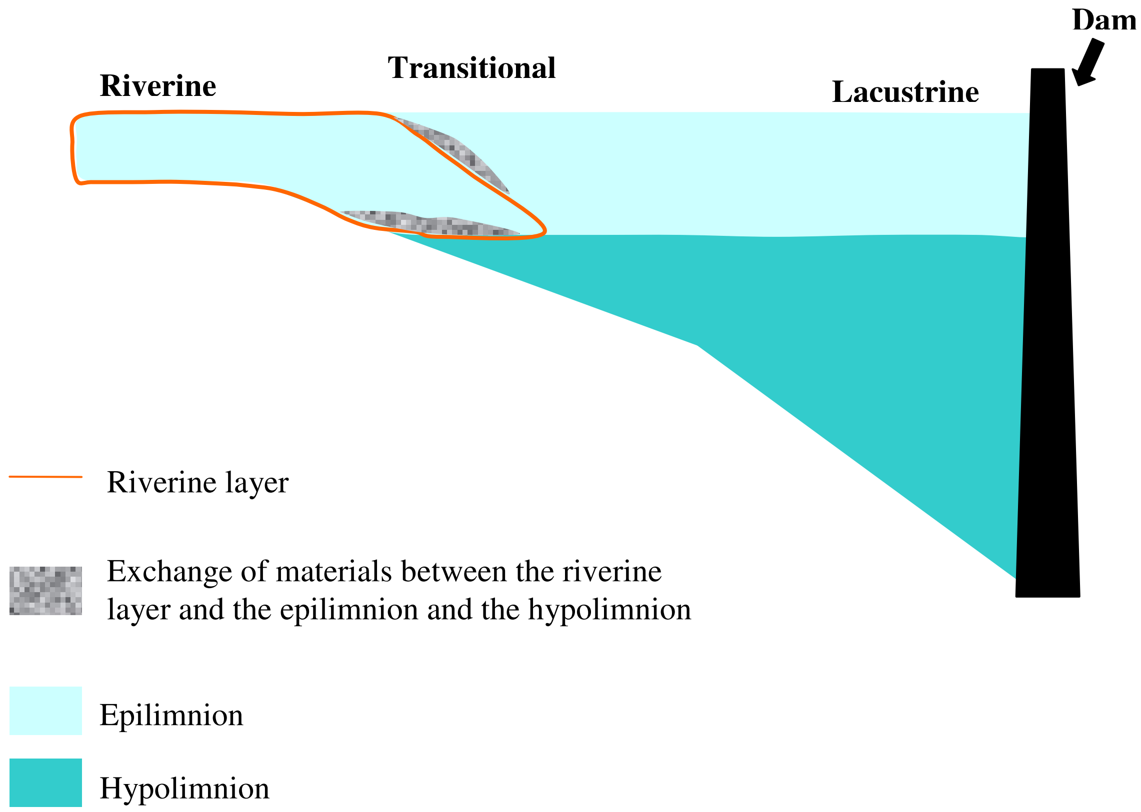


**Figure 19. Inflowing riverine layer and exchange of materials with the epilimnion and hypolimnion.** The downward direction of the riverine flow as it enters the transitional zone illustrates the plunge point. The plunge point is illustrated in greater detail in Figure 20.

### *3.4.8.2.1 Plunge Point*

The inflows from the watershed enter the reservoir in the riverine zone. Often, the density of inflow will be different from the density of the surface waters in the reservoirs. This density difference can be the result of total dissolved solids and suspended solids concentrations, and temperature. Temperature plays a major role in the propagation of density currents. The resultant density difference makes the inflow enter the reservoir as a density current. If the density of the inflow is less than that of the surface waters, then the inflow enters the reservoir as an ‘overflow’. At the point where the density of the inflow is greater than that of the surface waters, the inflow plunges into the reservoir. That location is called the plunge point. If the inflow follows the old river channel bottom, it is called an ‘underflow’. The density current, often during mid- and late summer, leaves the bottom of the reservoir and flows horizontally through the stratified layers of the reservoir. It is called an ‘interflow’. This occurs when the temperature of the inflow is less than that of the surface waters, but greater than that in the hypolimnion. Figure 20 depicts an interflow, an overflow and an underflow.

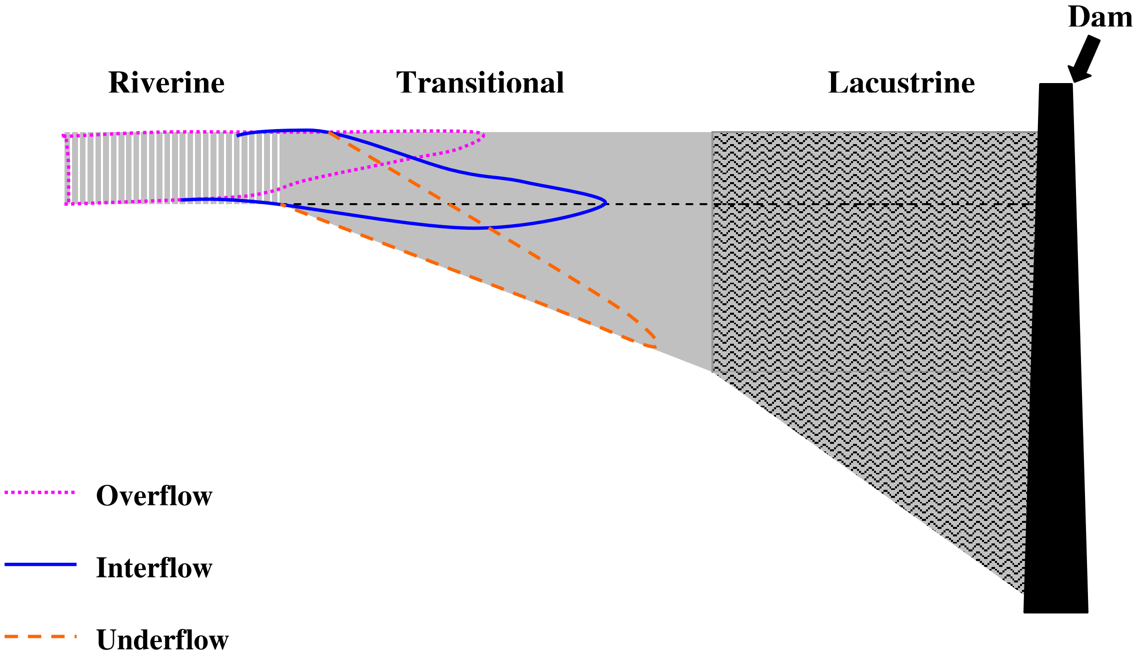


**Figure 20. Density inflows in reservoirs.** At the plunge point, located at the start of the transitional zone, the flow direction of incoming current depends on the density.

The plunge point occurs in the transition zone of the reservoir. The upper and lower boundaries of the transition zone can be set in the following manner: The upper boundary is set by the location of the plunge point during low flow conditions. The lower boundary is set by locating the plunge point under high flow conditions. The plunge point keeps moving within the transition zone depending on the flow conditions (Kimmel et al. 1990).

### 3.4.8.3 Phytoplankton Productivity in the Lacustrine Zone

During summer, the lacustrine zone in a reservoir is stratified. As a result, there is no mixing between the different layers. Over a period of time the nutrient supply dwindles, and this limits the phytoplankton productivity. During this time, however, an interflowing riverine flow might enter the system and, under the influence of wind-generated mixing, exchange nutrients with the epilimnion. This enhances the nutrient supply a little, but not by a whole lot. Most of the nutrient supply available is primarily due to in situ nutrient cycling. Planktonic productivity in the lacustrine zone is therefore nutrient limited (Kimmel et al. 1990).

Table 9 is a summary of the phytoplankton productivity in reservoirs having different trophic states. It is mentioned in the literature by Kimmel et al. (1990) that phytoplankton productivity is generally nutrient limited. But, in the case of oligotrophic lakes (especially the lower values), it was found to be light limited, contrary to what was expected. The fact that phytoplankton productivity was expected to be nutrient limited shows that the table represents phytoplankton productivity in the lacustrine region of the reservoir.

**Table 9. Phytoplankton productivity in reservoirs.**

| **Reservoirs** | **Mean daily productivity for entire year (mg C·m$^{-2}$·day$^{-1}$)** | **Range observed (mg C·m$^{-2}$·day$^{-1}$)** | **Annual productivity (g C·m$^{-2}$·yr$^{-1}$)** |
|---|---|---|---|
| Oligotrophic (Data from 10 reservoirs) | 151 | 67 – 235 | 55 |
| Mesotrophic (Data from 36 reservoirs) | 570 | 260 – 940 | 208 |
| Eutrophic (Data from 21 reservoirs) | 2019 | 1125 – 3975 | 737 |

**Source:** Wetzel (2001); data from (Kimmel et al. 1990). © Elsevier Science (USA). Used with permission

### 3.4.8.4 Measuring Phytoplankton Productivity

Phytoplanktonic productivity is measured using the $^{14}$C and light and dark bottle techniques (Wetzel 2001). These techniques give values close to the net productivity under most in situ conditions. However, under extreme conditions like very low productivity (low algal biomass) or very high productivity (high algal biomass), it is difficult to obtain an accurate estimate of the productivity using these techniques. The $^{14}$C technique cannot be used to determine respiration.

#### *3.4.8.4.1 Light and Dark Bottle Technique*

Water samples are taken at different depths and these samples are stored in dark and light bottles. The light bottles are generally made of high quality glass (e.g., Pyrex®) and allow light to pass through them. The dark bottles are generally glass bottles covered with a double layer of black, plastic electrician's tape. This ensures that light is completely excluded from the bottle. These bottles (multiple light ones and one dark one for each depth) are filled up as rapidly as possible. The bottles are generally flushed three times and filled. They are then stoppered and stored in a light proof box till all the samples have been collected. Duplicate light bottles are needed for each depth at which samples are taken. The bottles are then clipped to a bottle spreader, with the dark bottles at the center and the light bottles to the sides, and they are lowered to the depths from which the samples were taken. The bottles are now left to incubate for some period of time. The period of time is determined from the intensity of photosynthetic activity. There should be enough incubation time such that there is a sufficiently large measurable change in oxygen concentrations. Under conditions of moderate algal productivity, 2 to 4 hours of incubation time is adequate (Wetzel and Likens 1990).

When the oxygen demand is primarily due to algal photosynthesis and respiration:

Respiratory activity per unit volume per time interval = IB – DB

Net photosynthetic activity per unit volume per time interval = LB – IB

Gross photosynthetic activity = (LB – IB) + (IB-DB)

where,

IB = Initial oxygen concentration at any given depth

DB = The lower concentration of oxygen in the dark bottle after the incubation period as a result of respiration

LB = The lower oxygen concentration in the light bottle after the incubation period as a result of the combined action of respiration and photosynthesis

Gross photosynthesis is the true synthesis of organic matter in presence of sunlight, while net photosynthesis is formation of organic matter after taking into account losses due to respiration and cellular metabolism.

The Photosynthetic Quotient (PQ) and the Respiratory Quotient (RQ) are dimensionless numbers which indicate the relative amounts of oxygen and carbon involved in the processes of photosynthesis and respiration.

$$\text{PQ}=\frac{\text{molecules of oxygen liberated during photosynthesis}}{\text{molecules of CO}_2\text{ assimilated}}$$

$$\text{RQ}=\frac{\text{molecules of CO}_2\text{ liberated during respiration}}{\text{molecules of oxygen consumed}}$$

To convert from mass of oxygen to mass of carbon, the oxygen production and consumption are multiplied by the ratio of moles of carbon to moles of oxygen (2 mg C /32 mg $0_2$ = 0.375):

$$\text{Gross photosynthesis (mg C/m}^3\text{/h)}=\frac{\left[(\text{O}_2,\text{LB})\text{-}(\text{O}_2,\text{DB})\right](1000)\ (0.375)}{(\text{PQ})\ (\text{t})}$$

$$\text{Net photosynthesis (mg C/m}^3\text{/h)}=\frac{\left[(\text{O}_2,\text{IB})\text{-}(\text{O}_2,\text{LB})\right](1000)\ (0.375)}{(\text{PQ})\ (\text{t})}$$

$$\text{Respiration (mg/m}^3\text{/h)}=\frac{\left[(O_2, \text{IB})\text{-}(O_2, \text{DB})\right]\text{(RQ) (1000) (0.375)}}{t}$$

#### *3.4.8.4.2 $^{14}C$ Uptake Technique*

Phytoplankton can take up and incorporate tracer amounts of radio isotopes into organic matter during photosynthesis. By measuring the amount of radioactive isotopes, the rate of phytoplankton productivity can be estimated. Generally, tracer amounts of $^{14}CO_2$ are added as radioactive bicarbonate ($H^{14}CO_3^-$). The total amount of $CO_2$ in water is measured. After the appropriate incubation time, the total amount of $^{14}C$ present in the phytoplankton is measured. The amount of carbon assimilated can then be calculated from the following relationship:

$$\frac{^{14}\text{C available}}{^{14}\text{C assimilated}}=\frac{^{12}\text{C available}}{^{12}\text{C assimilated}}$$

### 3.4.9 Organic Matter

Organic matter includes plant, microbial and animal products undergoing decomposition, and also other substances synthesized biologically and chemically. Organic matter can either be allochthonous or autochthonous in origin. This whole process of input, synthesis and decomposition has many implications on the reservoir ecosystem. Organic matter present can either be Dissolved Organic Matter (DOM) or Particulate Organic Matter (POM). The amount of POM and DOM entering a reservoir varies seasonally, depending on the flow rate, retention time in the stream, decay cycle, and climate. Depending on their ease of degradation by microbes, organic compounds are also classified as humic and non-humic substances.

### 3.4.9.1 Dissolved Organic Matter (DOM)

DOM is a broad classification for organic compounds having varied origin and composition. It is generally separated from POM by filtration through a 0.5 µm size filter. The cut-off size for DOM is, therefore, generally 0.5 µm. Hence, DOM includes a colloidal fraction as well as a dissolved fraction. Between 50 – 80% of DOM is composed of humic substances (Wetzel and Likens 1990; Wetzel 2001).

### 3.4.9.2 Particulate Organic Matter (POM)

POM generally includes particles that are greater than 0.5 µm in size, and includes organisms that contain organic matter. However, it is the particulate detritus that dominates over the living detritus (Wetzel 2001).

### 3.4.9.3 Non-Humic Substances

Non-humic substances include carbohydrates, proteins, peptides, amino acids, fats, resins, pigments, and other low molecular weight organic substances. These substances are easily hydrolyzed by the enzymes produced by microorganisms. Because non-humic substances are readily degradable, they are not present in large quantities in water (Wetzel 2001).

#### 3.4.9.4 Humic Substances

About 70 – 80% of the organic substance in soil and water is humic. These are complex compounds having high molecular weight and are generally dark-colored. Humic substances are not easily degraded by microorganisms, and are usually formed by partial decomposition of plant tissue by microbes. Any further decomposition of the humic substances is generally possible only abiotically (Wetzel 2001).

#### 3.4.9.5 Organic Matter in the Riverine Zone

The riverine zone gets input from the parent river. All the nutrients and substances from the watershed first enter the lake or reservoir in the riverine zone, and it has relatively higher flow rate and higher turbidity. Due to the turbidity, phytoplankton productivity in this zone is light limited. Therefore, the organic matter present here is basically allochthonous in nature (Kimmel et al. 1990).

#### 3.4.9.6 Organic Matter in the Transitional Zone

In the transitional zone, the flow rate is reduced and so is the turbidity. In this zone the phytoplankton make use of the nutrients available in water and their productivity is very high. The death or senescence of phytoplankton makes available both POM and DOM for degradation. Sedimentation rates in this region are also very high. Most of the allochthonous substances from the riverine zone are deposited in the transitional zone. Allochthonous organic matter from phytoplankton is also present. Therefore, the organic matter in this zone varies from allochthonous to autochthonous (Kimmel et al. 1990; Thornton 1990).

### 3.4.9.7 Organic Matter in the Lacustrine Zone

The lacustrine zone of a reservoir is lentic in nature and is also thermally stratified during summer. The epilimnion in the lacustrine zone is rich in phytoplankton, but, as summer progresses, the nutrient input decreases, and productivity decreases as the zone becomes nutrient limited. The allochthonous materials all generally settle out in the transition zone. The organic matter in the lacustrine zone is from the death or senescence of phytoplankton and other organisms. Therefore, the organic matter in the lacustrine zone is primarily autochthonous in nature (Kimmel et al. 1990).

### 3.4.9.8 Differentiating Between Allochthonous and Autochthonous Organic Matter

Autochthonous and allochthonous organic matter can be differentiated based on the Dissolved Organic Carbon to Dissolved Organic Nitrogen (DOC: DON) ratio. DOM that is allochthonous in origin has a lower percentage of nitrogen associated with it. Typical allochthonous DOC: DON ratios are in the range of 50:1. In the case of autochthonous materials the ratio is about 12:1, indicating a higher percentage of nitrogen (Wetzel 2001).

### 3.4.10 Nutrient Supply

The quality of water and the productivity in reservoirs all depend on the nutrient supply into a reservoir. The nutrient supply into a reservoir can be allochthonous and autochthonous. The primary source of allochthonous nutrient supply into the reservoir is the parent river. The nature of this nutrient input also depends on climate, season, land use, soil type, and watershed characteristics. The transport mechanism of nutrients along the reservoir also varies. Therefore, the chemical and biological processes associated with the nutrients also vary along the length of a reservoir.

#### 3.4.10.1 Factors Affecting Nutrient Supply Along a Reservoir

Nutrient supply in reservoirs depends on many factors. It is the combined result of all the parameters discussed below. Much of the information in the following subsections is derived from Kennedy and Walker (1990).

##### *3.4.10.1.1 Flow*

Advective flow is predominant in reservoirs. Advection involves transport by an imposed current system. In the narrow and shallow riverine region of the reservoir, the flow is advective with a higher velocity. The concentration of nutrients here is also higher. In the transitional zone, the transport of nutrients by advection is reduced. The transitional zone is wider and deeper, and, as a result, the currents are dissipated and advective flow is reduced. Because the flow is spread over a wider area, the concentration of nutrients is lower here. In the lacustrine zone, the nutrients are generally autochthonous in nature and this zone is generally lentic. Here, advective flow plays hardly any role. The changes in concentration of nutrients as flow spreads from the riverine to the lacustrine zone are illustrated in Figure 21.

### *3.4.10.1.2 Morphology*

Morphology of the reservoir plays an important role in distribution of nutrients along the reservoir. Consider two unstratified reservoirs: one deep and broad and the other narrow and shallow, both having the same flow of nutrients through them. The broad and deep reservoir will have a higher residence time as compared to the narrow and shallow one. Therefore, more nutrients will be retained in the reservoir with the higher residence time.

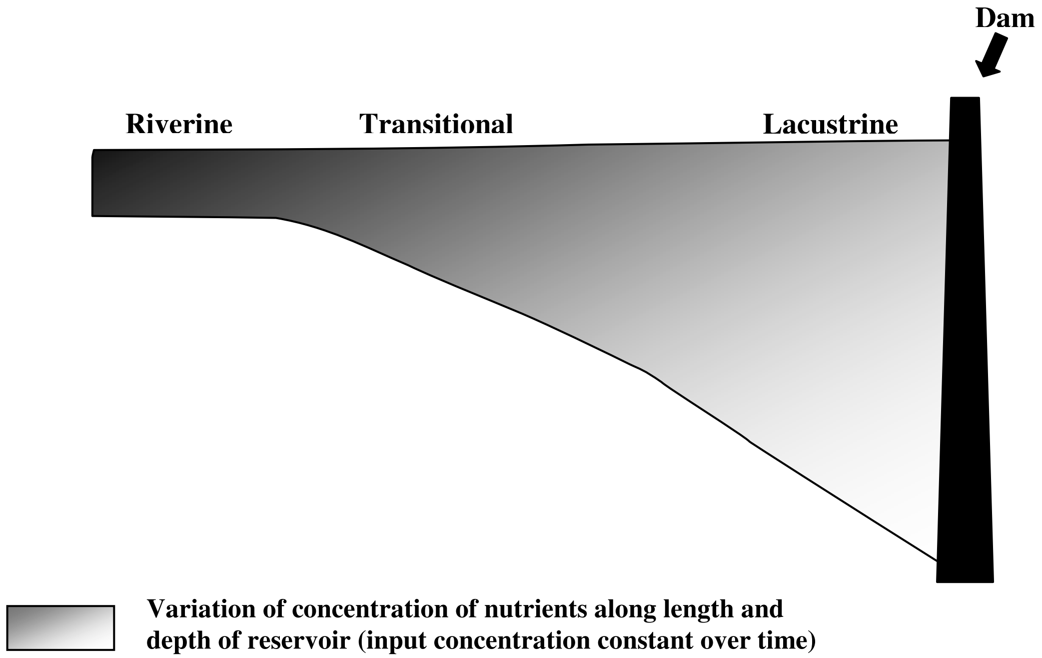


**Figure 21. Changes in concentration of nutrients along a reservoir.**

### *3.4.10.1.3 Density Flows*

As discussed earlier (see subsection 3.4.8.2.1), density currents enter the reservoir and are responsible for carrying nutrients along the reservoir. These density currents have been discussed in detail in the section on phytoplankton productivity (section 3.4.8) because they have a direct influence on the phytoplankton productivity, especially when the lake is stratified.

### *3.4.10.1.4 Sedimentation*

The nutrients dissolved in water associate with biotic and abiotic particles. This results in loss of nutrients from the water column to the sediment bed. There are also seasonal trends in sedimentation patterns. During spring, according to data from DeGray Lake, the nutrients associated with sediments were primarily allochthonous in nature, while during late summer and fall the nutrients that associated with sediments were autochthonous in nature. Studies have shown that sediments in the riverine zone of the reservoir are low in organic matter and phosphorus concentrations, while in the lacustrine zone, where the flow is characteristically low, the organic content and phosphorus concentration in the sediments is high. Sediments in the lacustrine zone were also high in moisture content. Therefore, in the riverine zone, where advective flows dominate the sediments are low in organic content, moisture content, and phosphorus concentrations. In the lacustrine zone, where advective flows have little role, the sediments are high in organic content, moisture content and phosphorus concentrations. The variations in nutrient supply from different sources along the reservoir are illustrated in Figure 22. As one moves down the reservoir, the nutrients are utilized by the phytoplankton. The organic detritus from the phytoplankton, together with clay, silt and nutrients attached to these particles, result in an accumulation of organic nutrient-rich sediments of high moisture content in the deeper waters.

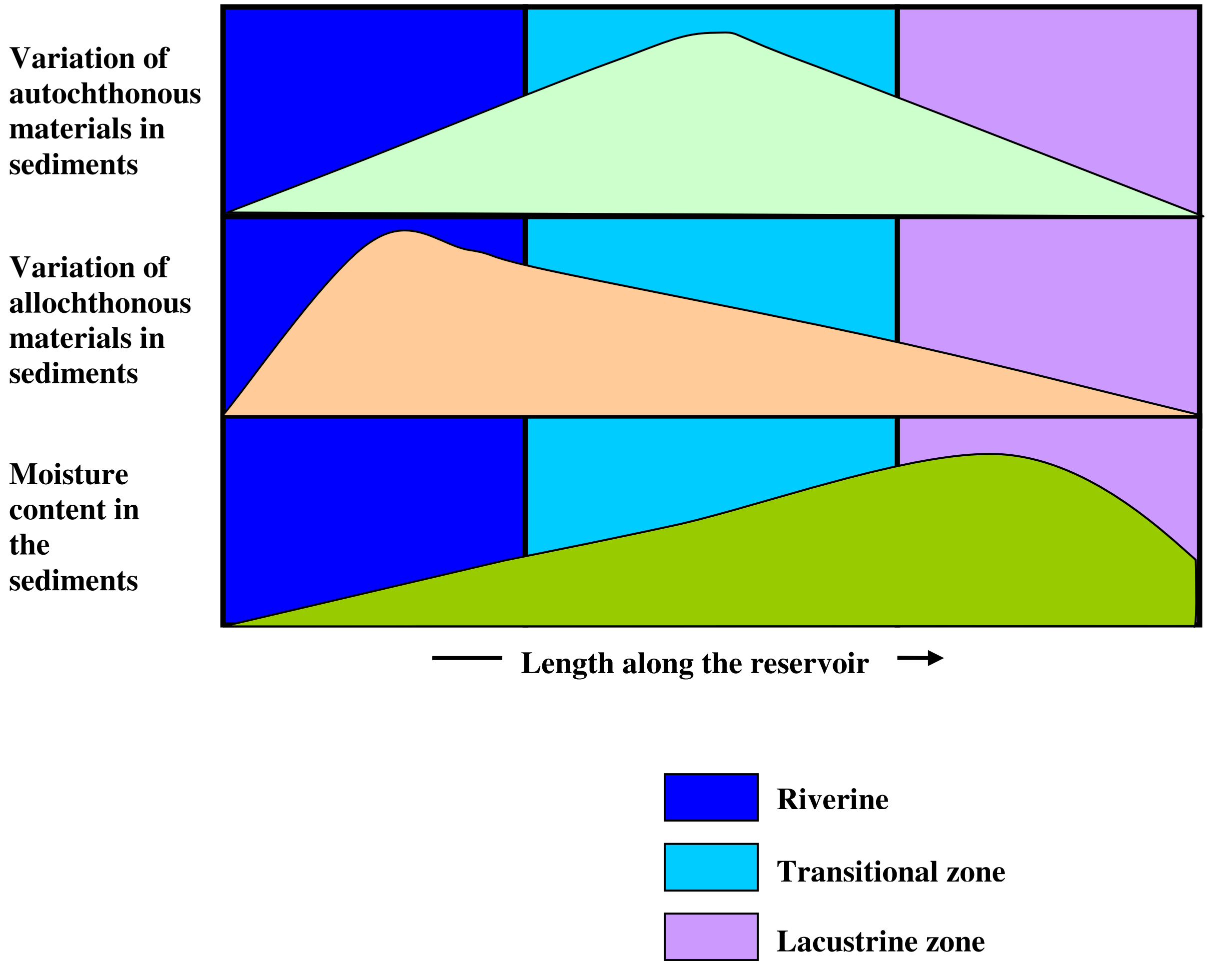


**Figure 22.** **Variation in phytoplankton and nutrient concentration along a reservoir.**

##### *3.4.10.1.5 Nutrients From Within the Reservoir*

Internal loadings within the reservoir are related to the trophic state, the sedimentation history, and the oxygen demand dynamics existing in the reservoir. Internal loadings are especially important during periods when external loadings are minimal. Anoxia in the sediments can cause release of nutrients from the sediments into the water column above. These nutrients, by diffusion across the thermocline, can be available in the epilimnion. Therefore, internal loading can be of some importance in the lacustrine zone of a reservoir where anoxia develops during summer stratification.

### 3.4.10.2 Nutrient Supply and Flow in the Riverine Zone

The nutrient supply is allochthonous in nature. Because water here flows through shallow, narrow channels, the concentration of nutrients in this zone is high. The flow is advective in nature, and is associated with sediments with low organic content, low phosphorus concentrations, and low moisture content.

### 3.4.10.3 Nutrient Supply and Flow in the Transitional Zone

Due to an increase in channel width and reduction in flow velocity, the advective flow of nutrients is reduced in this zone. This zone is associated with allochthonous-to-autochthonous nutrient supply, and primary production is high. The sediments, therefore, have some organic content, some phosphorus concentration, and some moisture content.

### 3.4.10.4 Nutrient Supply and Flow in the Lacustrine Zone

The lacustrine zone is lentic. Therefore, advective flow plays little or no role here, and the nutrient supply is by internal recycling. The sediments in this zone have high organic content, high phosphorus concentrations, and high moisture content.

## 3.4.11 Fetch

Fetch is defined as the distance over which wind can blow unhindered by lake shores. Wind plays an important role in reservoir dynamics. When stratified, water in the epilimnion is mixed by wind action, and it is wind that initiates the fall overturn and the period of mixing that follows the period of stratification. Wind is also responsible for dispersion of algae and others in the plankton community. Fetch is, in a way, a measure of the distance over which wind has considerable effect.

### 3.4.11.1 Determining Fetch

Fetch can be calculated in either of the following ways:

i) The maximum length of the lake which is the same as the effective length defined below (Wetzel 2001).

ii) Fetch = (L+W)/2

where, *L* and *W* are "effective" length and width, respectively, as defined by Welch in 1978 (Kalff 2001).

Effective length is defined as the distance on the lake surface between two remote points on the lake shore that is uninterrupted by land, and effective width is defined as the maximum distance on the lake surface at a right angle to the effective length.

Effective width = Area of the lake/Maximum length of the lake

iii) $A^{0.5}$, where A is the surface area of the lake. This is used to determine the average fetch in lakes with convoluted shorelines (Davies-Colley 1988).

### 3.4.11.2 Fetch and the Riverine Zone

The riverine zone is narrow. Therefore, within the riverine zone fetch is small. Here, the waters are well-mixed, and this is due to the shallow depth and the turbulence associated with a higher velocity of flow.

### 3.4.11.3 Fetch and the Transitional Zone

The transitional zone is wider and deeper, with comparatively reduced flow velocities. The fetch is higher in this zone than in the riverine zone. During stratification, it is wind that mixes the water in the epilimnion.

#### 3.4.11.4 Fetch and the Lacustrine Zone

The lacustrine zone is the widest and the deepest. Here the fetch is largest. During stratification, as in the transitional zone, wind is responsible for keeping the epilimnion well-aerated.

### 3.4.12 Macrozooplankton

The term ‘plankton’ refers to organisms that grow and live suspended in open waters. Most of them move around at the mercy of currents. Some have limited mobility with the aid of flagella. The animal component of the plankton community is called zooplankton.

Zooplankton vary in size from less than 2 μm to several centimeters. These include both macrozooplankton and microzooplankton. Microzooplankton are less than 200 μm in size, while the macrozooplankton are greater than 200 μm in size. It is the macrozooplankton that have been widely studied by limnologists, as they are easier to sample with traditional plankton nets and traps. They are mainly constituted of crustaceans. The cladocerans, copepods and ostracods are the three major groups of crustaceans (Kalff 2001).

#### 3.4.12.1 Sampling of Macrozooplankton

Macrozooplankton sampling is primarily done by the use of nets. These nets generally have mesh openings of 60 – 70 μm. While sampling, vertical hauls are made with the nets and samples are collected from what is retained in the net. Nets, however, provide resistance to flow. Therefore, in reality, less water flows through them, resulting in an inaccurate estimation of the abundance and biomass of the sampled organisms. So, very often, a flow meter is placed at the mouth of the net to give an idea of the actual flow through the net. Traps have been developed to facilitate zooplankton sampling. The Schindler-Patalas trap is one such example and it is made of transparent plastic. These traps give the light-sensitive zooplankton very little warning, and are more effective in collecting a better and more accurate sample (Kalff 2001).

#### 3.4.12.2 Flushing (Dilution) Rate

The zooplankton generally move in the horizontal direction at the mercy of water currents. The rate of flow of water through the water body determines the flushing rate. It is a measure of how long water is retained in a water body. A low water residence time means a high flushing rate, and vice versa.

#### 3.4.12.3 Growth (Doubling) Rate

Growth (doubling) rate is actually a measure of the time required for a population to double itself. Only if conditions are optimal for a population to double itself will the species propagate.

#### 3.4.12.4 Washout

When the water residence time is less than the growth rate of plankton, the species is washed out. What this implies is that, due to rapid flushing out from the system, there is a sharp decline in the population strength, diversity and biomass. The plankton population is pushed or flushed out of the system before it has time to reproduce.

### 3.4.12.5 Water Residence Time and Plankton Growth Rates

Planktonic diversity and population strength depends on the water residence time and temperature. Considering the copepods, the development time under optimal conditions at 10°C is about 30 days, at 20°C about 14 days, and at 25°C about 7.5 days (Kalff 2001). When compared to cladocerans, their development at the same temperature is 25% slower. Therefore, what happens is that when the water residence time is less that that required for a particular species of organism to double itself, they experience washout. The macrozooplankton have a longer life cycle when compared to other plankton, therefore their presence, community structure, and development is most impacted by the water residence time (WRT). The flushing out of herbivorous macrozooplankton has an indirect effect on the productivity, growth and community structure of phytoplankton. The minimum WRT required for a rapidly growing species to reach maximum biomass in temperate lakes is 5 - 7 days.

### 3.4.12.6 Macrozooplankton in the Riverine Zone

In the riverine zone the water residence time is low, and the water is well mixed and turbid. Conditions for photosynthesis are not optimal. Hence, very little phytoplankton are present here and the food available for the zooplankton is limited and their numbers are very low. Different species have different optimal conditions and growth rates. If the flushing rate is higher than the growth rate, the species eventually dies out. In the riverine zone, where the flushing rate is high, very few species survive, and there is not much diversity in the community present here (Wetzel 2001).

### 3.4.12.7 Macrozooplankton in the Transitional Zone

In the transitional zone, the WRT is intermediate and depending on the flow conditions (high flow or low flow), the flushing rate may be greater or less than the growth rate. However, productivity is highest in the transitional zone as the temperature, light and nutrient conditions are optimal. The high productivity allows for a thriving population of zooplankton to filter-feed off the phytoplankton, if the WRT is optimal for its growth. Hence, in this zone there can be variable zooplankton populations with much diversity (Wetzel 2001).

### 3.4.12.8 Macrozooplankton in the Lacustrine Zone

The WRT is highest in the lacustrine zone of a reservoir, and the flushing rate is lowest. Here the growth rate is greater than the flushing rate. However, in this zone the phytoplankton productivity can be nutrient limited, especially in late summer. This can have an adverse effect on the macrozooplankton population. The macrozooplankton population in this zone is therefore intermediate, though more stable (Wetzel 2001).

### 3.4.13 Algal Cell Losses

The algae found in reservoirs are the phytoplankton. The phytoplankton community includes different varieties of algae and photosynthetic bacteria. These varying forms have varying physiological needs and respond differently to light, temperature, nutrient availability, and other existing physical and chemical conditions in the reservoir.

#### 3.4.13.1 Factors Affecting Sedimentation of Algal Cells

The movement of phytoplankton in a reservoir is at the mercy of the currents. Therefore, the morphological characteristics, together with flow characteristics, have a profound effect on the movement of phytoplankton, both vertically and horizontally along a reservoir. Listed below are a few parameters that are important to the vertical transport that takes place during sedimentation of phytoplankton. The information is derived principally from Kimmel et al. (1990) and Wetzel (2001).

##### *3.4.13.1.1 Density*

The density of the freshwater plankton is slightly more than that of water. Therefore, they have a tendency to sink in relatively undisturbed waters. Many of these plankton have gas vacuoles which help them to float in water and also help them to move to the optimum location in the water column. The vacuoles help balance the sinking effect of higher density. The tendency to float or sink depends on the presence or absence of these vacuoles.

### *3.4.13.1.2 Gas Vacuoles*

Gas vacuoles are present in the protoplasm of bacteria. It is these vacuoles that keep the organisms buoyant by decreasing the density of the organism to less than that of water. However, at a certain critical pressure, which is often reached at greater depths, the gas vacuoles collapse and no longer provide buoyancy.

### *3.4.13.1.3 Particle Size*

According to Stoke's law, spherical particles having a mean diameter of less than 0.5 mm will sink. The velocity of sinking depends on three factors. It:

i. Varies inversely as the viscosity of the medium,
ii. Varies directly as the square of the diameter, and,
iii. Varies directly as the difference in the density of the particle and the medium.

Therefore, taking into account planktonic communities, the velocity of sinking is highest for relatively large, dense, particles. When cells sink, they are removed from the photic zone. This can have adverse and fatal effects on the phytoplankton life cycle. However, this movement, if within the photic zone, can cause disruption of nutrient gradients around the cell and bring the cell in contact with the required nutrients. This is beneficial for the phytoplankton and can enhance its productivity.

#### *3.4.13.1.4 Mucilage Production*

Mucilage is the gelatinous sheath around the algae cell. It has a lower density when compared with the cell, which decreases the sinking velocity. However, presence of the mucilage increases the size of the cell, which in turn increases the velocity. The sheath also reduces the nutrient uptake efficiency of the organism.

### 3.4.13.2 Algal Cell Losses in the Riverine Zone

The riverine zone is narrow, shallow and turbid. The flow in this zone is basically advective. Turbidity limits light in this zone. Although well-mixed and rich in nutrients, the absence of light often proves fatal for the phytoplankton. The presence of zooplankton which grazes on the phytoplankton is limited in flowing waters. For plankton to survive in high flow conditions, it is essential that the rate of reproduction must be higher that the downstream displacement by the current. In this zone, sedimentation of sand and coarse silt occurs. Algae can get attached to these particles and be deposited at the bottom of the reservoir channel. In this zone, therefore, the basic reasons for algal cell losses are sedimentation and advective flow. The effect and variation of all the parameters mentioned above is shown in Figure 23 for the riverine zone (Kimmel et al. 1990; Thornton 1990; Wetzel 2001).

### 3.4.13.3 Algal Cell Losses in the Transitional Zone

In the transitional zone, the flow rate decreases and the channel basin increases in width. The sand and coarser particles having settled out, the water is much less turbid and the decreased velocities promote higher settling rates of silts and coarser clays. The sedimentation rate is high in this zone, and so is phytoplankton productivity. Higher sedimentation rates can lead to more phytoplankton being attached to sediments. Here the flow is still partly advective and this, too, accounts for cell losses. Figure 23, below, illustrates the variation of all these parameters along the reservoir (Kimmel et al. 1990; Thornton 1990; Wetzel 2001).

#### 3.4.13.4 Algal Cell Losses in the Lacustrine Zone

In the lacustrine zone, phytoplankton communities are seen to exhibit coexistence of a large number of algal species. Very often one of more of the species may be dominant when compared to the others. In this region, the flow is at a minimum and the turbidity is very low. However the nutrient source is fast depleted, especially when stratified. Therefore, productivity here is nutrient limited. The sedimentation rates in this zone, too, are very low. There is hardly any advective flow. The variation of these characteristics from headwaters to the dam in a reservoir is shown in Figure 23. Low flow conditions here favor the growth of zooplankton. Therefore, the primary reason for loss of algal cells here is zooplankton grazing (Kimmel et al. 1990; Thornton 1990; Wetzel 2001).

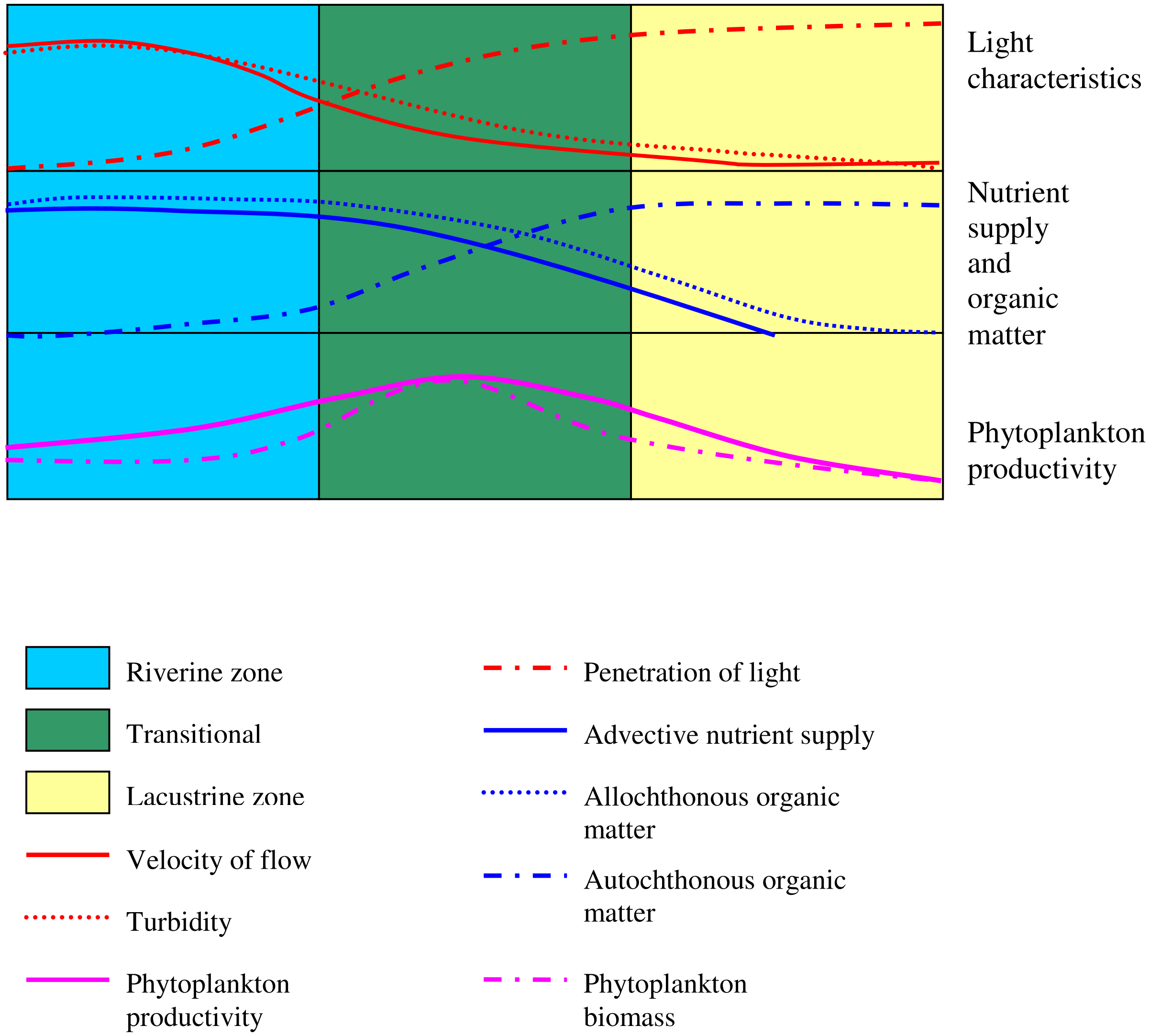


**Figure 23. Parameters which affect algal cell losses and their variation along a reservoir.**

### 3.4.14 Flow and Flushing Rate

The net flow in reservoirs is unidirectional. It is observed that the depth of the reservoir increases from the point of inflow to the dam. This implies a continuous downward slope of the reservoir bed, supporting flow in that direction. Along with increase in depth, there is also an increase in channel width in the same direction. All these factors, together with wind, influence the flow along a reservoir. The flushing rate in the reservoir is directly related to the flow rate.

### 3.4.14.1 Factors Influencing Flow and Flushing Rate Along a Reservoir

The flow through a reservoir is dependent on a variety of factors. They are discussed in the subsections below, which are derived from information contained in Kennedy and Walker (1990) and Straskraba (2005).

#### *3.4.14.1.1 Physical Characteristics*

Reservoirs are generally long and narrow. They receive water from the parent river at a single point of entry which is generally distant from the point of discharge. When the water initially enters the reservoir, the flow is higher as the channel is still narrow. As one progresses downstream along the reservoir, it gets broader and deeper. This causes a reduction in the rate of flow. When the flow rate is high, the quantity of material retained in the basin is low and the amount of material washed out is high. Therefore, the flushing rate is high.

#### *3.4.14.1.2 Water Retention Time (WRT)*

Water Retention Time (WRT) gives an idea of the water renewal rates in lakes and reservoirs. The lower the WRT, the faster water flows through the lake or reservoir, and vice versa. Therefore, the greater the WRT, the lower the flushing rate. The WRT is lowest in the riverine zone and highest in the lacustrine zone. The flushing rate is higher in narrow and shallow reservoirs, as compared to broad and deep reservoirs. The variation of flow velocity as we go from the riverine to the lacustrine zone in a reservoir is illustrated in Figure 24.

