Guidelines for Liming Acidified Lakes and Ponds

Virginia Water Resources Research Center

Virginia Tech

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

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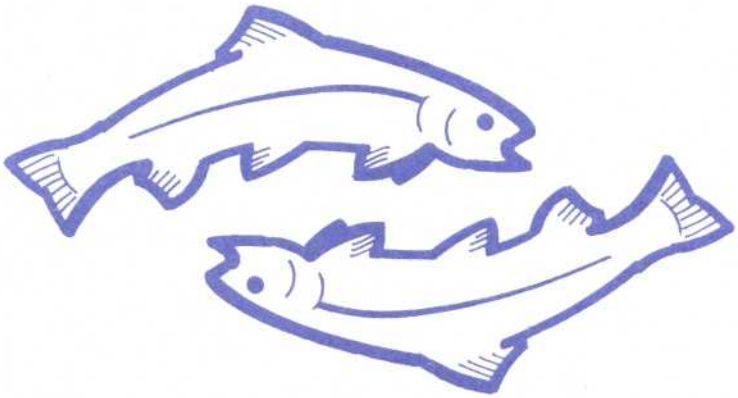

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Guidelines for Liming Acidified Lakes and Ponds

What Is Liming?

"Liming," as the word suggests, is the addition of limestone (calcite), primarily calcium carbonate ($CaCO_3$), to neutralize acid waters and soils and buffer them from rapid fluctuations in pH. Limestone typically is applied to lawns, gardens, pastures, and croplands to supply calcium, an essential plant nutrient, and to decrease soil acidity.

Limestone can also be applied to lakes, ponds, and their surrounding watersheds to protect them from acidification, to add calcium, and to restore their important ecological, economic, and recreational values. Adding limestone to maintain a pH greater than 6.5 keeps lake and pond water safe for aquatic life.

What's in This Publication?

This publication provides information on the protection and restoration of acidic surface waters and their fisheries by adding limestone. Tables in Appendix A give units and conversion factors for length, area, volume, and weight in the English and metric systems, and Appendix B offers one example of a lime dose model used for calculating application rates. After reading this publication you should be able to determine:

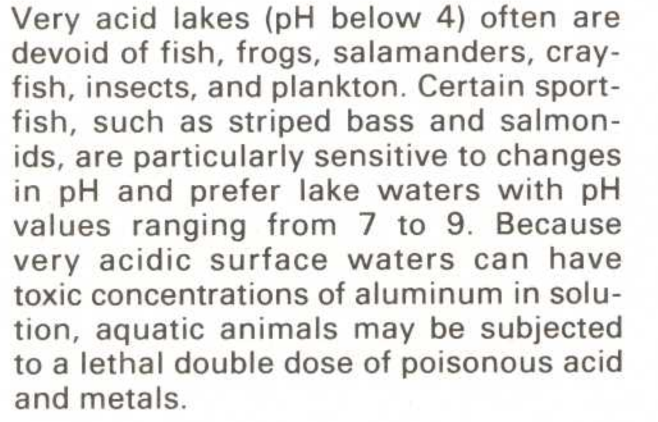
- Whether to treat
- Where to treat
- When to treat
- What limestone to use
- How to apply limestone
- What to expect after application
- How to obtain a permit
- Costs to treat

Why Lime?

Liming is one of the most cost-effective methods of slowing the effects of acidification, restoring acid waters, and enhancing the abundance and diversity of aquatic life. It also reduces the toxic effects of metals, especially aluminum, copper, cadmium, lead, nickel, and zinc, which can threaten both fish and human health.

Very acid lakes (pH below 4) often are devoid of fish, frogs, salamanders, crayfish, insects, and plankton. Certain sportfish, such as striped bass and salmonids, are particularly sensitive to changes in pH and prefer lake waters with pH values ranging from 7 to 9. Because very acidic surface waters can have toxic concentrations of aluminum in solution, aquatic animals may be subjected to a lethal double dose of poisonous acid and metals.

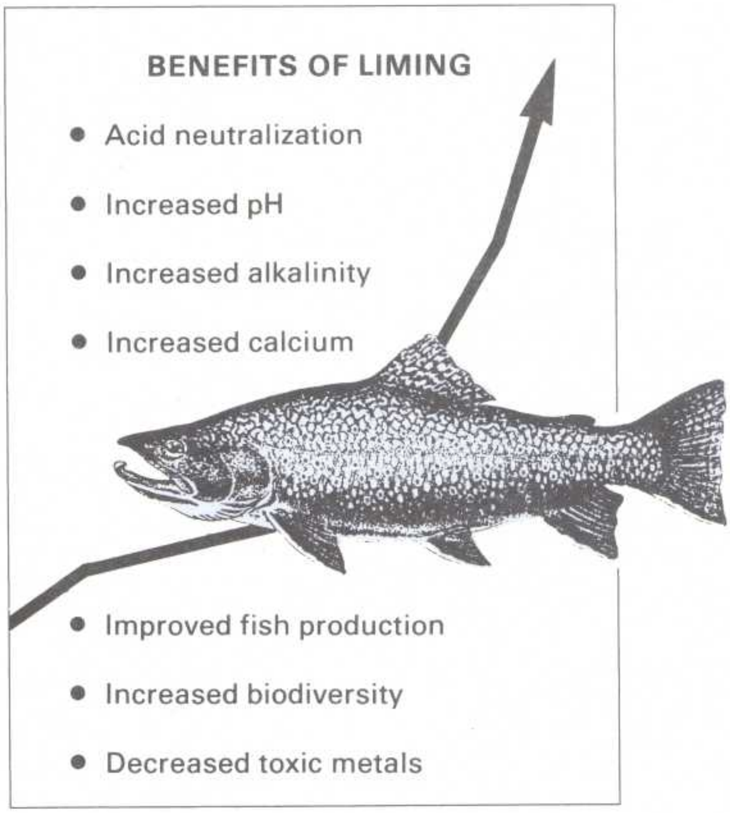
By neutralizing acid waters and reducing toxic dissolved metals, liming improves reproduction and survival of aquatic life and promotes healthy, balanced fish populations. The calcium in lime is used by mussels and crayfish to develop their protective shells and by young and adult fish for bone development and growth.

