ow that we’ve been introduced to some of the basic concepts and terminology related to lake morphometry, we can turn our attention toward a dynamic that is extremely important to lake management and yet often overlooked: wind mixing (a.k.a. water mixing) in lakes.

In the following pages, we’ll explore the influence that wind and waves can have on the movement and/or mixing of water within a lake, as well as the role that lake morphometry plays.

Wind

As any boater soon learns while navigating across open water, there is a strong correlation between wind and waves (i.e., the stronger the wind, the larger the waves). However, aside from wave activity on the surface, there are other types of water movement occurring below the waves that we never see. For instance, underwater currents tend to move water particles horizontally through the water column. At the same time, water particles are also being distributed in an irregular swirling motion known as turbulence. It works like this:

Currents

Winds blowing across the surface of a lake interact with lake water and cause the water to move in a downward direction. The resulting water currents can move across the lake with the wind, or they can move along the shore when the winds approach the shoreline at an angle.

If the wind blows from one direction for a while, it can cause the water to pile up along the downwind shore, so that the water level is actually higher on one side of the lake than another — usually by a fraction of an inch, but sometimes much more in a large lake.

An extreme example of this dynamic was seen in 1928 when hurricane winds piled water upon Lake Okeechobee’s northern shore, causing the city of Lake Okeechobee to flood. As water piled up along the north shore of the lake, waters receded substantially along the southern shoreline. Hours later, when the hurricane force winds changed direction, lake waters then returned to the southern shore and caused massive flooding there as well, resulting in hundreds of deaths. This single event prompted the call for the construction of what is now known as the Hoover Dike.

Under normal conditions however, the difference in water elevation across a lake is minimal — just enough to generate water currents. These currents move water back to the other side of the lake to even out the elevation difference. Sometimes the currents flow along the shore, but often the water flows as a return current below the surface of the lake. Thus the wind may be moving a surface layer of water in one direction and the return current moves a layer of water in the opposite direction. (Anglers sometimes notice that the direction of the current changes as they lower their baited hook down through the water column.)

Turbulence

In most lake currents, the water does not flow smoothly, but rather tends to move in a more
chaotic, irregular manner known as *turbulent flow*. It is like the motion of smoke as it comes out of a large, industrial smokestack. While the dominant movement might be in one direction, the particles within the flow are moving in a series of swirls of different sizes.

The importance of turbulent flow is that it results in the mixing of the water mass. Among other things, turbulent flow keeps plankton (i.e., algae and zooplankton) in suspension, it moves dissolved oxygen from the surface of the lake to deeper waters, it evens out water temperatures in the upper part of the lake, and distributes dissolved substances like plant nutrients throughout the lake.

**Waves**

While water currents tend to move particles in one direction, simple surface waves are rhythmic movements of water particles that in theory end up in the same place that they start. These water particles rotate at the surface in circular orbits, completing one circle in the time that it takes for one wave crest to be replaced by another (i.e., the wave period). The radius of these orbits gets smaller as they move downward in the water column and become negligible at a depth of about one-half the wavelength.

There are other factors that come into play as well. For example, the longer the fetch distance, the greater the wavelengths and wave heights will be. Likewise, the greater the wind speed, the greater the wavelengths and wave heights.

As waves get larger, they are able to exert energy to greater depths, resulting in significant water movements. As a rule-of-thumb, if the water depth is less than one-half the wavelength, waves can potentially have a scouring effect on a lake’s bottom sediments. Lake scientists often refer to this scouring effect as *resuspension*.

**Figure 4-1** Aside from the energy that waves exert on the surface of a lake, there is also a substantial amount of energy exerted below the surface. Notice that the radius of the downward orbits is reduced as one moves downward in the water column. At a depth of about one-half the wavelength distance, the orbits become negligible. A rule-of-thumb: if the water depth is less than one-half the wavelength, the waves have the potential to disturb and resuspend bottom sediments.
Based on the dynamics just described, it is possible to use standard engineering equations to calculate the sizes of surface waves for various combinations of wind speed and fetch. Once the size of a wave is known, one can then use the one-half wavelength rule mentioned earlier to determine the depths at which waves can be expected to disturb or resuspend fine bottom sediments in a lake. We have provided this information for quick reference in the Table 4-1 on page 25.

Note: The possibility for resuspension also depends upon the characteristics of the sediments and the roughness of the bottom. For instance, heavy particles like sand are less likely to be resuspended than are smaller particles like silts and clays.

**Water Mixing**

Scientists are particularly interested in the energy that waves set in motion below the surface because they know that this type of water movement or **water mixing** has the potential to influence one or more of the following processes:

**Oxygen in the water column**

Turbulent water movements that are generated by waves assist the movement of oxygen from the air into the water. In fact, this is one of the main sources of oxygen in lakes. As mentioned earlier, it can help to move oxygen from surface waters to deeper waters. It should be mentioned however, that even with the help of turbulent water movements distributing oxygen from the air, there are times when the respiration of organisms within a lake (i.e., bacteria, macrophytes, and animals) can consume so much oxygen that a fish kill can occur. This is common after several consecutive **calm** cloudy days when the loss of sunlight prevents algae and macrophytes from making their usual contribution of oxygen to the water column, via photosynthesis.