### 3.4.14.2 Flow and Flushing Rate in the Riverine Zone

The flow rate in this zone varies according to the flow rate in the parent river. In this zone, the river channel is still narrow, like in the river, and the flow rate, though lower than that of the parent river, is still high. The narrow channels help maintain the high flow rate. The high flow rates ensure high flushing rates. Flushing rate plays a crucial role in maintaining the plankton population. If the flushing rate is higher than the growth rate, then the population dwindles away. The high flushing rates also flushes the nutrients and sediments faster from this zone. Very little sedimentation of the finer particles having high settling rates takes place in this zone.

### 3.4.14.3 Flow and Flushing Rate in the Transitional Zone

In the transitional zone, the channel widens and deepens. As a result, flow is dispersed over a larger area and the flow rate is reduced. Low flow rates indicate a lower flushing rate. The flushing rate in the transition zone has a major role to play in the productivity of plankton and the plankton community structure. A lower flushing rate ensures that the plankton population is not washed away before it can reproduce adequately. Therefore, a healthy plankton population can be observed in this zone. Also, sedimentation in this region is higher as water retention time is higher, and a thriving plankton community results in more biomass.

#### 3.4.14.4 Flow and Flushing Rate in the Lacustrine Zone

The lacustrine zone is located in the widest and deepest part of a reservoir. This part of the reservoir is lentic and associated with low flows. The flushing rate here is very low.

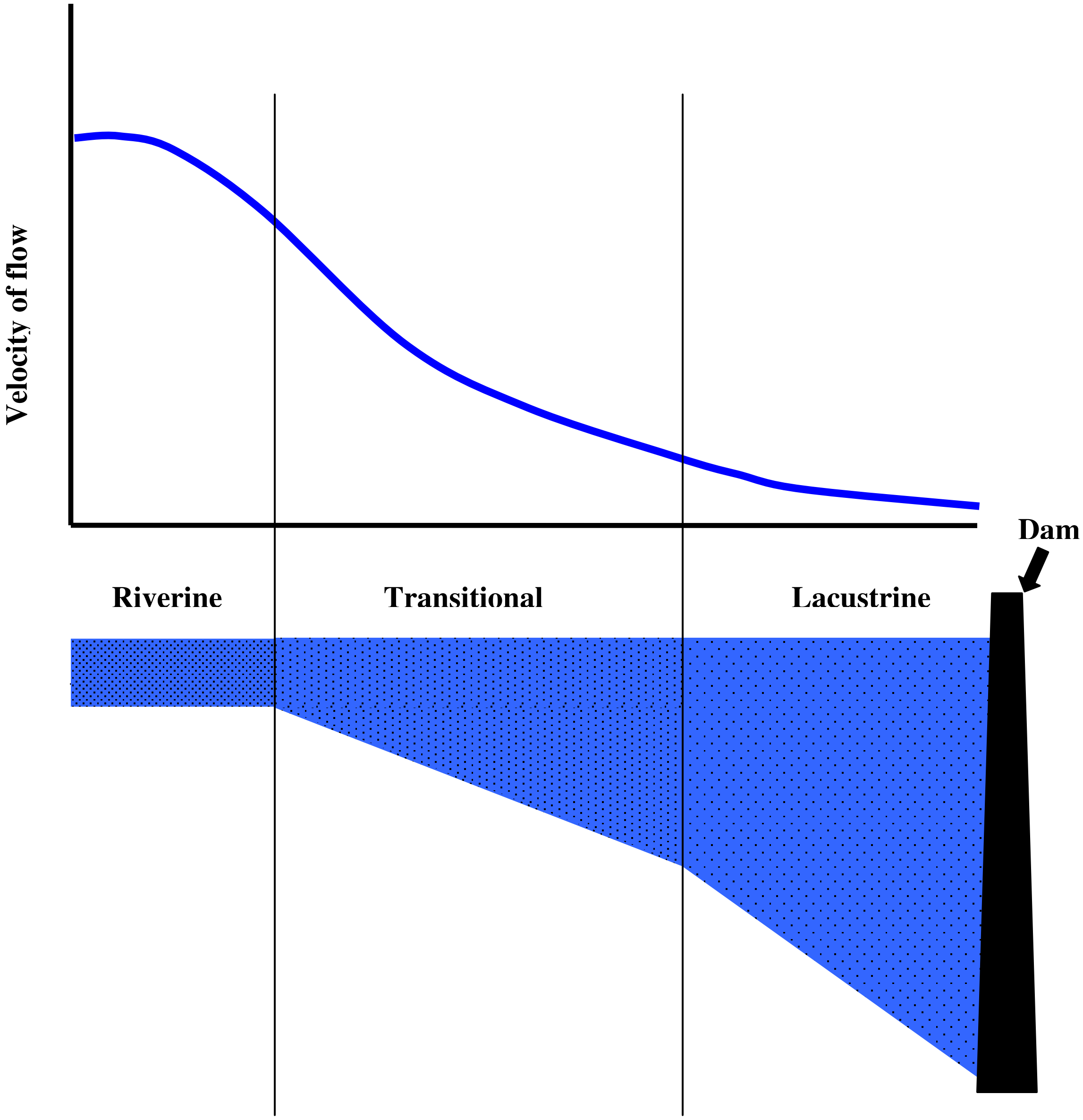


Figure 24. Variation of flow velocity along the length of a reservoir.

# 4 APPLICATION OF METHOD DEVELOPED ON LAKE MANASSAS AND THE OCCOQUAN RESERVOIR

The method developed and discussed above was tested on Lake Manassas and the Occoquan Reservoir. The data available for these two reservoirs were analyzed based on the table of parameters, until a reasonable identification of zones was made.

## *4.1 Approach to Determining Zones in a Reservoir*

The method involves applying each parameter, starting at the top of the table, until successful zonation is achieved. The key parameters are the ones that are listed at the top of the table. Explanation is provided in the table of parameters (Table 1), as to how these parameters differ in characteristics in the different zones. The change in characteristics of a few important parameters, the usage of which will, in most cases, be sufficient to make successful zone identification, is discussed below. It is recommended that at least two characteristics be considered before a final zone determination is made.

## *4.2 Test Site for Application of Method*

As a test, this method was first applied to Lake Manassas. Lake Manassas is located in Prince William County, Virginia, about sixteen miles from the city of Manassas. It is a man-made impoundment, which was created between 1968 and 1971, by the building of a dam on Broad Run. In 1995, an inflatable rubber bladder was added on top of the existing dam to add an additional 5 feet of height to the dam. The primary purpose of the reservoir is to serve the region as a drinking water source. However, the lake and the area surrounding it are also a popular spot for recreational activities.

The method was then applied to the Occoquan Reservoir, located in Northern Virginia. The Occoquan Reservoir is bordered by Fairfax County on the north, and Prince William County on the south. It is a man made impoundment and is the primary source of drinking water to more than one million residents who live in Northern Virginia. The reservoir and the area surrounding it are also a popular spot for recreational activities.

## *4.3 Zonation Approach for Lake Manassas*

Zone identification is essential for Lake Manassas as the new Water Quality Standards (WQS) adopted by the Virginia department of Environmental Quality (DEQ), puts forward a separate set of standards for lakes and reservoirs and the standards are primarily applied in the lacustrine zone of the reservoir.

The sampling program in Lake Manassas is extensive and extends over decades. As a result, a lot of data are available. The deciding factor for determining the time frame, for which data can be analyzed in this case, was the assessment period that DEQ requires. For DEQ, the assessment period is from April 1 through October 31, with monthly sampling, in any single calendar year. Normally, most lakes and reservoirs were only sampled for one year (7 month period) during the six-year assessment cycle, but regional staff need to do a second year within the six year window of sampling, if the chlorophyll *a* or phosphorous criteria were exceeded during any given assessment period. Keeping the DEQ’s sampling period in mind, five years of data were examined and analyzed. Another factor to be taken into consideration is bias. Conditions vary from year to year. One of the calendar years in consideration might be a typical year, while another one might have some extreme hydrological events associated with it. Therefore, by analyzing five years of data, it can be ensured that the analysis attempts to include different conditions that may exist during the different years.

There are eight monitoring stations located in Lake Manassas. Data are collected at each of these stations throughout the year by the staff at the Occoquan Watershed Monitoring Laboratory (OWML). During spring, summer and fall, sampling is done bi-weekly, and during winter months, sampling is done once a month. Data from each of those stations was considered for analysis. Figure 25, displays the location of the monitoring stations in Lake Manassas.

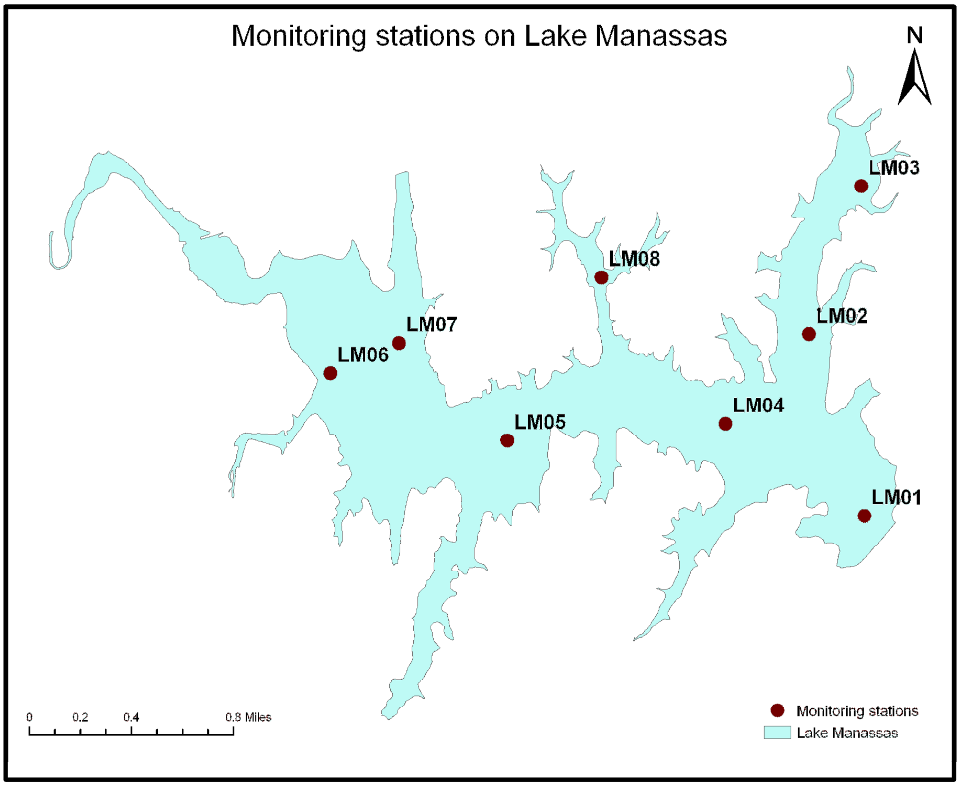


**Figure 25.** **Monitoring stations in Lake Manassas.**

The first parameter to be analyzed for zone identification is stratification. Each parameter considered in the decision-making process is discussed below in great detail.

### 4.3.1 Thermal Stratification in Lake Manassas

Lake Manassas stratifies in summer. Data from each of the stations was examined to determine if stratification was stable or not. For analyzing stratification, temperature vs. depth profiles were examined at every station.

Data were analyzed for each of the eight monitoring stations on Lake Manassas, for the five most recent years from 2002 to 2006. The temperature vs depth profiles were plotted for each station, for each year. These plots were examined to determine if the thermocline gradient was >1°C/m, if the pattern of stratification was consistent throughout summer and if a thick hypolimnion was present. The dates for which stable stratification was first and last observed at each station were recorded. Very often, stratification exhibited a tendency to disrupt, even after an initial stable profile. These tendencies were more prominent during spring and fall and also in the shallower areas. These are discussed in later sections in detail, as they were observed at the different stations.

Stratification primarily occurs during summer. However, in the analysis below, mostly because of the availability of data, the stratification analysis was performed for all four seasons. For the purpose of analysis, the four seasons have been spanned as follows. Spring extends from March to May. June to August are the summer months. Fall starts in September and extends till November. The remaining three months December, January and February are the winter months.

While the analysis done on the data is extensive, the discussion below for each station is done such that the data represented in the discussion portrays the entire range of stratification patterns that was observed and recorded at each of the station. For every station, temperature profiles for two years have been discussed. These years were chosen such that a fair representation of stratification patterns that was observed at that station, during the period of study, was made. Depending on the explanation of the differences observed from year to year and recurrence of consistent patterns, the collective strength of stratification for every station was determined. This is the first step in the process.

#### 4.3.1.1 Winter Profiles in Lake Manassas

During winter months the waters are generally well-mixed and cold. All throughout this period, irrespective of depth or station, the temperature profiles indicate that there is no stratification. Unlike other seasons, where the profiles vary from station to station, winter profiles have similar trends at all stations. Therefore, the winter profiles have all been consolidated to one section. The profiles below, taken at different stations indicate that the thermal profiles in winter were consistent at every station. The winter profiles for the year 2005-06 are shown in Figure 26 and Figure 27. The year 2005 was chosen because it was the most recent winter for the period during which the analysis was carried out.

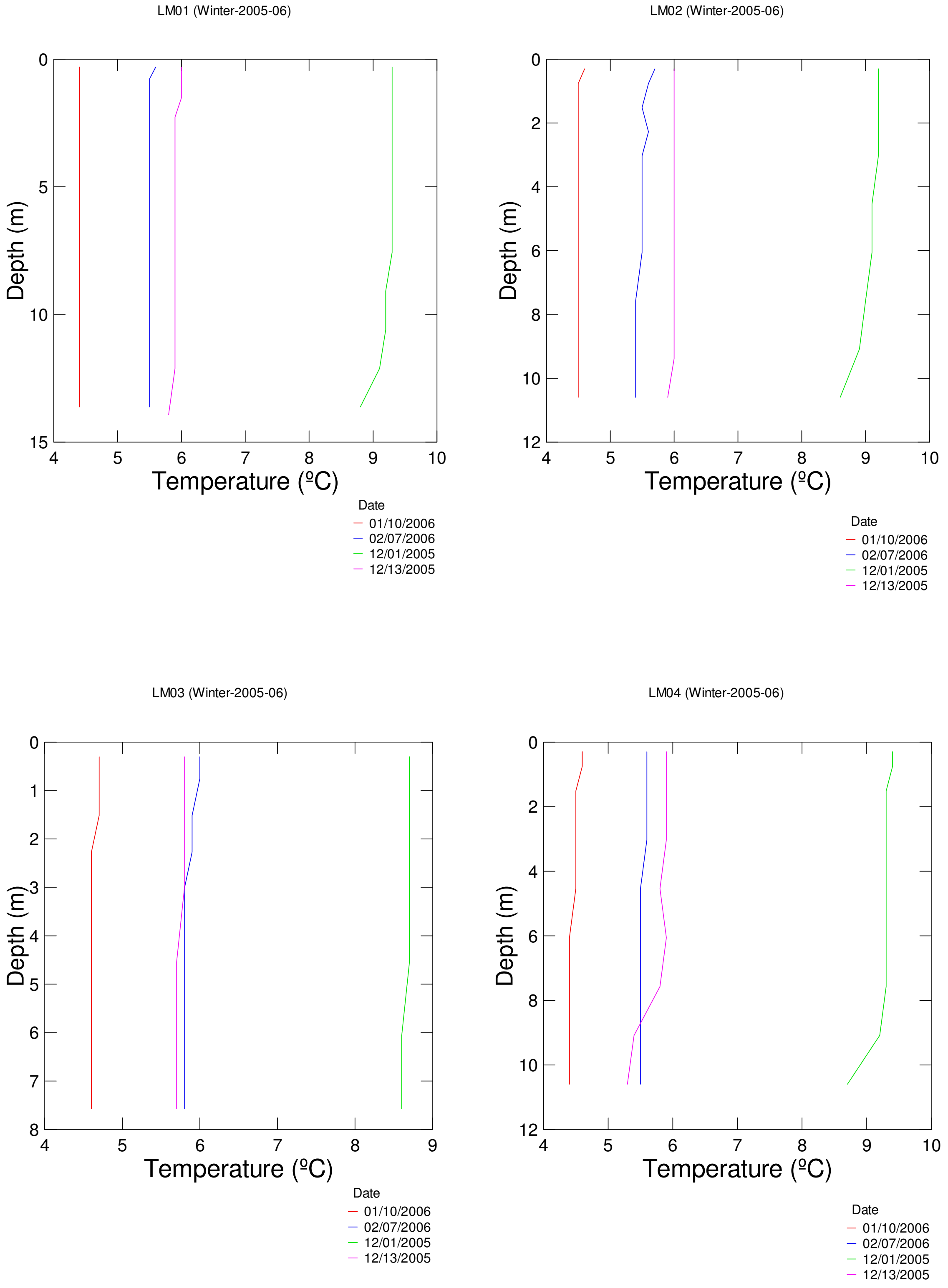


**Figure 26. Temperature–depth profiles at all eight stations in winter (2005-06).**

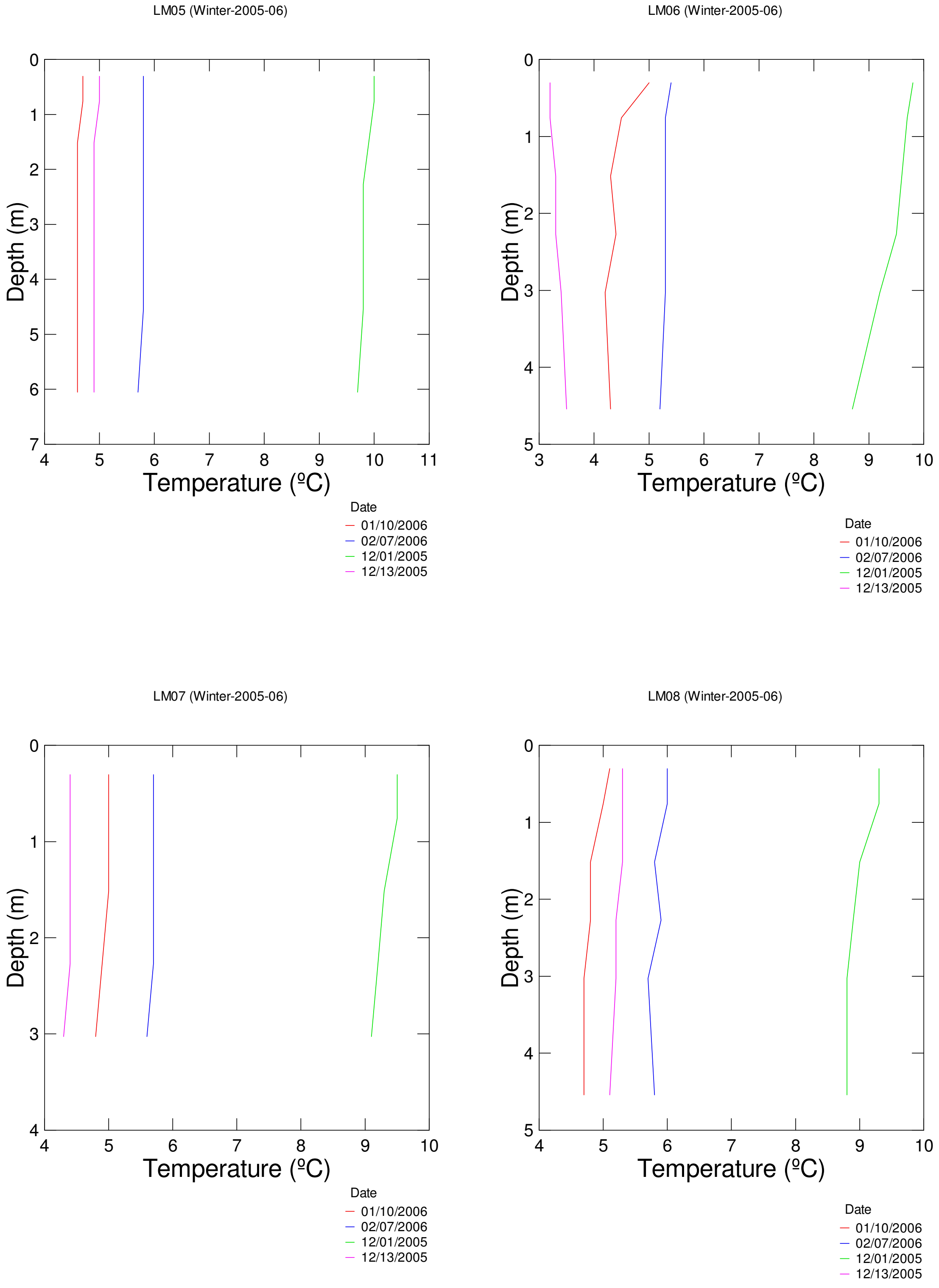


**Figure 27. Temperature–depth profiles at all eight stations in winter (2005-06) (continued).**

The winter temperature–depth profiles for the year 2005-06 indicate that stratification did not exist at any of the stations considered. A slight difference of temperature between the top and bottom waters was observed at station LM06. However the difference in temperature did not constitute stratification, as none of the conditions required for a body of water to be stably stratified were met. Though only profiles for the year 2005-06 are represented here, the study included profiles from the year 2002 to 2006. It was observed that all the profiles, from the other years in consideration, also exhibited similar trends. Stratification did not exist during winter, at any of the stations in Lake Manassas. A discussion of the stratification observed at each station during the other seasons follows.

### 4.3.1.2 Thermal Stratification at Station LM01

Station LM01 is located near the dam and is in the deepest part of the lake. Five years of data, from 2002–2006, were examined. Table 10 lists the recorded dates during which stratification was first and last observed at station LM01. The trends observed during stratification at different seasons are discussed in detail in the sections below.

**Table 10. Period of stratification for station LM01.**

| Year | Date stratification was first recorded | Date stratification was last recorded |
|---|---|---|
| 2002 | 17th April 2002 | 23rd October 2002 |
| 2003 | 7th May 2003 | 10th September 2003 |
| 2004 | 21st April 2004 | 11th August 2004 |
| 2005 | 13th April 2005 | 18th October 2005 |
| 2006 | 19th April 2006 | 27th September 2006 |

From the table above, it is clear stratification existed during spring, for all the years under consideration, at station LM01. It is possible that there were breakups in between these recorded dates. A detailed analysis of the profiles for every season will portray a better picture.

##### *4.3.1.2.1 Thermal Stratification in Spring at Station LM01*

Five years of temperature-depth data were plotted. It was observed that towards the latter half of spring, the temperature profiles displayed the presence of an epilimnion, thermocline and a hypolimnion. The thermocline met the >1°C/m criteria. The general trend observed while examining the data for station LM01 was that strong and stable stratification existed during mid- to late spring. The representative years 2002 and 2005 were chosen as the representative years for discussion, as these years exhibited the range of stratification profiles possible at station LM01, for the entire period of study (Figure 28).

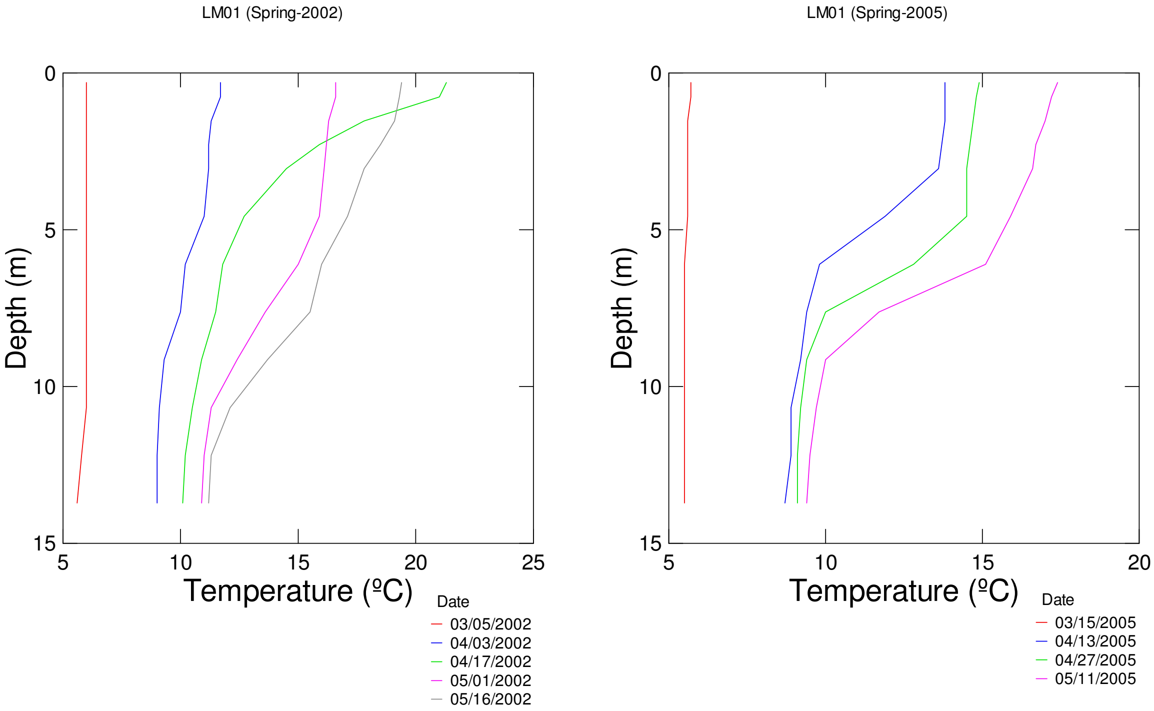


**Figure 28. Temperature–depth profiles at station LM01 in spring (2002 and 2005).**

On analyzing the temperature–depth profiles for the year 2002, no sign of stratification was observed in early spring. The temperature was uniform from top to bottom. As spring progressed, the onset of stratification was observed. Stratification was first recorded on April 17th with a thermocline gradient of >1°C/m and a hypolimnion over 7 m thick. A thin epilimnion was also present. Therefore, all the conditions for stable stratification were satisfied. As spring progressed, the stratification weakened with decrease in the thermocline gradient. This might be a result decrease in temperature. The hypolimnion too decreased considerably in thickness.

On examining the temperature–depth profiles for the year 2005, the onset of stratification was observed around April 13th. At that time, the thermocline gradient was >1°C/m, the hypolimnion was over 7 m thick and an epilimnion was present. As spring progressed, the thermocline gradient increased. The hypolimnion deceased in thickness but it was still over 4 m thick. Therefore, after the onset of stratification, the profiles above indicate that stratification was strong and stable in 2005.

The temperature profiles seen in spring for all the other years in consideration were similar to the profiles observed during the year 2005. All these indicate that stable stratification was common at station LM01 during late spring.

##### *4.3.1.2.2 Thermal Stratification in Summer at Station LM01*

Stratification is most prominent in summer. This is, therefore, the most appropriate time to check for stratification. Here again, though five years worth of data was considered, plots for the representative years 2002 and 2005 will be discussed in detail (Figure 29).

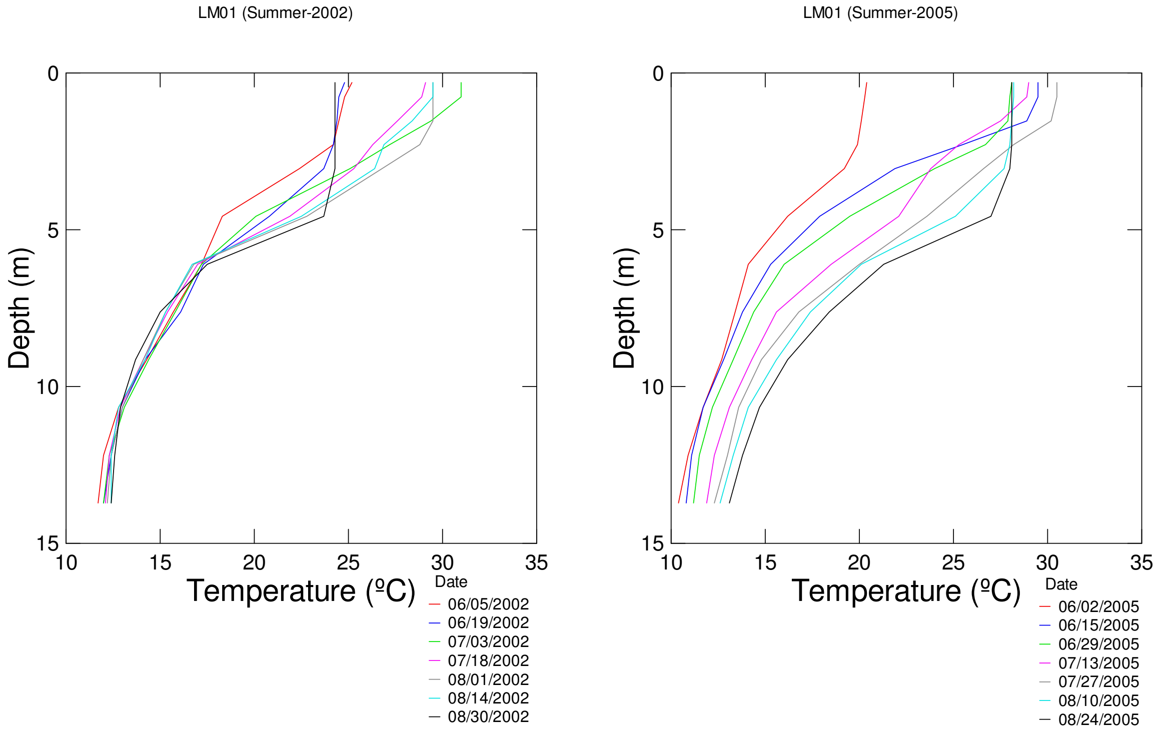


**Figure 29. Temperature–depth profiles at station LM01 in summer (2002 and 2005).**

The temperature-depth profiles for the year 2002 indicate that stratification was stable throughout summer. The thermocline gradient was >1°C/m and the hypolimnion was over 7m thick. An epilimnion was also present. Therefore, the observed stratification was strong and stable.

For the year 2005, the profiles indicate that throughout summer the thermocline gradient was >1°C/m, with a hypolimnion over 3m thick and an epilimnion. All these together satisfy the conditions required for stable stratification.

The profiles for the other years in consideration exhibited similar trends. The stratification at station LM01 was stable, strong and consistent throughout summer.

#### *4.3.1.2.3 Thermal Stratification in Fall at Station LM01*

With the onset of fall, temperatures start to drop. This results in a decrease in the surface temperature of water. As the temperature continues to drop, at one point the temperature of the surface waters equals the temperature of the deep waters. It is at this point that fall overturn occurs. Fall overturn marks the end of the period of stratification. It generally occurs sometime during mid- to late fall. After this, the waters are completely mixed. Figure 30, below, displays the fall profiles for station LM01 for the representative years 2002 and 2005. As explained in the above sections, these two years have been chosen as the representative years, to explain the trends of stratification at this station.

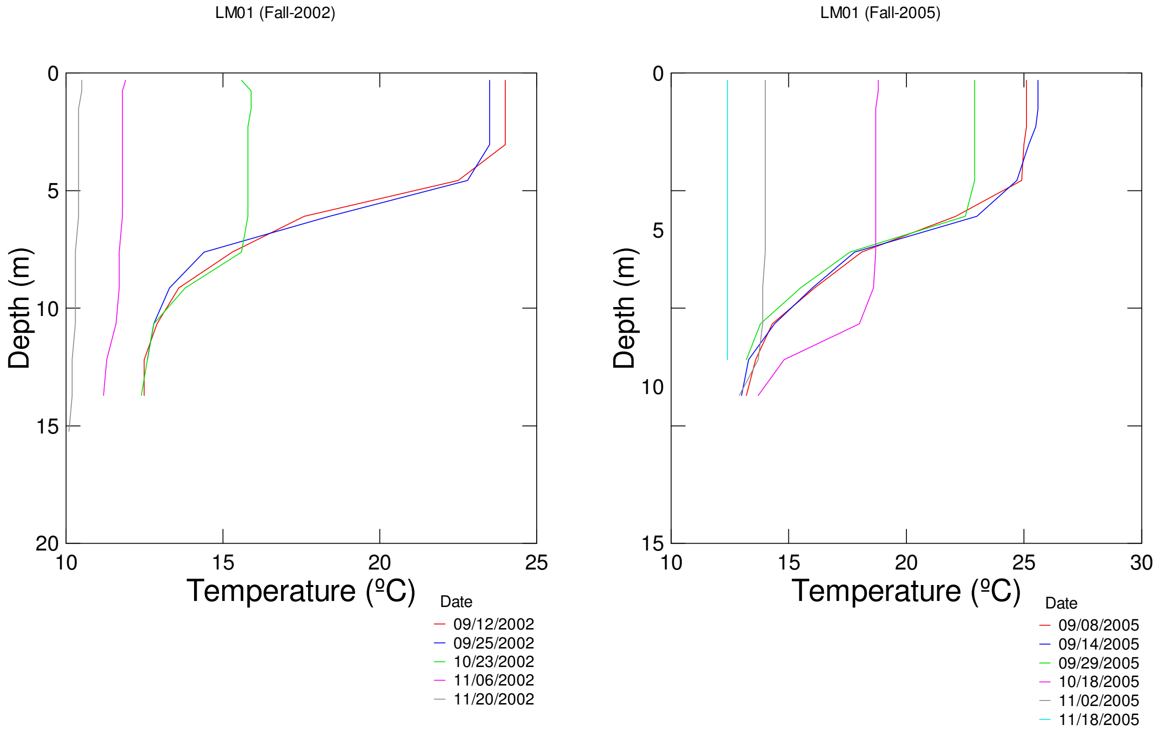


**Figure 30. Temperature–depth profiles at station LM01 in fall (2002 and 2005).**

The profiles for the year 2002 indicate that the waters were stratified stably until after mid-fall. However, it was observed that starting from the beginning of fall, the strength of stratification decreased progressively. This was observed in the declining strength of the thermocline gradient. The profiles after October 23rd, indicate that stratification was disrupted completely, sometime between then and November 6th. After that point onwards, the waters were well-mixed.

The profiles for the year 2005 indicate that strong and stable stratification continued well into fall. Strong temperature–depth profiles, with a thermocline gradient of >1°C/m, epilimnion and a thick hypolimnion were observed. Though a decrease in the thickness of the hypolimnion was observed, when compared to the thickness seen during summer, it was still around 2 m thick. The last recorded date for stratification was October 18th. From the onset of fall until the date of the last observed stratification, a gradual decrease in the thermocline gradient was observed. Finally, somewhere between then and November 2nd, fall overturn occurred.

For all the other years under consideration similar trends were observed during fall. The waters were always stratified in the beginning of fall but became destratified soon afterwards.

##### *4.3.1.2.4 Conclusion for Station LM01 Based on Thermal Stratification*

For station LM01, the stratification was stable with a thick hypolimnion and strong thermocline. The profiles for 2002 and 2005 (as the representative years), demonstrates that stratification was not broken intermittently during summer. Though the period of stratification was longer for some years, on the whole it can be concluded that for any particular year, while the stratification existed, it was strong, stable and consistent for a reasonable period of time. All these indicate that based on the thermal stratification parameter, station LM01 falls in the lacustrine zone.

#### 4.3.1.3 Thermal Stratification at Station LM02

Station LM02 is located in the arm nearest to the dam. Five years of data were also examined for station LM02. Temperature–depth profiles for all five years were examined to determine the period of stratification. Table 11, below, lists the recorded dates for which stratification was initially and finally observed at station LM02.

**Table 11. Period of stratification for station LM02.**

| Year | Date stratification was first recorded | Date stratification was last recorded |
|---|---|---|
| 2002 | 17th April 2002 | 25th August 2002 |
| 2003 | 7th May 2003 | 9th October 2003 |
| 2004 | 21st April 2004 | 25th August 2004 |
| 2005 | 13th April 2005 | 29th September 2005 |
| 2006 | 19th April 2006 | 23rd August 2006 |

Temperature–depth profiles for each of the five years were examined, to determine the strength and stability of stratification. The temperature–depth profiles of representative years 2002 and 2005 will be examined in greater detail in the sections below.

##### *4.3.1.3.1 Thermal Stratification in Spring at Station LM02*

At the onset of spring, the waters were cold and no stratification was observed. As spring progressed and the days became warmer, the difference in temperature between the top and bottom waters initiated stratification. The profiles below are for the representative years 2002 and 2005. Figure 31, displays in greater detail the trends of stratification, as they occur at station LM02.

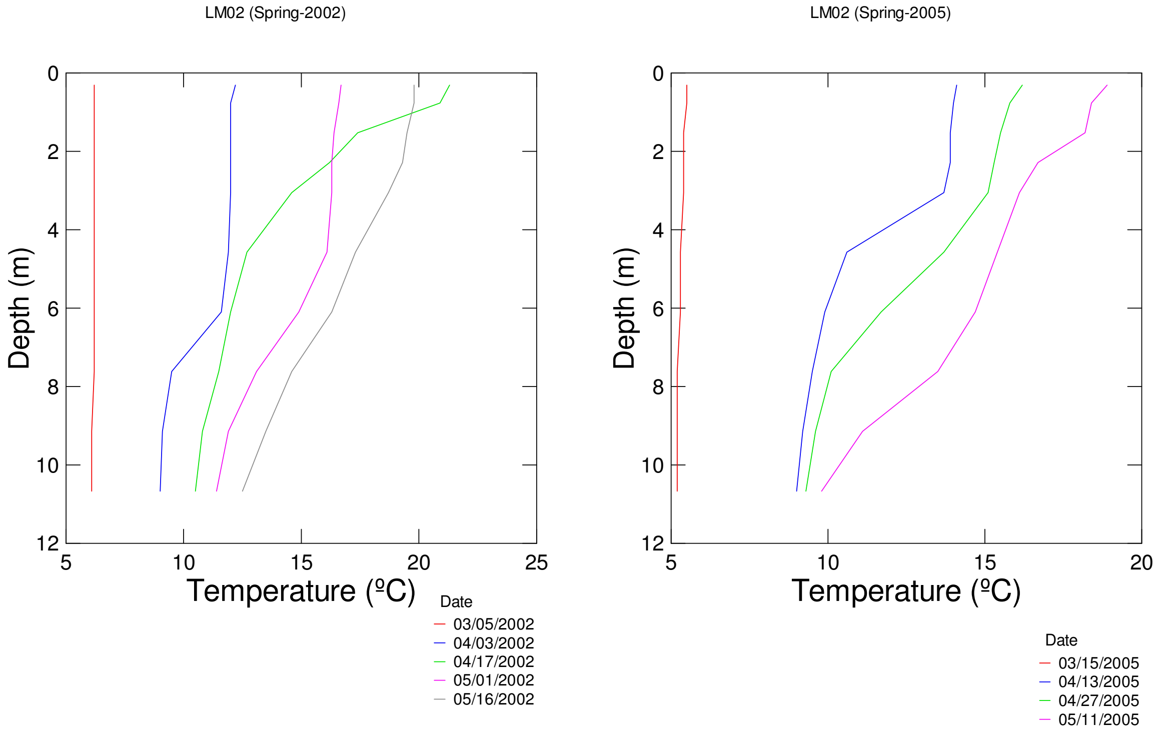


**Figure 31.** **Temperature–depth profiles at station LM02 in spring (2002 and 2005).**

The profiles for the spring of 2002 indicate that stratification was first recorded on April 17th. At that time, there was a strong thermocline gradient and a thick hypolimnion. The epilimnion was very thin. Though at this stage, all the conditions for stable stratification were satisfied, at the next recorded date (May 1st), the stratification was disrupted with the thermocline gradient no longer meeting the requirements. A very thin epilimnion can often result in breaking up the stratification, with a little help from the wind. Stratification for the year 2002 was weak and unstable during spring.

The profiles for the spring of 2005 indicate that the waters were well mixed in the beginning. The next recorded profile on April 13th indicated stable stratification. The thermocline gradient and the thickness of the hypolimnion were both adequate and remained stable throughout spring.

A mixed trend was observed for stratification in spring at station LM02. Stratification was strong at times and weak during other times.

#### *4.3.1.3.2 Thermal Stratification in Summer at Station LM02*

Stratification is most readily and easily visible during summer. If a station does not stratify in summer, it is most likely that it never stratifies. Figure 32, below, represents the summer profiles for the representative years 2002 and 2005, for station LM02.

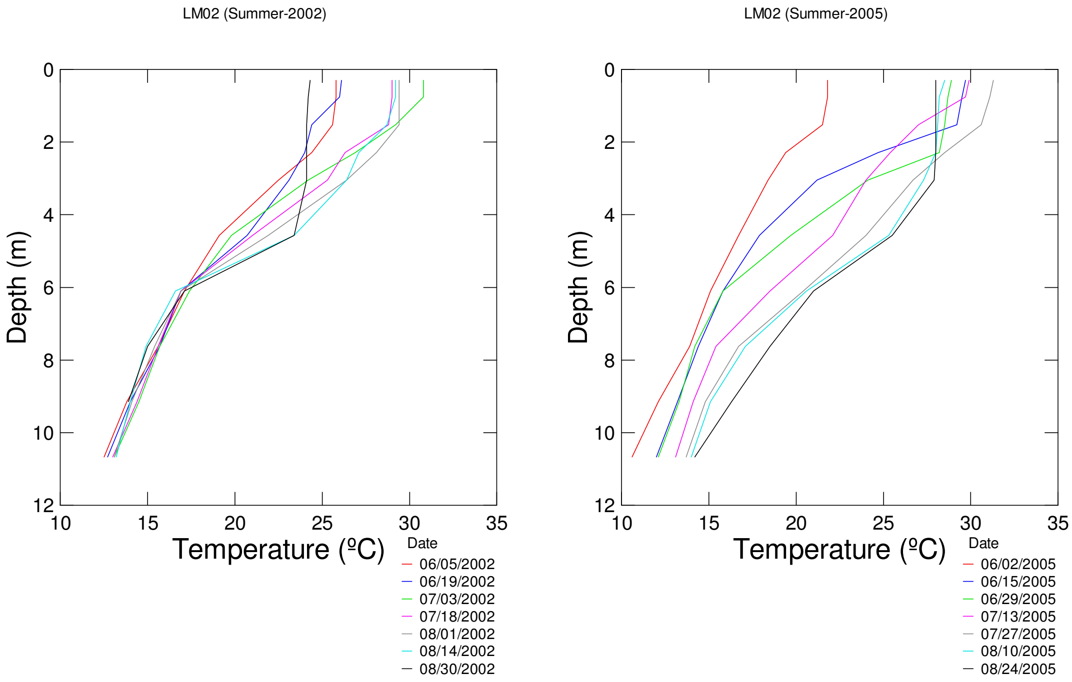


**Figure 32. Temperature–depth profiles at station LM02 in summer (2002 and 2005).**

Though spring profiles for the year 2002 suggested weak, unstable stratification, the summer profiles indicate strong and stable stratification with a strong thermocline and a hypolimnion around 4.5 m thick. Throughout summer this stable stratification remained established.

For the year 2005, the strong stratification that existed during the later part of spring, extended over the entire summer months. The thermocline gradient was consistent and the hypolimnion was over 3 m thick.

The profiles for all other years in consideration were also strong and stable. Therefore, stratification was stable and strong on the whole, during the summer months.

##### *4.3.1.3.3 Thermal Stratification in Fall at Station LM02*

As the temperature cools down with the onset of fall, stratification starts breaking up, until finally the waters become well mixed. Figure 33, below, displays the temperature–depth profile for the representative years 2002 and 2005.