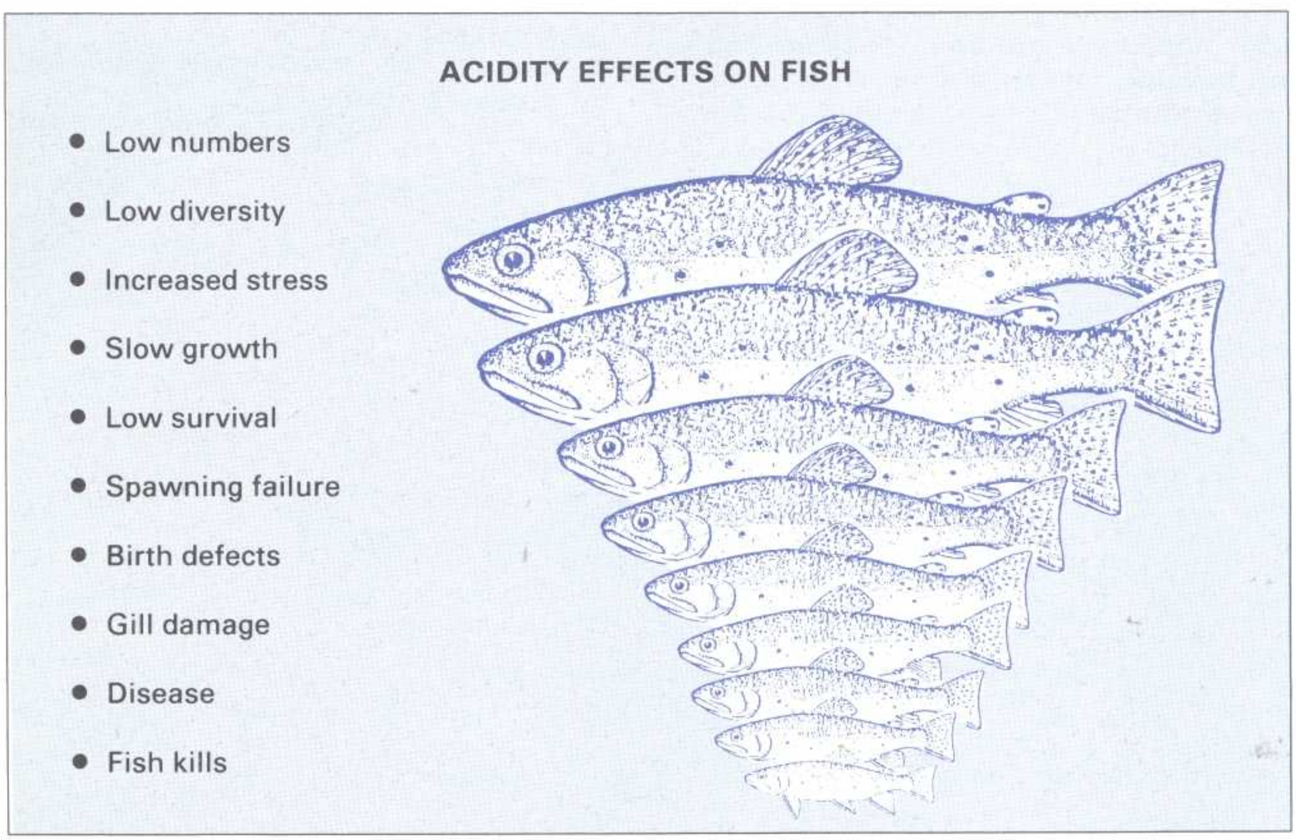


Does Liming Improve Sport Fisheries?

Liming benefits sport fish populations in many ways. Liming improves overall water quality and fish health in acidified lakes and ponds. Fish in acidic waters are stressed, have lower resistance to disease, and grow more slowly to a smaller maximum size than fish in alkaline lakes. High acidity and toxic metals kill fish eggs and larvae and reduce spawning success. Liming can neutralize acidic waters, minimize stress, and detoxify heavy metals.

Liming enriches a lake by adding calcium, an important nutrient, and releasing phosphorus, another important nutrient, from the lake bottom muds. Production of the entire food chain (plankton-insects-fish) is stimulated by liming, and the increased abundance of natural food items support sport fish growth and reproduction. Enhanced growth of rooted aquatic plants that serve as nursery areas for young sport fish can result from liming.





What Are the Considerations Before Liming?

Make sure that acidification is the problem before liming. Symptoms similar to acidification may result from other problems. For example, poor fishing and declining numbers may be caused by overfishing, rather than poor reproduction resulting from acidic water.

Liming alkaline waters is unnecessary; the pH should be tested over an extended period of time to reliably determine the range of pH values. Generally, if the lake is an almost acidic, soft-water system with pH values less than 6.5 (and acid neutralizing capacity less than 50 microequivalents per liter), total alkalinity levels less than 20 milligrams per liter (mg/L), and total hardness concentrations below 25 mg/L, liming may be beneficial.

Test and monitor the water quality; seek the advice of the state fishery agency, a professional biologist, or an experienced environmental consulting firm with fishery expertise; find out which regulations apply and if a legal permit is required; and use the following criteria (affirmative responses) to help decide whether to lime.