**Water temperature changes**

In shallow lakes, water movements can keep the temperature uniform from the surface of the lake to the bottom. In deep lakes, warm water will float on top of the cold water isolating deeper waters from the atmosphere — its major source of oxygen (i.e., stratification). This can have a detrimental affect on fish by reducing the availability of oxygen, particularly after a sudden thunderstorm.

**Nutrient transport within the water column**

Nutrients are distributed vertically by turbulence in much the same way that oxygen and water temperatures are mixed. This can facilitate the recycling of nutrients from the sediments and deeper waters and, in some instances, result in an increase in biological productivity.

**Disruption of bottom sediments**

Several studies have shown that the resuspension of sediments by wind-driven waves can play a significant role in affecting water quality in large shallow lakes — particularly in Florida where shallow lakes are abundant.

**Water quality problems caused by sediment resuspension**

- Resuspended sediments increase the turbidity of the water and reduce light penetration. This reduces the depth at which algae and aquatic plants can grow in a lake.
- Nutrients stored in bottom sediments are often introduced back into the water column resulting in an increase in the growth of algae. This may or may not be desirable, depending on the intended use of the lake.
- In some shallow lakes, there is a layer of algae that grows on the surface of the sediments. These algae are resuspended along with the sediments during strong wind events and can result in significant increases in the amount of algae in the lake water.
- The resuspension process, along with the effects of the waves themselves, can form a layer of fluid-like sediments on the lake bed that is too unstable to allow for the rooting of aquatic plants. This can prevent the reestablishment of aquatic plants in a lake that previously had plants.
Interaction between lake morphometry and bottom sediments

As we’ve discussed before, wind-driven waves often can cause enough turbulence in shallow waters to resuspend fine sediments. Some of these particles will be suspended in the water column and can move about the lake with water currents. Eventually, they will settle back to the lakebed when the water becomes calm. If they settle in a shallow area with exposure to the wind, they will be resuspended again at some time in the future.

On the other hand, particles settling in deep areas of the lake may be protected from resuspension and will remain undisturbed. In such a lake, the fine particles may go through several cycles of settlement and resuspension but in time they will end up being trapped in the deep holes. As a result, shallower exposed areas will tend to have sediments dominated by larger particles such as sands. Deep areas will contain fine particles like silts, clays, and fragments of dead plants and animals.

In a shallow lake, there may not be a place that can remain undisturbed by water motions developed by surface waves. As a result, fine sediments can cover the entire lakebed and sediment resuspension may be a frequent event.

Aquatic plants and bottom sediments

Large beds of aquatic plants can alter sedimentation patterns in a lake in several ways:

- The plants themselves greatly reduce the amount of turbulence within the plant beds, resulting in an accumulation of fine particles in shallow areas that are dominated by plants. This can happen even though there may be deep areas within the lake.

- Plant beds can interfere with the development of waves in a lake. Thus, shallow lakes filled with plants may not develop large waves and the fine sediments will be protected from resuspension. Such plant-dominated lakes tend to appear clear due to a lack of turbulence that would otherwise keep fine particles and algae in suspension.

The effect that plants can have on a lake is demonstrated effectively when, for one reason or another, a plant-dominated lake loses its aquatic plants. This might happen when plants are removed on purpose with the use of grass carp or herbicides or when they are lost due to increased water levels or ripped up by hurricane-force winds. If any of these events should occur, the usual effect is for the water to become more turbid as wind-driven waves are able to resuspend sediments and algae are able to grow due to lack of competition from large plants and associated algae.
How can we estimate if lake bottom sediments are subject to resuspension?

1 If we want to know if a particular spot in a lake is subject to resuspension, we can use the information provided in Table 4-1.

First, we would use a map to find the fetches in all directions and then find the maximum fetch. Suppose the fetch was 10,000 feet in the north direction. If we look to see the effect of a 10 mile per hour (mph) wind from the north for that fetch in Table 4-1, we see that we might expect mixing to a depth of 6.0 feet. In other words, if the water depth at that point were 6 feet or less and the sediments were of a fine consistency, we might expect some of the sediments to be resuspended. If the wind were say 25 mph, the table shows a mixing depth of about 16 feet.

Note: These calculations assume that there are no beds of aquatic plants along the fetch that might reduce the buildup of waves.

See Fetch on page 19, Table 4-1 on page 25 and Figure 4-1 Anatomy of a Wave on page 21.

2 If we are interested in knowing how often sediments might be disturbed at one particular spot in a lake, we could start by finding the fetches for the four major compass directions.

If we know the depth of the water for that location, we can estimate the minimum wind velocity from each direction that could cause sediments to be disturbed. For example, suppose our location on the lake was six feet deep and the east fetch was 8000 feet. From Table 4-1 we can see that a wind between 10 and 12 mph (11 mph would be pretty close) would produce waves sufficient to disturb the bottom at 6 feet.