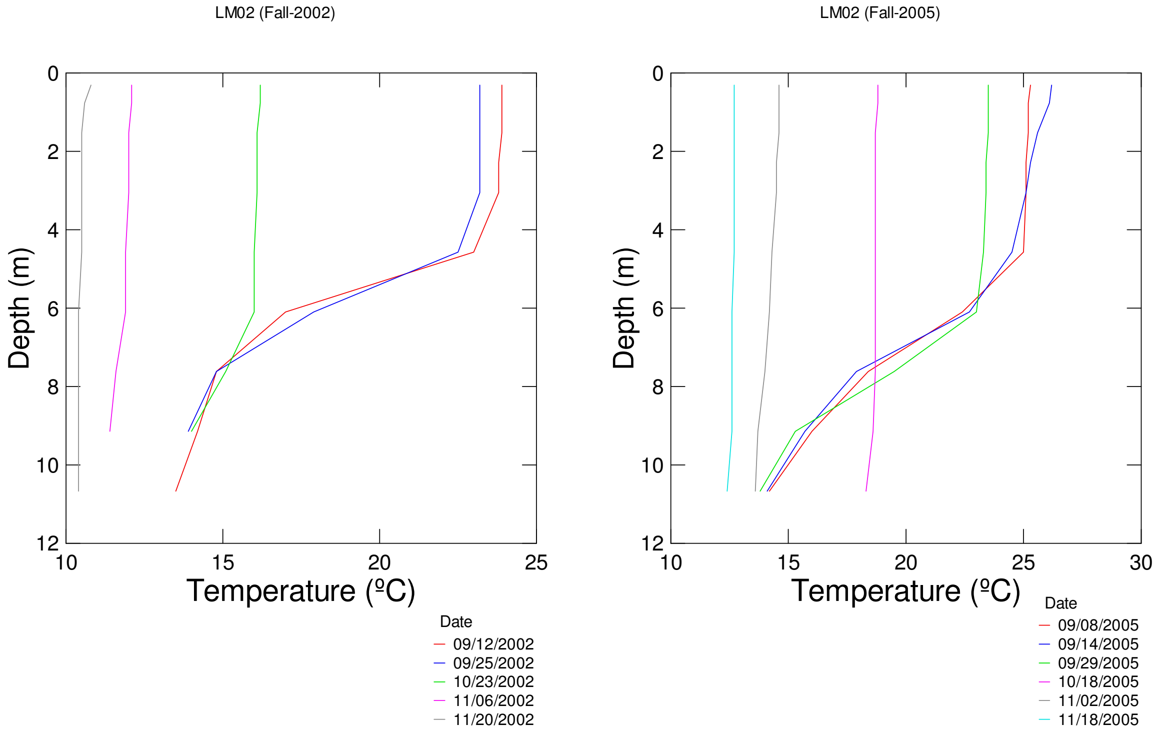


**Figure 33. Temperature–depth profiles at station LM02 in fall (2002 and 2005).**

The temperature–depth profiles for the year 2002 indicate that strong and stable stratification was last recorded on September 25th. From the onset of fall until the time of disruption, the stratification progressively weakened. This could be observed from the decline in the thermocline gradient. After the last recorded date of stable stratification, stratification became so weak, that it barely existed and finally fall overturn occurred. The waters became well-mixed after that.

The temperature–depth profiles for the year 2005 indicated the presence of strong and stable stratification from the onset of fall until around September 29th. Sometime after that stratification completely broke up and the next observed profile on October 18th displayed a well-mixed water body.

For all the other profiles examined, similar trends were observed. Stratification at station LM02 was disrupted by mid-fall. The waters were well mixed after that.

##### *4.3.1.3.4 Conclusion for Station LM02 Based on Thermal Stratification*

At station LM02, stratification first occurred during spring but was easily disrupted. There were no observed intermittent disruptions during the summer months. Stratification extended into the beginning of fall and it was somewhere during mid fall that fall overturn finally occurred. The presence of a strong hypolimnion and a strong thermocline throughout summer, all indicate that stratification was strong and stable at this station. Therefore, based on the thermal stratification parameter station LM02 falls in the lacustrine zone.

#### 4.3.1.4 Thermal Stratification at Station LM03

Station LM03 is located further into the arm away from the dam, where station LM02 is located. By analyzing the stratification data, the dates when stratification was first and last recorded for each of the five years considered, are listed in Table 12.

**Table 12. Period of stratification for station LM03.**

| **Year** | **Date stratification was first recorded** | **Date stratification was last recorded** |
|---|---|---|
| 2002 | 17th April 2002 | 12th September 2002 |
| 2003 | 7th May 2003 | 27th August 2003 |
| 2004 | 21st April 2004 | 28th August 2004 |
| 2005 | 13th April 2005 | 27th July 2005 |
| 2006 | 19th April 2006 | 9th August 2006 |

The years 2002 and 2006 were chosen as the representative years. The pattern of stratification observed is analyzed further in the sections below.

### *4.3.1.4.1 Thermal Stratification in Spring at Station LM03*

During spring, the temperature starts to warm up. Figure 34, below, displays the temperature profiles, for station LM03, for the representative years 2002 and 2006.

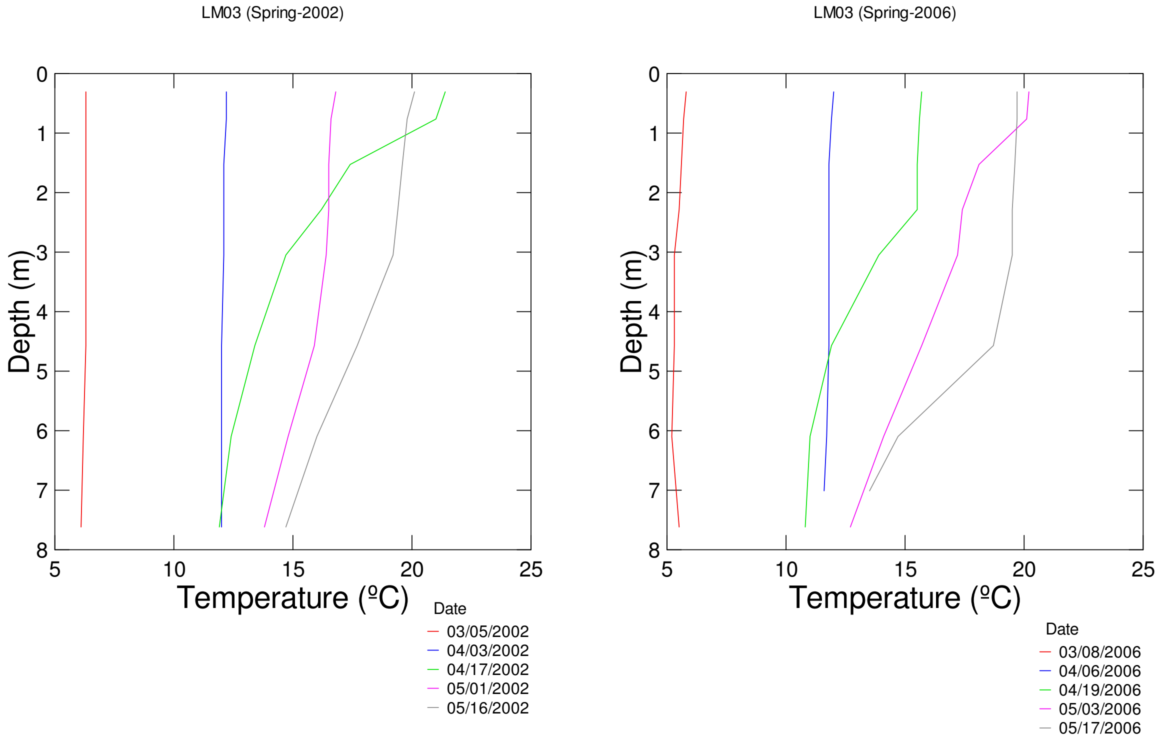


**Figure 34.** **Temperature–depth profiles at station LM03 in spring (2002 and 2006).**

The onset of stratification was observed around April 17th for the year 2002. At that time, the thermocline gradient was strong and the hypolimnion was thick. The epilimnion was less than 1 m in thickness. The next observed profile displayed a disruption in stratification. A thin epilimnion often facilitates the disruption of stratification.

For the year 2006, stable stratification was first observed on April 19th. The next profile, observed on May 3rd too had a stable thermocline and a thick epilimnion. The last profile depicted a very thick epilimnion, a stable thermocline but, with a hypolimnion that was less than 1 m in thickness. That profile indicated weak stratification.

All the other profiles for station LM03 displayed similar trends. At times, a stable stratification was reached. Soon afterwards the stratification weakened. The pattern of stratification was therefore not consistent and disruptions were frequent.

#### *4.3.1.4.2 Thermal Stratification in Summer at Station LM03*

Thermal stratification is most prominent during the summer months. Figure 35 below displays the summer profiles for the representative years 2002 and 2006 for station LM03.

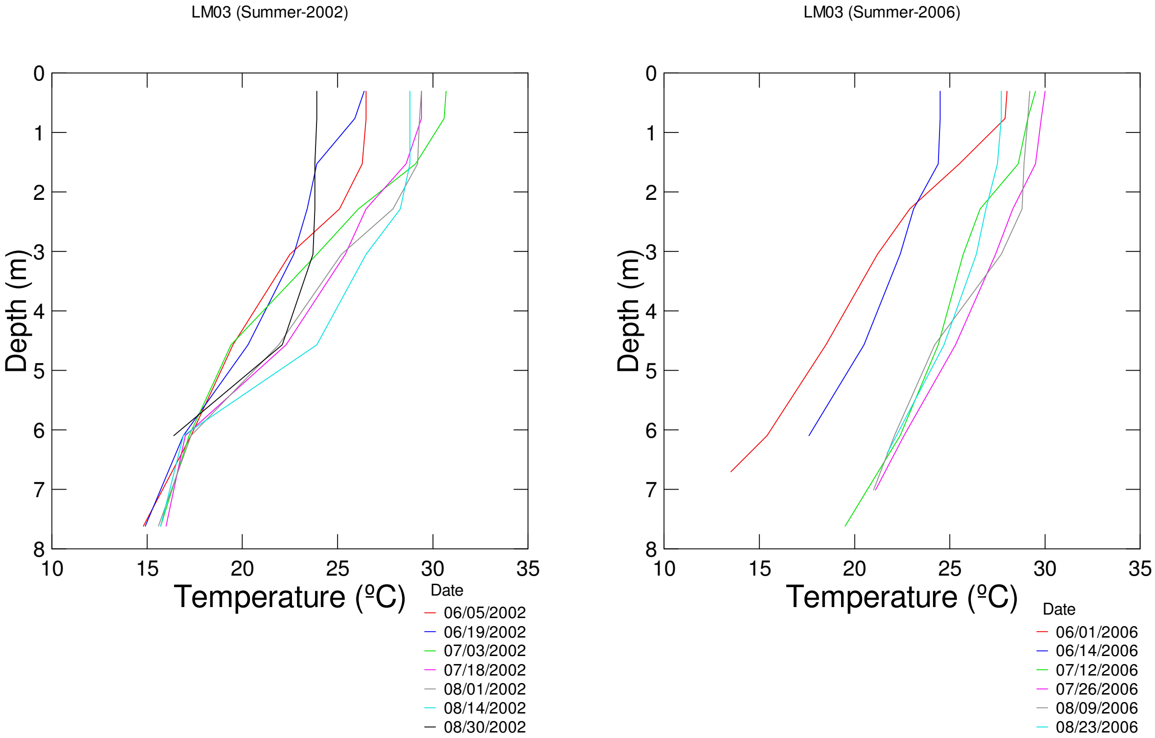


**Figure 35. Temperature–depth profiles at station LM03 in summer (2002 and 2006).**

The picture of stratification portrayed for the year 2002 was strong and stable. The thermocline gradient was consistent and the hypolimnion was greater than 1m in thickness.

The profiles for the year 2006, however, portrayed poor stratification. A proper thermocline gradient was not established for most of summer and the profiles did not indicate the presence of a hypolimnion.

All the other summer profiles, studied for station LM03 also indicated that stratification at station LM03 was not consistent. Stratification varied as depicted in the profiles above.

#### *4.3.1.4.3 Thermal Stratification in Fall at Station LM03*

The lowering of temperature in fall promotes mixing of the water column. Figure 36, below, displays the profiles existing at station LM03, for the representative years 2002 and 2006.

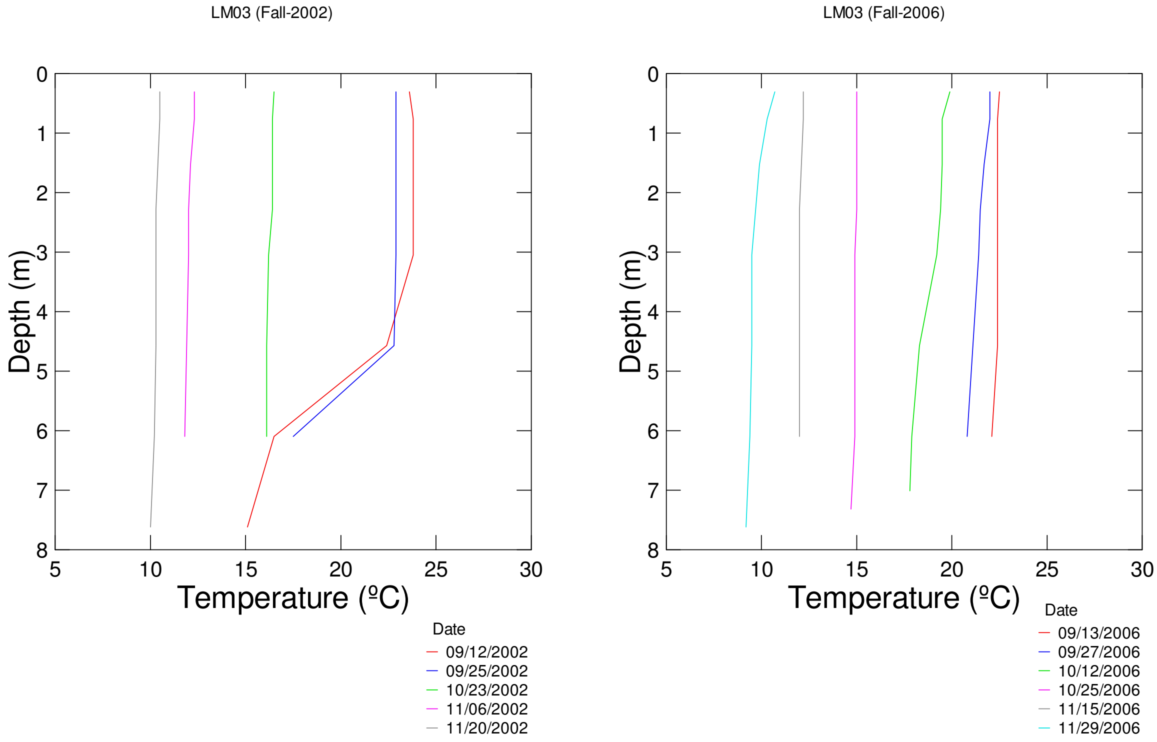


**Figure 36. Temperature–depth profiles at station LM03 in fall (2002 and 2006).**

The profiles for the year 2002 indicate the existence of stratification in the beginning of fall. As time progressed, disruption in stratification was observed, starting from the second recorded profile in fall. The profiles also indicated that the water was drawn down at that point. Fall overturn occurred during mid-fall. A drawdown of water can cause the fall overturn to occur at an earlier time.

The profiles for the year 2006 indicated that water was drawn down right in the beginning of fall. The profiles indicate that stratification broke up by the end of summer and did not extend into fall.

All the profiles studied for station LM03 indicate that stratification was easily and readily disrupted in fall. Waters were well-mixed at station LM03, for most part of fall.

##### *4.3.1.4.4 Conclusion for Station LM03 Based on Thermal Stratification*

Stratification data for station LM03 displays a mixed picture. Strong stratification was observed during the year 2002 but the year 2006 exhibited weak stratification. There were also years in between where stratification was intermediate. Unlike stations LM01 and LM02 which exhibited strong stratification over a reasonable period of time, from year to year, station LM03 varied in the degree of stability of stratification from year to year. Thus, even though stratification existed at station LM03, for the period of study, it was not consistent. Therefore, based on the thermal stratification parameter, station LM03 falls in the transitional zone.

#### 4.3.1.5 Thermal Stratification at Station LM04

Station LM04 is located in the main body of the reservoir, a little away from the dam. Temperature–depth profiles were examined for station LM04. The dates when stratification was first and last recorded are listed below in Table 13.

**Table 13. Period of stratification for station LM04.**

| Year | Date when stratification was first recorded | Date when stratification was last recorded |
|---|---|---|
| 2002 | 17th April 2002 | 25th September 2002 |
| 2003 | 7th May 2003 | 9th October 2003 |
| 2004 | 21st April 2004 | 28th July 2004 |
| 2005 | 13th April 2005 | 29th September 2005 |
| 2006 | 19th April 2006 | 23rd August 2006 |

The years 2005 and 2006 were chosen as the representative years for station LM04. The sections below discuss the profiles for these two years in greater detail.

#### *4.3.1.5.1 Thermal Stratification in Spring at Station LM04*

Warm temperatures in spring initiate stratification. The spring profiles for station LM04 for the representative years 2005 and 2006 are displayed below in Figure 37.

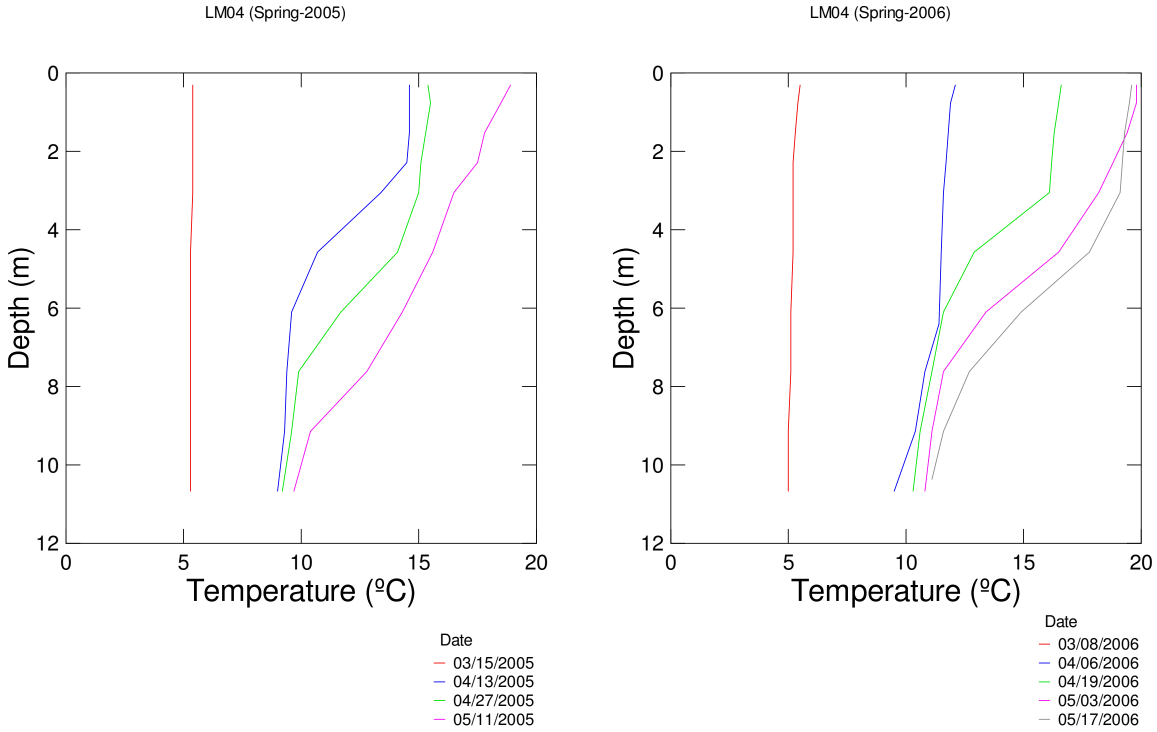


**Figure 37. Temperature–depth profiles at station LM04 in spring (2005 and 2006).**

For the year 2005, the onset of stratification was observed around mid–spring. The first stable stratification was observed on 13th April. As spring progressed, stratification strengthened. The hypolimnion varied between 2 m – 4.5 m in depth and the thermocline exhibited a stable gradient.

Similar trends were observed for the year 2006. Stable stratification was first recorded on 19th April. Stratification was strong and stable for the remainder of spring.

Most of the other profiles studied for station LM04 exhibited stable stratification during spring. The summer profiles are examined next.

### *4.3.1.5.2 Thermal Stratification in Summer at Station LM04*

Stratification is most prominent in summer. Figure 38, below, displays the temperature–depth profiles for the representative years 2005 and 2006.

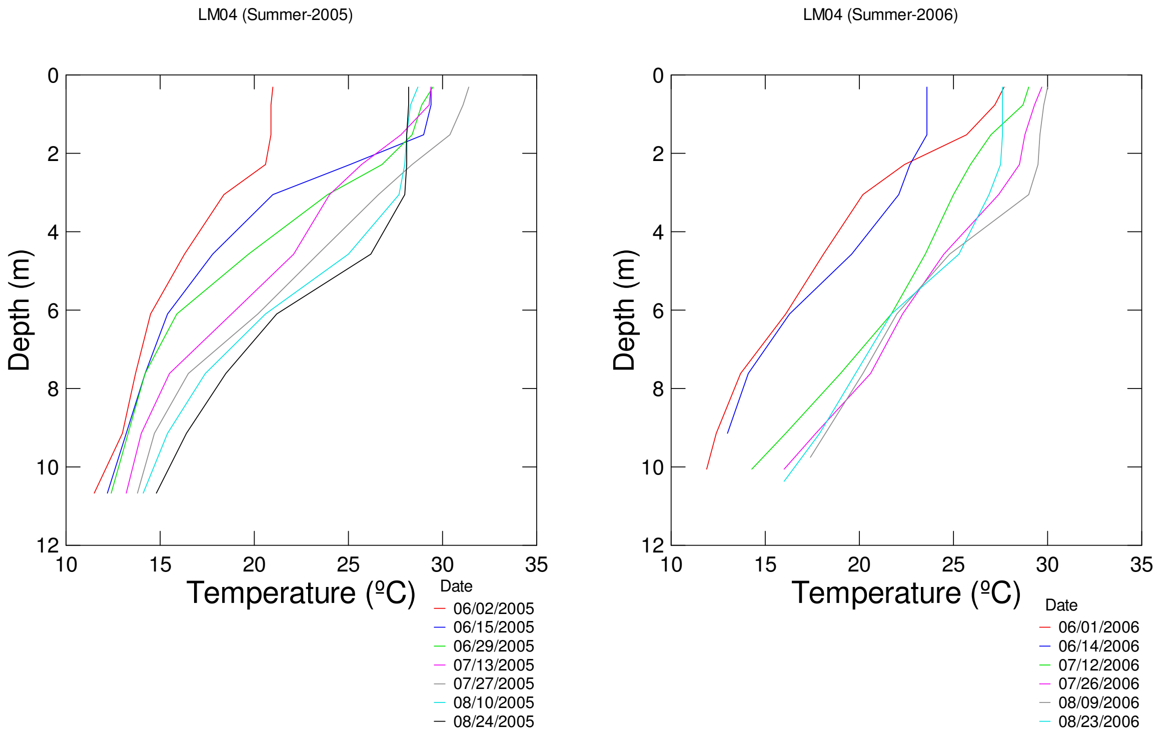


**Figure 38. Temperature–depth profiles at station LM04 in summer (2005 and 2006).**

The profiles for the year 2005 indicate that stable and strong stratification existed during summer. The profiles had both strong thermocline gradient and thickness of hypolimnion. The pattern of stratification was therefore consistent throughout summer.

For the year 2006, a stable thermocline gradient of >1°C/m, was observed for most of the profiles. The hypolimnion at station LM04 during this period was between 2 – 4.5 m thick.

All the profiles studied for station LM04 indicated consistent and stable stratification for most of summer. Although the thermocline gradient varied from year to year, it was on majority of the occasions >1°C/m.

#### *4.3.1.5.3 Thermal Stratification in Fall at Station LM04*

Fall is the time of the year when stratification tends to break up. Figure 39, below, exhibits the temperature–depth profiles for station LM04, for the representative years 2005 and 2006.

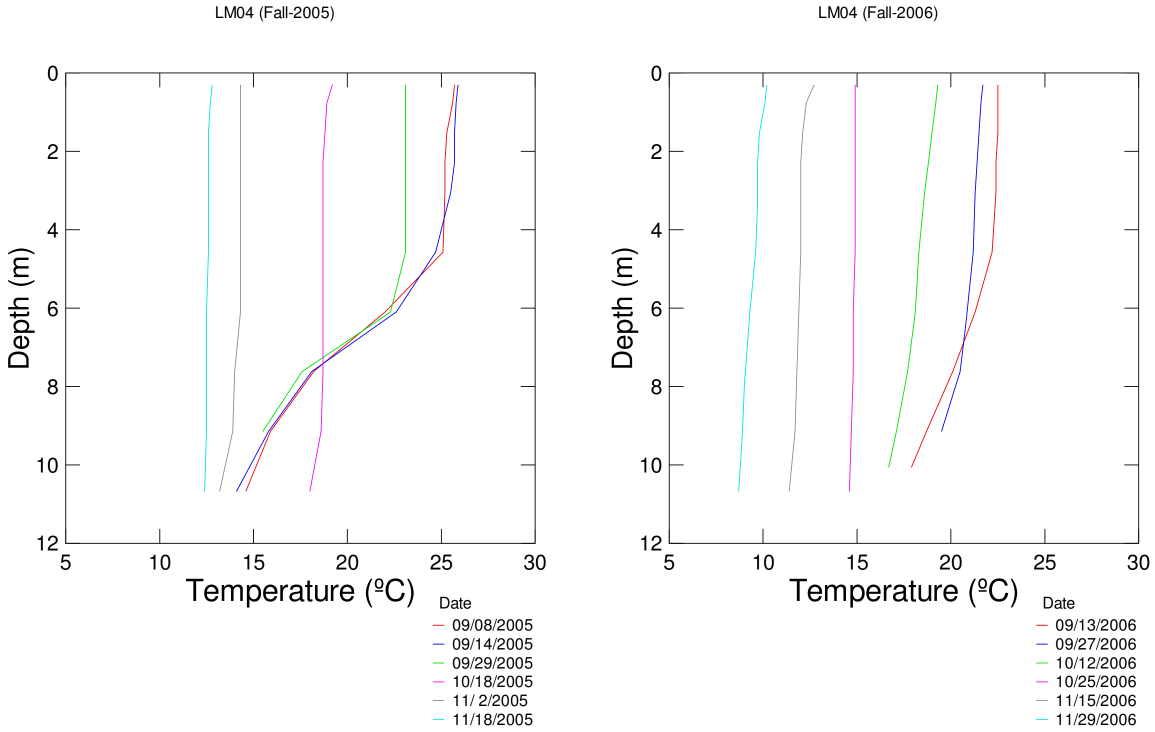


**Figure 39. Temperature–depth profiles at station LM04 in fall (2005 and 2006).**

The profiles for the year 2005, indicate that stratification extended into early fall, before finally breaking up on October 18th. The strength of stratification progressively decreased, as fall progressed. Fall overturn occurred sometime during the later half of fall.

The profiles for the year 2006 indicate that there was very little stratification observed during fall. The waters appeared to be well-mixed, right from the beginning. Fall overturn occurred sometime towards the end of summer.

Stratification extended into early fall, for some of the years in consideration. For other years, the waters were well-mixed throughout fall. Station LM04 had mixed trends for stratification during fall.

##### *4.3.1.5.4 Conclusion for Station LM04 Based on Thermal Stratification*

Station LM04 exhibited a reasonable period of stratification, for most of the years under consideration. During this period of stratification, mostly during summer, a strong and stable thermocline and a thick hypolimnion were observed. Therefore, based on the thermal stratification parameter, station LM04 falls in the lacustrine zone.

#### 4.3.1.6 Thermal Stratification at Station LM05

Station LM05 is located in the main body of the reservoir, almost in the middle of the reservoir, away from the dam. By analyzing the temperature–depth profiles for each of the five years in consideration, the dates when stratification was first and last recorded was determined. Table 14 below, lists the dates as recorded.

**Table 14. Period of stratification for station LM05.**

| **Year** | **Date stratification was first recorded** | **Date stratification was last recorded** |
|---|---|---|
| 2002 | 17th April 2002 | 14th August 2002 |
| 2003 | 7th May 2003 | 27th August 2003 |
| 2004 | 21st April 2004 | 2nd June 2004 |
| 2005 | 11th May 2005 | 29th June 2005 |
| 2006 | 17th May 2006 | 17th May 2006 |

The year 2006, as seen from Table 14, has no recorded period of strong and stable stratification. This year is excluded from the discussion. The complete absence of a recorded period of stratification for a particular year indicates shallower waters. The years 2003 and 2005 have been chosen as the representative years

#### *4.3.1.6.1 Thermal Stratification in Spring at Station LM05*

Figure 40, below, depicts the spring profiles for station LM05, for the representative years 2003 and 2005.

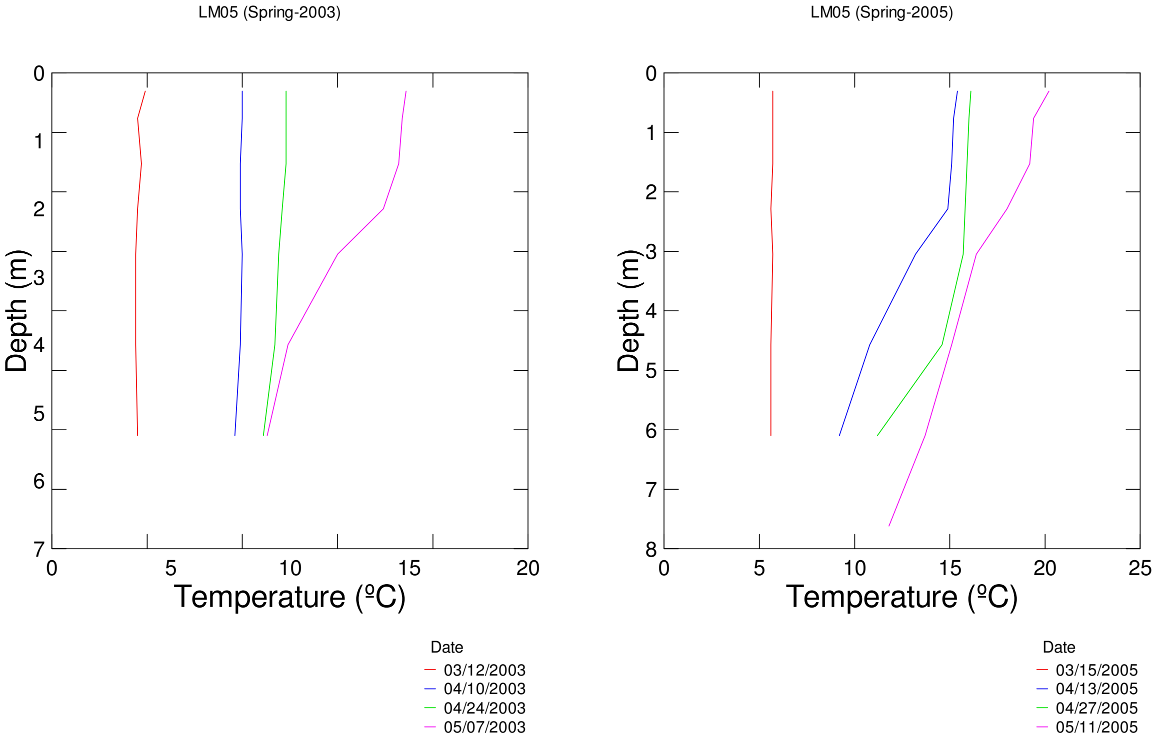


**Figure 40. Temperature–depth profiles at station LM05 in spring (2003 and 2005).**

The profiles for the year 2003 indicate that stratification was first observed on May 11th. All the requirements for a stably stratified mass of water were met.

For the year 2005, signs of stratification were visible early in spring. However, it was around May 11th, towards the end of spring, that stable stratification was observed.

From all the data analyzed, it was observed that stable stratification existed at station LM05 mostly, towards the end of spring. In the next section, the summer profiles are discussed.

##### *4.3.1.6.2 Thermal Stratification in Summer at Station LM05*

Summer profiles are important in determining whether a station is stratified stably or not. Figure 41, below, depicts the summer profiles for the representative years 2003 and 2005.

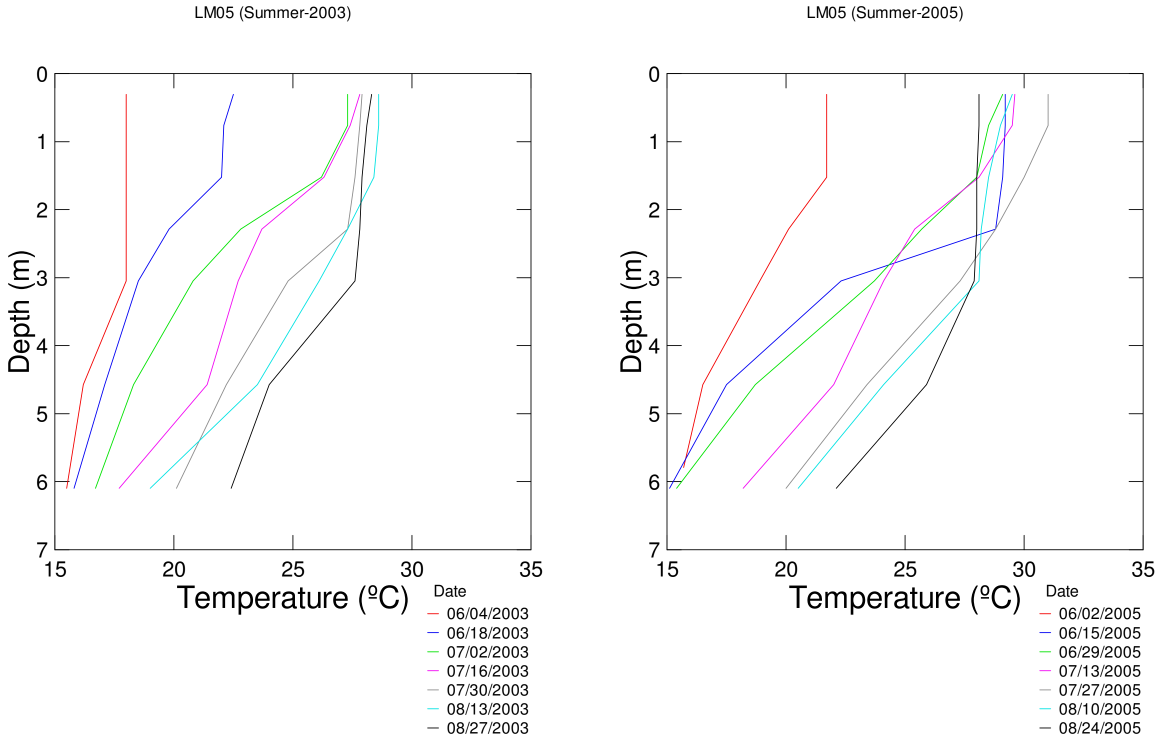


**Figure 41. Temperature–depth profiles at station LM05 in summer (2003 and 2005).**

Referring to the profiles for the year 2003, stable stratification was observed through most of the summer, with a stable and strong thermocline and a thick hypolimnion. Even though the conditions for stable stratification were met, when compared to the summer profiles from stations LM01 (Figure 29), LM02 (Figure 32) and LM03 (Figure 35), the thermocline gradients were not as established. A weaker gradient indicates that stratification may break with ease.

The summer profiles for the year 2005 indicate that the stable stratification observed during late spring (Figure 40) broke up early in summer, by late June or early July. Stratification was unstable.

Stable stratification was observed throughout summer during two of the four years considered. There was a year with no recorded period of stratification. On the whole, stratification was inconsistent year to year.

#### *4.3.1.6.3 Thermal Stratification in Fall at Station LM05*

Stratification starts weakening during fall. Figure 42, depicts the temperature–depth for station LM05 in fall, for the representative years 2003 and 2005.

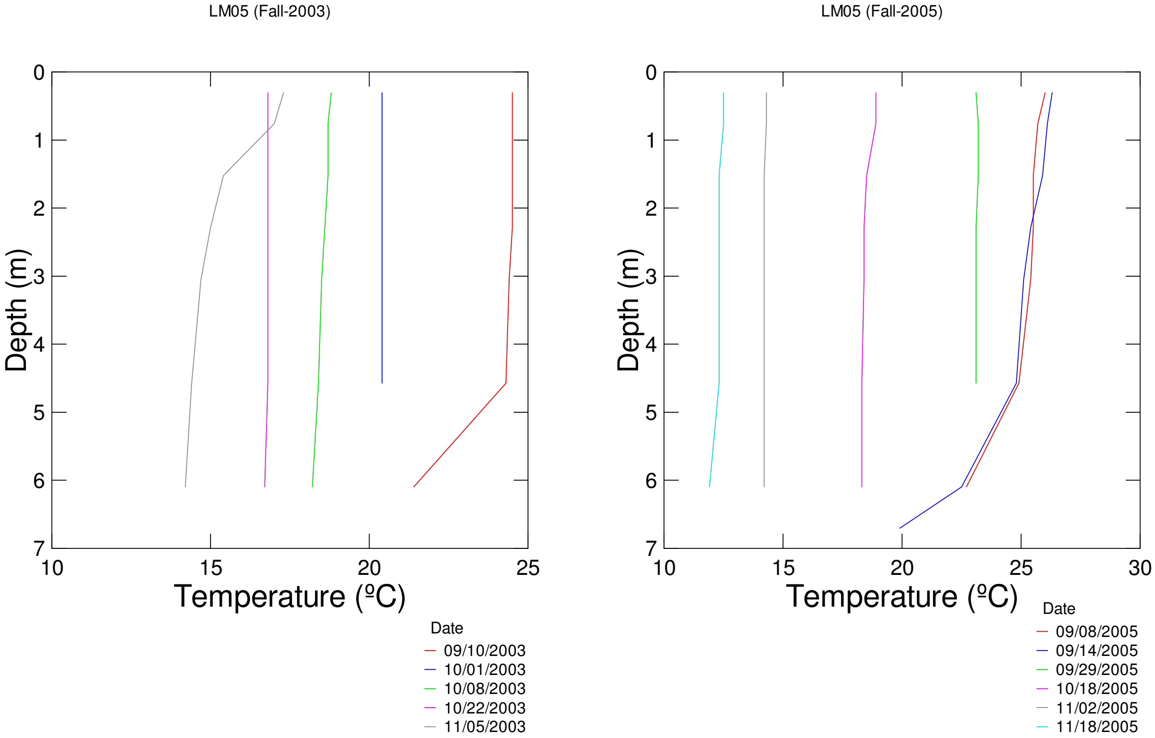


**Figure 42. Temperature–depth profiles at station LM05 in fall (2003 and 2005).**

The profiles for the year 2003 indicate that stratification was unstable. By October 10th, fall overturn has already occurred. After that the waters were well mixed.

The profiles for the year 2005 indicated that unstable stratification existed in the beginning of fall. By August 29th, the waters became well mixed.

For all the years data was analyzed, poor or no stratification existed at station LM05, during fall. In most cases, by mid fall the waters were well mixed.

#### *4.3.1.6.4 Conclusion for Station LM05 Based on Thermal Stratification*

At station LM05, for all the five years considered, stable stratification was generally observed late in spring. Stratification was inconsistent year after year in summer. By mid fall the waters became well mixed. For the year 2006, there was no recorded period of stratification. That, together with the fact that stratification was not consistent year after year in summer, suggests that station LM05 did not have strong stratification characteristics. Therefore, based on the thermal stratification parameter, station LM05 falls in the transitional zone.

### 4.3.1.7 Thermal Stratification at Station LM06

Station LM06 is located at the tail end of the reservoir. It is one of the stations furthest away from the dam, within the main body of the reservoir. Listed below, in Table 15 are the dates indicating the time around which stable stratification was first and last recorded at station LM06.

**Table 15. Period of stratification for station LM06.**

| Year | Date stratification was first recorded | Date stratification was last recorded |
|---|---|---|
| 2002 | 6th May 2002 | 6th May 2002 |
| 2003 | 4th June 2003 | 2nd July 2003 |
| 2004 | 21st April 2004 | 21st April 2004 |
| 2005 | 11th May 2005 | 13th July 2005 |
| 2006 | 1st June 2006 | 1st June 2006 |

For the years 2002, 2004 and 2006, there was no recorded period of stable stratification. The profiles discussed below will explain in greater detail the trends of stratification at station LM06. The years 2003 and 2005 have been chosen as the representative years to discuss the trends observed for stratification at this station. The remaining years as observed from above, have no recorded periods of stable stratification.

### *4.3.1.7.1 Thermal Stratification in Spring at Station LM06*

The onset of stratification is first observed during spring. Figure 43, below, depicts the thermal stratification, as it was observed at station LM06, for the representative years 2003 and 2005.

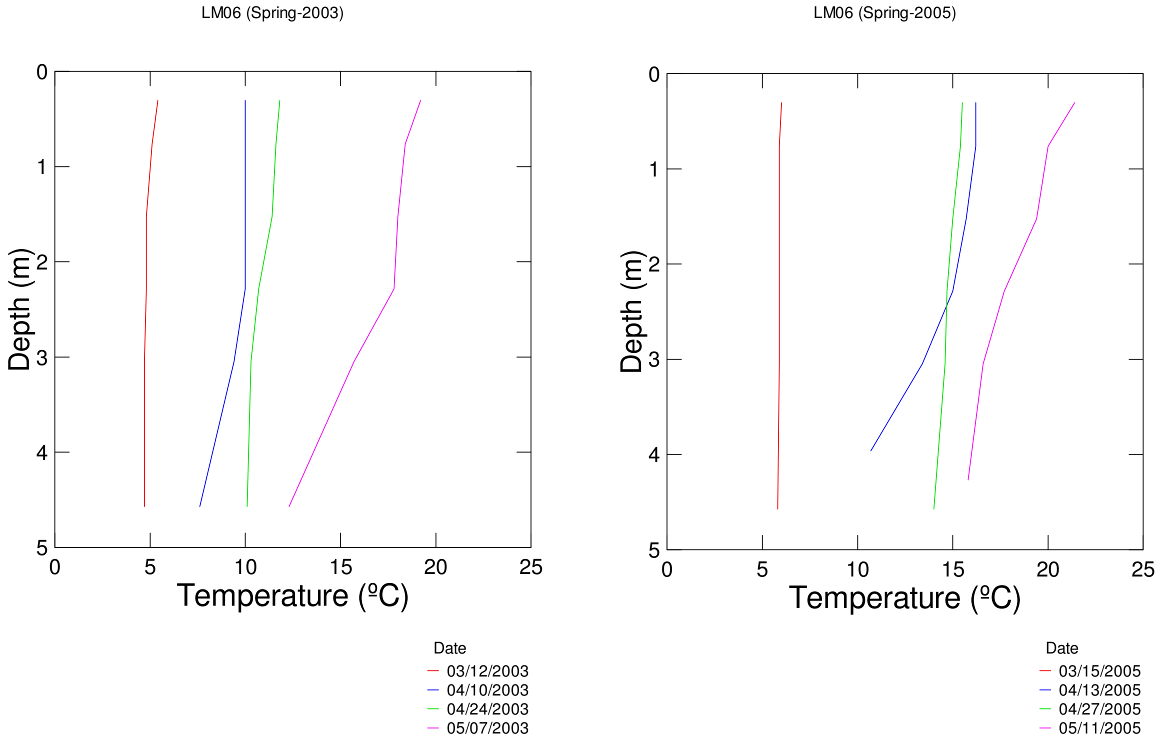


**Figure 43. Temperature–depth profiles at station LM06 in spring (2003 and 2005).**

The profiles for the year 2003 indicate that the waters were well mixed during the beginning of spring. Some stratification was observed in the last profile, however it was unstable.