A. Evidence of Acidification

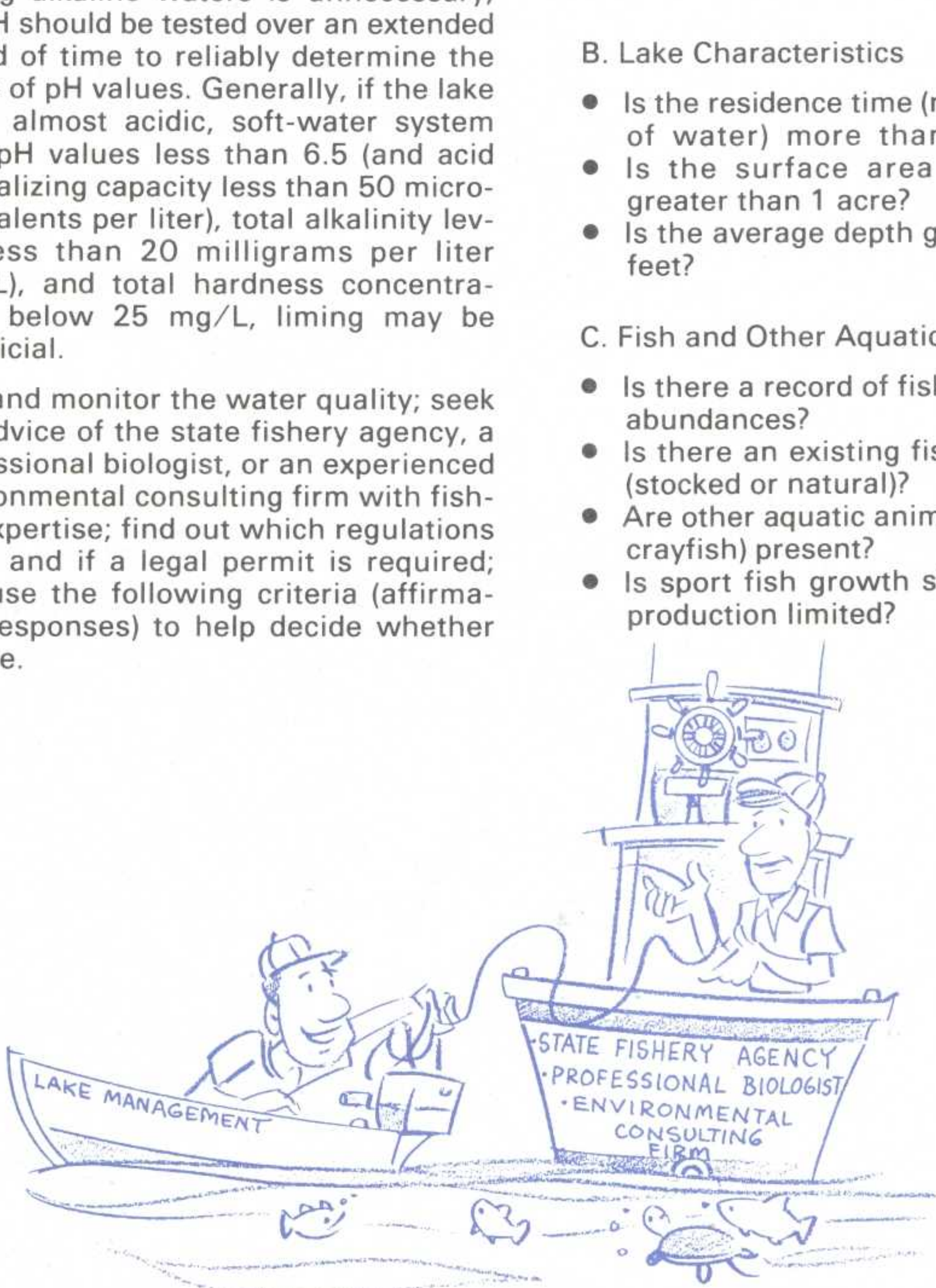
- Is the lake almost acidic (pH below 6.5)?
- Does the daily pH fluctuate widely (over 2 units in 24 hrs)?
- Is this a soft-water lake (alkalinity below 10 mg/L and hardness less than 25 mg/L)?
- Are metal (Al, Zn, Ni, Cu, Cd, Pb) levels increasing?

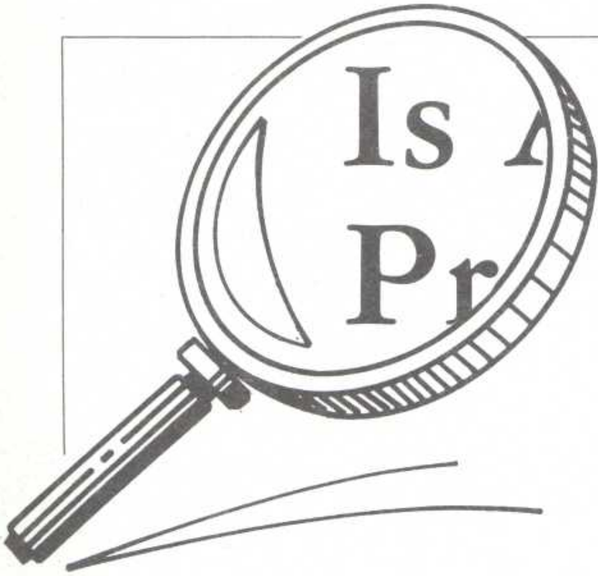
B. Lake Characteristics

- Is the residence time (retention time of water) more than 3 months?
- Is the surface area of the lake greater than 1 acre?
- Is the average depth greater than 8 feet?

C. Fish and Other Aquatic Life

- Is there a record of fish species and abundances?
- Is there an existing fish population (stocked or natural)?
- Are other aquatic animals (mussels, crayfish) present?
- Is sport fish growth slow and food production limited?



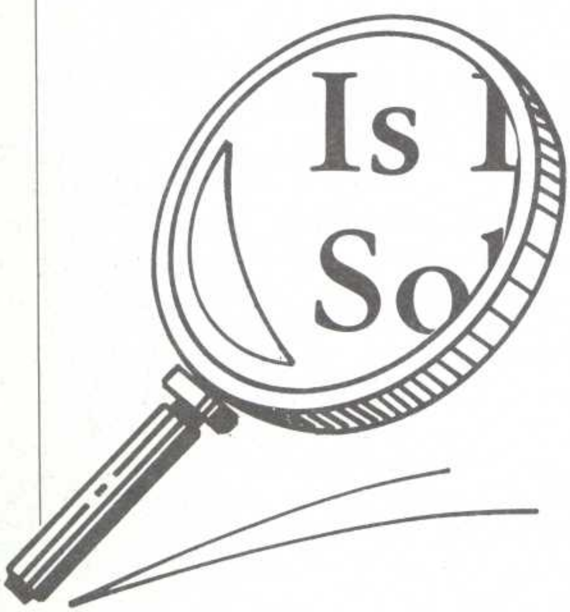


Is Acidification the Problem?

Yes

If:

- Lake pH < 6.5
- Large pH fluctuations daily
- Soft-water lake
- Certain metals increasing