Our next step would be to use wind records from a nearby recording station (i.e., an airport) to determine how often we could expect an easterly wind to exceed 11 mph. For example, if an east wind blew 11 mph or more for 2% of the time, then we would expect east winds to disturb the bottom 2% of the time.

We could then make the same calculations for winds from a north, south, and west direction. By adding all of these individual percentages together, we can obtain the per cent of time that we would expect winds to disturb the sediments at that point on the lake.

3 We can compare lakes for their extent of wave disturbance by looking at several points within a lake.

For example, as shown in Figure 4-2 on page 26, we made the above calculations for several points within two Florida lakes.

However, instead of using a table like the one in Table 4-1 we used engineering equations directly to find the minimum velocities. Also, instead of using the four basic wind directions mentioned earlier, we used 36 different wind directions to calculate the per cent of time that we would expect lake sediments to be disturbed by wind-driven waves.

The lakes used for our comparison in Figure 4-2 were chosen because they are so different from one another: one lake being large and shallow (Lake Istokpoga) and the other relatively smaller and deeper (Lake Thonotosassa). Notice that in Lake Istokpoga every single point on the lakebed is frequently disturbed by the waves (i.e., every number is greater than 0). In contrast, Lake Thonotosassa has a large area with no sediment disturbance (i.e., numbers are 0 or less than 1).

4 Another way to make comparisons between lakes is to summarize the calculated percents for all points in a lake.

For instance, we could determine what percent of the points or lake locations were disturbed 90% of the time or more, followed by the percent of points that were disturbed 80% of the time or more, and so on down to the percent of points disturbed 0% of the time or more.

These numbers can then be plotted on a graph, with percent of time on the horizontal axis and percent of the lake area on the vertical axis as we did in Figure 4-3 on page 27.

We can use the same approach to make comparisons of different water levels within an individual lake. For instance, the graph shown
Depth of wave mixing in feet for various fetch distances and wind velocities

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<th>Wind Velocity in Miles Per Hour</th>
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<tr>
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</tr>
</tbody>
</table>

**Table 4-1**

Using the table above, we can quickly determine the depth at which a wave’s energy is felt below the surface based on wind speed and fetch. The table was assembled using the one-half wavelength rule in combination with standard engineering equations to calculate the sizes of surface waves for numerous combinations of wind speed and fetch.

*Note: When evaluating the fetch distances shown here, remember that 1 mile is equivalent to 5,280 feet.*
Figure 4-2 The numbers shown here, within the lake shapes in the bottom portion of the figure, reflect the percentage of time that the lake's bottom sediments are disturbed by wind-driven waves at each of the individual locations. Notice that in Lake Istokpoga (on the right) all the points on the lakebed are frequently disturbed by the waves, while Lake Thonotosassa, a smaller and deeper lake, has a large area with no sediment disturbance.
There is a shortcut method for estimating the impact of wave mixing on a whole lake. First, we divide the square root of the lake area in units of square kilometers, by lake mean depth in meters. The resulting number is called a dynamic ratio and was originally developed by a lake scientist named Lars Håkanson for a different purpose. However, a recent study of Florida lakes found a relationship between the dynamic ratio and the percent of the lakebed that can be disturbed by waves.\(^\text{12}\)

Lakes with dynamic ratios above 0.8 were subject to wave disturbance at all areas of the lakebed at least some of the time.

Notice: This calculation is made on the assumption that there were not significant amounts of aquatic plants in the lake. If plants are present in large quantities, the wind disturbance could be substantially less than this calculation would indicate.

Lakes with dynamic ratio values below 0.8 showed a linear decrease in areas disturbed at one time or another. If for example the ratio were 0.4, only about 50% of the lakebed would be disturbed at one time or another. Here in Figure 4-4 shows the calculated effects that changes in water level might have on Lake Apopka in central Florida.

Notice that changes in lake level are indicated by the numbers in the center of the graph. The “0” curve represents Lake Apopka at its mean lake level and curves to the left of it represent lake level increases in 1-foot increments. Curves to the right of the “0” curve represent lake level decreases in one-foot increments.

The graph clearly illustrates that lowered lake levels can increase the extent of the lakebed that is susceptible to wave action, while increases in water levels can prevent waves from reaching the lakebed in areas where they could under normal lake levels. This is a good example of how important water level changes can be in shallow lakes.

Studies of several Florida lakes indicate that the percent of lake bottom subject to wave disturbance at one time or another ranges from 6% to 100%.

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In closing, we’d like to encourage anyone that is interested in learning more about their lake to take the time to obtain and/or make a bathymetric map of the waterbody. With a map, one can calculate the morphometric parameters discussed in this circular and then use the information as a solid basis for comparison with other lakes. It can also serve as an invaluable tool for developing a lake management plan for your lake or others in your area.

We’d further like to suggest that calculations of wave disturbance frequencies and the dynamic ratio also be considered when working with lakes. These two relatively simple approaches can offer fresh insight into the diagnosis and management of shallow lakes in Florida and elsewhere. As one scientist observes, “This is particularly important in Florida lakes, as it has recently been recognized that there are important differences between how deep lakes and shallow lakes function (Bachmann 2000).”

References and Recommended Readings