The profiles for the year 2005 display similar trends. Weak and unstable stratification was observed during the later half of spring. Stratification was generally weak and unstable at station LM06 during spring for all the years under consideration.

#### *4.3.1.7.2 Thermal Stratification in Summer at Station LM06*

The summer temperature profiles at station LM06 indicated that stratification was stronger in summer when compared to spring. Figure 44 below, displays summer profiles for station LM06.

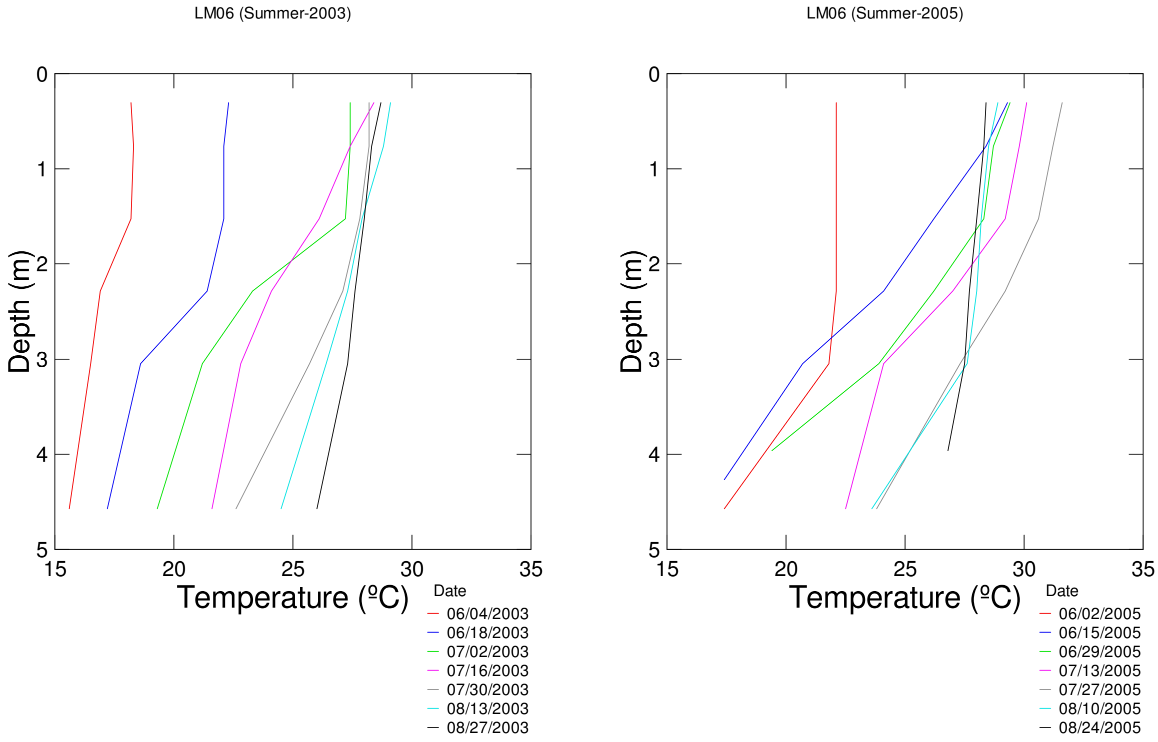


**Figure 44. Temperature–depth profiles at station LM06 in summer (2003 and 2005).**

The summer profiles for the year 2003 indicate that stratification was stable during the early part of summer, with a stable thermocline and a thick hypolimnion. However, by mid July stratification weakened and the weakening progressed until the end of summer.

The last observed profile for stable stratification was on 2nd July. By the end of summer, there was hardly any stratification at station LM06.

The temperature profiles for the year 2005, exhibit a similar pattern. By mid July, the stratification had weakened significantly. The last recorded date of stable stratification was on 13th July. By the end of summer, stratification ceased to exist.

For the other years in consideration, there were no recorded periods of stratification. Stable stratification was observed on just one profile, in most cases. Most of the other profiles suggested weak and unstable stratification.

#### *4.3.1.7.3 Thermal Stratification in Fall at Station LM06*

Fall brings about fall overturn and the waters become well mixed. Figure 45, below, depicts the fall profiles, for the representative years 2003 and 2005.

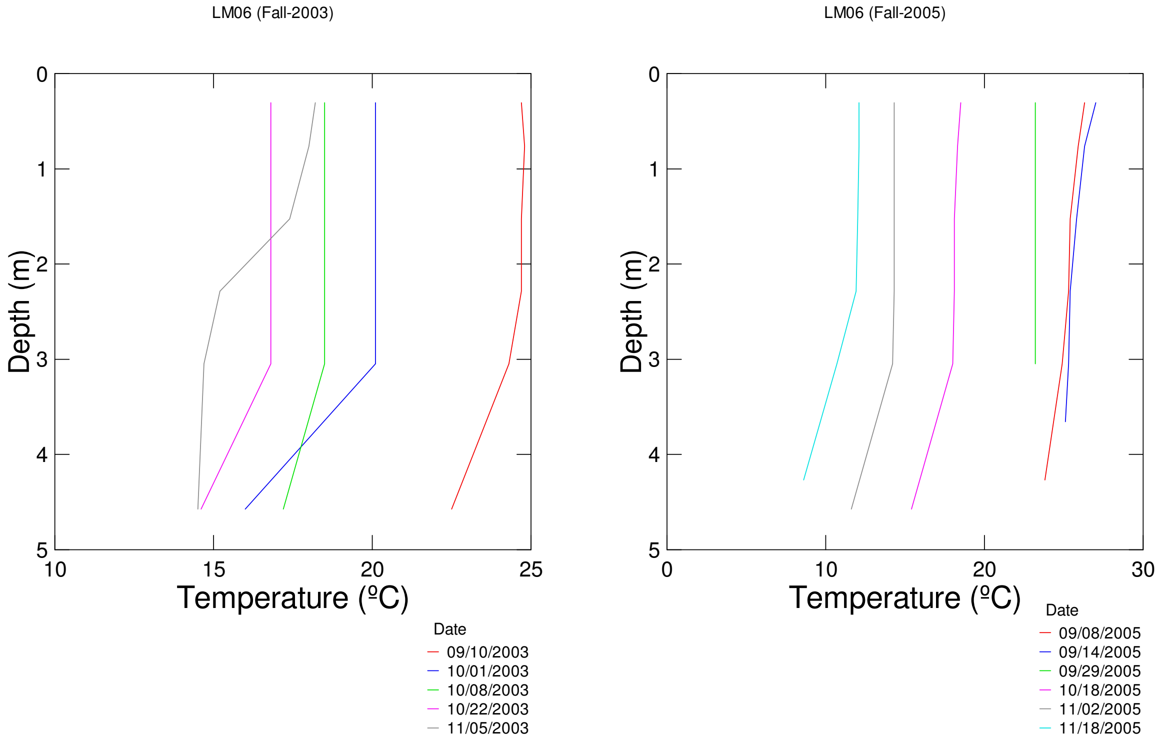


**Figure 45. Temperature–depth profiles at station LM06 in fall (2003 and 2005).**

Profiles for both years 2003 and 2005, indicate a difference in temperature between the top and bottom waters. This difference in temperature did not constitute the presence of a distinct epilimnion, thermocline and hypolimnion. Without these three distinct layers, the waters cannot be categorized as stratified. For the year 2003, from the profiles in Figure 45, during early November, a stable profile with a thermocline, a thick hypolimnion and epilimnion was observed. This was the result of unseasonal warming of surface waters and therefore an anomaly.

For all the other years in consideration, no stable stratification was observed during fall, at station LM06. For most part of fall, the waters were well mixed.

#### *4.3.1.7.4 Conclusion for Station LM06 Based on Thermal Stratification*

The temperature profiles for station LM06 indicate that stratification was stable only for a short period of time. By mid-summer, the stratification started to weaken and by the end of the summer it was almost non-existent. By early fall, the waters appeared to be well mixed. The weak, easily broken stratification indicate that station LM06 falls in the transitional zone, based on the thermal stratification parameter. The very short period of stratification, the complete absence of a period of stratification, for some years under consideration and the tendency for the stratification to break up easily, all suggest that station LM06 lies somewhere near the boundary of the transitional zone with the riverine zone.

### 4.3.1.8 Thermal Stratification at Station LM07

Station LM07 is located near station LM06, at the tail end of the reservoir, within its main body. It is one of the stations farthest away from the dam. Table 16 below, lists dates during which stable stratification was first and last observed at station LM07.

**Table 16. Period of stratification for station LM07.**

| Year | Date stratification was first recorded | Date stratification was last recorded |
|---|---|---|
| 2002 | – | – |
| 2003 | 16th July 2003 | 16th July 2003 |
| 2004 | 21st April 2004 | 21st April 2004 |
| 2005 | 15th June 2005 | 29th June 2005 |
| 2006 | 12th July 2006 | 12th July 2006 |

From Table 16, it is clear that very little stratification existed at station LM07. The period of stratification was either very short or non-existent. For the year 2002, there was no recorded profile of stable stratification. For the years 2003, 2004 and 2006, there was just one recorded profile showing stable stratification. The year 2005 exhibited the presence of stable stratification but the window of stable stratification was very narrow. The years 2004 and 2005 are chosen as the representative years to discuss the trends observed with regard to thermal stratification, at station LM07. In the sections above, discussion for the years where there was no recorded period of stratification was omitted. Since no data other than that for the year 2005, has a recorded period of stratification, data available for the year 2004 was considered.

#### *4.3.1.8.1 Thermal Stratification in Spring at Station LM07*

Stratification during spring is often not very prominent. Figure 46, below, depicts the-stratification, at station LM07, in spring, for the representative years 2004 and 2005.

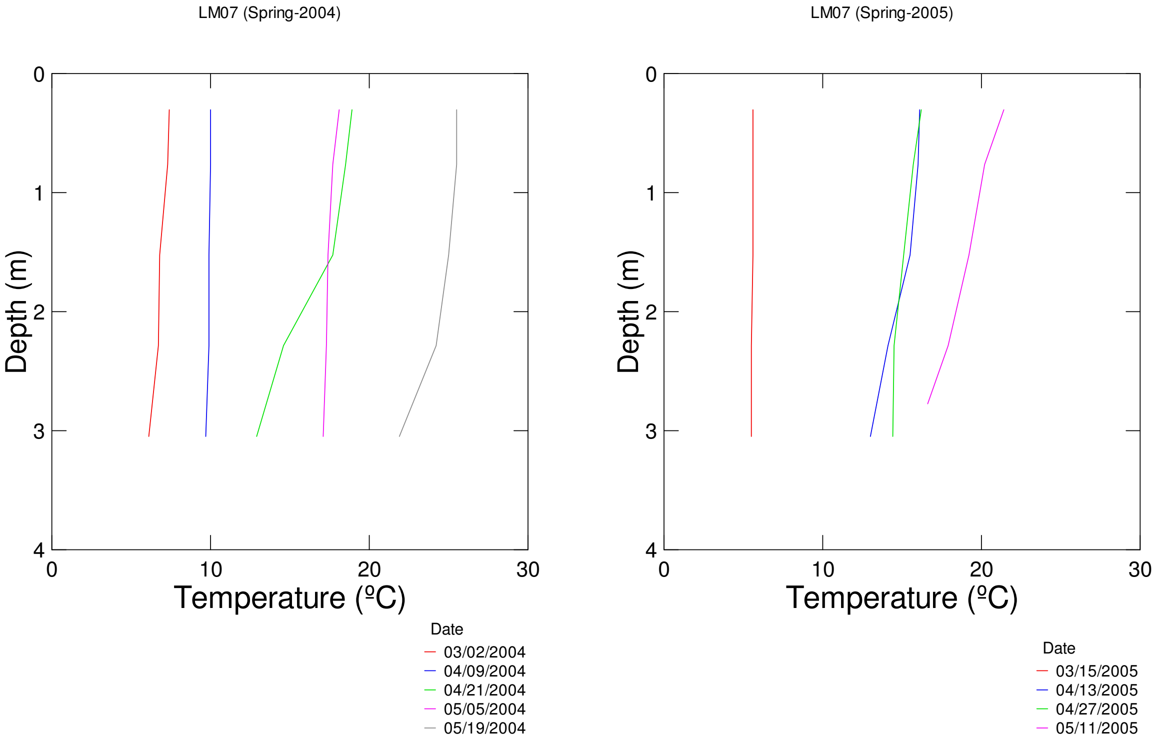


**Figure 46.** **Temperature–depth profiles at station LM07 in spring (2004 and 2005).**

The profiles for the year 2004 indicate that stable stratification was first recorded on April 21st. But profiles recorded after that, indicate that stratification had weakened considerably. For most of spring, there was no stable thermocline and the waters appeared to be well mixed.

During early spring, the profiles for the year 2005 exhibited uniformity in temperature from top to bottom. As spring progressed, a difference of a few degrees was observed between the top and bottom waters but this difference did not give rise to an epilimnion, thermocline and hypolimnion, as is the case with a stratified mass of water.

For all the years considered, the spring profiles suggest very little stratification. The waters were well-mixed for most part.

#### *4.3.1.8.2 Thermal Stratification in Summer at Station LM07*

Summer profiles exhibit stratification the strongest. Figure 47, below, depicts the summer profiles for the station LM07, for the representative years 2004 and 2005.

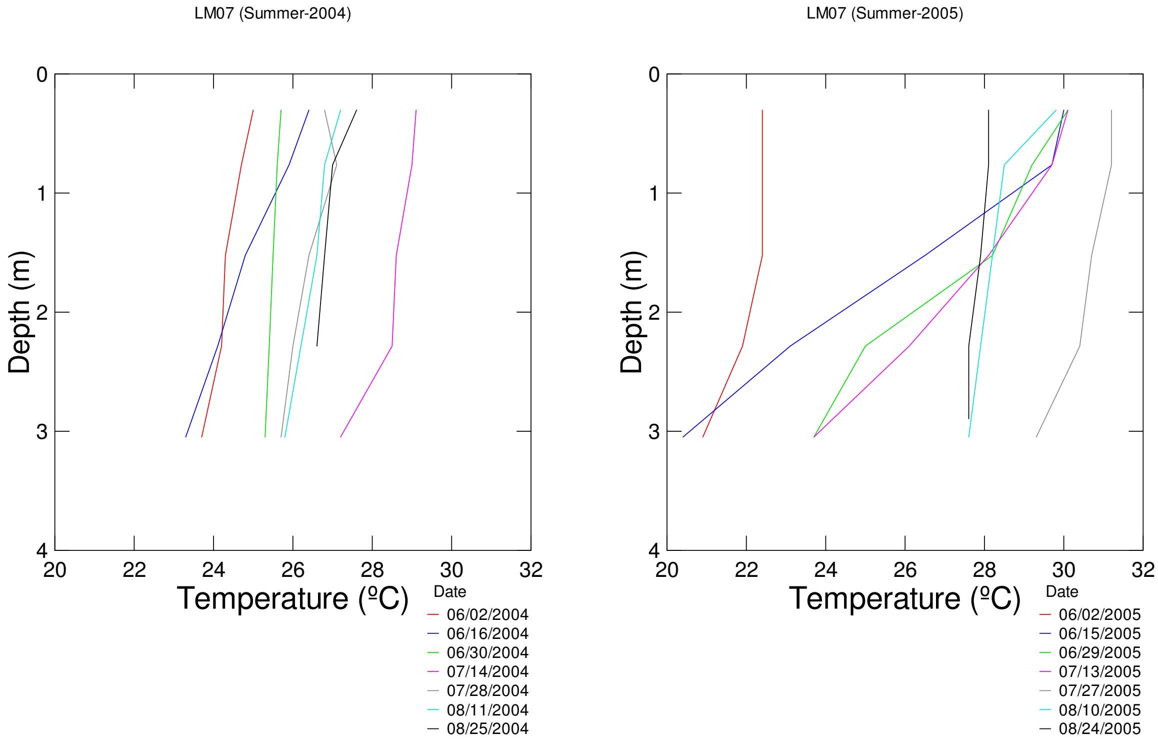


**Figure 47. Temperature–depth profiles at station LM07 in summer (2004 and 2005).**

The profiles for the year 2004, in Figure 47, display a temperature difference of a few degrees between the top and bottom waters. This temperature difference does not constitute stratification because of absence the epilimnion, thermocline and hypolimnion. The waters were unstratified through most of summer.

The profiles for 2005 indicated unstratified waters in the beginning of summer. The second recorded profile, on June 15th exhibited stable stratification. This stratification weakened progressively, until around June 29th and then dissipated. From then on, until the end of summer, the waters were unstratified.

Summer profiles for station LM07 indicate that stratification often occurred early in summer but within a span of a few weeks, it weakened. For the year 2002, there were no profiles indicating stable stratification and for the other years in consideration, summer profiles hardly showed stable stratification.

#### *4.3.1.8.3 Thermal Stratification in Fall at Station LM07*

The cooling temperatures help break up stratification in fall. Figure 48, below, depicts the fall profiles for station LM07, for the representative years 2004 and 2005.

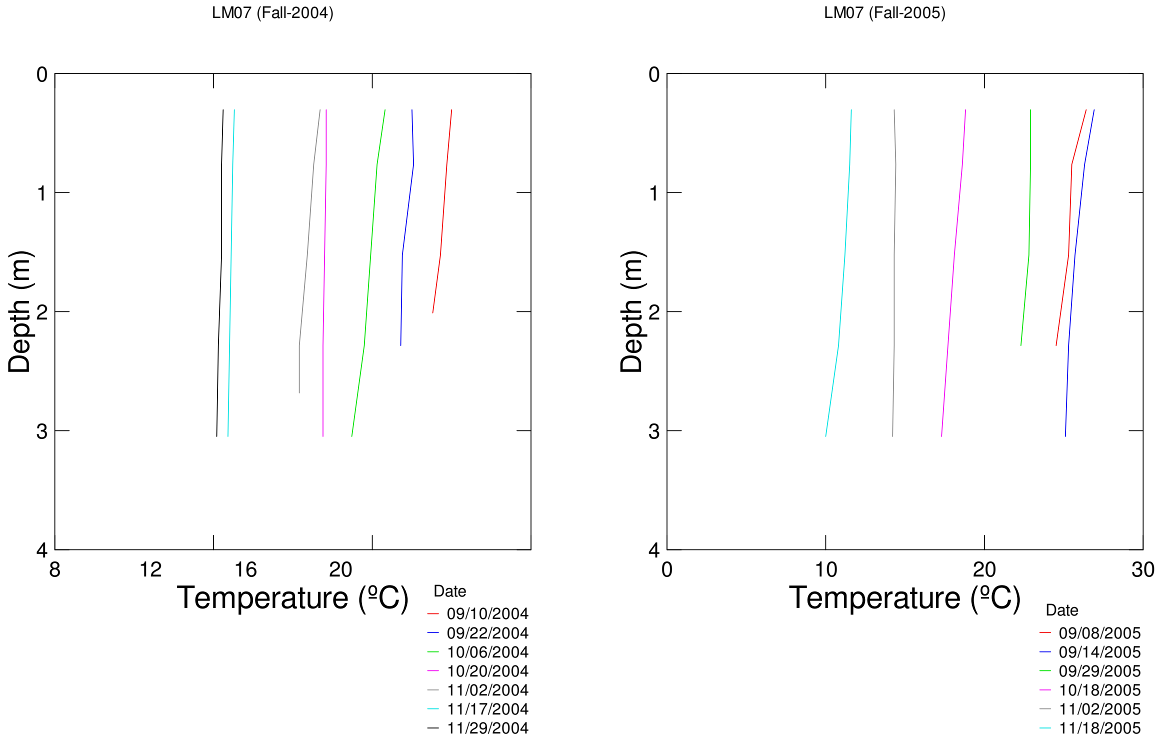


**Figure 48. Temperature–depth profiles at station LM07 in fall (2004 and 2005).**

The profiles for both the years in consideration indicated that the waters were well-mixed throughout fall. There appeared to be no signs of stratification.

The temperature profiles for fall indicated that stratification broke up completely by late summer and rarely extended into fall. Once the stratification broke up, the waters were well mixed. This was true for all the years of data examined.

#### *4.3.1.8.4 Conclusion for Station LM07 Based on Thermal Stratification*

Station LM07 exhibited some stratification during summer. The stratification was stable only for a very short period of time. Very often strong stratification was recorded only on a single profile. There were also years present, when not a single stable profile was recorded. All these together indicate that in terms of stratification, station LM07 exhibited weak characteristics. Therefore, based on the thermal stratification parameter, station LM07 falls in the transitional zone. The presence of very short periods of stratification and no period of stratification, indicates that based on this parameter; station LM07 should fall somewhere near the boundary of the transitional zone with the riverine zone.

### 4.3.1.9 Thermal Stratification at Station LM08

Station LM08 is located in one of the arms of Lake Manassas, away from the dam. By analyzing the temperature depth profiles over several years, the dates during which stable stratification was first and last recorded are compiled in Table 17.

**Table 17. Period of stratification for station LM08.**

| **Year** | **Date when stratification was first recorded** | **Date when stratification was last recorded** |
|---|---|---|
| 2002 | 5th June 2002 | 30th August 2002 |
| 2003 | 24th June 2003 | 30th July 2003 |
| 2004 | 21st April 2004 | 21st April 2004 |
| 2005 | 15th June 2005 | 27th July 2005 |
| 2006 | 1st June 2006 | 1st June 2006 |

Looking at the dates above, for every year considered, some stratification was observed, ranging from a few days to more than a month. For the years 2004 and 2006, there were no recorded periods of stable stratification. For all the other years considered, there existed more than one profile with stable stratification. The years 2002 and 2005 have been chosen as the representative years to describe the trends in stratification that were observed at station LM08, during the period of study.

#### *4.3.1.9.1 Thermal Stratification in Spring at Station LM08*

Stratification is often first observed during spring in deeper parts of the reservoir. As the reservoir gets shallower, stratification too takes a back seat. Figure 49, below, depicts stratification at station LM08, in spring, for the representative years 2002 and 2005.

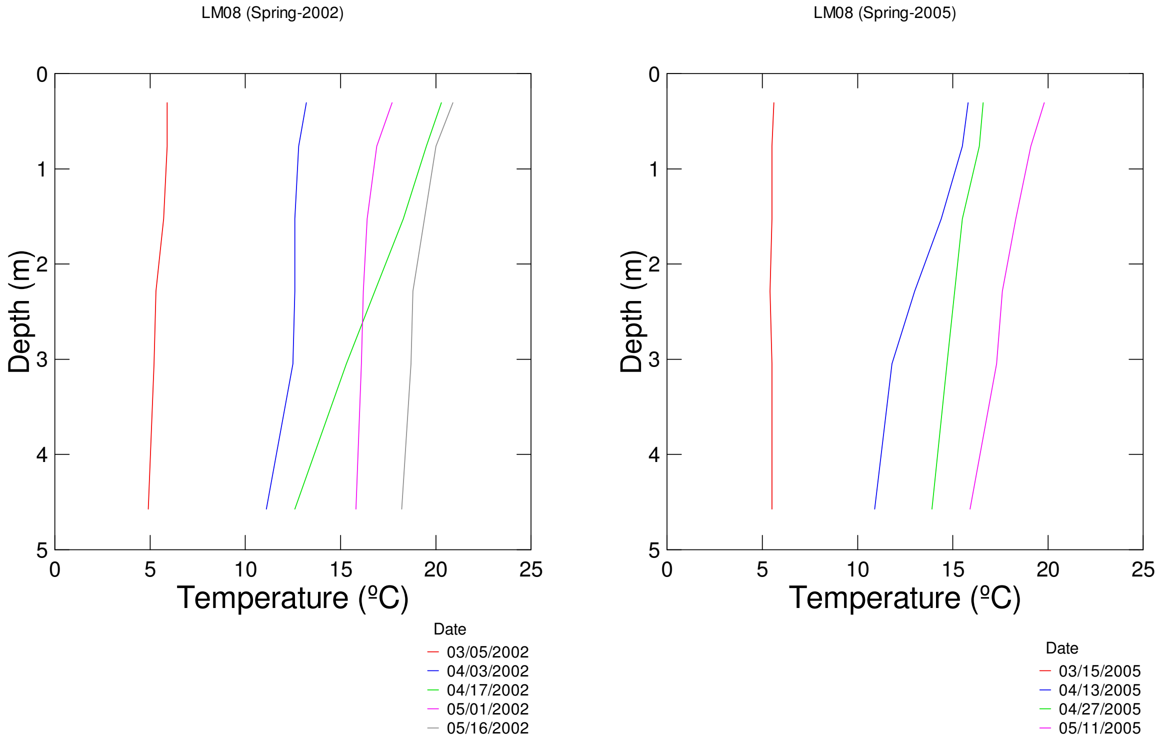


**Figure 49. Temperature–depth profiles at station LM08 in spring (2002 and 2005).**

The profiles for the year 2002 indicate that stratification was not recorded during spring. The same was observed from the profiles, for the year 2005.

During spring, at station LM08, there was hardly any stratification. Sometimes a difference in temperature between the top and bottom waters was observed. However, this did not constitute stratification, as it did not meet the requirements for a stable thermocline or a hypolimnion. This was true for all the years under consideration. The only stable stratification observed during spring was in the year 2004. As it happens, that was the only stable profile recorded during the entire year 2004.

### *4.3.1.9.2 Thermal Stratification in Summer at Station LM08*

Stratification, when it exists is always strongest in summer. Figure 50, below, portrays the trends in stratification, at station LM08, for the representative years 2002 and 2005.

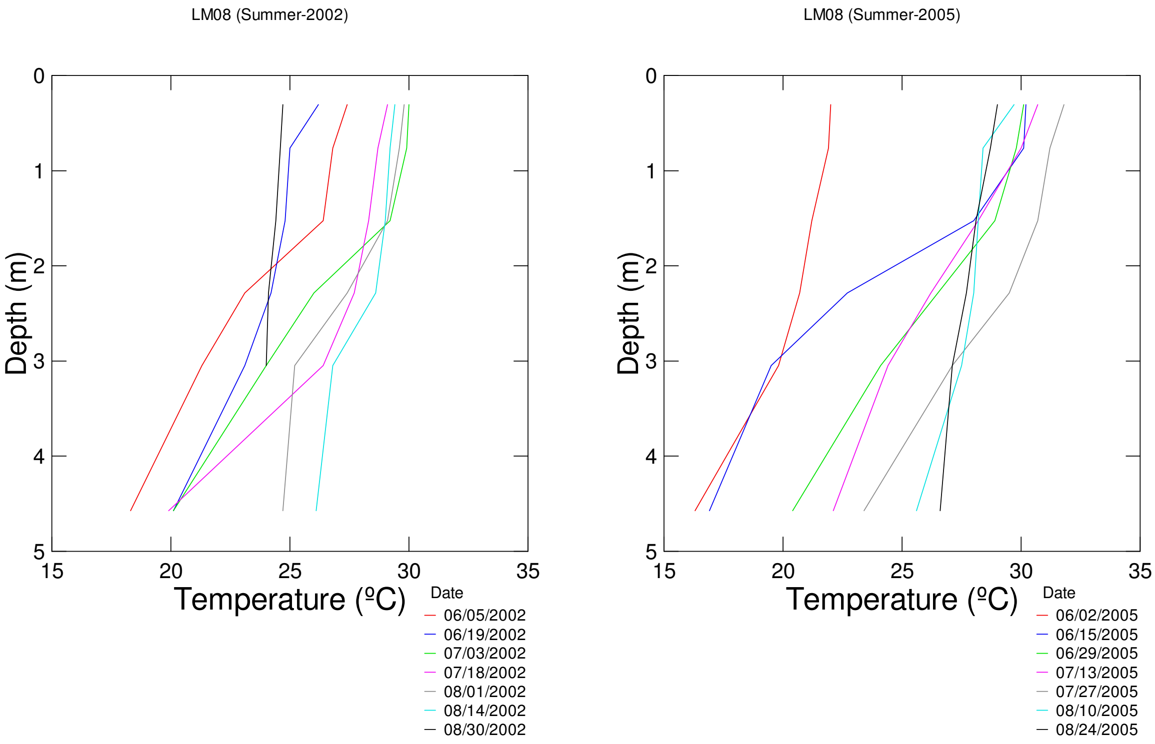


**Figure 50. Temperature–depth profiles at station LM08 in summer (2002 and 2005).**

The profiles for the year 2002 indicate that strong and stable stratification existed during summer at station LM08. The first observed instance of stable stratification was on June 5th. An intermittent disruption was observed on July 18th. However, after that, the stratification was stable until near the end of summer, when it started to weaken.

The profiles for the year 2005, from the above figure, indicate that stratification was not stable at the onset of summer but the next observed profile indicated the presence of stable stratification with three distinct layers. The first stable stratification in summer was observed on June 15th. However, stratification weakened soon after July 27th. After that, progressive weakening of stratification was observed.

For the year 2004, there was hardly any stratification observed during summer. For the year 2006, there was just one stable profile. In the year 2003, there was a brief period of stable stratification. Therefore, considering all the data available, it can be concluded that station LM08, did not exhibit strong stratification characteristics during summer.

#### *4.3.1.9.3 Thermal Stratification in Fall at Station LM08*

With the onset of fall, the temperature begins to drop. The drop in temperature is instrumental in bringing about fall overturn. Figure 51, depicts the profiles for fall at station LM08, for the representative years 2002 and 2005.

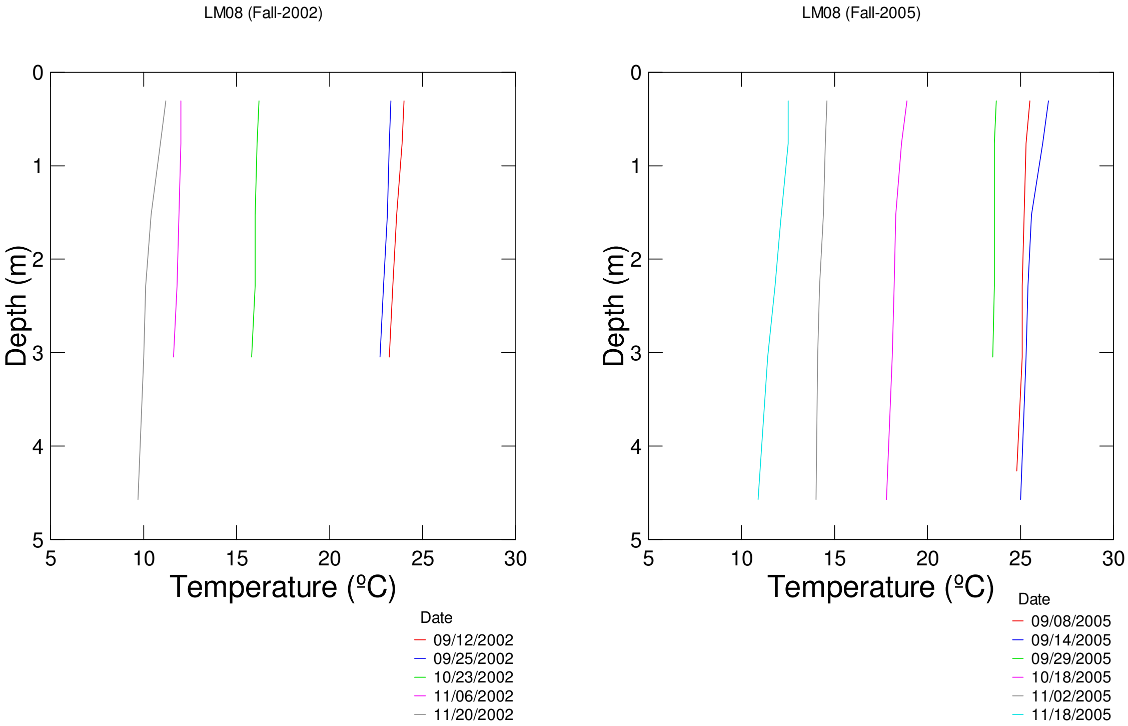


**Figure 51. Temperature–depth profiles at station LM08 in fall (2002 and 2005).**

As seen in the figure above, the fall profiles for both years 2002 and 2005, indicated no sign of stratification. Stratification was disrupted by the end of summer at station LM08. This was true for all the years considered.

#### *4.3.1.9.4 Conclusion for Station LM08 Based on Thermal Stratification*

The temperature profiles at station LM08 indicate that stratification existed here only for a short period of time. Although some of the profiles indicated stable stratification with a three distinct layers, a stable thermocline and a hypolimnion, it was easily broken up. There were years in between where there was no recorded period of stratification. When stratification existed, it was often just one stable profile. All these indicate that stratification was not strong and stable at station LM08. Therefore, based on the thermal stratification parameter, station LM08 falls in the transitional zone. As there were years in between with no sign of stratification, it most probably lies near the well-mixed zone. Hence, station LM08 can be considered to fall somewhere near the boundary of the transitional zone with the riverine zone.

#### 4.3.1.10 Zonation in Lake Manassas Based on Thermal Stratification

Based on the stratification parameter, the lacustrine zone should exhibit strong and stable stratification, typically starting late in spring. In the transitional zone, stratification is weak, unstable and intermittently broken. In the riverine zone there is no stratification and the waters are well mixed.  Taking all this into consideration and based on the temperature profiles studied above, an initial zone determination of Lake Manassas was performed (Figure 52). This is the first step towards lake zonation and will be further refined when additional parameters are taken in account.

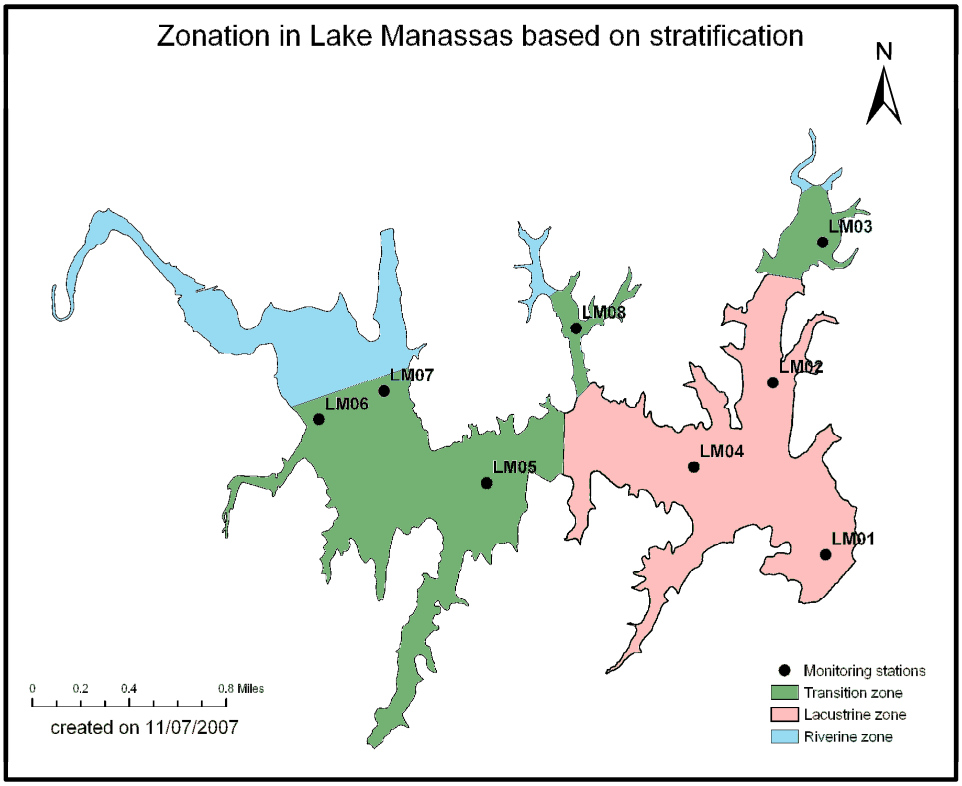


**Figure 52. Zonation in Lake Manassas based on the parameter stratification.**

In Figure 52, certain regions have been assigned as riverine zones, especially in the arms even though no temperature –depth profiles were available. This has been based on the assumption that towards the shoreline, the depth is expected to be shallow and therefore the waters will be well mixed. Stratification is highly unlikely to exist there.

### 4.3.2 Morphometry of Lake Manassas

Lake Manassas is modeled as part of the Occoquan model, maintained at Occoquan Watershed Monitoring Laboratory (OWML) and is currently modeled with a CE-QUAL-

W2 model (an Army Corp of Engineers 2-dimensional model), for water quality purposes. For the purpose of the model, the entire lake has been divided into various segments. These segments, based on the bathymetry of the Lake can help in analyzing the morphometry. Further analysis of the lake based on shape, width and depth, is required to determine the different zones with further detail. Lake Manassas is divided into segments as seen in Figure 53 for use by the water quality model.

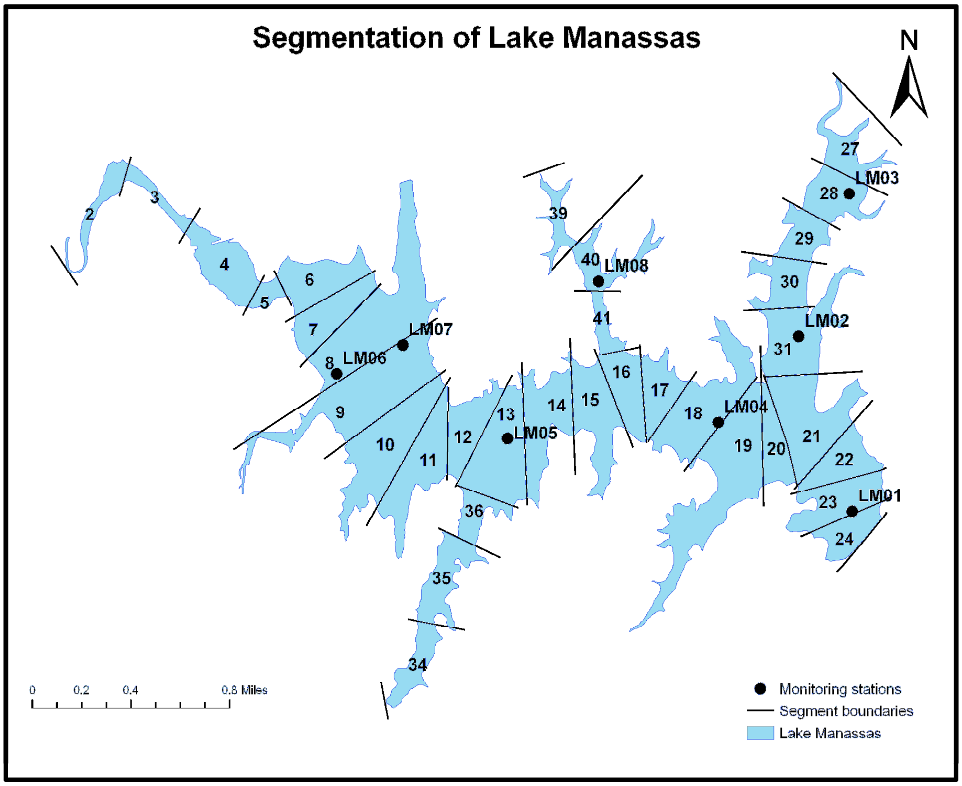


**Figure 53. Segmentation of Lake Manassas in the water quality model.**

Lake Manassas is divided into four branches. Branch 1 includes segments 2 to 24, branch 2 includes segments 27 through 31, branch 3 includes segments 34 to 36 and branch 4 includes segments 39 to 41.Missing segment numbers are boundary elements of zero volume that are used by the model but are not pertinent to this analysis.

#### 4.3.2.1 Analysis Based on Shape

Analysis based on shape takes into account the width and nature of the shoreline. The narrow dendritic portion of a reservoir is generally considered to be riverine in nature. The transitional zone is wider and the lacustrine zone is widest and is almost ovoid in shape.

As seen from Figure 53, segments 2 to 6 are narrow and dendritic in nature. The same can be said for segments 34 to 36 and segments 39 to 41. There are also a few other arms which appear to be narrow and dendritic (for example the northern area in segment 8). These arms have not been segmented as separate segments. However, their narrow dendritic shape, suggests that they belong to the riverine zone. The widest portion of the reservoir near the dam and a considerable portion in the main body of the reservoir are lacustrine. This determination can be reinforced only after it has sufficient support from depth analysis. The portion of the reservoir between the wide lacustrine zone and the narrow dendritic riverine zone is the transitional zone. Shape, though important in determining the zones of a reservoir, needs to have other supporting factors, especially in run-of-the-river reservoirs. This is because these reservoirs are often narrow and winding. Therefore, apart from shape, depth, too, must be analyzed in greater detail before a decision can be reached. The next section deals with depth analysis.

#### 4.3.2.2 Analysis Based on Depth of Segments

For analysis of depth, the bathymetry of the reservoir was studied. The segmentation of Lake Manassas for purpose of the model was done such that a particular segment had similar depth and other characteristics throughout its length. For each of the segments, the average depth of the segment is known. Figure 54 below, exhibits the depth of each segment, in each of the four branches.

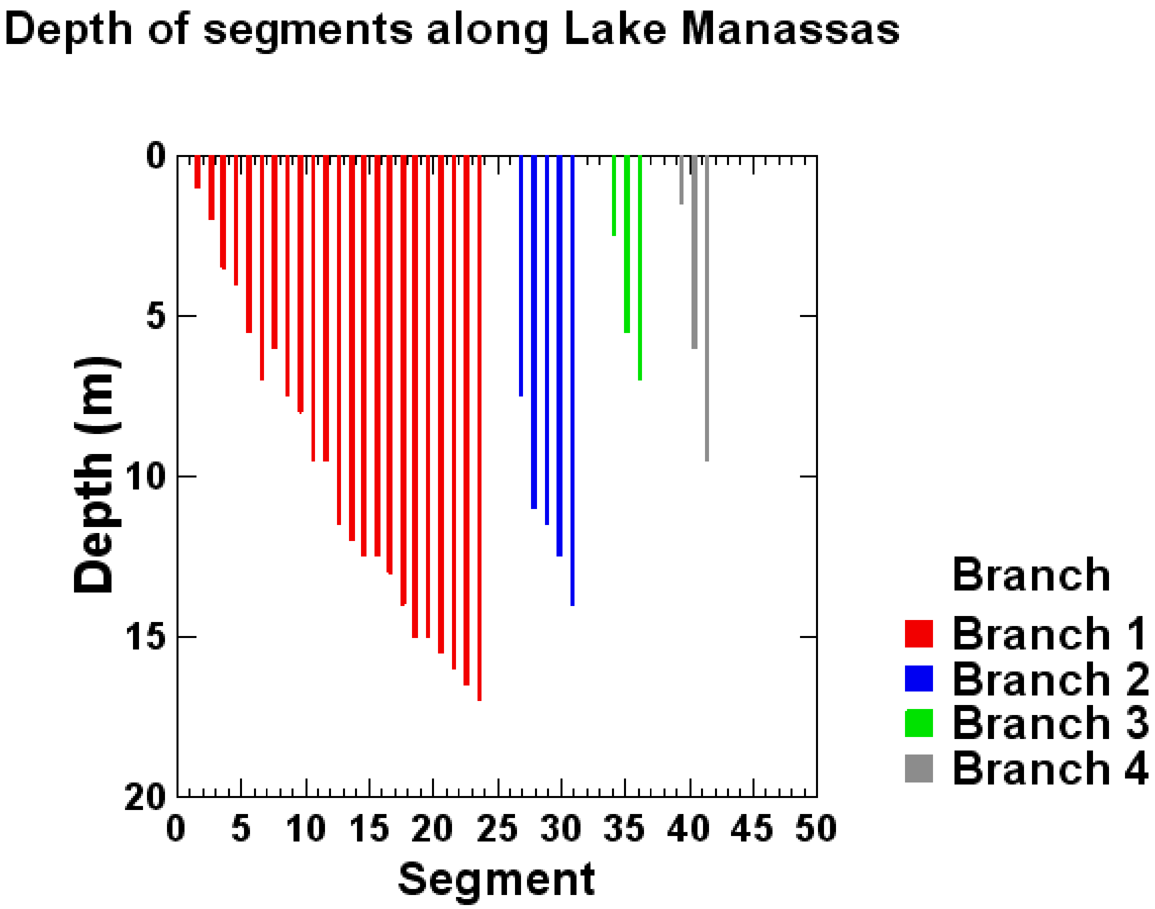


Figure 54. Average depth of segments along Lake Manassas.