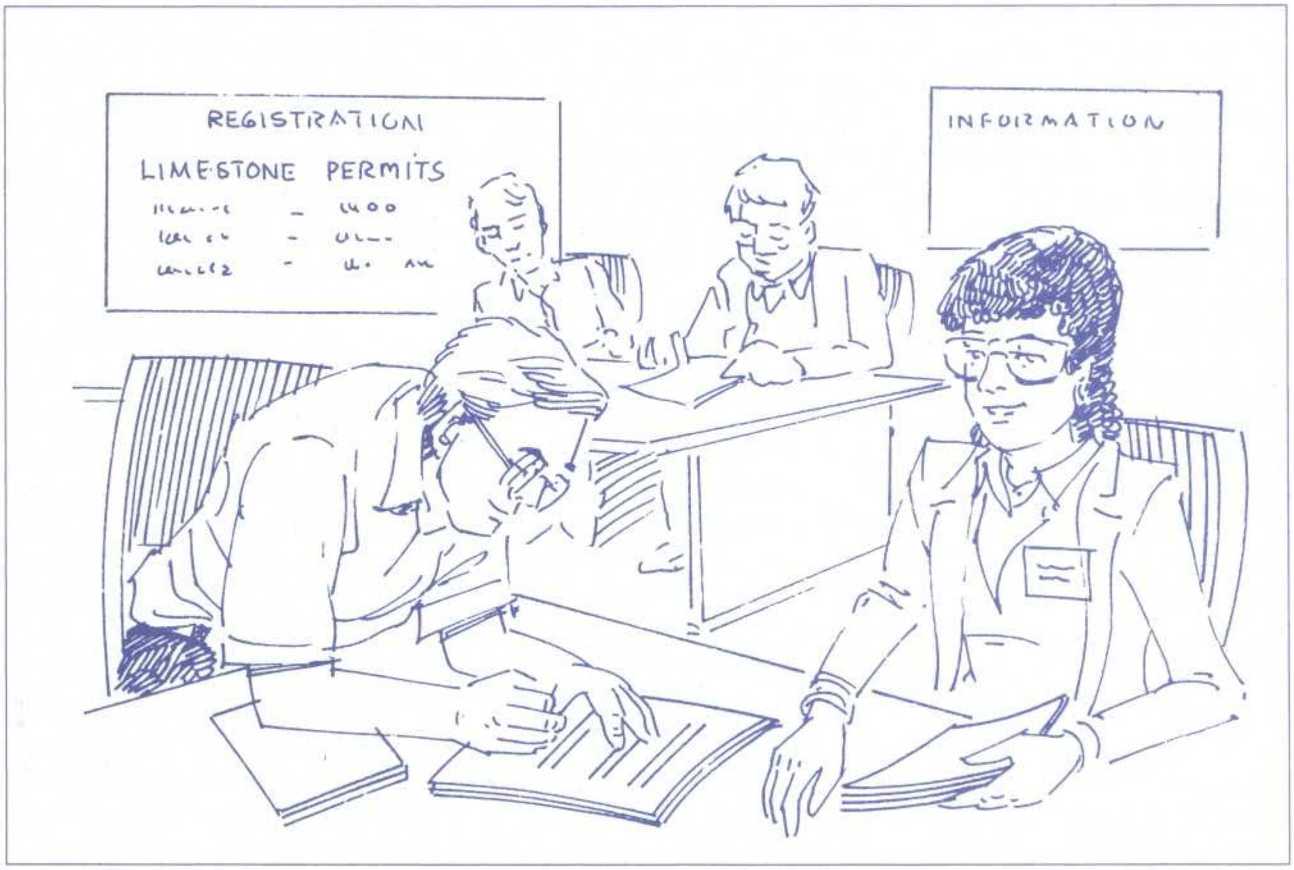


Is Liming a Solution?

Yes

If:

- Retention time > 3 months
- Surface area > 1 acre
- Average depth > 8 feet
- Evidence of historical (existing) fish populations is available
- Slow fish growth and low food production occurs



What About Permits for Liming?

Liming public or private surface waters may require permits from state and federal agencies. Private lake and pond owners may or may not need permits but they are liable for chemically altering downstream waters. Some states such as New York have adopted detailed policies and guidelines for liming surface waters. Others evaluate liming on a site-specific basis.

Permit applications and regulatory information usually are available from state natural resource agencies. Generally, the information required for a permit is similar to that needed for designing and defining the treatment, including (a) the proposed treatment material and application rate and (b) the data specific to that lake on baseline water quality, aquatic plants, and physical and hydrologic characteristics.

Liming may be harmful to naturally acidic wetlands (bogs, swamps, and marshes) and their associated acid-loving plants (sphagnum moss, black spruce, cranberry, leather leaf). Liming wetlands is not recommended, because it can alter water chemistry, thereby permanently changing the plant and animal community and reducing habitat and biodiversity. Some acid-tolerant, wetland plants or animals may be listed as federal or state threatened or endangered species. Detailed environmental assessments may be required in these sensitive ecosystems.

Public notification of the date, time, method of liming, and general precautions for recreational users is recommended on private lakes and typically required on public waters. Because liming may discolor the water temporarily, stimulate short-term algal blooms, and alter the taste and mineral content of drinking water, a preliming public education program is recommended when liming water-supply reservoirs.

What Is pH?

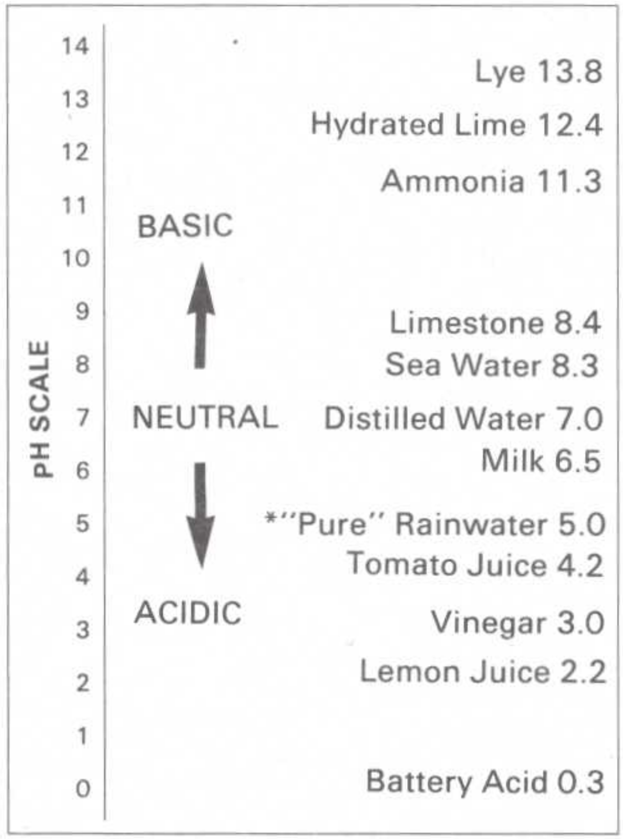
The pH of water is an expression of its acid or base content. The pH scale ranges from 0 (very acidic) to 14 (very basic). For example, battery acid has a pH below 1, and lye has a pH above 13; both are very caustic compounds, harmful to human and aquatic life.

Water with a pH reading of 0 to 6.9 is acidic, that with a pH of 7.1 to 14 is basic (alkaline). Most natural lake waters range from pH 6 to 9 and are slightly basic due to the presence of carbonates and bicarbonates. Fish production generally is higher in alkaline (pH 7.1-9) waters.

What Is Alkalinity?

The alkalinity of water refers to its capacity to neutralize acids or to resist changes in pH. Alkalinity is a measure of the concentrations of three basic ions: carbonates ($CO_3^=$), bicarbonates (HCO_3^-), and hydroxides (OH^-) in water expressed as mg/L equivalents of calcium carbonate. In general, soft waters with low alkalinities (less than 30 mg/L) contain few basic ions, have a low buffering capacity to resist pH fluctuations, and are more susceptible to acidification. Hard waters usually have high alkalinities (greater than 100 mg/L), many basic ions, a high buffering capacity, and are less sensitive to acidification.

Remember — *The pH scale is logarithmic: Each full unit drop in pH represents a tenfold increase in acidity.*



**Rainwater tends to be naturally acid because carbon dioxide in the atmosphere reacts with rain and forms a weak acid (carbonic acid).*

What Is Hardness?

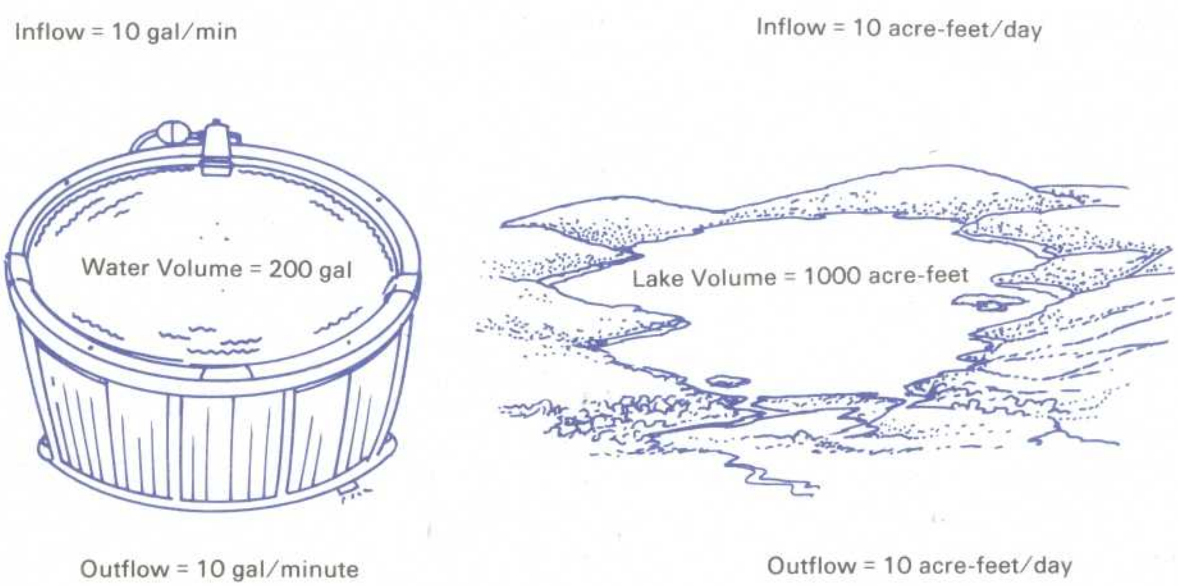
Total hardness of water is a measure of its mineral content, expressed as mg/L equivalents of calcium carbonate. Calcium and magnesium are the primary cause of hardness in natural waters, but other metal ions (Al, Fe, Zn, Mn) also contribute to water hardness. Soft waters (hardness values of less than 100 mg/L) generally have low alkalinities and little calcium and magnesium, and consequently, are susceptible to acidification. Hard waters (hardness greater than 100 mg/L) usually have high calcium and are less prone to acidification.

What Is Residence Time?

The residence time (retention time) is the amount of time required to replace all of the water in the lake. For example, in small lakes (less than ten acres) with a high flushing rate (large inflow and outflow), the residence time may be relatively short, perhaps weeks. Alternatively, in larger lakes with lower flushing rates (small inflow and outflow) the residence time may be much greater, perhaps years. Clearly, liming is more lasting and effective in lakes with a longer residence time.

RESIDENCE OR RETENTION TIME

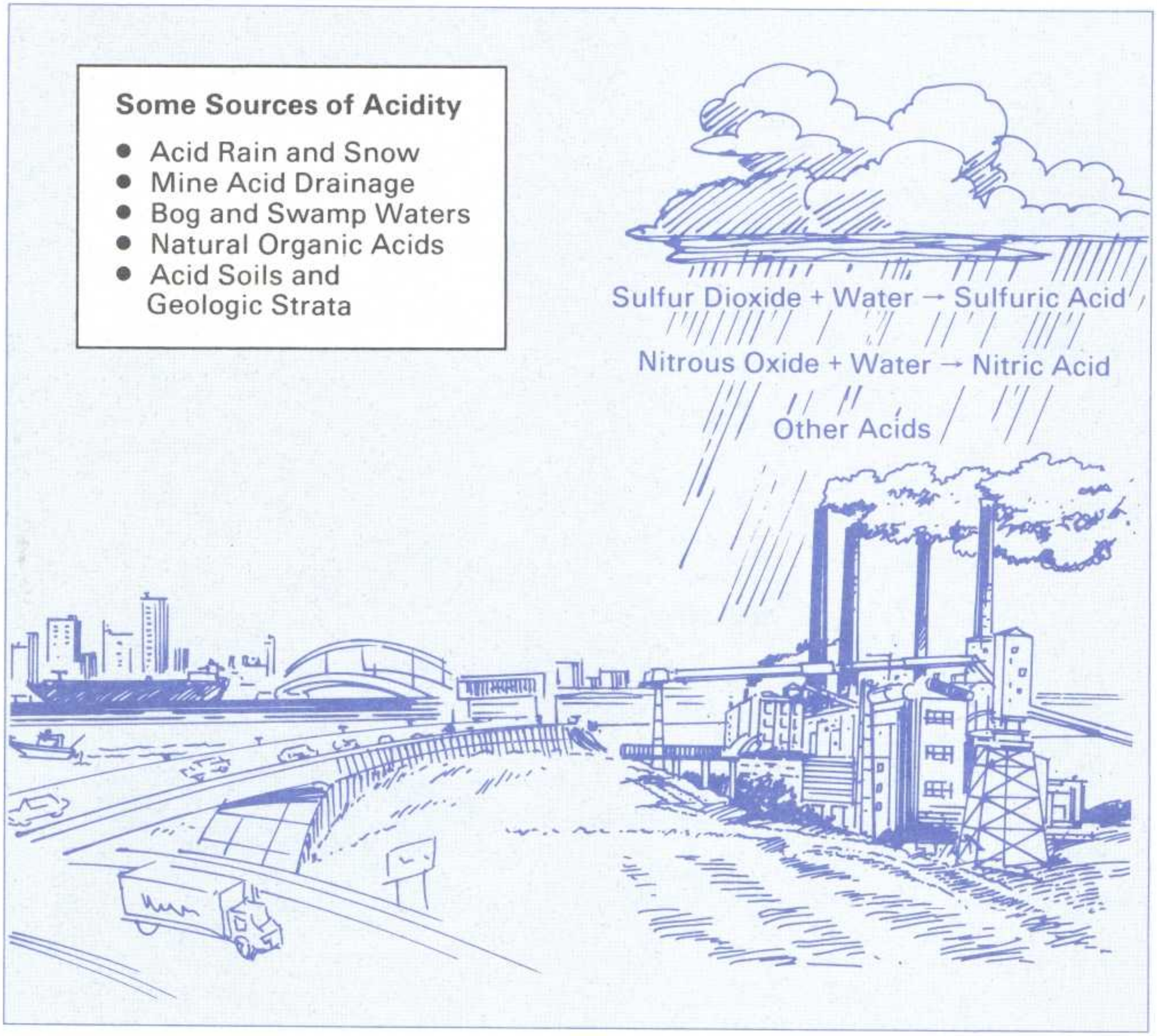
Residence or retention time is the average time required to completely renew a lake's water volume. For example, in a simple situation where inflow equals outflow, it might take 20 minutes to completely fill a hot tub with the tap fully open and the bottom drain closed. The water retention time of the hot tub is 20 minutes. With the tap and drain only half open, the residence time is 40 minutes.