The division of zones along branch 1 of Lake Manassas was considered first. As discussed earlier, the shape of segments 2 to 6 is narrow and dendritic. Their depth varies between 1 and 5 m. The shallow depth indicates that stratification is highly unlikely here. The shallow depth and the narrow dendritic shape indicate that these segments belong to the riverine zone.

The characteristics that indicate transition from the riverine zone to the transitional zone is a marked increase in depth. Segment 6 has an average depth of 5.5 m and segment 7 has an average depth of 7 m. This difference in depth is more pronounced than the difference in depth between the other adjacent segments. This suggests that the boundary between segment 6 and 7 is probably the borderline between the riverine zone and the transitional zone. To further reinforce this conclusion, the characteristics exhibited in segment 8 were taken into consideration. Station LM06, which is located in segment 8 has an average depth of 6.0 and is stratified unstably. It is safe to assume that segment 8 too stratified unstably. Segment 7, which is adjacent to it, has a greater depth of 7 m and therefore, is likely to be unstably stratified. The pronounced increase in depth between segment 6 and segment 7 and the possibility for presence of stratification in segment 7, indicate that the boundary between segment 6 and segment 7 can be considered as the boundary between the riverine and transitional zone.

The next monitoring station LM05 is located in segment 13. At station LM05, even though stratification existed, it was not stable. Therefore, segment 13 is definitely in the transitional zone. The next station, LM04, is located near the boundary between segment

18 and segment 19. This station exhibits strong and stable stratification. Therefore, segment 18 and 19 are both in the lacustrine zone. Since there are no other stations between station LM04 and station LM05, it cannot be determined with accuracy where the boundary between the transitional and lacustrine zone occurred, taking only stratification data into consideration.

To determine the demarcation between the two zones, the depth data were carefully analyzed. A noticeable difference in depth was observed around segment 17 and 18. Starting from segment 13 moving towards the dam, a 0.5 m increase in depth was observed between each segment, until the boundary between segment 17 and 18. Here, a 1 m increase in depth was observed. This more-rapid increase in depth indicates that this could be the dividing line between the transitional and lacustrine zone. Along branch 1 of Lake Manassas, the other existing station is LM01. This station is located near the dam in the deepest part of the reservoir and also exhibited strong stratification. Therefore all the segments starting from segment 18 towards the dam, in branch 1 of Lake Manassas, lie in the lacustrine zone.

The next step was to determine zonation along branch 2 of Lake Manassas. Station LM02, which lies in segment 31 along branch 2 was strongly and stably stratified. It also has an average depth of about 14 m. It is undoubtedly in the lacustrine zone. The depth decreases progressively towards the outer end of the arm. Station LM03, which lies near the outer end of this arm is in segment 28. The average depth there was 11 m. The stratification observed there was also unstable and it is in the transitional zone. Segment

28, therefore, lies in the transitional zone. To determine the dividing line between the lacustrine and transitional zones, the depth data were taken into consideration. Segment 30 and segment 29 each has an average depth of about 12.5 m and 11.5 m, respectively. However, between segment 31 and segment 30 an increased drop in depth of about 1.5 m was observed (Figure 30). Therefore the boundary between segment 31 and 30 was considered as the boundary between the lacustrine and transitional zone.

To further determine the demarcation between the riverine and transitional zone in branch 2, the depth of segments 28 and 27 were considered. Segment 28 has an average depth of 11 m, while segment 27 has an average depth of 7.5 m. There is a considerable reduction in depth between segment 28 and segment 27. Therefore, the boundary between segment 27 and 28 was considered as the boundary between the riverine and transitional zone, in branch 2 of Lake Manassas.

Considering segments 34, 35 and 36 along branch 3, there are no monitoring stations existing in this branch and no stratification data was available. Therefore, the analysis here is exclusively based on morphometry. Segment 13, which is adjacent to segment 36 is considerably wide and has an average depth of 11.5 m. It lies in the transitional zone as determined earlier. Segment 36 is narrow and has an average depth of 7 m. The pronounced drop in depth between adjacent segments, as observed between segment 13 and segment 36, together with the narrowing of shape, indicate that the boundary of segment 13 with 36 can be considered as the boundary between the riverine and transitional zone.

The final step involved determining zonation along branch 4. Station LM08 is located in branch 4, in segment 40. From analysis of the stratification data, it was observed that station LM08 exhibited unstable stratification. It is therefore in the transitional zone. Segment 16, which is in branch 1 of the reservoir, is in the transitional zone. The segments on either side of segment 41 are in the transitional zone. Therefore, it is safe to assume that segment 41 is also transitional in nature.

To determine the boundary between the transitional and riverine zone in branch 4, the depth data of segment 40 and 39 were analyzed. Segment 40 has an average depth of 6 m while segment 39 has an average depth of 1.5 m. Segment 39 is also narrow. The considerable difference in depth between segment 39 and segment 40 and the narrow structure of segment 39 all point to the fact that the boundary between segment 39 and segment 40 can be considered as the boundary between the transitional and riverine zone.

Therefore, all four branches as used by the model were successfully allocated zones based on the bathymetry. However, it was noticed that there are still regions where the allocation can be further refined. This can be done by analyzing the bathymetry of the lake in greater detail. A contour map can greatly help in analysis based on bathymetry. Analysis based on contour maps will be done later to refine the zonation in Lake Manassas.

#### 4.3.2.3 Zonation of Lake Manassas Based on Stratification and Segmentation of the Lake in the Water Quality Model

In the section above, it was demonstrated how the bathymetry based on segmentation in the water quality model, can be put to use to further refine the division of Lake Manassas. Analysis of stratification was the first step. It provided a rough division of the lake. However, the demarcation of boundaries in case of analysis based on stratification was based on assumptions made from the analysis of data from the eight monitoring stations. Bathymetry is a good tool to decide on the boundaries, as it takes into consideration all the regions of the lake, not just the monitoring stations. The boundaries between the different zones can be determined with better accuracy. However, the drawback in using segmentation, as it exists in the water quality model, is that some of the larger arms in the lake have not been segmented but are considered as part of the larger existing segments. This can however be rectified by analyzing the contour map of Lake Manassas. This has been done in later sections. Figure 55, below, represents the division of Lake Manassas into three zones based on analysis of stratification data and analysis of depth data, as taken from segmentation of the lake in the water quality model.

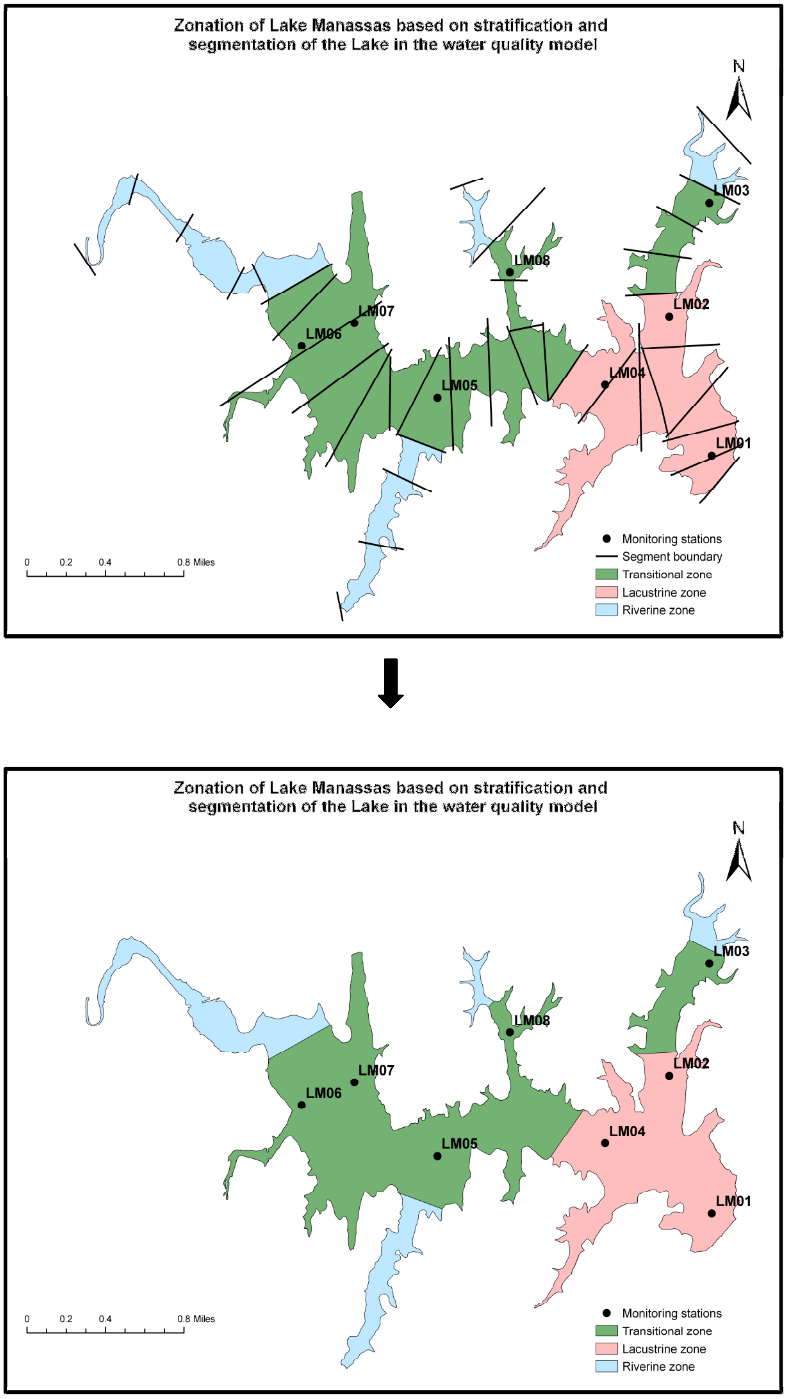


**Figure 55. Zonation of Lake Manassas based on stratification and segmentation of the Lake in the water quality model.**

### 4.3.2.4 Analysis Based on Contour Map of Lake Manassas

Contour maps can provide a good picture of the bathymetry of a lake or reservoir. To fine tune the zonation of Lake Manassas, the contour map was taken into consideration.

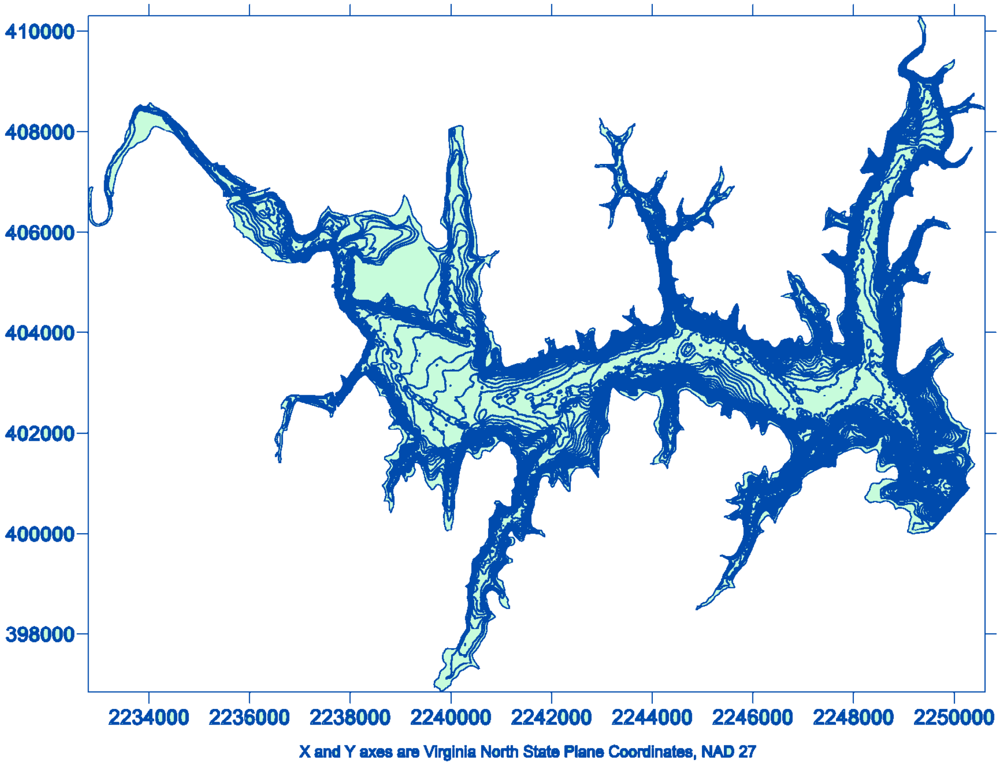


**Figure 56. Contour map of Lake Manassas based on the 2005 bathymetric survey.**

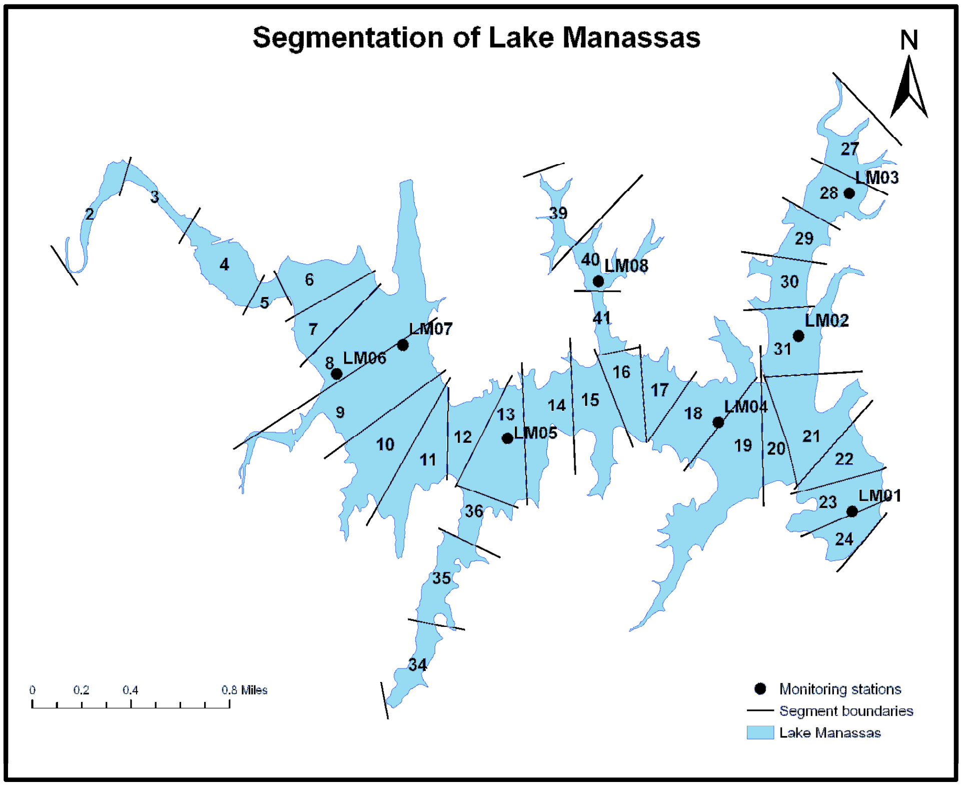


**Figure 57. Segmentation of Lake Manassas in the water quality model.**

Figure 56 displays the contour map of Lake Manassas. The contour lines are plotted at intervals of 2 ft (0.61 m). Based on the contour maps, the deeper portions of the reservoir can be easily distinguished from the shallower regions.

The arm branching off from segment 19 was considered first. Segment 19 is in the lacustrine zone with an average depth of 15 m. Away from the main section of segment 19, which is in the main body of the lake; the average depth is approximately 9 m. In this region, the width of the reservoir narrows. The difference in depth and the decrease in width both indicate a change from the lacustrine to the transitional zone. On analyzing the contours further, the depth decreases progressively as the arm narrows towards the south. However, a region was observed where the depth exhibited a pronounced decrease from adjacent regions. The average depth in this region was 4.5 m, and the width, too, decreases considerably after this point. This is considered as the starting point for the riverine zone. (This analysis was performed with the contour data, and using appropriate software to zoom in to the areas in question. Figure 56 cannot show the same level of detail.)

The next consideration was given for the arm branching off from segment 9. Segment 9 is transitional in nature. The arm branching off from segment 9 is narrow and has an average depth of about 3 m. The average depth of segment 9 is 7.5 m, the arm is riverine in nature.

Finally, depth analysis based on the contour map was performed on the arm branching from segment 8 which is transitional in nature. Segment 8 has an average depth of 6 m. The depth in the arm decreases progressively from the mouth to the end. At the mouth, the depth is around 4.8 m and it is also relatively narrow in width. This arm is, therefore, considered to be riverine in nature.

There are a few more arms in the reservoir which have not been considered in the analysis. These arms are relatively short in length. Therefore, they are assumed to be part of the segment from which they arise.

### 4.3.2.5 Zonation of Lake Manassas Based on Stratification, Segmentation of the Lake in the Water Quality Model, and Contour Map

The demarcation of the three zones has been fine-tuned using the contour maps. Figure 58 below, represents the zonation that has resulted from the consolidation of all the analyses carried out so far.

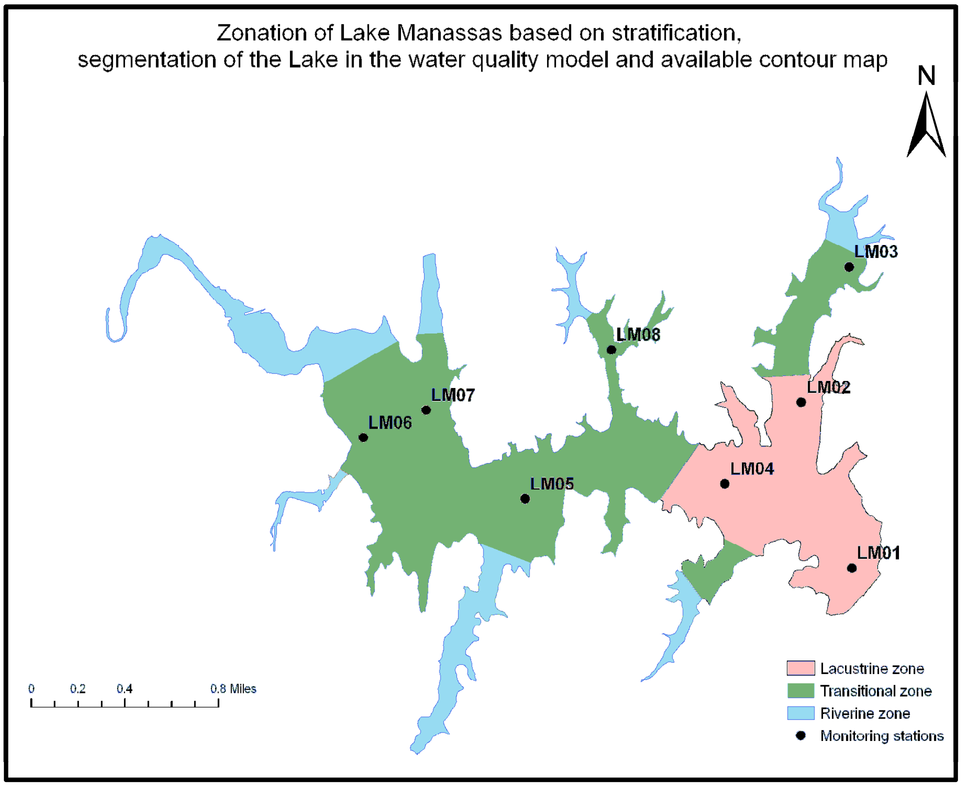


**Figure 58.** **Zonation of Lake Manassas based on stratification, segmentation of the lake in the water quality model and contour map.**

### 4.3.3 Final Zonation of Lake Manassas

By analyzing the data available with respect to stratification and depth, a satisfactory division of Lake Manassas into three separate zones; namely lacustrine, transitional and riverine has been possible. The zonation also appears to be reasonable. Therefore, the analysis was successfully completed using the first two parameters in the zonation table.

While considering stratification data, the analysis was confined to the eight monitoring stations. Data from these eight stations was sufficient to provide a general idea regarding how the reservoir can be divided, based on trends of stratification. This formed the basis of the initial division. The morphometry parameter was used to finalize the division. Depth characteristics helped in ascertaining the dividing lines between the different zones. Figure 59, conveys the process of division as the analysis progressed.

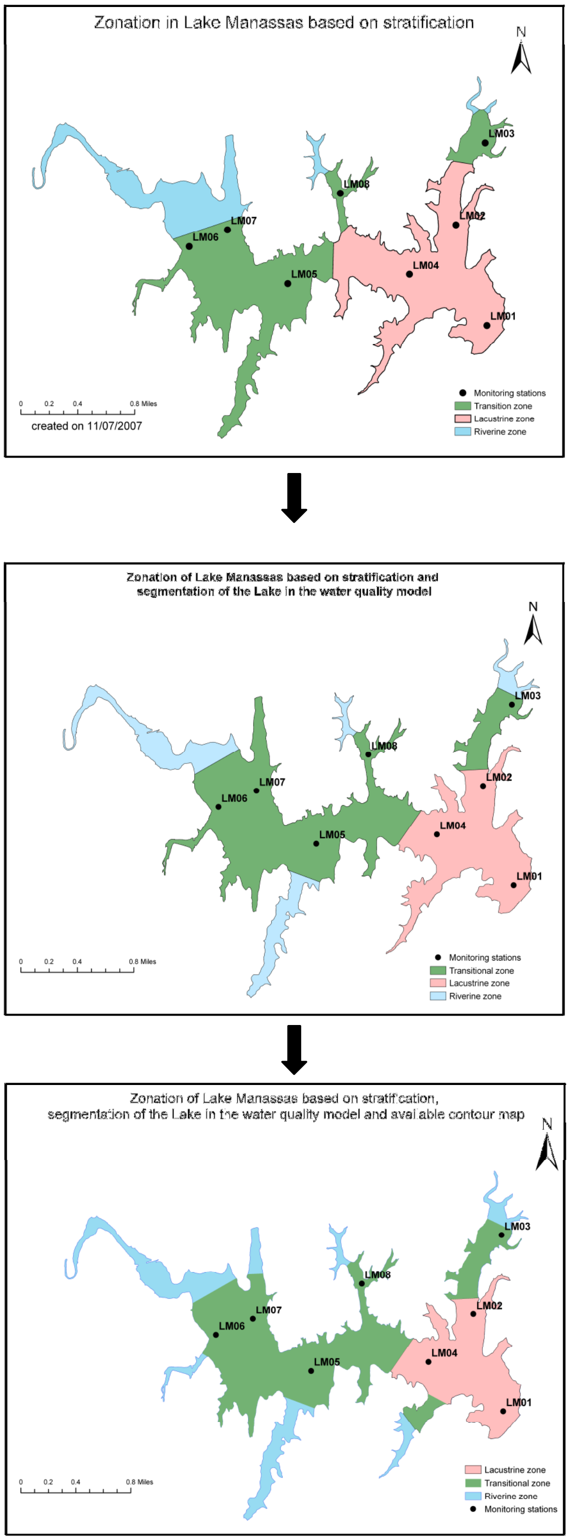


**Figure 59.** **Process of division of Lake Manassas into three zones.**

The table of parameters was successfully applied to Lake Manassas and a satisfactory division of the lake into the three zones namely lacustrine, riverine and transitional was obtained. In the case of Lake Manassas, because ample data were available on the first two parameters in the zonation table, there was no need to go further down the list. Moreover, application of these two parameters resulted in a satisfactory division of the reservoir. Figure 60 represents Lake Manassas with the final demarcation of the zones.

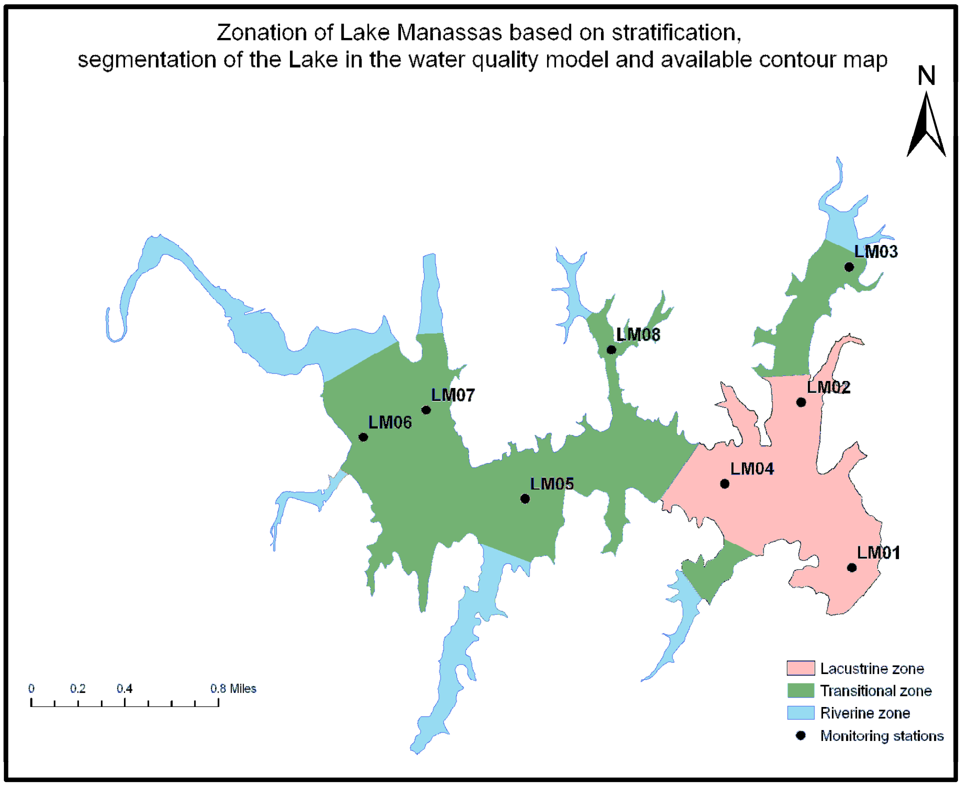


**Figure 60. Final zonation of Lake Manassas.**

## *4.4 Zonation Approach for the Occoquan Reservoir*

The Occoquan Reservoir is listed on the impaired water bodies list for dissolved oxygen criteria. When this list was made, reservoirs were evaluated on the same criteria as streams and rivers and the fact that reservoirs stratify in summer and have very low DO at the bottom was not considered. This was however rectified in the new Water Quality Standards (WQS) adopted by the Virginia Department of Environmental Quality (DEQ). The new WQS put forward a separate set of standards for lakes and reservoirs. The standards are primarily applied in the lacustrine zone of the reservoir. Therefore, zone identification is necessary for the Occoquan Reservoir.

The sampling program in the Occoquan Reservoir is extensive and extends over decades. A lot of data, which spans over a number of years, are available. The deciding factor for determining the time frame, for which data can be analyzed in this case, was the assessment period of DEQ as is discussed in section 4.3. A five year window was chosen for the study.

There are four monitoring stations located on the Occoquan Reservoir. Data are collected at each of these stations throughout the year by the staff at OWML. During spring, summer and fall, sampling is done weekly, and during winter months sampling is done twice a month. Data from each of these stations were used for analysis. Figure 61, displays the location of the monitoring stations on the Occoquan Reservoir.

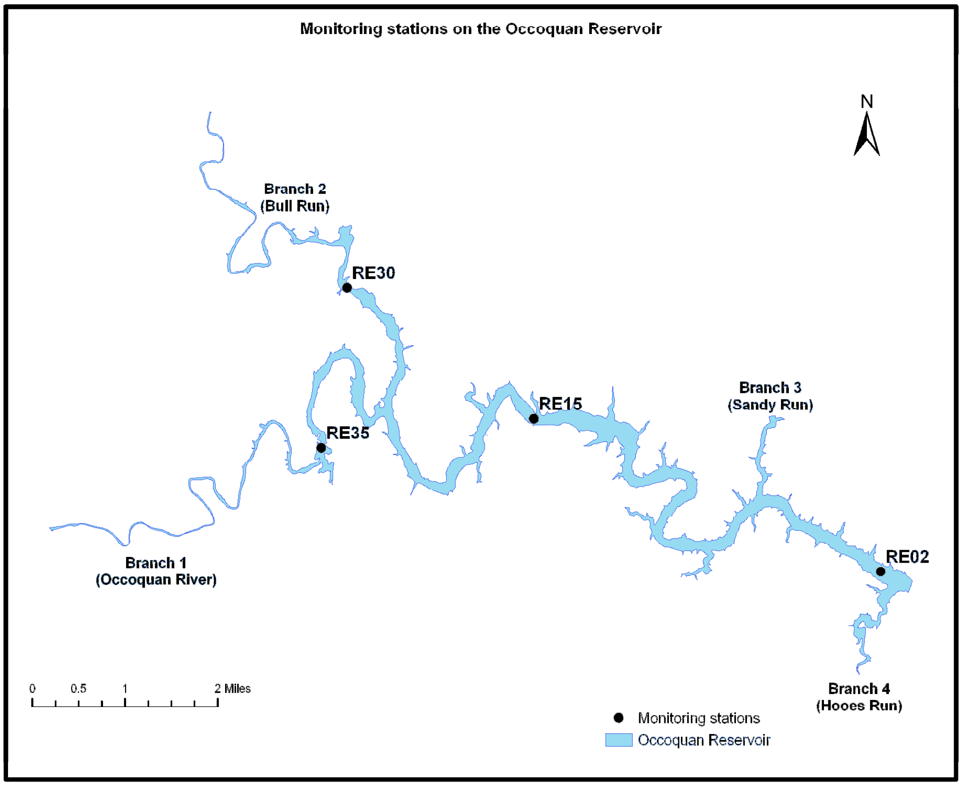


**Figure 61. Location of monitoring stations on the Occoquan Reservoir.**

The procedure as described above for Lake Manassas was also used for analyzing the data for the Occoquan Reservoir. The first parameter to be analyzed for zone identification was stratification.

In the sections below, there is adequate and ample discussion regarding the process and procedure involved in arriving at the final division of the Occoquan Reservoir into three separate zones. Each parameter considered in the process is discussed below in great detail.

### 4.4.1 Thermal Stratification in the Occoquan Reservoir

In the case of the Occoquan Reservoir, stratification was not an apt parameter. Though data on stratification was available, there was an unnatural condition existing at station RE02. This condition was probably the result of the presence, during the data analysis period, of hypolimnetic aeration around this station. It appeared that the aerators had the effect of destratifying the waters. This not only caused de-stratification, but also caused water low in dissolved oxygen (DO) from the bottom to mix with that at the top, resulting in lower DO values throughout the water column. Therefore, the data available on stratification did not represent the original picture of stratification, as it would normally occur at station RE02. Though the remaining stations were analyzed for stratification, station RE02 needed further analysis. Based on stratification, the remaining stations were assigned zones. This marked the first step towards zone identification.

Data were analyzed for each of the four monitoring stations on the Occoquan Reservoir, for the five most recent years from 2002 to 2006. Temperature vs. depth profiles were plotted for each station, for each of the years in consideration. These plots were examined to determine if the thermocline gradient was >1°C/m, if the pattern of stratification was consistent throughout summer and if a thick hypolimnion was present. The dates for which stable stratification was first and last observed at each station was recorded. Stratification primarily occurs during summer. Because of the availability of data, stratification analysis was performed for all four seasons.

While the analysis done on the data was extensive, the discussion below for each station is done such that the data represented in the discussion portrays the entire range of stratification patterns possible for each station. For every station, temperature profiles for two years are presented and discussed. These years were not chosen at random. The years were chosen such that they represented the entire range of stratification patterns that could possibly be observed during the period of study. Depending on the explanation for the differences observed from year to year and recurrence of consistent patterns, the collective strength of stratification for every station was determined. Data from all years were examined to reach conclusions, though not shown here.

#### 4.4.1.1 Winter Profiles in the Occoquan Reservoir

During winter months, the waters are generally well-mixed and cold. Throughout this period, irrespective of depth or station, the temperature profiles indicated that there was no stratification. Unlike other seasons where the profiles vary from station to station, winter profiles have similar trends for all stations. Therefore, the winter profiles have all been consolidated into one section. The profiles shown below, observed at different stations, indicate that the thermal profiles in winter were consistent at every station. The winter profiles for the year 2005 are shown in Figure 62. The year 2005 was chosen because it was the most recent winter for the period during which the analysis was carried out.

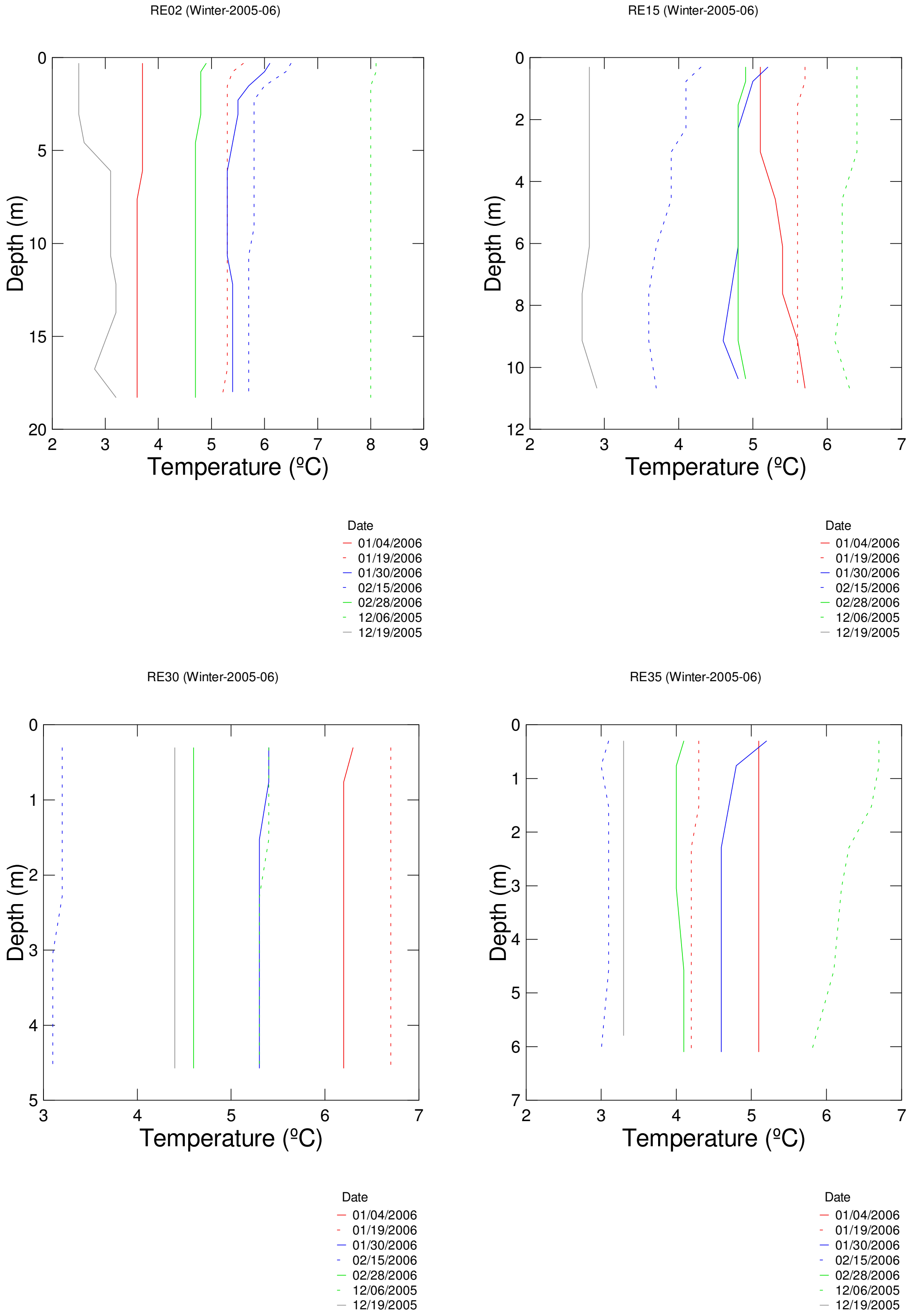


**Figure 62.** **Winter profiles for all monitoring stations in the Occoquan Reservoir.**

The temperature–depth profiles above indicate that stratification did not exist in winter at any of the stations considered. Station RE15 exhibited a difference in temperature between the top and bottom waters in the month of November. This, however, does not constitute stratification, as none of the requirements were met. Although only profiles for the year 2005 are represented here, the study included profiles from the year 2002 to 2006. It was observed that all the profiles from the other years in consideration, also, exhibited similar trends. The waters were well-mixed throughout the cold winter months. As expected, stratification did not exist during winter, at any of the stations in the Occoquan Reservoir.

#### 4.4.1.2 Thermal Stratification at Station RE02

Station RE02 is located near the dam along branch 1 and is in the deepest part of the reservoir. Table 18 lists the recorded dates during which stratification was first and last observed at station RE02.

**Table 18. Period of stratification for station RE02.**

| Year | Date stratification was first recorded | Date stratification was last recorded |
|---|---|---|
| 2002 | 3rd June 2002 | 3rd June 2003 |
| 2003 | - | - |
| 2004 | - | - |
| 2005 | - | - |
| 2006 | 18th April 2006 | 22nd August 2006 |

The table above indicates that stratification was not consistent at station RE02. There were years when there were no recorded stable stratification profiles. This is surprising, considering that station RE02 is located in the deepest part of the reservoir. The problem here is likely the result of hypolimnetic aeration at station RE02. A system of aerators has been placed along the reservoir bed near station RE02. The aeration produced by these aerators, apparently, is sufficient to cause anomalies with respect to the stratification at station RE02. Stratification, as it is defined in this document, is generally absent at station RE02. Since the conditions existing at this station are a result of seemingly unnatural circumstances, station RE02 cannot be analyzed satisfactorily based on stratification. However, a brief discussion of stratification, as it was recorded during the different seasons, is given in the appropriate sections below. Since there were no recorded profiles of stable stratification for the years 2003, 2004 and 2005, the profiles for the years 2002 and 2006 will be discussed in the sections below.

### *4.4.1.2.1 Thermal Stratification in Spring at Station RE02*

Based on the plots, it was observed that both the >1°C/m criteria for thermocline and the presence of a thick hypolimnion were not met in most cases. The years 2002 and 2006 have been chosen as the representative years for discussion, as these are the only years with a recorded period of stratification.

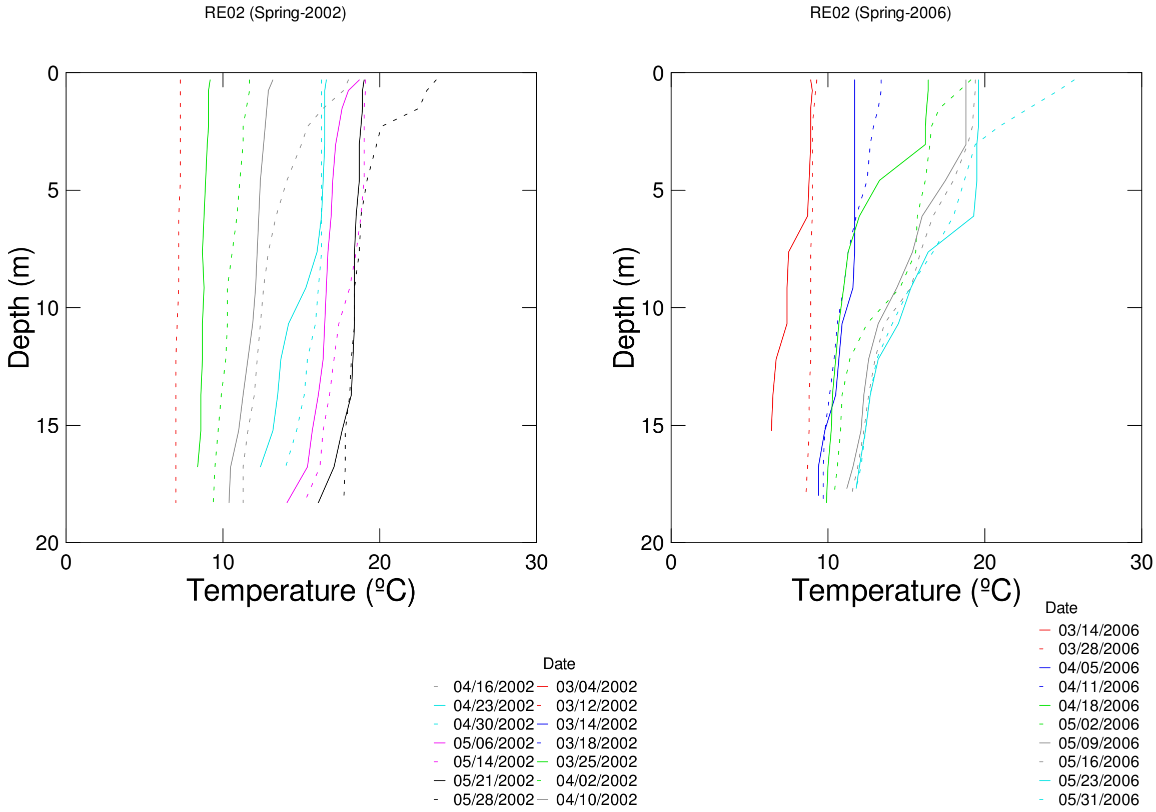


**Figure 63. Temperature–depth profiles at station RE02 in spring (2002 and 2006).**

On examining Figure 63, for the year 2002, there was hardly any stratification observed during spring. The waters appeared to be well-mixed, except towards the end of spring. A slight difference of temperature was observed between the top and bottom waters but this could not be considered as stratification, as it did not meet the requirements of a stable thermocline.

On examining Figure 63, for the year 2006, stratification was observed towards mid-spring. The stratification, although it was observed to be stable on some profiles, weakened intermittently. Therefore stratification was not consistent throughout spring.

No stable profiles were recorded for the remaining three years in the period of study. The profiles studied above also indicate that stratification was rare during spring at station RE02. When it was recorded, it was generally inconsistent.

### *4.4.1.2.2 Thermal Stratification in Summer at Station RE02*

Stratification is most prominent in summer. This is, therefore, normally the most appropriate time to check for stratification. Stratification at station RE02 was not recorded to be strong and stable (Figure 64). Here again, though five years worth of data have been considered, plots for the year 2002 and 2006 will be discussed in detail.