Residence time = Volume ÷ Flow Rate

200 gal ÷ 10 gal/minute = 20 minutes

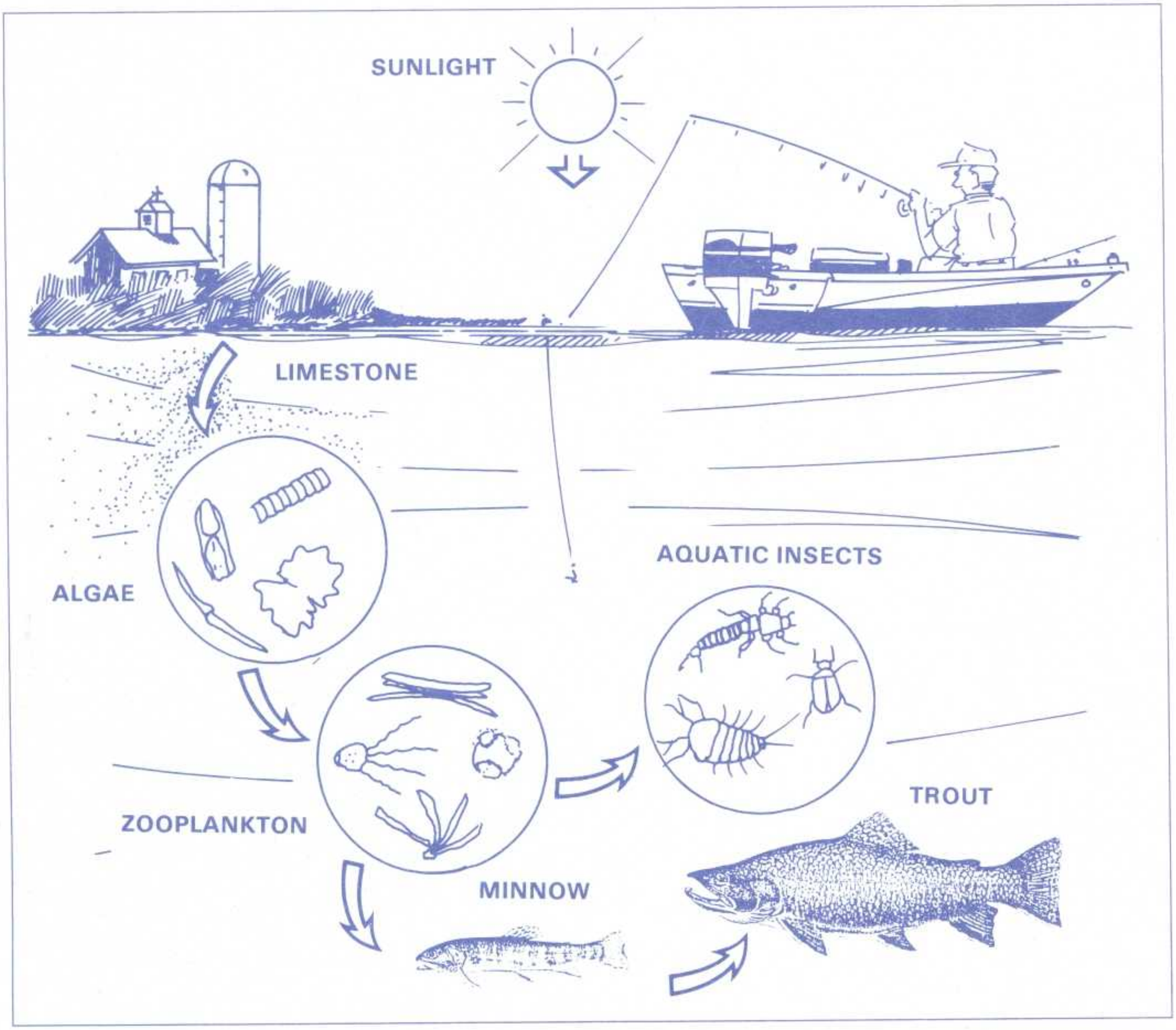
1000 acre-feet ÷ 10 acre-feet/day = 100 days



What Are the Sources of Acidity?

Acidification of lakes and ponds is not always caused by acid deposition. Some bog, swamp, and marsh waters contain high levels of naturally occurring humic and organic acids. In mining areas, especially coal country, acid mine drainage can occur when sulfur-bearing minerals are exposed to air and water. Mine acid runoff water is typically low in pH and has resulted in fish kills and poor water quality in lakes and streams in Pennsylvania, West Virginia, Virginia, and other states where coal mining is common.

Timber cutting and forest regrowth, building and road construction, and other types of land-use modifications can influence the acidity of surface waters. Land use changes can increase or decrease the acidity of lakes by altering the chemistry (acid-base ratios) in the drainage from the watershed. Even the natural weathering of geologic materials containing sulfide minerals such as pyrite can increase the acidity of surface waters.



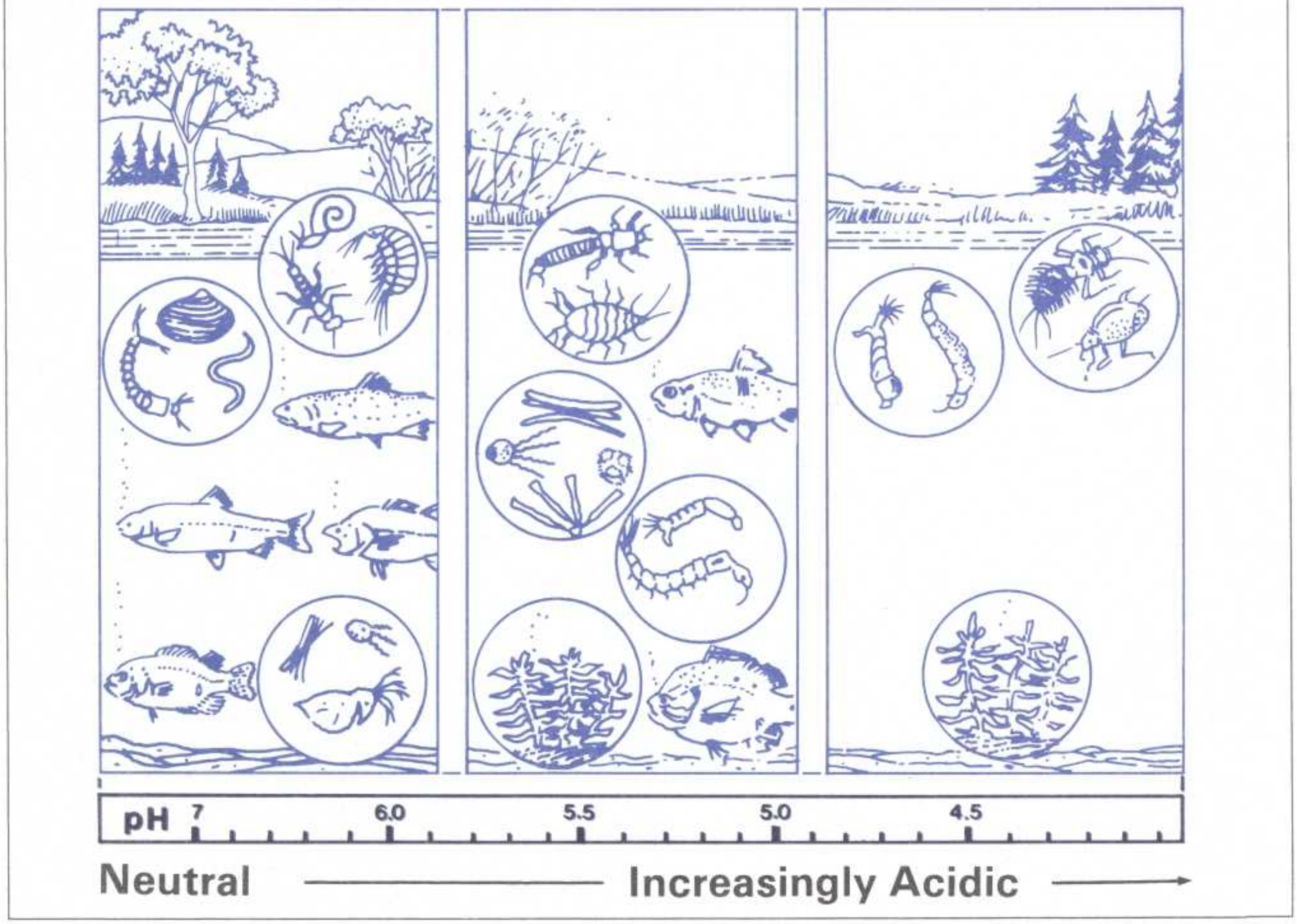
How Does Liming Improve Sport Fishing?

Soft water lakes and ponds seldom support abundant plankton and fish populations. Plankton, the basis of the food chain, is often limited in acidic waters with low alkalinities. Surface waters with low total alkalinities typically are acidic and infertile; few dissolved nutrients are present and most nutrients are unavailable, locked onto acidic bottom muds. Limestone neutralizes acidic bottom mud (increases soil pH) and promotes the release of phosphorus and other limiting nutrients such as carbon, needed for photosynthesis by green plants.

Liming surface waters neutralizes acidity and increases pH, alkalinity, and hardness to levels that encourage plankton and sport fish growth. Liming not only adds calcium, but releases adsorbed elements (phosphorus and carbon) important to the growth and support of aquatic life.

Adding limestone and fertilizer are conventional fisheries management practices for enhancing sport fish production in ponds, even in those waters that are not impacted by acid. These should not be applied simultaneously, since limestone may precipitate phosphorus reducing its availability.

Species Decline

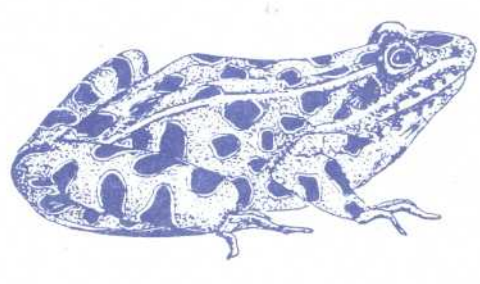


As acidity increases, the diversity of aquatic life declines. Protective liming helps maintain an appropriate pH for aquatic life.

Protective or Mitigative Liming?

Protective (preventative) liming is, as the name implies, used to prevent a lake or pond from becoming acidic by fortifying the water's alkalinity (buffering capacity). Susceptible soft-water lakes and ponds that have little buffering capacity and are located in areas receiving strong acid deposition are good targets for protective liming. This type of liming may require only periodic additions of limestone to the surface waters or the surrounding watershed. It is generally more cost-effective to prevent a lake from becoming acidic than to restore an acidified one.

Acidified lakes and ponds can be restored by mitigative liming. The objective of mitigative liming is to restore and protect water quality and promote the recovery of aquatic life in acidified lakes and ponds. Applications of limestone on a sustained basis and the use of other fisheries management techniques, such as stocking, may be required to promote full recovery of lake resources.



What Type of Limestone Should Be Applied?

Finely ground (pulverized) agricultural limestone (calcite, calcium carbonate) is recommended for liming lakes and ponds. Agricultural limestone (aglime) is a relatively inexpensive, widely available, easy to handle, natural and nontoxic compound, that dissolves (although not readily) in water. Aglime can be purchased in many particle sizes ranging from fine dust to rock. Fine limestone particles (less than 0.0098 inches or 0.025 cm) that will dissolve rapidly are preferred over coarser materials.

Try to obtain high-quality, contaminant-free ($<$5% of magnesium) and nutrient-free (low nitrates and phosphates) agricultural lime. Dolomitic limestone with high levels (5%) of magnesium carbonate ($MgCO_3$) may result in poor dissolution and neutralization. However, dolomitic limestone may be the only neutralizing material readily available in your locality and is an acceptable alternative to aglime.