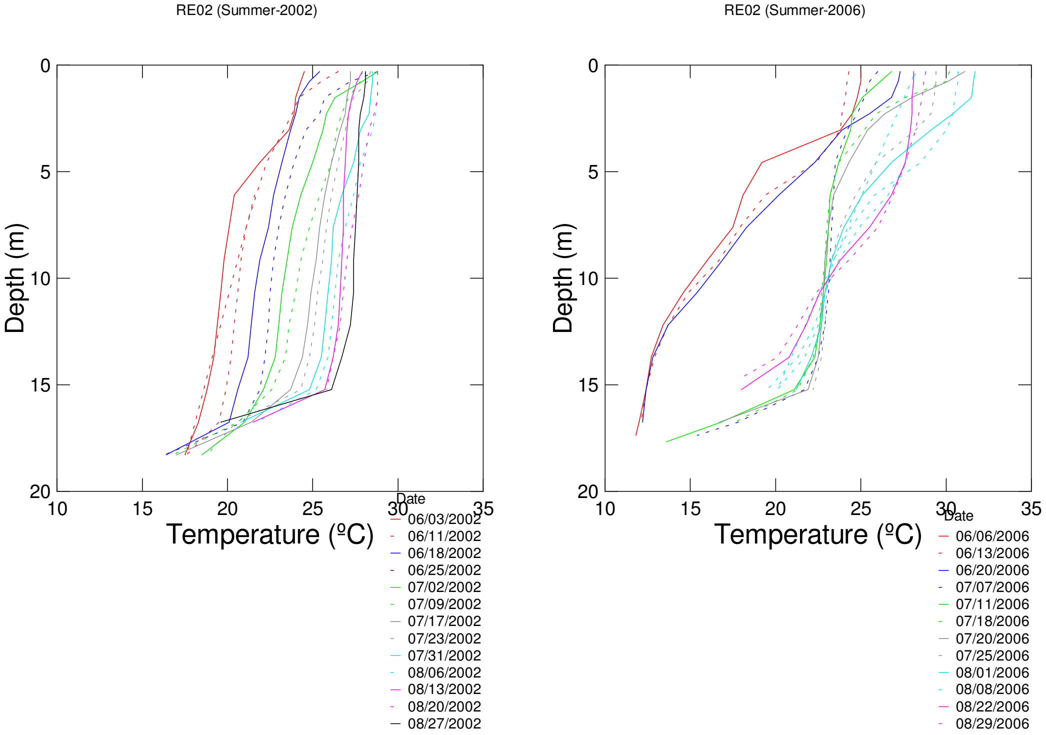


**Figure 64. Temperature–depth profiles at station RE02 in summer (2002 and 2006).**

On examining Figure 64, for the year 2002, there was just one profile, observed on June 3rd that met the requirements of stable stratification. Although the profiles indicated that the pattern of change in temperature between the top and bottom waters was consistent and similar throughout summer, they did not meet the requirements for stable stratification.

Examining the profiles for the year 2006, stable profiles were observed in spring. The beginning of summer exhibited stable profiles of stratification. However, by mid-summer, although a pattern was maintained regarding difference in temperature between the top and bottom waters, it did not meet the requirements for stable stratification. By the end of summer, a few more stable profiles were observed.

Stratification observed at station RE02 was mostly unstable for all the years under consideration. This is inconsistent with the fact that station RE02 is in the deepest region of the reservoir and is the station nearest to the dam. This inconsistency is likely due to the presence of the hypolimnetic aeration system.

#### *4.4.1.2.3 Thermal Stratification in Fall at Station RE02*

It is in fall that de-stratification takes place and the waters become well-mixed. As the temperatures start to cool down, the temperature of the surface waters, too, cool down. Finally, there is no difference in temperature between the surface and bottom waters and fall overturn occurs. The profiles for the years 2002 and 2006 were studied to analyze the fall stratification characteristics at station RE02 (Figure 65).

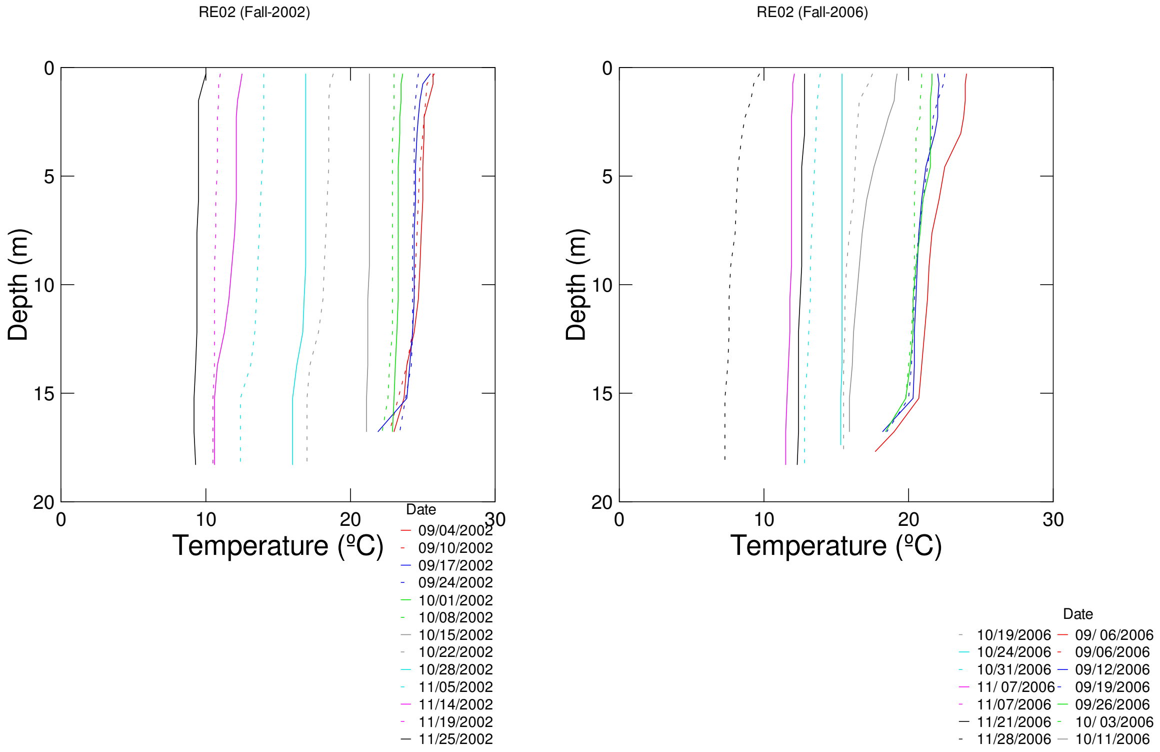


**Figure 65. Temperature–depth profiles at station RE02 in fall (2002 and 2006).**

The fall profiles for the year 2002, from Figure 65, indicate that right from the beginning of fall, the waters were well-mixed. Although a slight difference in temperature was observed between the top and bottom waters, this difference in temperature did not constitute stable stratification. Therefore, the profiles indicate that fall overturn took place sometime by the end of summer. The profiles for the year 2006 indicate a similar behavior.

For the other three years in consideration, there were no recorded stable profiles. The waters were generally well-mixed during fall.

##### *4.4.1.2.4 Conclusion for Station RE02 Based on Thermal Stratification*

Station RE02 lies in the deepest region of the reservoir and is nearest to the dam and ought to be strongly and stably stratified. However, the profiles studied above indicate just the opposite. The main reason for this could be the presence of an aeration system Therefore, the thermal stratification parameter, cannot be used at station RE02. The analysis for this station shows that local knowledge of the lake or reservoir can play a large role in the zonation analysis. Without knowledge of the presence of the hypolimnetic aeration system, a different conclusion might have been reached regarding station RE02.

#### 4.4.1.3 Thermal Stratification at Station RE15

Station RE15 is located in the main body of the reservoir upstream from station RE02. Data from 2002-2006 period have been analyzed. The dates when stratification was first and last recorded for each of the five years considered are listed in Table 19.

**Table 19. Period of stratification for station RE15.**

| Year | Date stratification was first recorded | Date stratification was last recorded |
|---|---|---|
| 2002 | 23rd April 2002 | 27th August 2002 |
| 2003 | 5th May 2003 | 26th August 2003 |
| 2004 | 27th April 2004 | 29th June 2004 |
| 2005 | 12th April 2005 | 14th June 2005 |
| 2006 | 31st May 2006 | 3rd October 2006 |

The years 2002 and 2006 were chosen as the representative years, as the profiles observed during these two years successfully convey the range of profiles that were observed at this station during the entire period of study. The pattern of stratification, as it was observed, is analyzed further in the sections below.

### *4.4.1.3.1 Thermal Stratification in Spring at Station RE15*

Stratification is usually first observed during spring. Figure 66, displays the temperature profiles for station RE15 for the representative years 2002 and 2006.

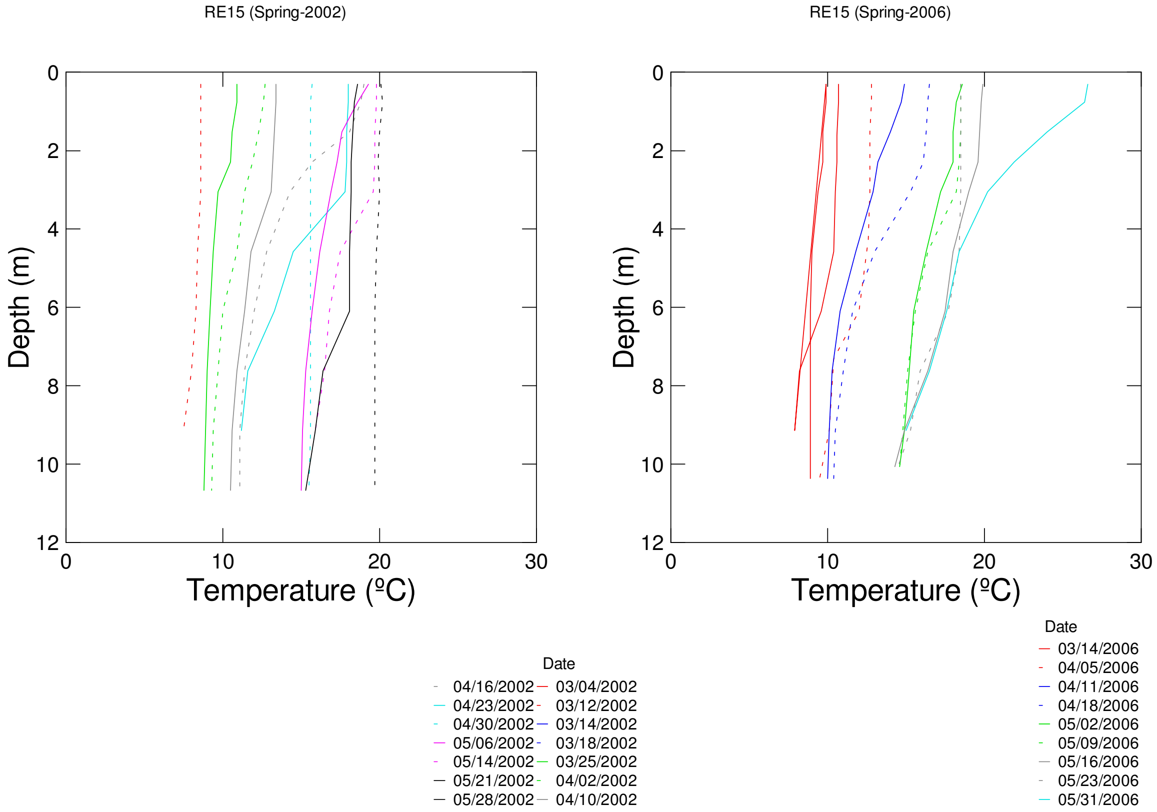


**Figure 66. Temperature–depth profiles at station RE15 in spring (2002 and 2006).**

For the year 2002, it was observed that strong and stable stratification with a stable thermocline and a thick hypolimnion was observed at station RE15 by April 23rd. All the other requirements for stable stratification were met. However, after that point the thermocline weakened considerably, so much so that it could no longer be considered stably stratified.

For the year 2006, stable stratification was observed on the last recorded profile for spring. Therefore, stratification was observed to set in only by the end of spring in 2006. Some of the other profiles, especially those recorded during mid-spring, exhibited a difference in temperature between the top and bottom waters. However, this difference in temperature did not constitute stratification, as none of the requirements were met.

For all the other years under consideration, stratification was observed during spring. Although stable profiles were observed, stratification did not extend throughout spring. Very often, the thermocline weakened. On the whole, for the period of study stable and consistent stratification did not occur at station RE15 during spring, and disruptions in stratification were frequent.

#### *4.4.1.3.2 Thermal Stratification in Summer at Station RE15*

Thermal stratification is most prominent during the summer months. Figure 67 represents the summer profiles at station RE15 for the representative years 2002 and 2006.

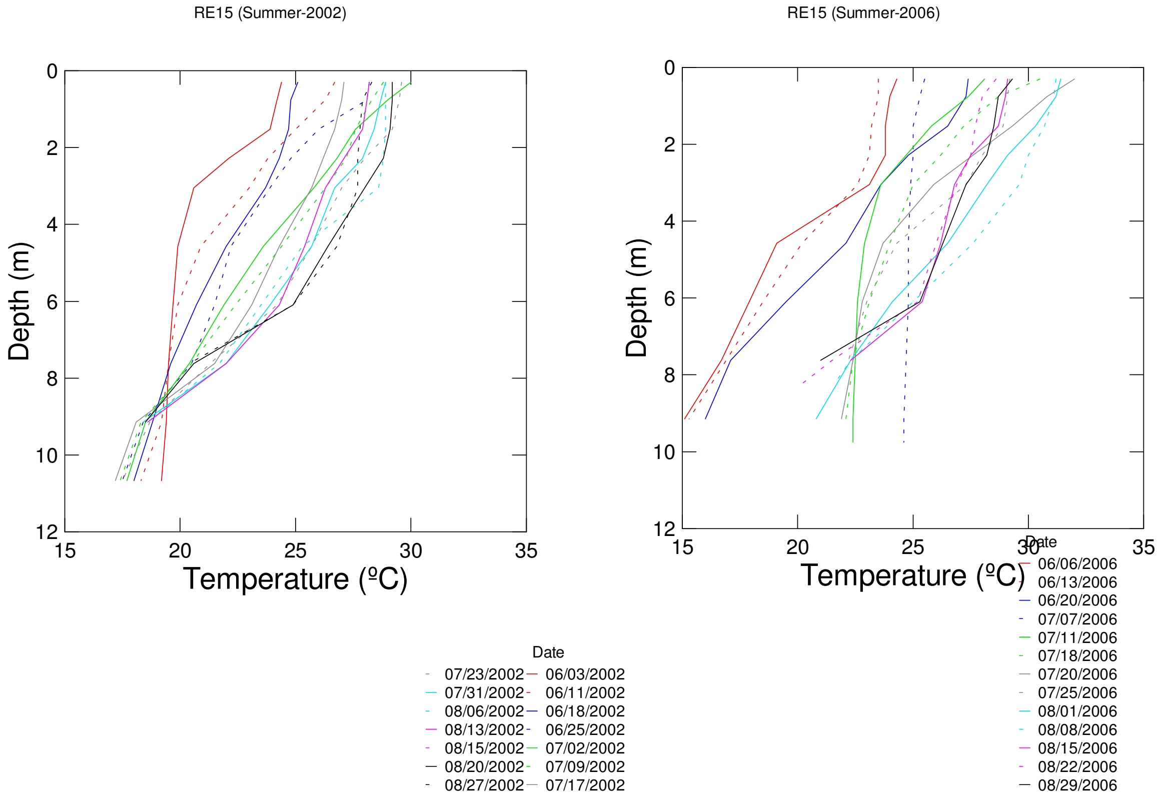


**Figure 67. Temperature–depth profiles at station RE15 in summer (2002 and 2006).**

On examining the summer profiles for the year 2002 (Figure 67), the conditions for a stable thermocline and a thick hypolimnion were met throughout summer. The hypolimnion was around 2 m thick and a thermocline gradient of >1°C/m was maintained.

For the year 2006 stratification existed during the early part of summer. Around 7th July, though, the waters appeared to be well-mixed. This was the result of a strong hydrological event during that time. However, after that event the waters were observed to quickly regain the lost stratification and remained stratified till July 25th. After that point, the thermocline weakened and stratification also weakened.

For the other years in consideration, stratification varied between stable to unstable. For the year 2004 and 2003, stratification was stable and consistent for most of summer. However, for the year 2005, stratification was intermittent. On the whole, considering all five years, for which data was considered, stratification was consistent for most of summer at station RE15.

#### *4.4.1.3.3 Thermal Stratification in Fall at Station RE15*

Fall brings about fall overturn and the waters become well-mixed. Figure 68 below, depicts the fall profiles for the years 2002 and 2006.

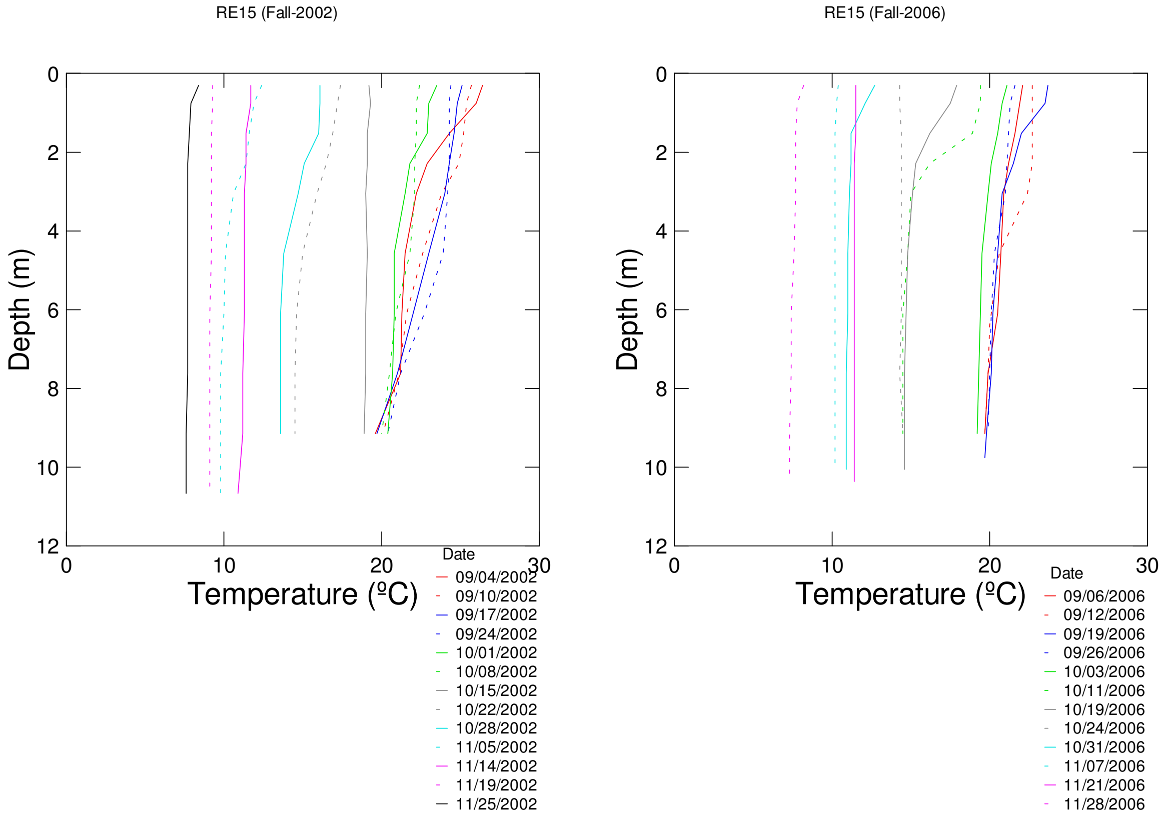


**Figure 68.** **Temperature–depth profiles at station RE15 in fall (2002 and 2006).**

On examination of the fall profiles for the year 2002 a slight difference in temperature between the top and bottom waters was observed. However, this difference in temperature did not satisfy any of the conditions required for stable stratification. By mid-fall the waters were well-mixed with uniform temperature from top to bottom.

Examination of fall profiles for the year 2006 indicated that there was no observed stratification in the beginning of fall. However, a stably stratified profile was observed on 3rd October. This was the result of unseasonably warm weather. Stratification broke up soon afterwards and the waters become well-mixed. On taking into account all the data analyzed, the waters were generally well-mixed during fall.

#### *4.4.1.3.4 Conclusion for Station RE15 Based on Thermal Stratification*

At station RE15, it was recorded that the start of stratification was generally observed during late spring. More often, although station RE15 was stratified during spring, stratification was easily disrupted. However, with the onset of summer, the stratification strengthened considerably. There were no observed intermittent disruptions of stratification during most summer months. There was a case in 2006 of a strong hydrological event occurring during summer and disruption of stratification as a result of that. However, such disruptions were soon reversed with passage of the event and lost stratification was regained. The presence of a strong hypolimnion and a strong thermocline throughout summer indicated that stratification was strong and stable at this station.

There could be one more reason for stable stratification existing at this station. This is the presence of Ryan's dam, just a few hundred feet downstream from the monitoring station. Ryan's dam is a deep and narrow submerged feature. The presence of a deep region just before a monitoring station can create a lake-like condition, which can contribute to stable stratification. Apart from this, this station is over 12 m deep. This depth is sufficient for stable stratification to exist. Therefore, based on the thermal stratification parameter, station RE15 is designated to the lacustrine zone. Whenever the profiles indicated stable stratification, the thermocline, as shown by data just met the requirements. All these indicate that station RE15 falls near the boundary between the lacustrine and transitional regions.

#### 4.4.1.4 Thermal Stratification at Station RE30

Station RE30 is located further into branch 2 (Bull Run branch) of the reservoir, away from the dam. The dates when stratification was first and last recorded for each of the five years considered, are listed in Table 20.

**Table 20. Period of stratification for station RE30.**

| **Year** | **Date stratification was first recorded** | **Date stratification was last recorded** |
|---|---|---|
| 2002 | 3rd June 2002 | 20th August 2002 |
| 2003 | 1st July 2003 | 26th August 2003 |
| 2004 | 3rd June 2004 | 30th August 2004 |
| 2005 | 10th May 2005 | 30th August 2005 |
| 2006 | 31st May 2006 | 18th July 2006 |

The years 2002 and 2005 are chosen as the representative years. The trends observed for stratification during these two years successfully convey the trends observed at station RE30. In the appropriate sections below, the trends observed with regard to stratification at different times of the year are discussed.

#### *4.4.1.4.1 Thermal Stratification in Spring at Station RE30*

Stratification is often first observed during spring. Figure 69, represents the stratification at station RE30, for the years 2002 and 2005.

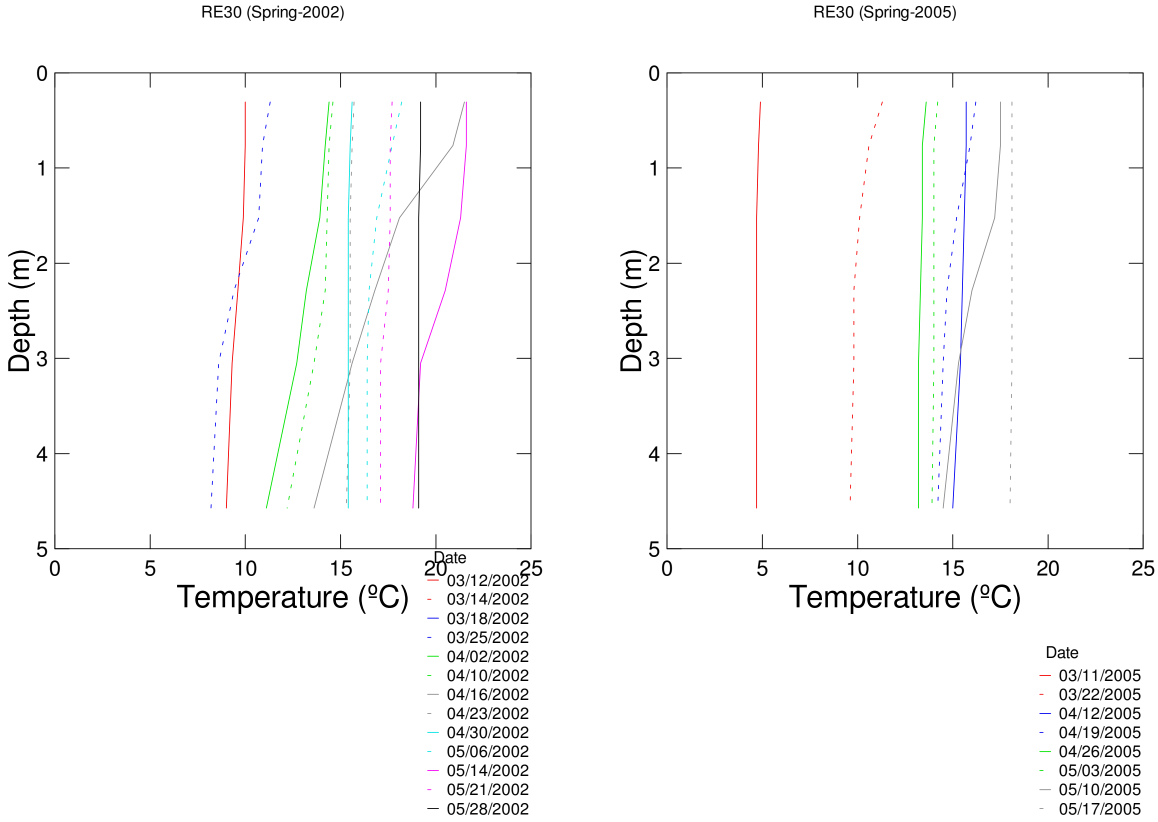


**Figure 69. Temperature–depth profiles at station RE30 in spring (2002 and 2005).**

On examining Figure 69, for the year 2002, it was observed that stratification did not exist early in spring. Some difference in temperature was observed between the top and bottom waters late in spring. However, these profiles did not meet the >1°C/m requirement for a stable thermocline. Therefore, these profiles could not be considered as stably stratified. For the year 2002, no stable profiles were observed during spring.

Close examination of spring profiles for the year 2005, from Figure 69, indicate that the waters were unstratified early in spring. Towards the end of spring, on May 10th, a stable profile was recorded. However, the next recorded profile on May 17th indicated well-mixed waters. Therefore, though stable stratification existed late in spring, it was easily disrupted.

For the other years in consideration, stable stratification was rare during spring. In the year 2006, a stable profile was recorded by the end of spring. Other than that, there were no other stable profiles. On the whole, for the period of study, stratification was rare during spring and even if stratification did exist, it was inconsistent.

#### *4.4.1.4.2 Thermal Stratification in Summer at Station RE30*

Stratification is strongest during the summer months. Figure 70, below, represents the summer profiles existing at station RE30 for the representative years 2002 and 2005.

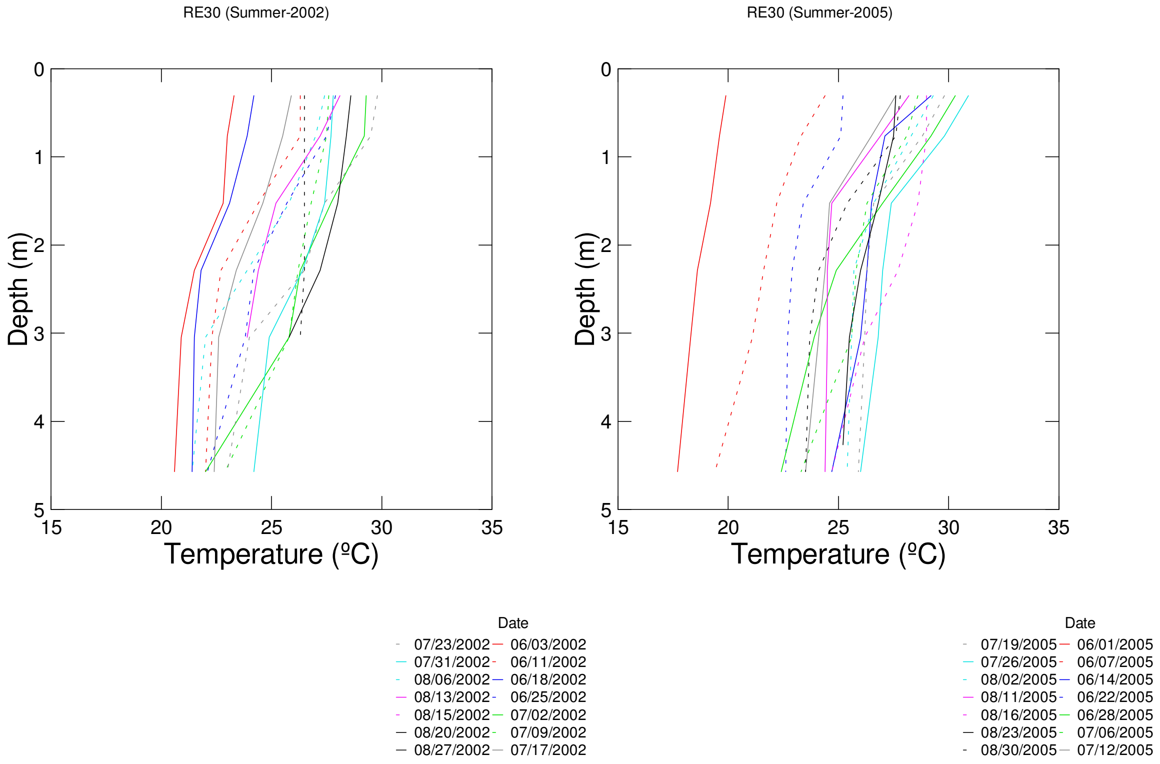


**Figure 70. Temperature–depth profiles at station RE30 in summer (2002 and 2005).**

Summer profiles for the year 2002 indicate that stratification was consistent almost throughout summer. A thermocline gradient of >1°C/m was maintained and the hypolimnion was 1.5 m thick. The last summer profile for the year 2002 indicated that the waters were considerably drawn down. This draw down could have resulted in the complete breakdown of stratification that was observed in the last profile.

Examination of the summer profiles for the year 2005, from Figure 70, indicated that stratification was unstable throughout most of summer. A stable profile was recorded by the end of summer on August 30th, but, other than that, there were no stable summer profiles for the year 2005.

For the other three years in consideration, stable and consistent profiles were not recorded for any continuous period of time during summer. Intermittent stable profiles were recorded, but these profiles were easily disrupted. Therefore, for the period of study, stratification was inconsistent throughout summer at station RE30.

### *4.4.1.4.3 Thermal Stratification in Fall at Station RE30*

Fall brings about well-mixed waters. Figure 71, below, represents the fall profiles at station RE30, for the representative years 2002 and 2005.

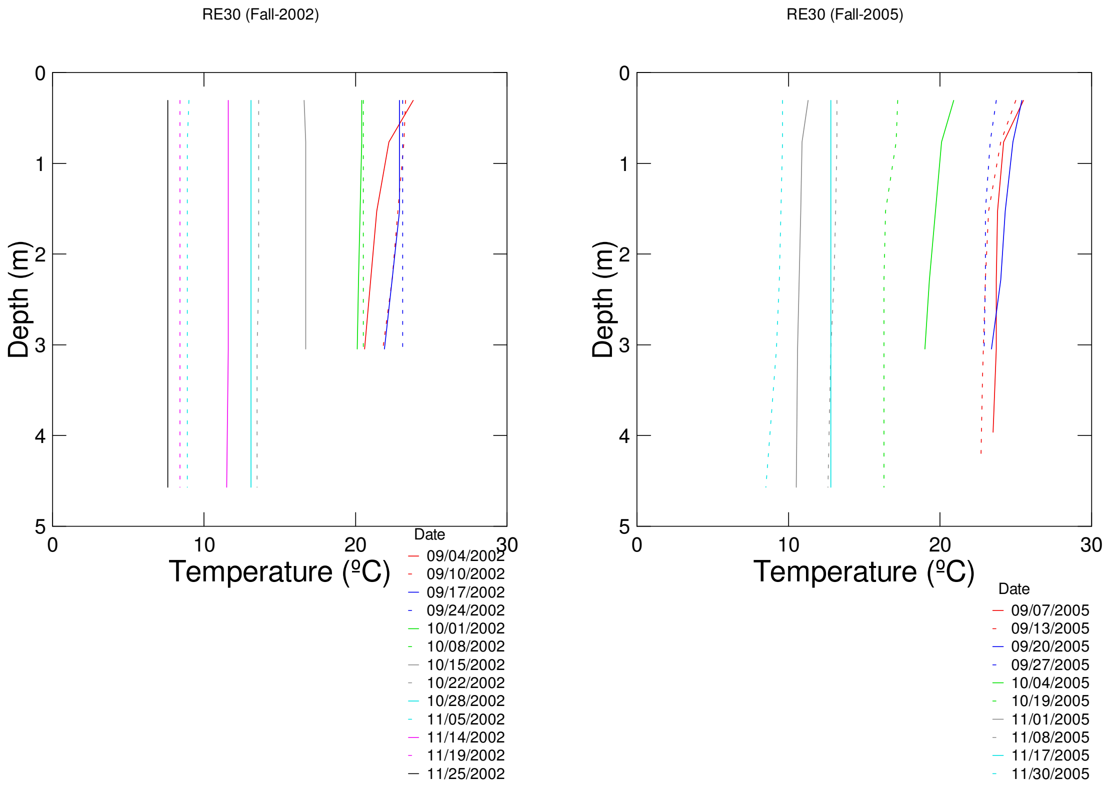


**Figure 71. Temperature–depth profiles at station RE30 in fall (2002 and 2005).**

The fall profiles for the year 2002 indicate that the waters were well-mixed. Although the first recorded profile on September 4th exhibited a slight difference in temperature between the top and bottom waters, this difference in temperature did not result in the formation of a thermocline. Therefore, it cannot be said to be stratified. Initially, during fall, the water was considerably drawn down. The fall profiles for the year 2005, from Figure 71 indicate that the waters were well-mixed throughout fall.

On examining all the other profiles for the remaining years over which the study spanned, the waters were generally well-mixed during fall. Stratification hardly existed at station RE30.

#### *4.4.1.4.4 Conclusion for Station RE30 Based on Thermal Stratification*

The profiles at station RE30 indicate that stratification existed occasionally during spring. However, it was not consistent and subject to frequent disruptions. Stratification in summer, too, was inconsistent and intermittent. By early fall the waters became well-mixed. The fact that stratification was not consistent year after year in summer, suggests that, based on the thermal stratification parameter, station RE30 falls in the transitional zone.

#### 4.4.1.5 Thermal Stratification at Station RE35

Station RE35 is located at the tail end of the reservoir, along branch 1 (Occoquan River arm). Listed below (in Table 21) are the dates around which stratification was first and last recorded at station RE35.

**Table 21. Period of stratification for station RE35.**

| Year | Date stratification was first recorded | Date stratification was last recorded |
|---|---|---|
| 2002 | 2nd April 2002 | 23rd July 2002 |
| 2003 | 29th April 2003 | 22nd July 2003 |
| 2004 | 18th May 2004 | 30th August 2004 |
| 2005 | 19th April 2005 | 16th August 2005 |
| 2006 | 31st May 2006 | 11th July 2006 |

The years 2004 and 2005 were chosen as the representative years as the profiles recorded during these two years were able to successfully convey the entire range of trends observed during stratification at station RE35. The sections below discuss in further detail the profiles recorded at station RE35 during different times of the year.

##### *4.4.1.5.1 Thermal Stratification in Spring at Station RE35*

Spring brings about warmer temperatures and stratification. Figure 72, represents the spring profiles recorded at station RE35 for the representative years 2004 and 2005.

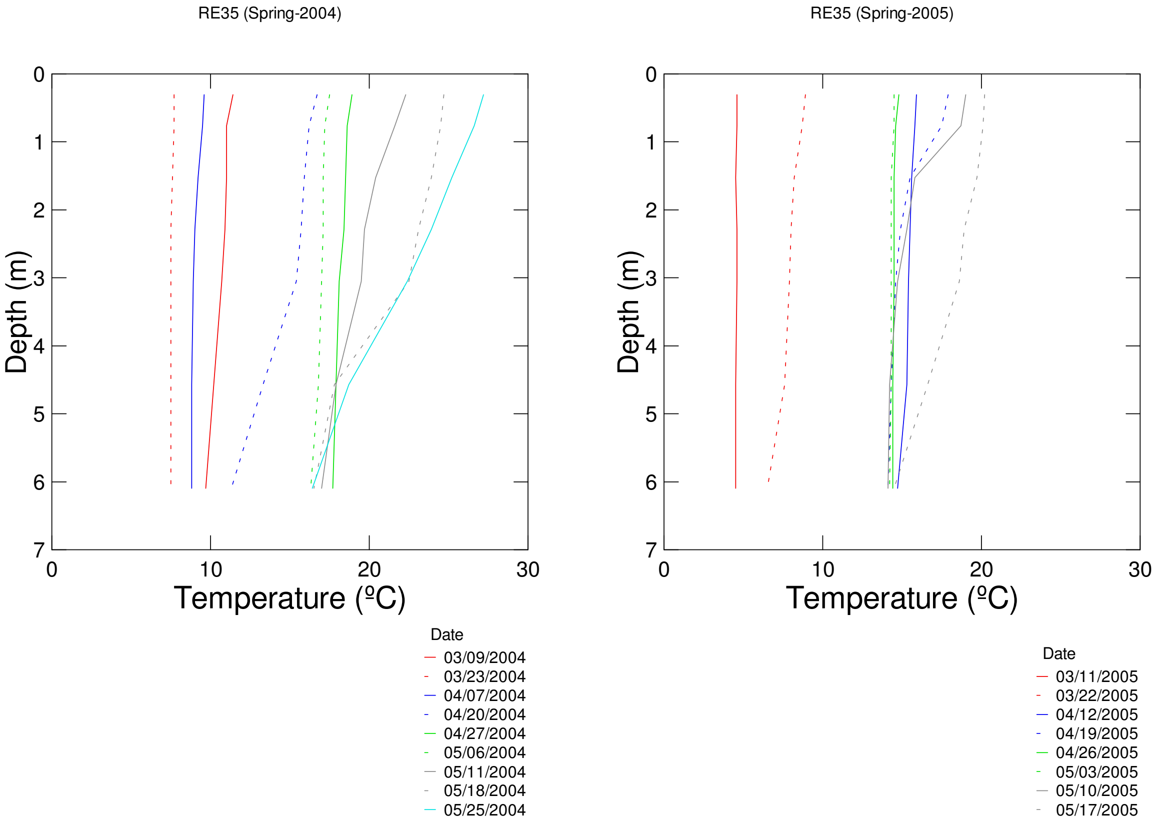


**Figure 72. Temperature–depth profiles at station RE35 in spring (2004 and 2005).**

Examination of the spring profiles for the year 2004 indicated that stratification set in late in spring. The first observed stable profile was recorded on May 18th. However, the next profile, on May 15th, exhibited disrupted stratification.

For 2005, the spring profiles indicated that stable stratification was observed during mid-spring, on April 19th. However, a couple of profiles later, stratification seemed to have been disrupted.

For all the other years considered, similar trends were observed. A couple of stable profiles were observed during spring. However, these profiles were easily disrupted. From the study of the spring profiles above, stratification during spring was inconsistent and easily disrupted at station RE35.

### *4.4.1.5.2 Thermal Stratification in Summer at Station RE35*

Stratification is generally most pronounced during the summer months. Figure 73, below, represents the summer profiles for the representative years 2004 and 2005.

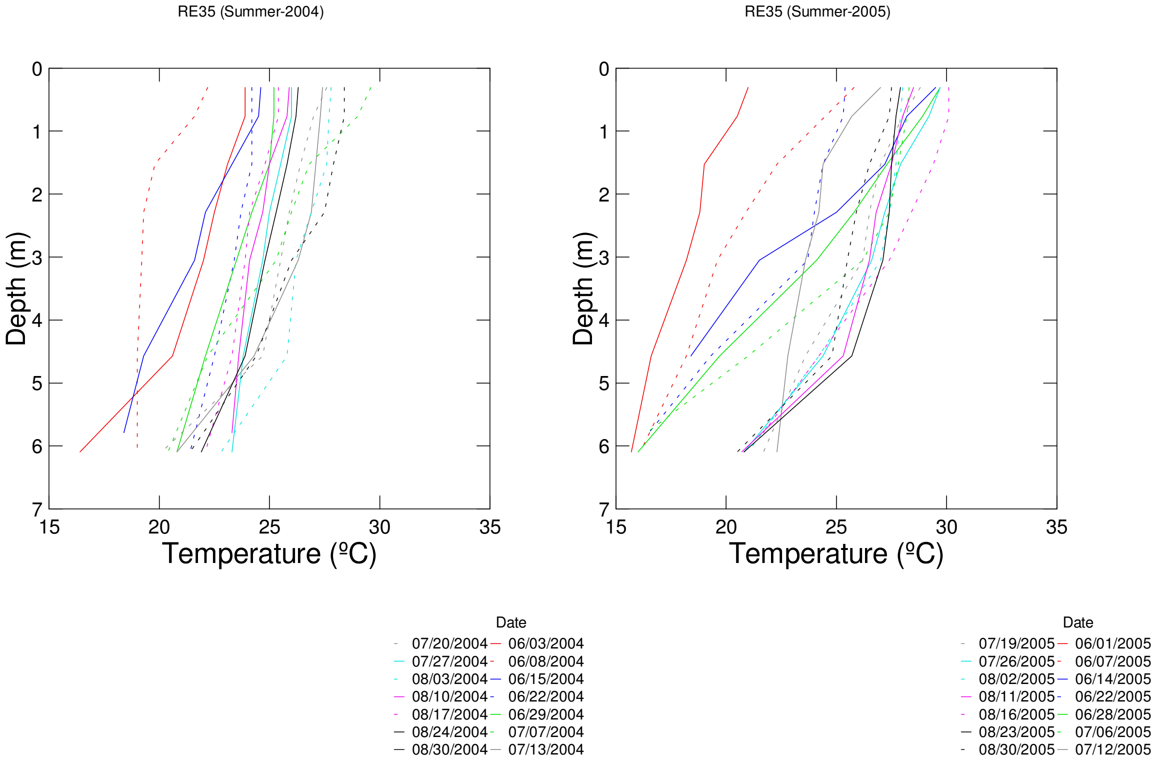


**Figure 73. Temperature–depth profiles at station RE35 in summer (2004 and 2005).**

The summer profiles for the year 2004 indicate that stratification was stable at the beginning of summer, but it soon destabilized. There were a few other profiles in between which depicted stable stratification. These stable profiles were easily disrupted. Therefore, for the year 2004, stratification during the summer months was inconsistent.

On examining the summer profiles for the year 2005, it was observed that throughout summer, both stable and unstable profiles were recorded. This suggested that stratification was intermittently broken up.

The data for the remaining three years also indicated that stratification was not consistent at station RE35, during summer. It was unstable and intermittently disrupted.

#### *4.4.1.5.3 Thermal Stratification in Fall at Station RE35*

The cooler temperatures during fall initiate the process of de-stratification. Figure 74, below, represents fall profiles observed at station RE35 for the representative years 2004 and 2005.

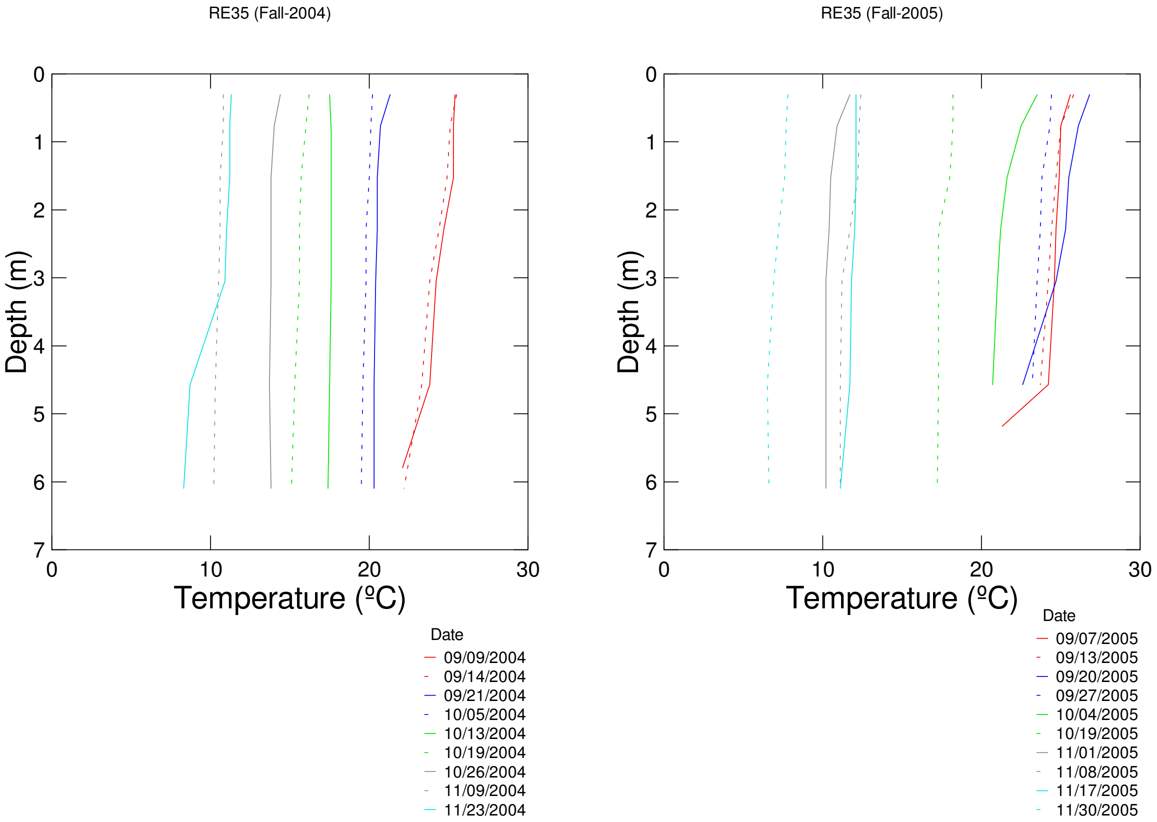


**Figure 74. Temperature–depth profiles at station RE35 in fall (2004 and 2005).**

The fall profiles for the year 2004 indicate that there was no stratification at station RE35, during fall. The waters were well-mixed. Similar trends were observed in the fall profiles, for the year 2005. The waters were well-mixed. Based on all the data analyzed for fall, for station RE35, the waters were not stratified during fall.

##### *4.4.1.5.4 Conclusion for Station RE35 Based on Thermal Stratification*

Stratification was rare during spring, at station RE35. Even though stable profiles were occasionally recorded, stratification was broken intermittently. The summer profiles too were inconsistent, with stable and unstable profiles strewn together. The waters were well-mixed during fall. All these together indicate that, based on the thermal stratification parameter, station RE35 falls in the transitional zone.

#### 4.4.1.6 Zonation of the Occoquan Reservoir Based on Thermal Stratification

The first parameter to be taken into consideration while dividing the reservoir into three distinct zones is stratification. Based on the temperature profiles studied above, Figure 75, below, displays the first division of the Occoquan Reservoir into three zones. This figure is the first step towards lake zonation. This zonation will be further refined when additional parameters are taken in account.

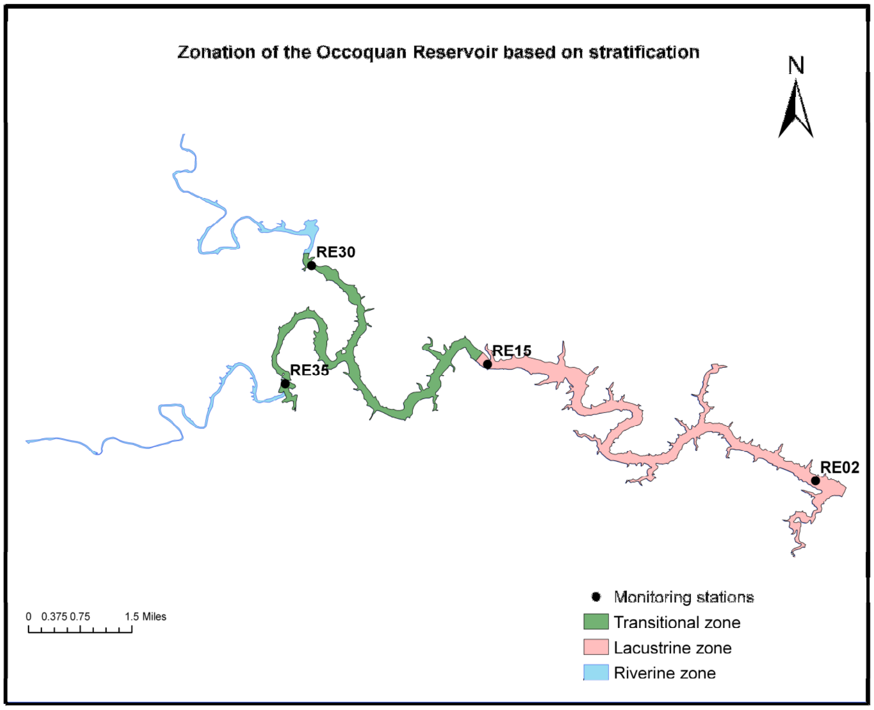


**Figure 75.** **Division of the Occoquan Reservoir into three zones based on the parameter thermal stratification.**

## 4.4.2 Morphometry of the Occoquan Reservoir

This identification of zones was further refined by taking into account and analyzing the next parameter: morphometry. The lake has been divided into several segments for use in a water quality model. Here again, data were analyzed for every segment. Based on the results from the analysis, a zone determination was made. Details on the segmentation done on the Occoquan Reservoir will be discussed in the appropriate sections below. The divisions based on the two parameters were consolidated.

Analysis of the morphometry of the Occoquan Reservoir includes analyzing the shape, width and depth along the reservoir, from one end to another. Taking into consideration the shape and width of the water body, the riverine region is generally narrow and dendritic. The transitional region is wider and broader than the riverine zone, but smaller in width when compared to the lacustrine zone. The lacustrine region is the widest portion of the reservoir. The lacustrine region is the deepest and the riverine region is the shallowest. The depth of the transitional region is in between the other two regions.

The Occoquan Reservoir is modeled as part of the Occoquan model maintained at Occoquan Watershed Monitoring Laboratory (OWML) and is currently modeled with a CE-QUAL-W2 model (an Army Corp of Engineers 2- dimensional model), for water quality purposes. For the purpose of the model, the entire lake has been divided into various segments. These segments, based on the bathymetry of the Lake can help in analyzing the morphometry. Further analysis of the lake based on shape, width and depth, is required to determine the different zones with further detail. Figure 76, below, depicts the Occoquan Reservoir as it is divided into segments for use in the water quality model.

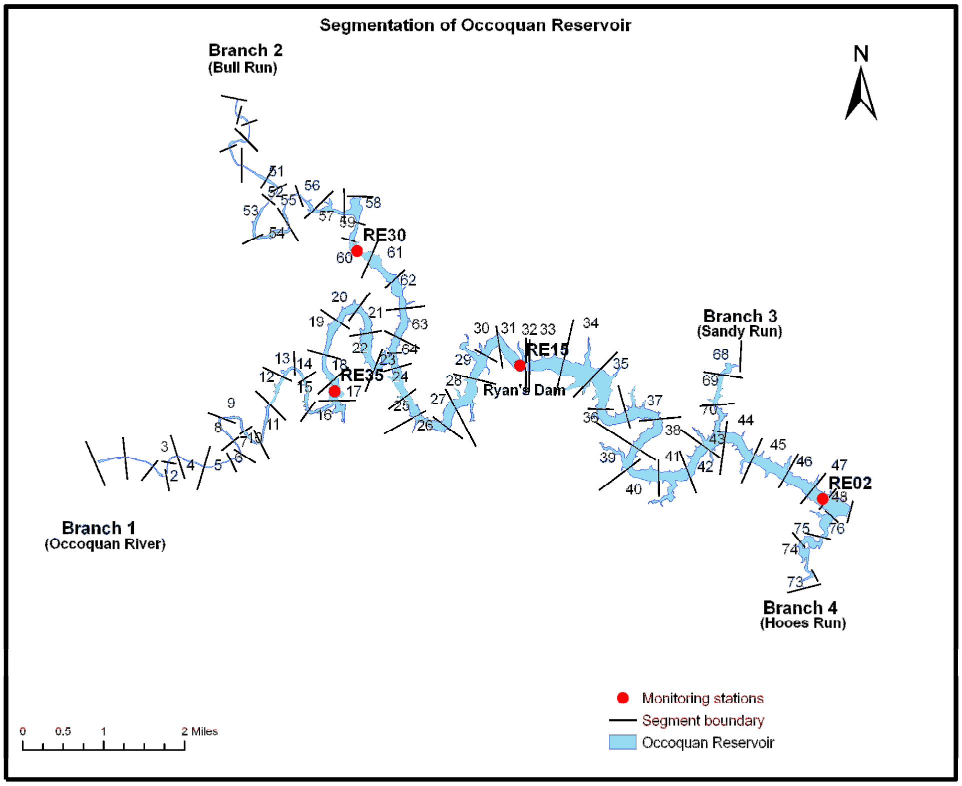


**Figure 76. Segmentation of the Occoquan Reservoir in the water quality model**

The Occoquan Reservoir is divided into four branches for purposes of the water quality model. Branch 1 (Occoquan River) includes segments 2 to 48, branch 2 (Bull Run) includes segments 51 through 64, branch 3 (Sandy Run) includes segments 68 to 70 and branch 4 (Hooes Run) includes segments 73 to 76. Missing segment numbers are boundary elements of zero volume that are used by the model but are not pertinent to this analysis.

#### 4.4.2.1 Analysis Based on Shape

Analysis based on shape takes into account the width and nature of shoreline at any particular portion of the reservoir. The narrow dendritic portion of a reservoir is generally considered riverine in nature. The transitional zone is wider and the lacustrine zone is the widest and is almost ovoid in shape.

As seen from Figure 61, the entire Occoquan Reservoir is narrow and dendritic in shape. It follows the narrow winding part of the parent river. Therefore, like many run-of-the-river reservoirs, it is difficult to assess the Occoquan Reservoir based on width at different regions. This attribute is, therefore, not very helpful in differentiating between the different zones.

Shoreline erosion is not an easy attribute to determine. It is based on a comparative study of the shoreline over many years. Data regarding shoreline erosion are not easy to obtain. Therefore, this attribute is not of much use while analyzing the morphometry of the Occoquan Reservoir.

#### 4.4.2.2 Analysis Based on Depth of Segments

The next attribute to be considered while analyzing the morphometry of the reservoir is depth. For analysis of depth, the bathymetry of the reservoir was studied. Analysis was done based on depth and depth gradient. The depth increases progressively from the riverine zone to the lacustrine zone. There is also a considerable difference in depth gradients at the boundary of the different zones. This is often seen as a considerable variation in depth along the reservoir bed.

The Occoquan Reservoir is already divided into segments based on bathymetry, for the Occoquan model. The segmentation has been done in such a manner that a particular segment has similar depth and other characteristics throughout its length. For each of the segments, the average depth of the segment is known. Figure 77, below, exhibits the depth of each segment in each of the four branches.

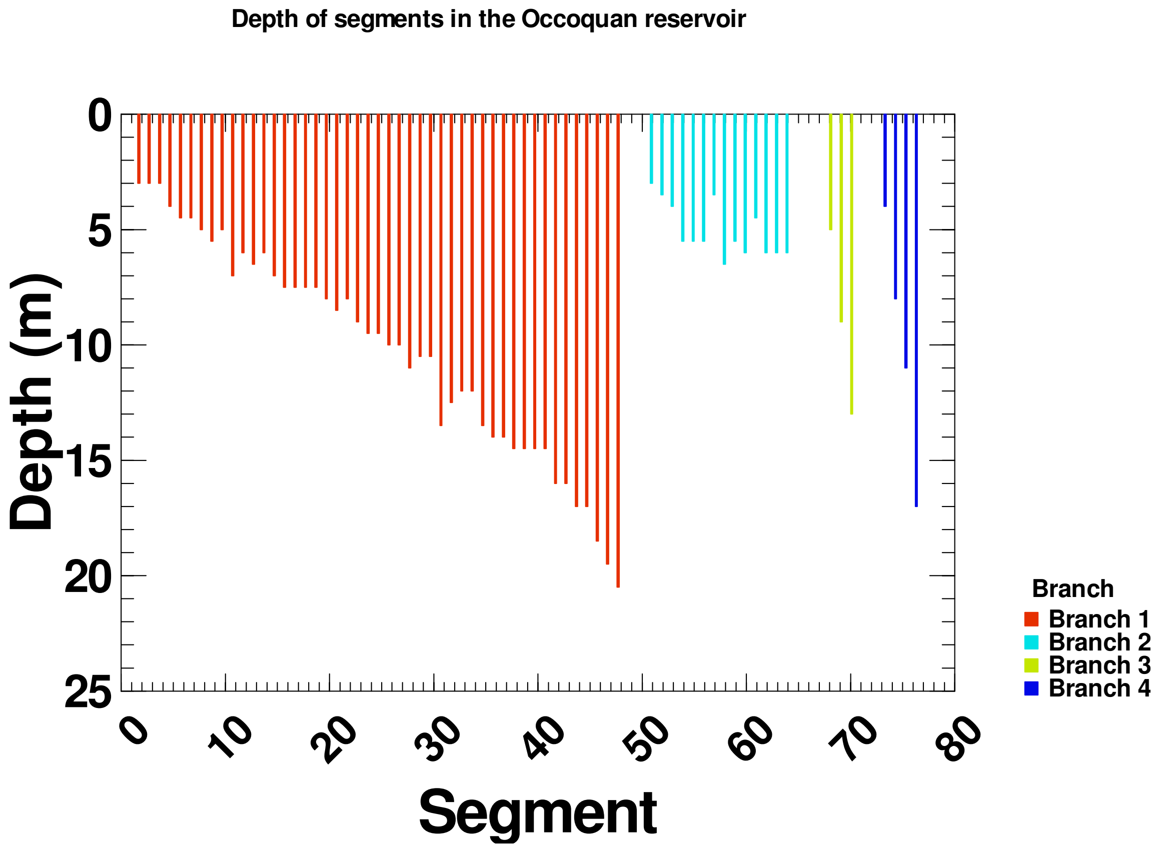


**Figure 77. Average depth of segments along the Occoquan Reservoir.**

The analysis of depth was done branch by branch. Branch 1 was considered first. Segments 2 to 48 are included in branch 1. Segments 2 to 10 were observed to be shallow in depth, the depth varying from 3-5 m. Segment 11 and segment 10 each had an average depth of 7 m and 5 m respectively. There was a difference of 2 m observed between the two segments. When compared to the difference in depth between the other adjacent segments, this change in depth was relatively substantial. Therefore, the boundary between segment 10 and 11 was designated as the boundary between the riverine and transitional zone.

On moving along branch 1, from segment 11 to segment 14, a gradual decrease in depth was observed, followed by gradual increase in depth from segment 15 to segment 30. Station RE35, which is in segment 17, was unstably stratified. Therefore, it lay in the transitional zone. Based on depth, the boundary between the transition and riverine zone was fixed along branch 1. Segments 11 to 17 can therefore be categorized as falling in the transitional zone. The next monitoring station (RE15) was located in segment 31 and stratification was observed to be stable there. Therefore, based on stratification it fell in the lacustrine zone. The boundary between the transitional and lacustrine zones needed to be fixed. The depth of the segments was considered in making this determination. The average depth of segment 30 was 10.5 m. Segment 31, which is adjacent to it, has an average depth of 13.5 m. When compared with the gradual increase in depth recorded up to that point (going from upstream to downstream), there was a noticeable change in depth between segment 30 and segment 31 (Figure 77). Therefore, the boundary of segment 30 with segment 31 was considered as the boundary of the transitional zone with the lacustrine zone. All the remaining segments along branch 1 were considered as part of the lacustrine zone, as the segments got deeper towards the dam.

The next step involved analysis of depth along branch 2 of the reservoir. Branch 2 included segments 64 to 51. Segment 23, along branch 1, is located adjacent to segment 64 and has an average depth of 9 m. Segment 24, on the other hand, has a depth of 6 m. The difference in depth is substantial. However, station RE30, which lies on branch 2 in segment 60, exhibited stratification, even though the stratification was unstable. Therefore, segments 64 to 61 which were deeper would also likely stratify, perhaps weakly. Taking this into consideration, segments 64 to 60 were placed in the transitional zone. The change in depth between segments 58 through 60 was observed to be gradual. The average depth of segment 58 was around 6.5 m and the average depth of segment 57 was around 3.5 m. There is a difference of 3 m between these two segments, which is considerable. Therefore, the boundary between segment 58 and 57 was considered as the boundary between the transitional and riverine zone along branch 2.

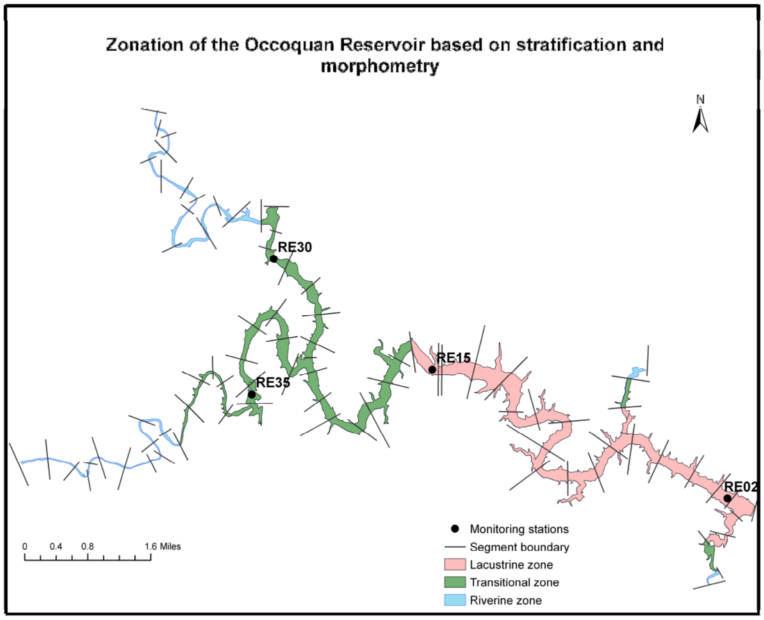
The demarcation of zones along branch 3 was addressed next. Branch 3 contains segments 67 through 70. Segment 43, along branch 1 is adjacent to segment 70. Segment 43 has an average depth of 16 m and belongs in the lacustrine zone. Segment 70 has an average depth of 13 m. Strong and stable stratification is generally expected at a depth of 13 m. Refer the discussion on the parameter stratification in section 3.4.1. Therefore, it can safely be assumed that segment 70 lies in the lacustrine zone. The average depth of segment 69 was 9 m. Stable stratification may or may not exist in this segment. Data based on stratification was unavailable for this segment. This is, therefore, a judgment call. The difference in depth between segment 70 and 69 was 4 m. The arm is narrow in width. The considerable difference in depth, and the narrow arm, both support the fact that segment 69 most likely falls in the transitional zone. Therefore, the boundary between segment 70 and 69 was considered as the boundary between the lacustrine zone and transitional zone along branch 3. Segment 68 has an average depth of 5 m. There is a substantial difference of 4 m between segment 69 and segment 68. The boundary between segment 68 and 69 was therefore considered as the boundary between the transitional zone and riverine zone. This completes the demarcation of zones along branch 3.

The segments along branch 4 were the last to be analyzed. Branch 4 included segments 73 to 76. Segment 48 along branch 1 is adjacent to segment 76. Segment 48 is the deepest segment in the Occoquan Reservoir and has an average depth of 20.5 m. It falls in the lacustrine zone. Segment 76 which is adjacent to it is around 17 m deep. Any part of a lake that is 17 m deep is expected to stratify. Therefore, it was assumed that segment 76 most likely fell in the lacustrine zone. Segment 75, has an average depth of 11 m. Based on depth, it is most likely that this segment, too, stratifies. Therefore, it was categorized as lacustrine. The average depth of segment 74 is 8 m. However, this segment is narrow and does not lie in the main body of the reservoir. Therefore, it will likely not stratify stably. Moreover, as a considerable difference in depth was observed between segment 75 and segment 74, the boundary between the two segments was considered as the boundary between the lacustrine and transitional zones. Segment 73 is about 4 m deep and is located near the shoreline. Therefore, it is expected to be well-mixed. Moreover, a considerable difference in depth was observed between segments 73 and 74. All these point to the fact that the boundary between segment 73 and segment 74 can be considered as the boundary between the transitional and riverine zones.

All the four branches as used by the model have been successfully allocated zones based on the bathymetry. When analysis based on stratification is supported by analysis based on morphometry, a better division of zones is obtained. As analysis based on stratification is limited to the monitoring stations. When depth characteristics are analyzed, the boundaries between the different zones can be determined better. A more complete picture of zonation can thus be obtained. However, as discussed earlier, at least two parameters need to be considered before a conclusive decision can be arrived at. In the case of station RE02, analysis based on stratification was not possible. Therefore to reinforce the conclusions made, it is necessary to go further down the table. The next parameter to be considered is Dissolved Oxygen (DO) concentration.

#### 4.4.2.3 Zonation of the Occoquan Reservoir Based on Thermal Stratification and Segmentation of the Lake in the Water Quality Model

The entire reservoir has been successfully divided into three zones based on analysis of data for the stratification and morphometry parameters. Depth is the key attribute considered during analysis using the parameter morphometry. Analysis based on stratification and morphometry are combined to arrive at the division below (Figure 78).



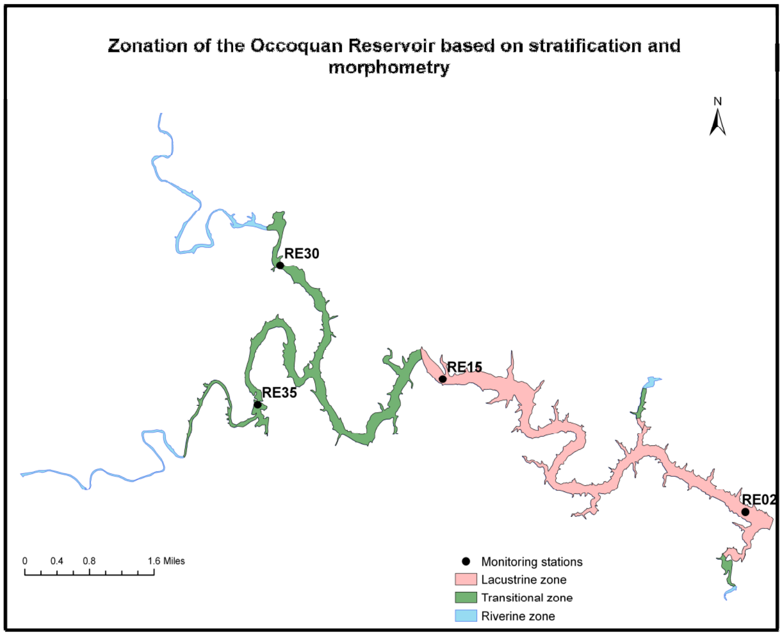


**Figure 78. Zonation of the Occoquan Reservoir based on thermal stratification and segmentation of the lake in the water quality model.**

While analyzing the segments, the larger arms have been divided into separate segments. The smaller arms, because of their size, are better analyzed as part of the larger adjacent segment.

The next step in the analysis is to take into consideration the DO profiles available. Data regarding dissolved oxygen are available for each of the monitoring stations. It is analyzed in the sections below.

### 4.4.3 Dissolved Oxygen Concentrations in the Occoquan Reservoir

As stratification data could not be effectively analyzed for all the monitoring stations, the need arose to go further down the list of parameters. The next parameter in the table is dissolved oxygen (DO). Data for dissolved oxygen was available and further analysis based on this parameter was done. The reservoir was then divided into three zones based on the analysis conducted and consolidated with the division made earlier. If the analyses based on all three parameters complement each other, no further analysis is required.

Dissolved oxygen concentration is the third parameter in the zonation guidance table. It has two attributes, namely, diel DO pulse, and DO concentrations with depth. Data on diel DO pulse are hard to obtain because it requires round the clock monitoring and, unless an automated system is in place, this is not practical. Therefore, analysis done in this section will be based on the variation of DO concentration with depth. Analysis of DO concentrations involves plotting the DO concentrations with depth and studying the obtained profiles. If the profiles obtained for DO are similar to the profiles obtained for stratification in a stably stratified body, then the DO profiles are consistent with the profiles that can be observed in the lacustrine zone of the reservoir

The waters are well-mixed in winter. Therefore, the level of DO in the waters is expected to be uniform from top to bottom during the winter months. This analysis will be confined to the other three seasons. The growing season is generally assumed to be from April 1 through October 31 during any given year. Therefore, the exclusion of analysis during the winter months will in no way affect the results expected.

#### 4.4.3.1 Dissolved Oxygen Concentrations at Station RE02

As before, data were analyzed for the years 2002-2006. While all five years of data were analyzed, the discussion below will pertain to two years. Since the variation in DO is closely linked to the strength of stratification, the discussion of variation of DO below will focus on the same years for which stratification was discussed. For station RE02, analysis of data with respect to stratification was not effective. However the two years which best exhibited stratification were discussed. The sections below deal with analysis of DO concentrations at station RE02, during the three seasons namely spring, summer and fall during the same years, 2002 and 2006.

#### *4.4.3.1.1 Dissolved Oxygen Concentrations in Spring at Station RE02*

Stratification is not often stable during spring; therefore there can be some variation in the DO concentrations. The profiles for the representative years 2002 and 2006 are shown below, in Figure 79.

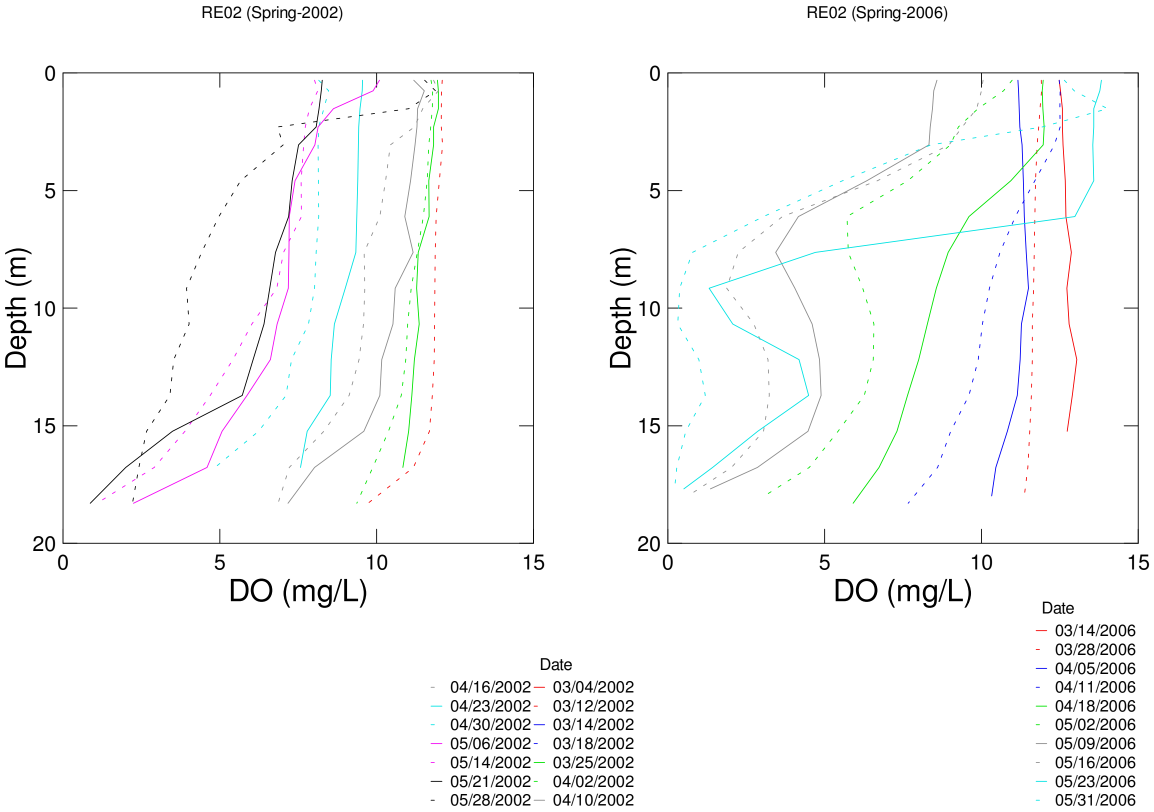


**Figure 79. DO–depth profiles at station RE02 in spring (2002 and 2006).**

The initial profiles during spring, for the year 2002, indicate that the DO concentrations were uniform from top to bottom. However, as spring progressed, especially towards the end, a slight difference in DO was observed between the top and bottom waters. This variation in DO observed was not as pronounced as observed in the year 2006. This was consistent with the fact that not much stratification was observed during spring for the year 2002 (Figure 28).

On examination of the DO profiles for the year 2006, from Figure 79, the initial profiles indicate uniform DO concentrations throughout the water column. However, a marked change in the shape of the profiles was observed towards the end of spring.

For all the other years in consideration, the trends observed were similar. No variation in DO concentrations was observed during the beginning of spring but slight variations were observed as spring progressed.

##### *4.4.3.1.2 Dissolved Oxygen Concentrations in Summer at Station RE02*

The variation in DO is best observed during the summer months. The profiles for the year 2002 and 2006 are displayed below in Figure 80.

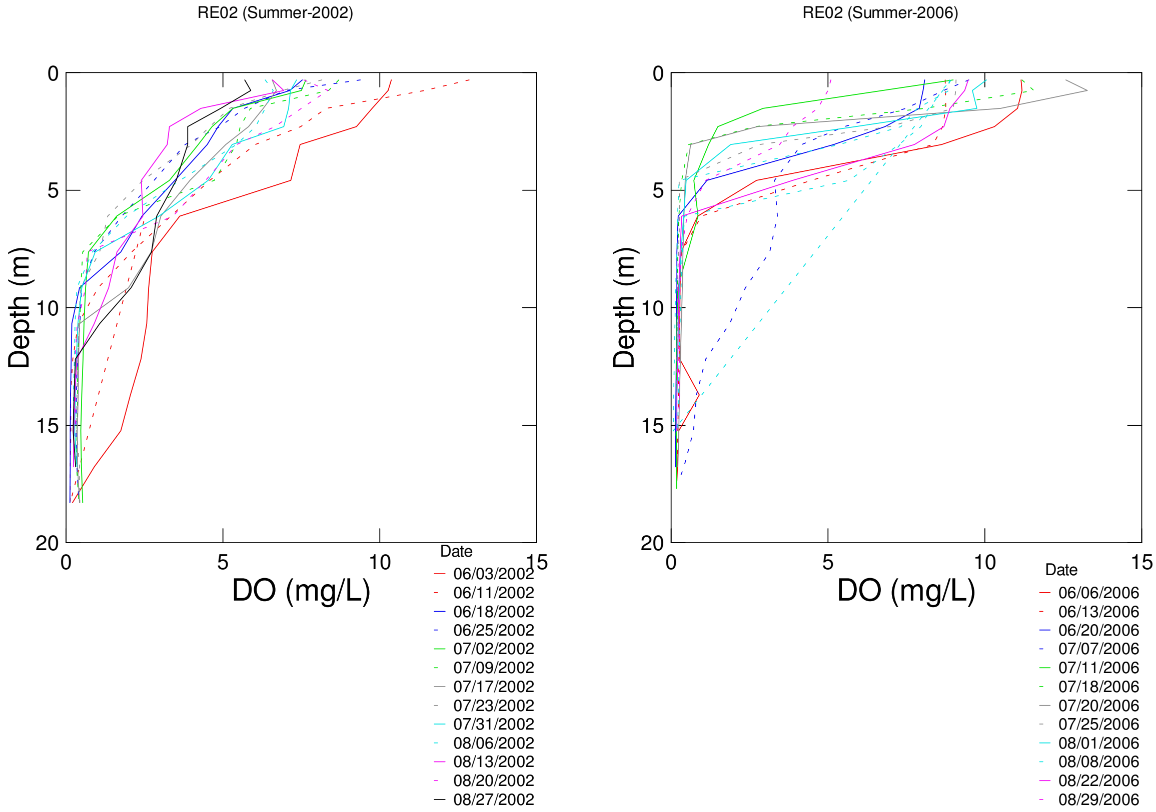


**Figure 80. DO–depth profiles at station RE02 in summer (2002 and 2006).**

The DO profiles for the year 2002 indicate that the DO in the bottom waters was depleted throughout summer. The waters at the top appeared to be well aerated. A marked decrease in DO concentrations was observed as depth increased. Although the summer temperature profiles for the year 2002 (Figure 64) were inadequate in establishing the stratification at station RE02, the DO profiles indicate that the DO concentrations were consistent with that expected in very deep waters.

The DO profiles for the year 2006 also indicate depleted DO concentrations in the bottom waters, generally well-aerated top waters, and a rapidly depleting mid-level region. This was consistent with the DO profiles expected in deep waters. Though temperature stratification data for RE02 were anomalous, the DO profiles were strong in indicating a deep, lake-like, behavior.

The DO profiles for all the other years in consideration also indicate that DO profiles were similar to that described above for most of summer.

#### *4.4.3.1.3 Dissolved Oxygen Concentrations in Fall at Station RE02*

It is during fall that the waters become well-mixed. Therefore, it is at this time that the depleted DO concentrations in the bottom waters are replenished. The end of fall generally exhibits uniform DO concentrations throughout the water column. The fall DO profiles for the representative years 2002 and 2006 are discussed below (Figure 81).

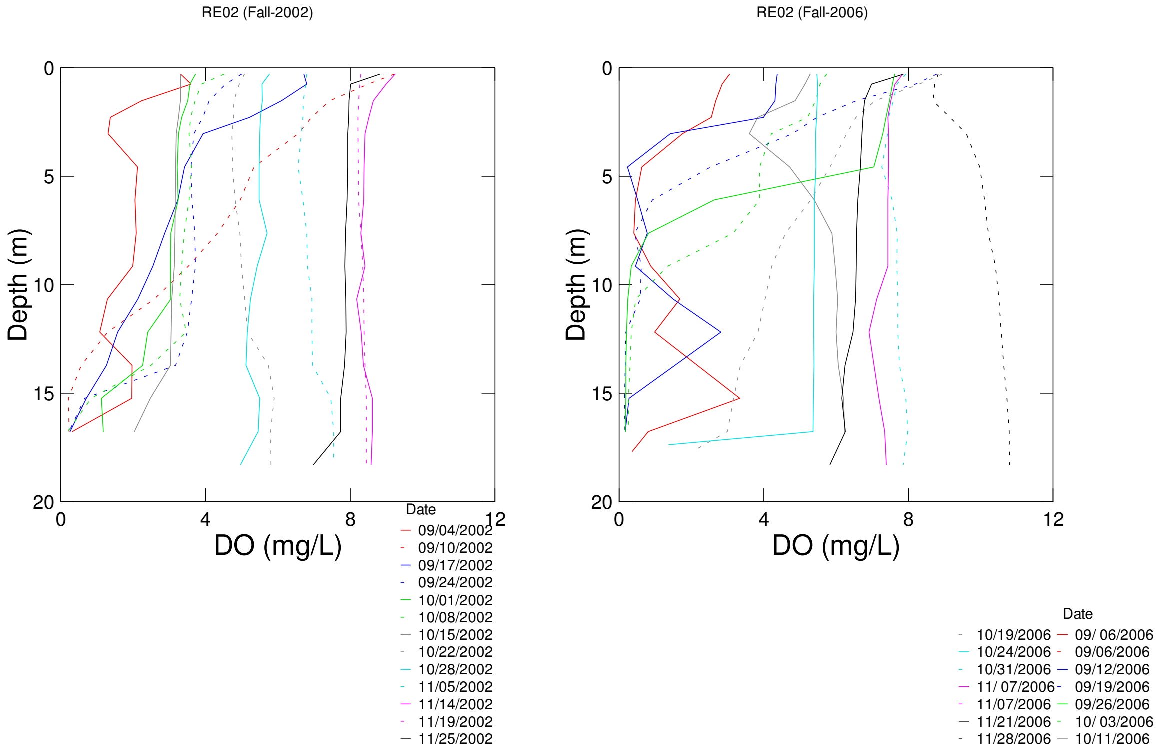


**Figure 81. DO–depth profiles at station RE02 in fall (2002 and 2006).**

Fall DO profiles for the year 2002 indicate that the bottom waters were still low in DO during the beginning of fall. As fall progressed, DO concentrations became more and more uniform, until finally at the end of fall, the DO concentration was uniform throughout the water column.

The fall DO profile for the year 2006, also exhibited similar trends. In the beginning of fall, the DO in the bottom waters was low. However, as the waters became progressively well-mixed, the DO in the bottom waters was replenished. By the end of fall, the DO concentration was uniform throughout the depth of the water body.

Similar trends were observed during fall for all the remaining years under consideration. The waters exhibited uniform DO concentrations by the end of fall.

##### *4.4.3.1.4 Conclusion for Station RE02 Based on Dissolved Oxygen Concentrations*

At station RE02, the DO concentrations were uniform during the beginning of spring. The DO in the bottom waters exhibited signs of depletion later in spring. By summer, the DO in the bottom waters was completely depleted. With the onset of fall, the waters at the bottom were slowly replenished, until at the end uniform DO concentrations were observed throughout the depth at station RE02. Therefore, the summer DO profiles observed were similar in shape to the DO profiles for a strongly-stratified, deep, water body. Therefore, based on the DO concentration parameter, station RE02 falls in the lacustrine zone.

#### 4.4.3.2 Dissolved Oxygen Concentrations at Station RE15

Station RE15 is the second farthest station from the dam. It lies along the mainstream of the Occoquan Reservoir, just upstream of Ryan's Dam. The presence of this deep region just downstream of station RE15 has some lake-like effect on the characteristics observed at this station. The profiles observed for the years 2002 and 2006 are discussed below. These are the same years for which temperature stratification was discussed. The DO concentrations are closely linked to stratification.

### *4.4.3.2.1 Dissolved Oxygen Concentrations in Spring at Station RE15*

The DO profiles observed during spring for the representative years 2002 and 2006 are shown in Figure 82.

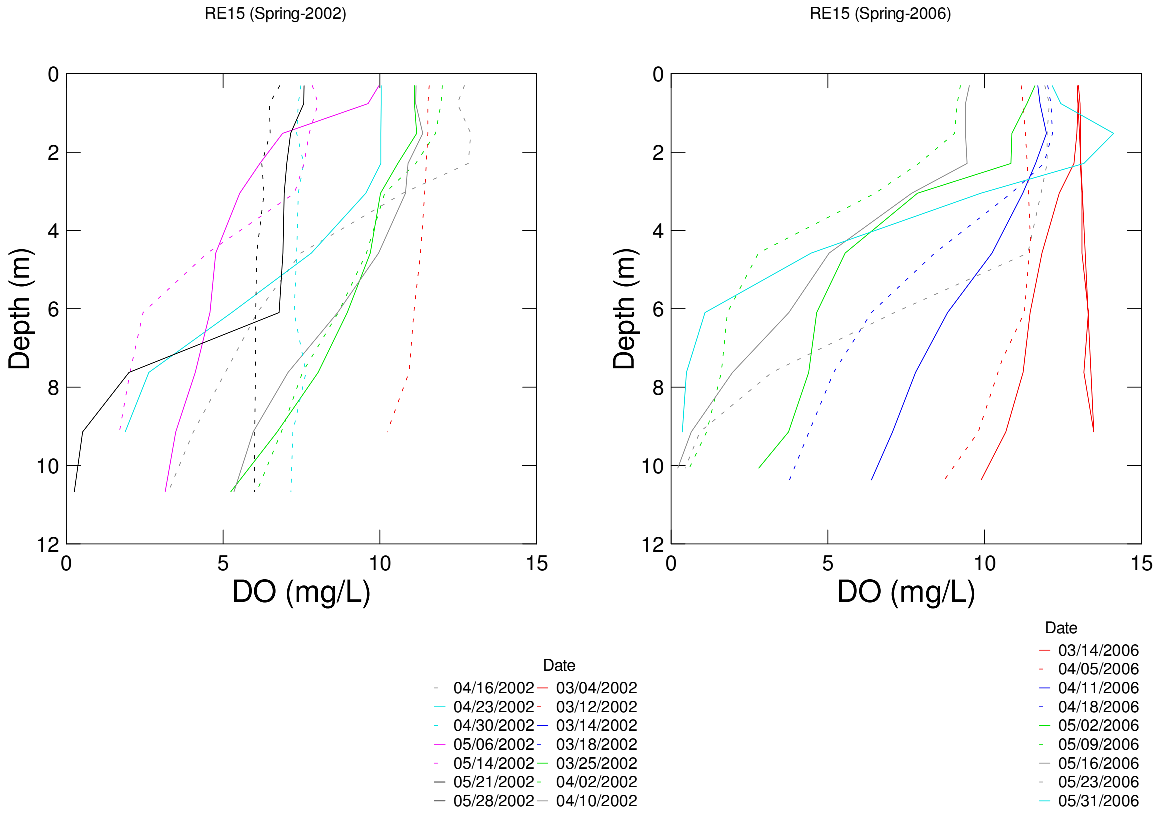


**Figure 82. DO–depth profiles at station RE15 in spring (2002 and 2006).**

The DO profiles observed during spring for the year 2002 indicate that the DO concentrations were uniform early in spring. However, variations were observed as spring progressed. The DO concentrations in the bottom waters became very low by the end of spring.

The DO profiles for the year 2006 indicate that at the beginning of spring, the waters were uniform in DO concentration. As spring progressed, a marked variation was observed between the top and bottom waters. Similar trends were observed during the other three years under consideration. The DO generally started to deplete in the bottom waters by the end of spring.

##### *4.4.3.2.2 Dissolved Oxygen Concentrations in Summer at Station RE15*

Strong stratification during the summer months often results in DO depleted bottom waters. Figure 83, below, displays the summer DO profiles for the representative years 2002 and 2006.

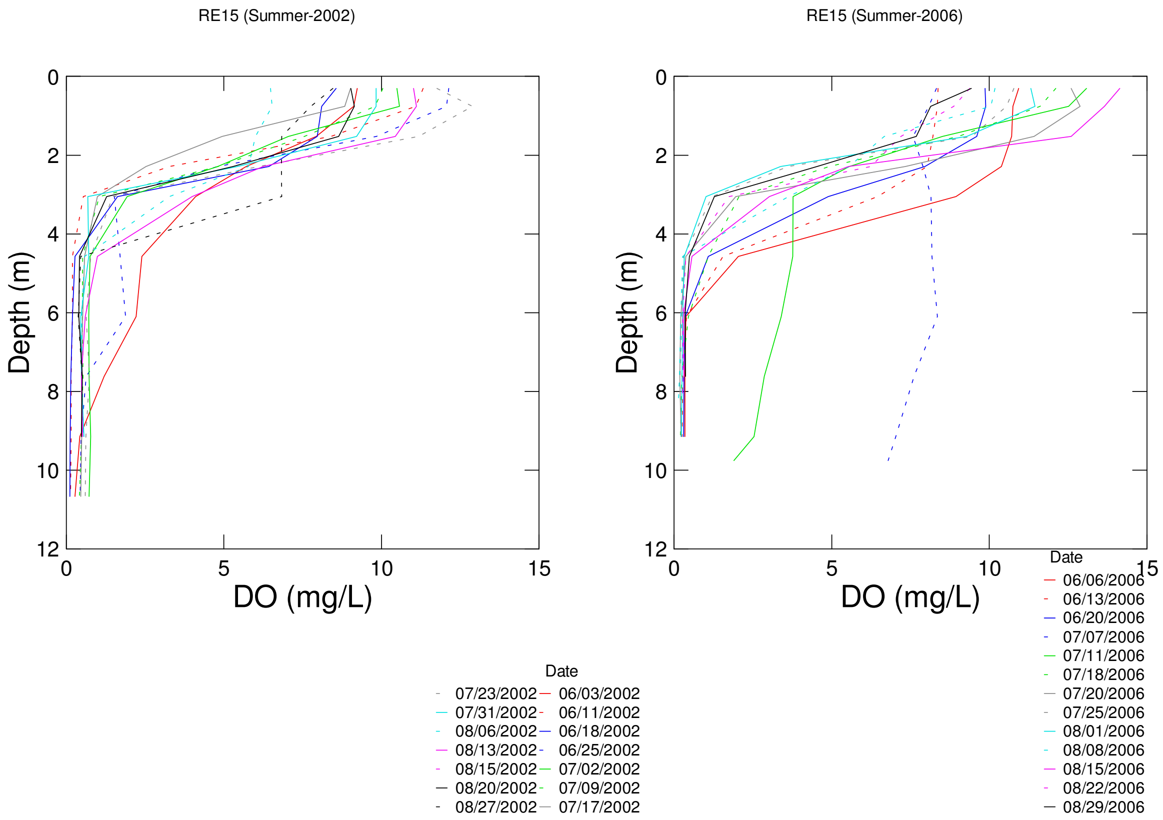


**Figure 83.** **DO–depth profiles at station RE15 in summer (2002 and 2006)**.

The summer DO profiles for the year 2002 indicate the presence of very low DO in the bottom waters throughout summer. The top waters, on the other hand, were well aerated. This difference in DO observed during summer is typical of that observed in deep waters.

Examination of the DO profiles for the year 2006 indicated almost similar trends. However, the profile observed on July 7th indicated that the waters were well-mixed at that time. The hydrological data for the year 2006 indicated the occurrence of a very strong hydrological event during that time. Strong hydrological events can cause temporary mixing of the waters. However, the next profile observed, exhibited depleting

DO in the bottom waters. From then on until the end of summer, the bottom waters have very little DO.

This trend of low DO in the bottom waters during summer, holds good for all the other years in consideration, although for some years (2003 and 2005) the depletion of DO in the bottom waters was observed only after the first couple of profiles. On the whole, for the period of study, the bottom waters were low in DO almost throughout summer.

##### *4.4.3.2.3 Dissolved Oxygen Concentrations in Fall at Station RE15*

The DO profiles observed during fall for the representative years 2002 and 2006 are displayed in Figure 84.

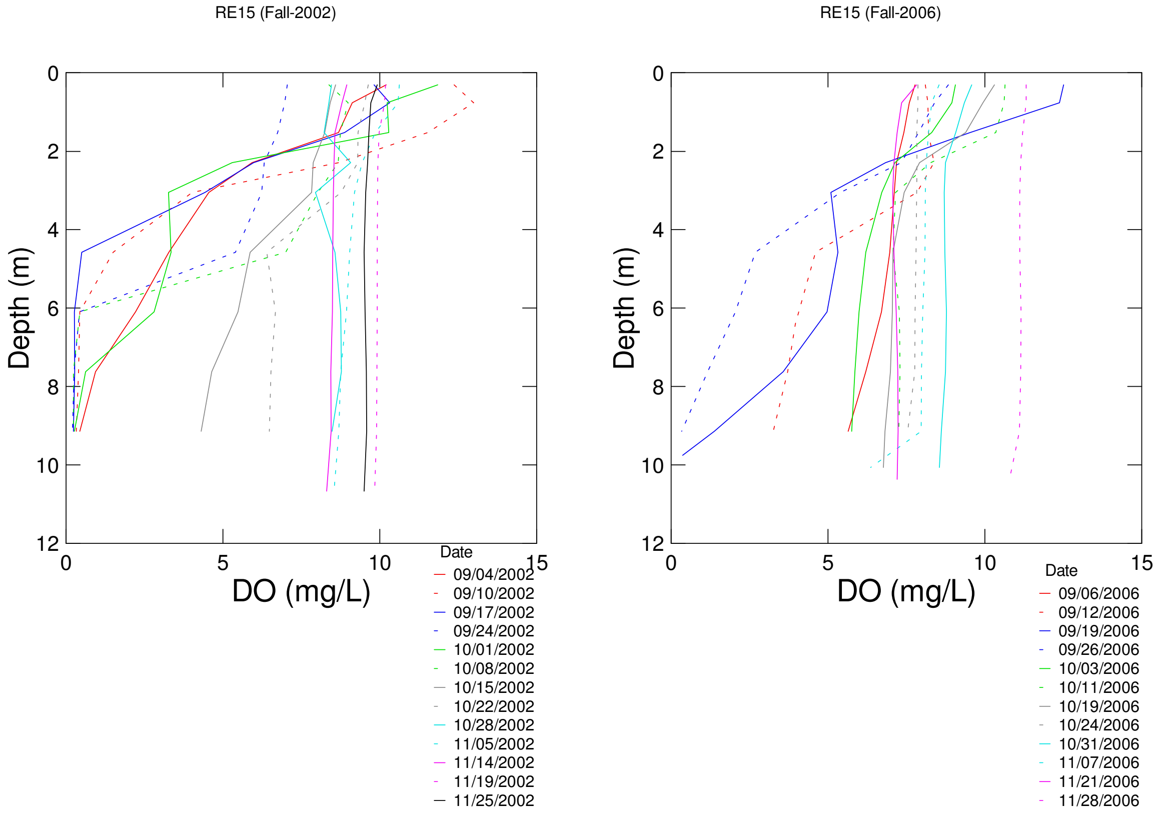


**Figure 84. DO–depth profiles at station RE15 in fall (2002 and 2006).**

The fall profiles for the year 2002 indicate that at the beginning of fall, the bottom waters were still low on DO. As fall progressed, the DO in the bottom waters was replenished. By the end of fall, it was observed that uniform DO concentrations were maintained throughout the depth of the water body.

On examination of the profiles for the year 2006, low DO concentrations were observed in the bottom waters in the beginning of fall. However, as fall progressed and the waters became well-mixed, the DO concentrations in the water column became uniform.

Similar trends were observed in the variation of DO at station RE15 during spring for the other three years in consideration. DO profiles exhibited a uniformly oxygenated water column by the end of fall.

##### *4.4.3.2.4 Conclusion for Station RE15 Based on Dissolved Oxygen Concentrations*

For station RE15, low DO concentration was observed in the bottom waters by the end of spring. Throughout summer the DO concentration was very low in the bottom waters. The DO concentration was also low during the beginning of fall. However, as fall progressed, the waters became well-mixed and DO concentrations in the bottom waters were replenished. The DO profiles observed at station RE15, especially during summer, exhibit very low to zero DO in the bottom waters and sufficient DO in the top waters. The top and the bottom waters were connected by layers in between which exhibited rapidly depleting DO. These profiles were consistent with the profiles expected in the lacustrine zone. Therefore, based on the DO concentration parameter, station RE15 falls in the lacustrine zone.

#### 4.4.3.3 Dissolved Oxygen Concentrations at Station RE30

Station RE30 is located along branch 2 of the Occoquan Reservoir (Figure 61). It is located considerably upstream of the dam. For station RE30, the DO profiles for the years 2002 and 2005 have been discussed below.

### *4.4.3.3.1 Dissolved Oxygen Concentrations in Spring at Station RE30*

The DO profiles for the representative years 2002 and 2005 are displayed below in Figure 85.

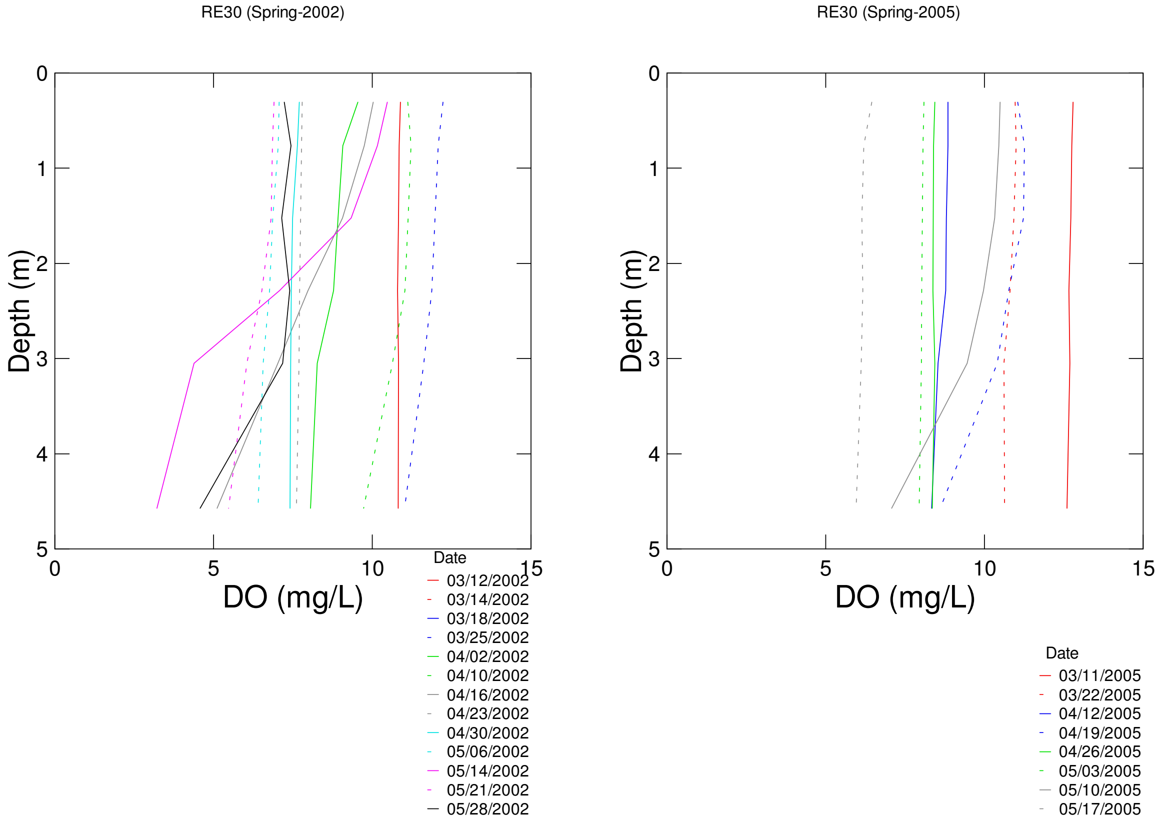


**Figure 85. DO–depth profiles at station RE30 in spring (2002 and 2005).**

The DO profiles in spring, for the year 2002, indicate that, during the beginning of spring, the DO concentrations were uniform throughout the water column. By end of spring, depletion in DO concentration was observed in the bottom waters, but the profiles indicate that the DO was not very low.

The DO profiles for the year 2005 indicate that almost throughout spring, the DO profiles exhibited uniformity throughout the water column. Some decrease in DO was observed in the bottom waters on some of the profiles, but this depletion was not pronounced.

For all the other years in consideration, similar trends were observed. The decrease in DO, if present, in the bottom waters during spring was slight.

###### *4.4.3.3.2 Dissolved Oxygen Concentrations in Summer at Station RE30*

The depletion of DO in the bottom waters is generally most pronounced during the summer months. Figure 86, below, displays the summer DO profiles for the representative years 2002 and 2005.

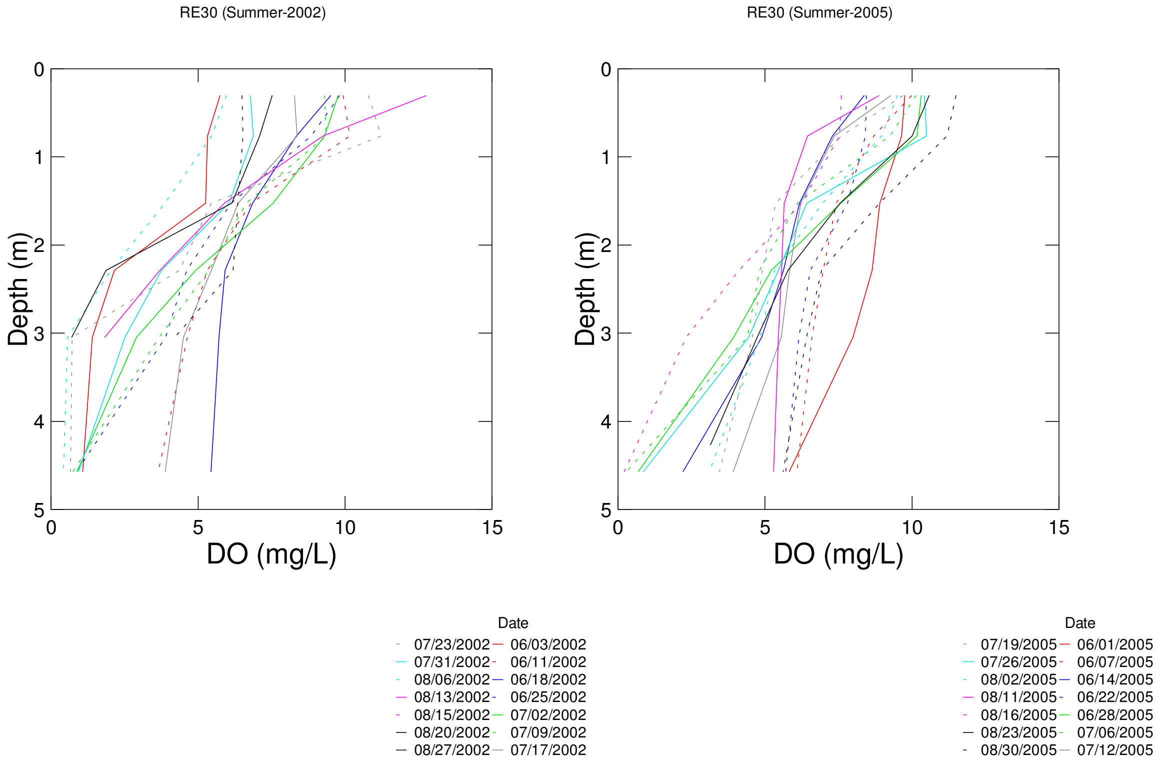


**Figure 86.** **DO–depth profiles at station RE30 in summer (2002 and 2005).**

The DO profiles for the year 2002 indicate that in the beginning of summer the DO was very low in the bottom waters. As summer progressed, some DO in the bottom waters was replenished. Although the profiles indicate low bottom DO, the variation of DO between the top and bottom waters was not as pronounced as that observed at stations RE02 and RE15.

Examination of the DO profiles for the year 2005 indicated low DO in the bottom waters. The DO got replenished, though not to the full extent. The variation in DO between the top and bottom waters was not as pronounced, as in the profiles at stations RE15 and RE02.

The general trend observed at station RE30 during summer was low DO during the initial months. However, the DO got replenished, to a certain degree. The variation of DO between the top and bottom waters was gradual.

### *4.4.3.3.3 Dissolved Oxygen Concentrations in Summer at Station RE30*

The DO concentrations typically are replenished completely after mixing, caused by fall overturn. Figure 87, below, displays the fall DO profiles for the representative years 2002 and 2005.

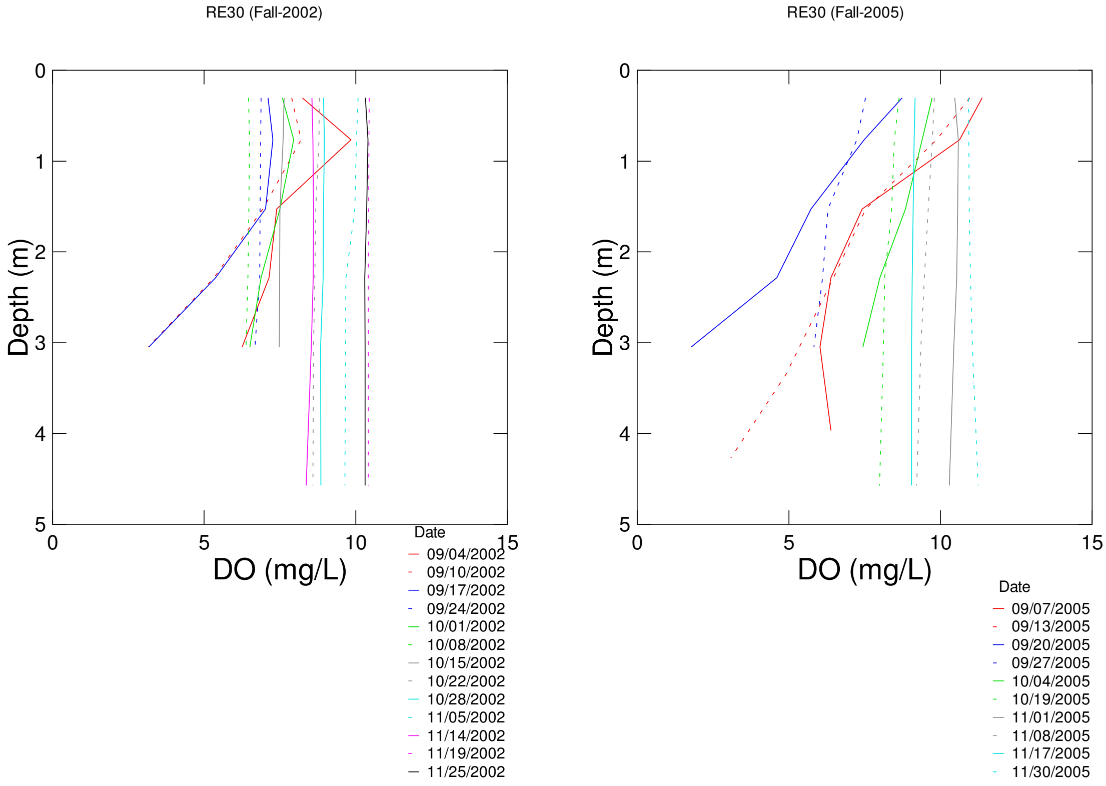


**Figure 87. DO–depth profiles at station RE30 in fall (2002 and 2005).**

On examining Figure 87, for the fall DO profiles exhibited during the year 2002, little variation in DO was observed in profiles in the beginning of fall. Soon afterwards, the DO in the entire water column was uniform. The same can be said for the profiles for the year 2005.

The remaining profiles for the other years in consideration also exhibit similar trends. After early fall, the DO distribution in the entire water column was uniform.

##### *4.4.3.3.4 Conclusion for Station RE30 Based on Dissolved Oxygen Concentrations*

The DO profiles observed at station RE30 indicate that the DO in the water column was uniform at the beginning of spring. Towards the end of spring, some variation in DO concentration between the top and bottom waters was observed. Throughout summer the DO in the bottom waters was low, when compared to the well-aerated surface waters. However, the variation in DO concentration between the top and bottom waters was not as pronounced, as that observed at stations RE02 and RE15. Variation in DO concentration was also observed during the beginning of fall. Soon afterwards, the DO concentration in the water column became uniform. As the DO concentration in the bottom waters did not get depleted during summer, there was some intermittent mixing of water, which might be due to weak stratification. Therefore, based on the DO concentration parameter, station RE30 falls in the transitional zone.

### 4.4.3.4 Dissolved Oxygen Concentrations at Station RE35

Station RE35 lies along branch 1 in the upstream reaches of the Occoquan Reservoir. This is one of the farthest stations from the dam. The years 2004 and 2005 have been chosen as the representative years in this case.

#### *4.4.3.4.1 Dissolved Oxygen Concentrations in Spring at Station RE35*

During early spring, the waters are generally well-mixed and this is reflected in the DO concentrations in the water column. Figure 88, below, displays the DO profiles during spring at station RE35.

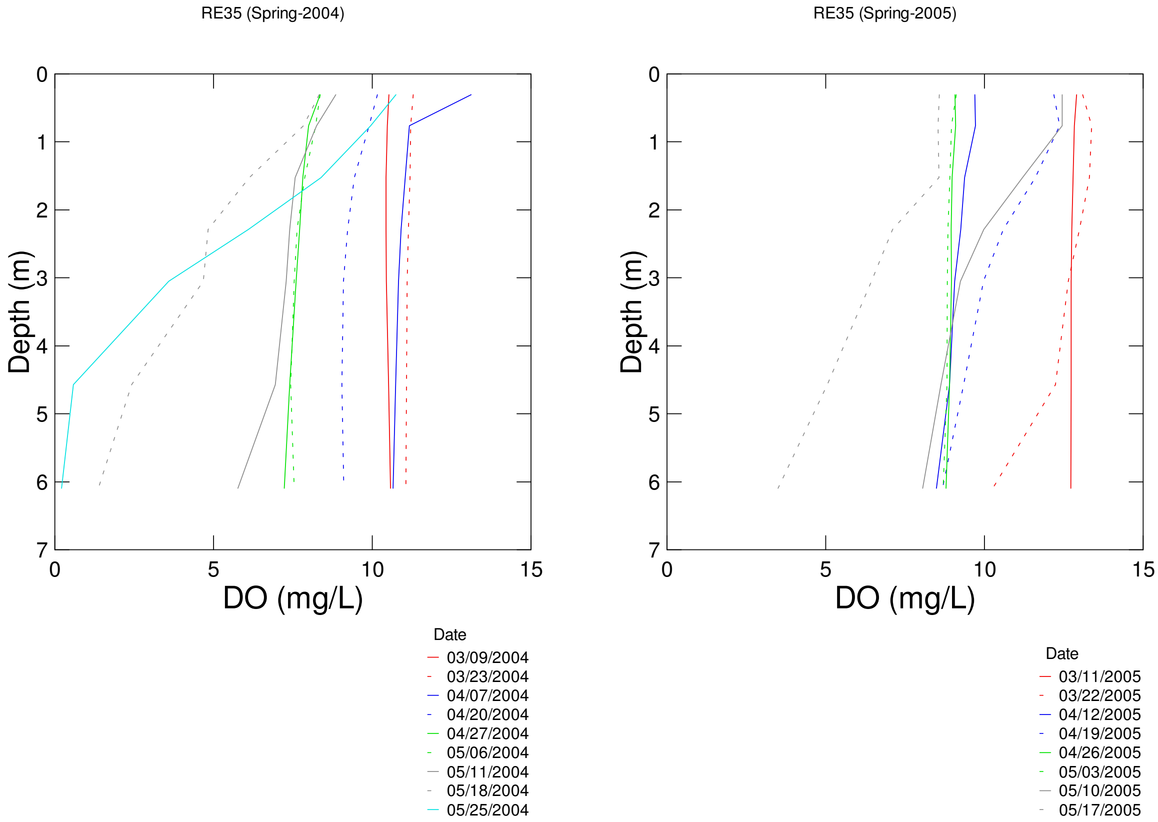


**Figure 88.** **DO–depth profiles at station RE35 in spring (2004 and 2005).**

On examining Figure 88, for the initial DO profiles observed during spring of the year 2004, exhibited no variation in DO concentrations throughout the water column. However, as spring progressed, the DO concentrations in the bottom waters became depleted.

The DO profiles for the year 2005 exhibited a similar trend. DO depletion occurred only late in spring in the bottom waters. Similar trends were observed for all the other years considered in the analysis.

#### *4.4.3.4.2 Dissolved Oxygen Concentrations in Summer at Station RE35*

Summer is the time when maximum depletion of oxygen can take place in the bottom waters, especially when stratification is strong. The DO profiles for the years 2004 and 2005 have been displayed in Figure 89 below.

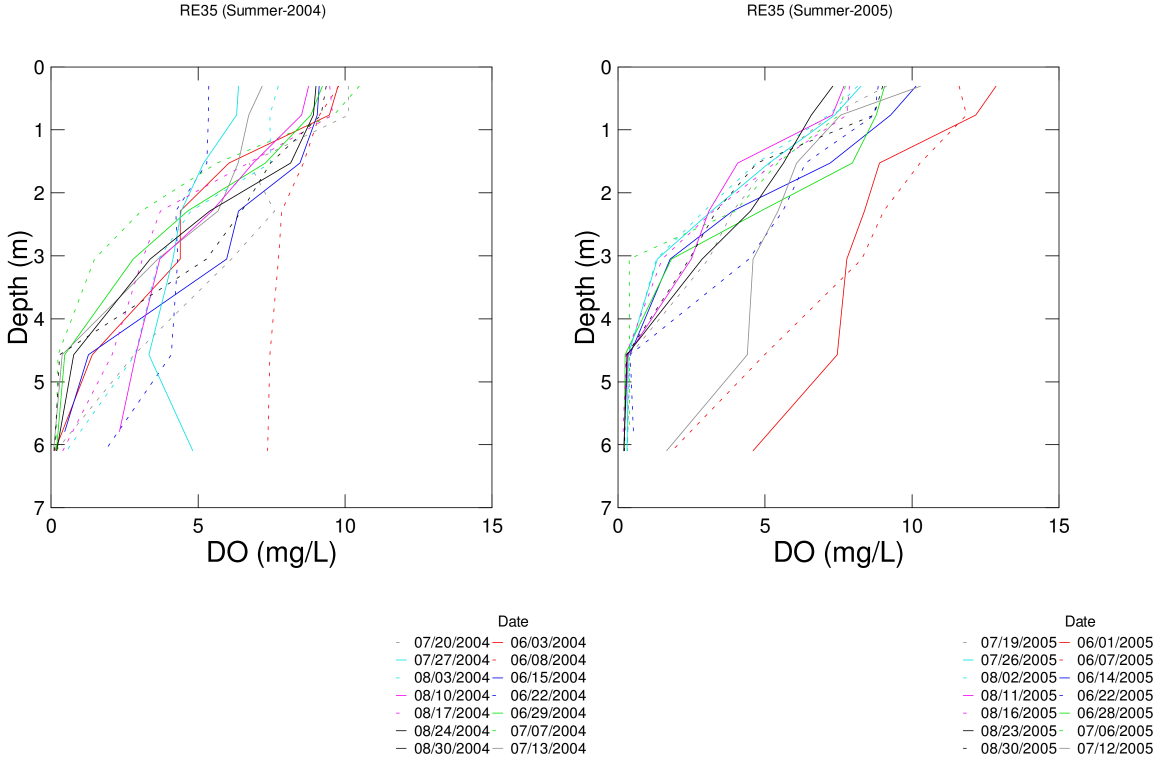


**Figure 89. DO–depth profiles at station RE35 in summer (2004 and 2005).**

The summer profiles for DO in the year 2004 illustrate the presence of well aerated top waters and poorly aerated bottom waters. However, it is only by the end of summer that near-complete depletion of DO in the bottom waters was observed. This is not consistent with the fact that very low DO is generally present in the bottom waters throughout summer in deep waters. This indicates the existence of some level of mixing in the bottom waters.

The profiles for the year 2005 indicate that as summer progressed, the DO in the bottom waters got depleted. This indicated that throughout summer there was no mixing between the top and bottom waters. Similar variation in DO profiles were observed during the year 2002. However, during the other two years, the variation in DO between the top and bottom waters was not consistent. Therefore, on the whole, the variation of DO concentrations in summer between the top and bottom waters cannot be considered consistent with a strongly stratified profile.

##### *4.4.3.4.3 Dissolved Oxygen Concentrations in Fall at Station RE35*

It is during fall that the water column regains its uniformity in DO concentration. Figure 90, below, displays the fall DO profiles for the representative years 2004 and 2005.

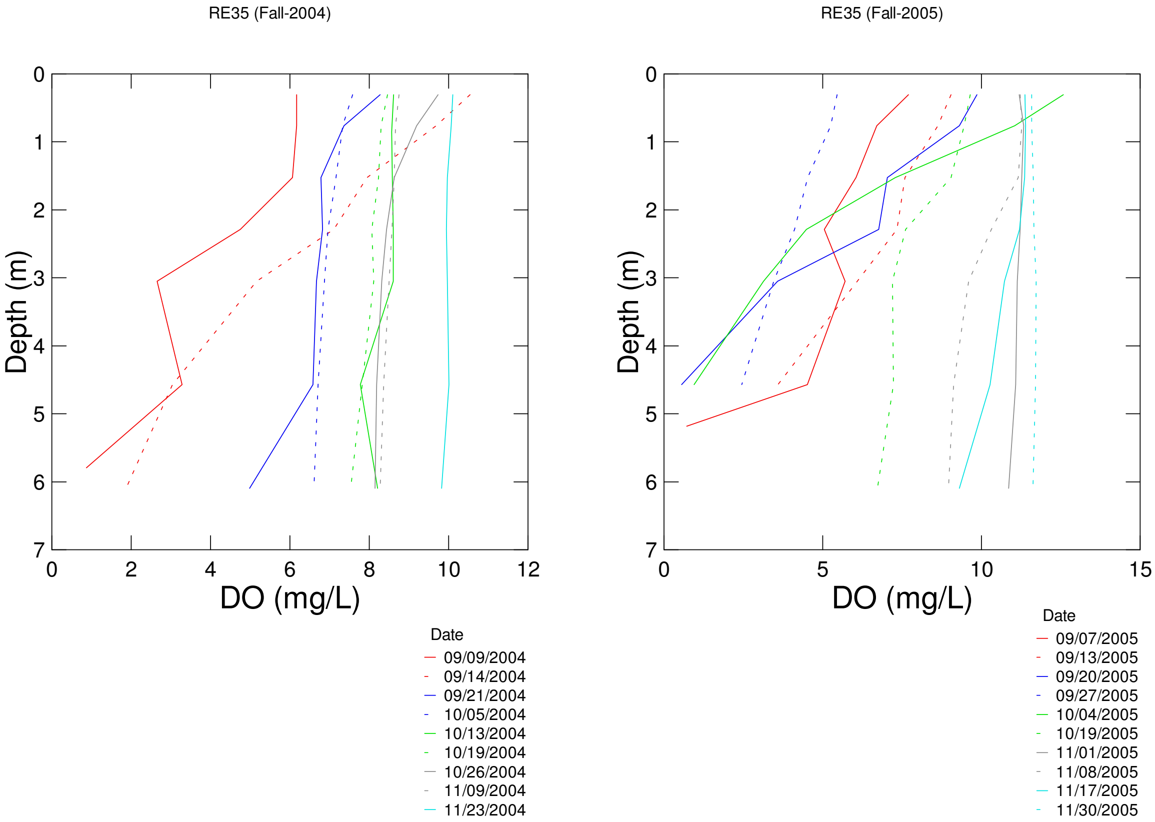


**Figure 90.** **DO–depth profiles at station RE35 in fall (2004 and 2005).**

The DO profiles for the year 2004 indicate that the bottom waters had depleted DO levels during the beginning of fall. However, soon afterwards, the profiles indicate mixing of waters and a uniform level of DO was maintained throughout the entire water column.

The DO profiles for the year 2005, too, exhibit low DO levels in the bottom waters during the beginning of fall. However, by the end of fall the waters were well-mixed and well aerated. Similar trends were observed for the remaining three years in consideration.

#### *4.4.3.4.4 Conclusion for Station RE35 Based on Dissolved Oxygen Concentrations*

For all the years in the period of study, the waters were well aerated in the beginning of spring. However, depletion in the DO levels in the bottom waters were observed, starting often during late spring. During summer, extreme low DO concentrations were observed in the bottom waters for two of the five years under consideration. For the remaining three years, very low DO was observed in the bottom waters only by the end of summer, indicating that some mixing of the waters took place. Depleted DO levels were also observed during the beginning of fall in the bottom waters. Soon afterwards, the waters became well-aerated and well-mixed. Therefore, DO profiles did not exhibit a consistent pattern year after year. The DO levels in the bottom waters during the summer months fluctuated from year to year. This indicates that based on the DO concentration parameter,, station RE35 falls in the transitional zone.

### 4.4.3.5 Zonation of the Occoquan Reservoir Based on Dissolved Oxygen Concentrations

Data from all four stations were analyzed with respect to DO concentrations. Depending on the consistency in the level of DO concentrations in the bottom waters, especially during summer, the zone in which each station belonged was determined. Analysis with the DO concentration parameter was performed because data pertaining to temperature stratification at station RE02 could not be effectively analyzed. Therefore, station RE02 was characterized to be in the lacustrine zone based on the assumption that, in the absence of the hypolimnetic aeration system, deep waters such as those at station RE02 are most likely to stratify stably. This was further supported by evidence from the morphometric analysis. However, for best results, two parameters need to be successfully considered before a conclusive division can be arrived upon. Therefore, the need arose for analysis of the third parameter. Analysis of data for each of the stations, based on DO concentrations drew the same conclusions as the other two analyses. As DO data are available only at the monitoring stations, this data cannot be utilized to reinforce the boundaries between the different zones. However, this analysis further supports the earlier division and there was no further change in the boundaries between the different zones as determined by the analyses for the other two parameters. Figure 91, exhibits the zonation of the Occoquan Reservoir as a result of all three analyses.

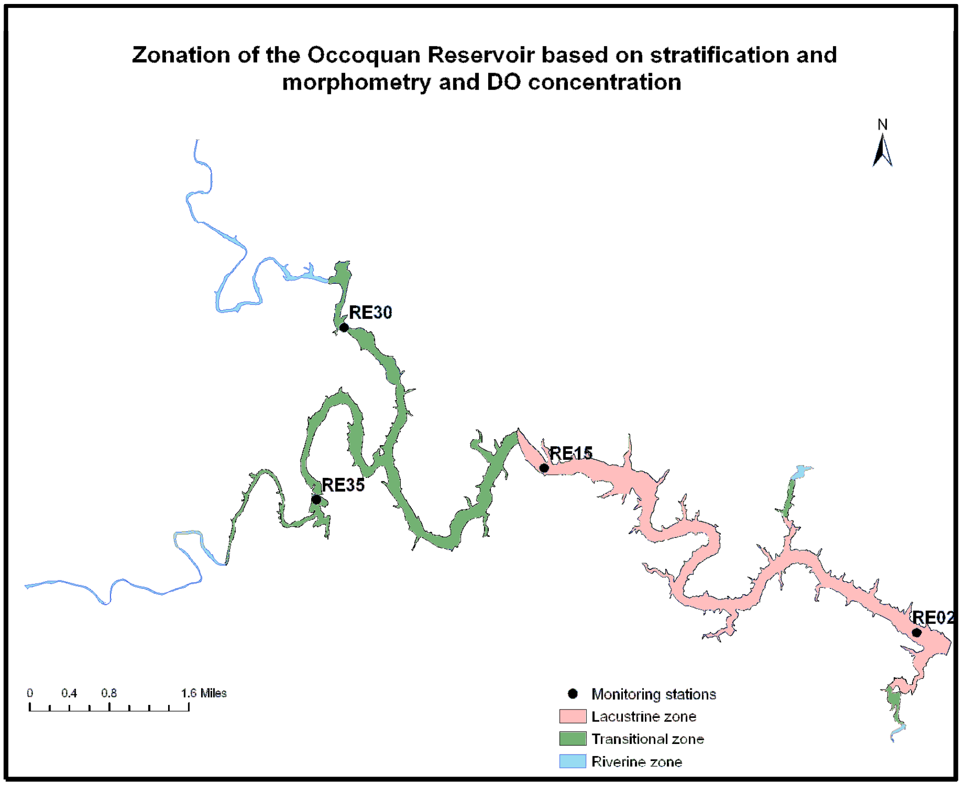


**Figure 91.** **Zonation of the Occoquan Reservoir based on thermal stratification, morphometry and DO concentration.**

### 4.4.4 Final Zonation of the Occoquan Reservoir

The Occoquan Reservoir has been successfully divided into three zones. Analysis done for arriving at this division was based on the first three parameters in the table, namely: stratification, morphometry and DO concentrations.

The first division was based on the temperature stratification parameter. The next parameter, morphometry, was used to fine-tune this division. Analysis based on this parameter was instrumental in determining the boundaries between the three zones. The

DO concentration parameter was used to reinforce and provide supporting evidence for the existing division of the Occoquan Reservoir. Figure 92, below, exhibits the process of zonation, as the analysis progressed.

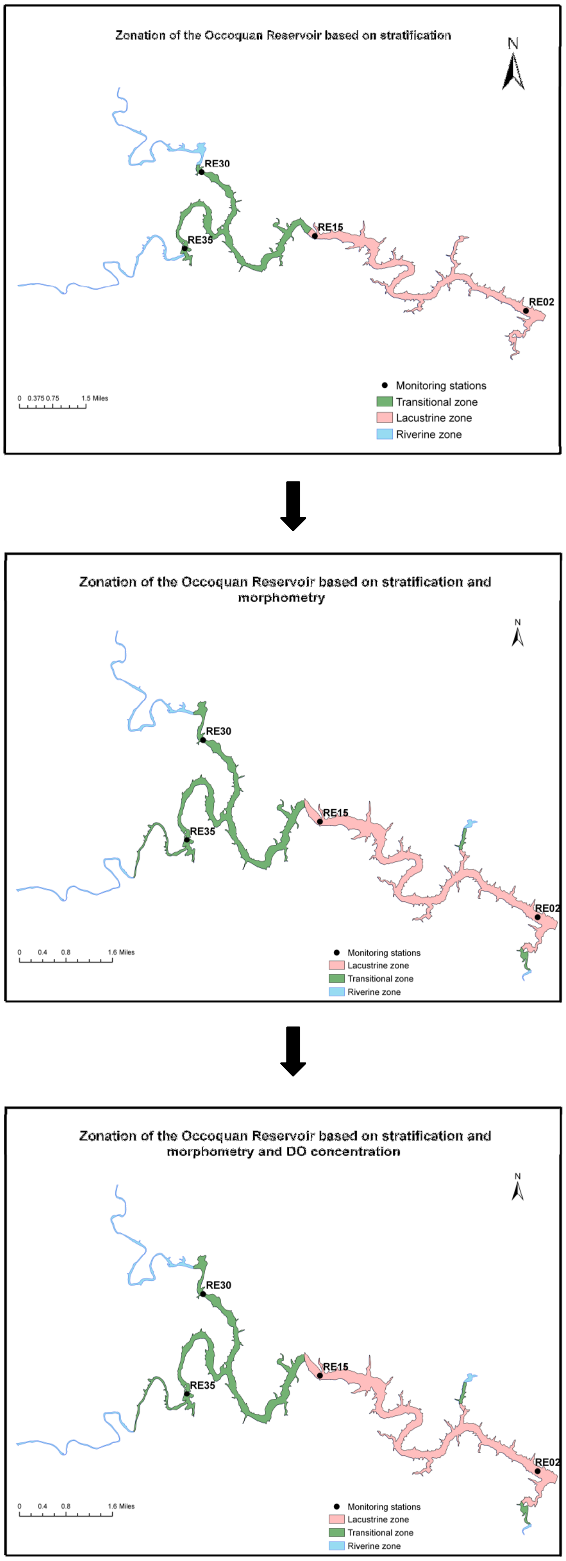


**Figure 92. Process of zonation of the Occoquan Reservoir.**

The table of parameters was successfully applied to the Occoquan Reservoir and adequate identification of the three zones has been made. Evidence from all three parameters considered, support each other. Therefore, it is safe to stop the analysis at this point. There is no need to go further down the table. Figure 93, below, displays the final zonation of the Occoquan Reservoir.

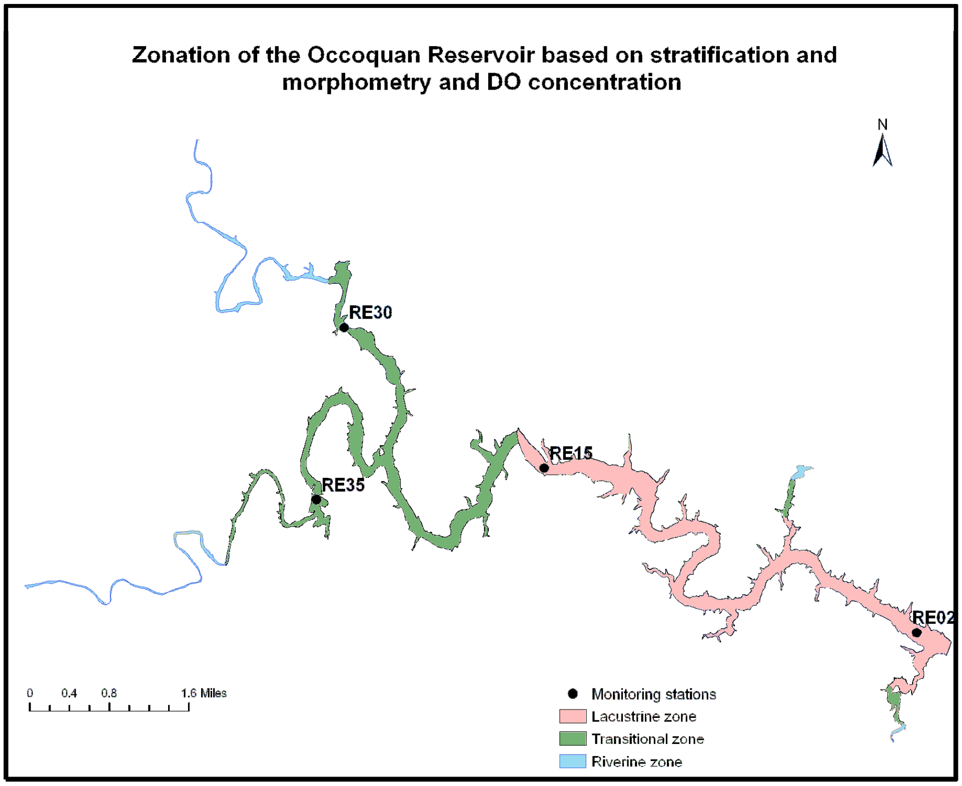


Figure 93. **Final zonation of the Occoquan Reservoir.**

# 5 CONCLUSIONS AND RECOMMENDATIONS

A method was developed for dividing reservoirs into three separate zones, namely riverine, transitional and lacustrine. The method developed was successfully tested on Lake Manassas and the Occoquan Reservoir. The key, for division of any reservoir into three zones is availability of data. As seen from the analyses conducted above, just analysis of the first parameter, ‘stratification’, is sufficient to divide the reservoir roughly into three zones. However, when only one parameter is considered, the demarcation between the different zones is somewhat rough. In the case of Lake Manassas stratification and morphometric data were sufficient to divide the lake into three zones. On the other hand for the Occoquan reservoir, stratification, morphometry and DO concentration analyses were performed to satisfactorily divide the reservoir into three zones. Although the two cases included in this document used 2-3 parameters, there is no limitation to the number of parameters to be considered while making successful zone identification. Good judgment and judicious analysis of data are both key to successful implementation of this method.

Recommendations while using this method are as follows:

**i.** It is recommended that at least two parameters be considered before a final division of any reservoir is proposed. Very often data regarding a particular parameter may be limited. For example in case of the stratification parameter, data are typically available at monitoring stations, while data regarding morphometry typically encompasses the entire lake or reservoir. Analysis of at least two parameters will ensure that zonation is more certain and clear.

**ii.** It is not necessary to exhaust the entire table. In most cases, two or three parameters are sufficient to arrive at a reasonable division. This is a judgment call.

**iii.** Some parameters help in identifying zones, better than the others. Also, some parameters have characteristics about which data can be easily gathered. Those parameters which help in identifying zones better and have easily measurable data associated with them are placed at the top of the table. Therefore, it is recommended that data be analyzed in the order parameters are placed in the table. When data are unavailable for the parameters towards the top of the table, parameters further down the table can be analyzed. The latter situation may require analysis based on more parameters than just two.

**iv.** While analyzing data, it is advisable that the analysis spans several years. Conditions vary from year to year. Availability of data is also an issue. Therefore, it is recommended that at least two years of data must be analyzed before arriving at any conclusion on zonation.

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