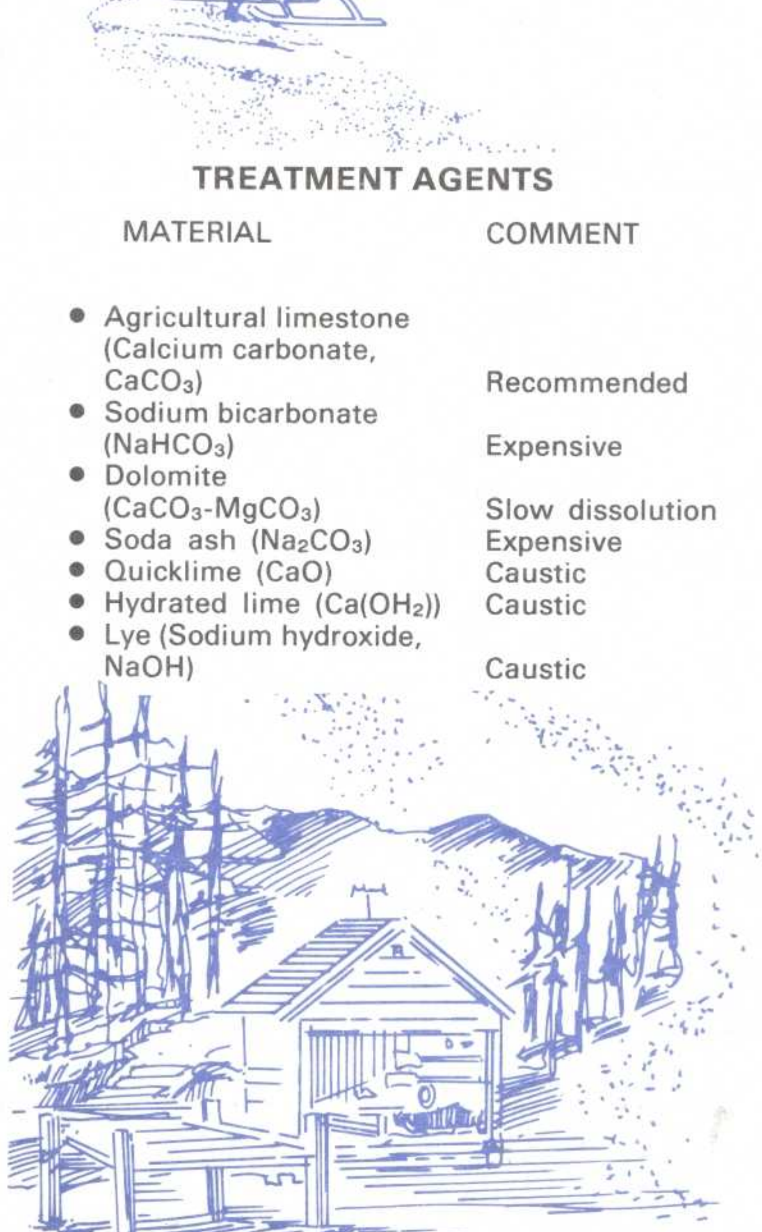
The calcium content of the limestone relates directly to its capacity to neutralize acidity. Calcium contentshould be at least 70% and preferably 90-100% $CaCO_3$ by weight.

The acid neutralizing value of limestone is critical to determining how much acid can be neutralized and the limestone dosage required. Pure calcium carbonate has an acid neutralizing capacity of 100% and aglime ranges from 85-100%. To calculate the amount of limestone needed, simply divide the estimated lime requirement by its neutralizing value (%).

For example, if 2 tons per surface acre of water is the estimated limestone requirement, and the limestone to be applied is only 85% pure, then 2.4 tons of limestone per surface acre (2 tons divided by 0.85 = 2.4 tons per acre) must be applied. In contrast, because of their higher acid neutralizing capacities, less hydrated lime or slaked lime (136% acid neutralizing capacity) and quicklime or burned lime (179% acid neutralizing capacity) would be required.

TREATMENT AGENTS

MATERIAL	COMMENT
• Agricultural limestone (Calcium carbonate, $CaCO_3$)	Recommended
• Sodium bicarbonate ($NaHCO_3$)	Expensive
• Dolomite ($CaCO_3$-$MgCO_3$)	Slow dissolution
• Soda ash (Na_2CO_3)	Expensive
• Quicklime (CaO)	Caustic
• Hydrated lime ($Ca(OH_2)$)	Caustic
• Lye (Sodium hydroxide, $NaOH$)	Caustic



However, hydrated lime (calcium hydroxide, $Ca(OH)_2$) and quicklime (calcium oxide, CaO) generally are not recommended for treating surface waters, since they are corrosive, difficult to control, and may not be legal to apply. Hydrated lime and quicklime have been used for acid neutralization because less is needed (they have higher neutralizing values than pure limestone), but both are caustic.

Hydrated lime applications can kill fish at rates in excess of 50 pounds per surface acre. In fact, hydrated lime and quicklime are often used to disinfect ponds from fish parasites and to sterilize ponds prior to stocking fish. Hydrated lime contains about 54% calcium and quicklime contains about 71% calcium. Agricultural gypsum (calcium sulfate, $CaSO_4 \bullet 2H_2O$) is not a liming material.

Soda ash or sodium carbonate (Na_2CO_3) has been used infrequently to neutralize acidified surface waters. It has also been injected into lake sediments on an experimental basis. However, soda ash is three to five times more expensive than limestone and does not contribute beneficial calcium ions.

ADVANTAGES OF LIME

- Inexpensive
- Available
- Non-toxic
- Natural Mineral
- Easy to distribute
- Dissolves in water

How Much Limestone Should Be Used?

The typical application rate for acidic waters is 1-2 tons of agricultural limestone ($CaCO_3$) per surface acre for the initial liming. If necessary, consultants can use computer models or small-scale laboratory tests to estimate limestone dosage rates for lake owners.

In Appendix B is an example of a lime dose model that requires data on lake pH prior to liming, lake retention time, lake volume, average limestone particle size, and calcium content of the limestone to calculate the required dose in tonnes. In practice, however, it may be simpler to add about 1 ton per acre and monitor the changes in pH and alkalinity after treatment.

Relatively inexpensive chemical test kits are available to measure pH and alkalinity levels. In most states, the Cooperative Extension Service and the Soil Conservation Service can provide information on soil acidity. These organizations provide a soil testing service for agricultural lands that also can be used to test lake waters and bottom soils.

Calculating exactly how much limestone to add to neutralize an acidic lake is complicated by many factors, including

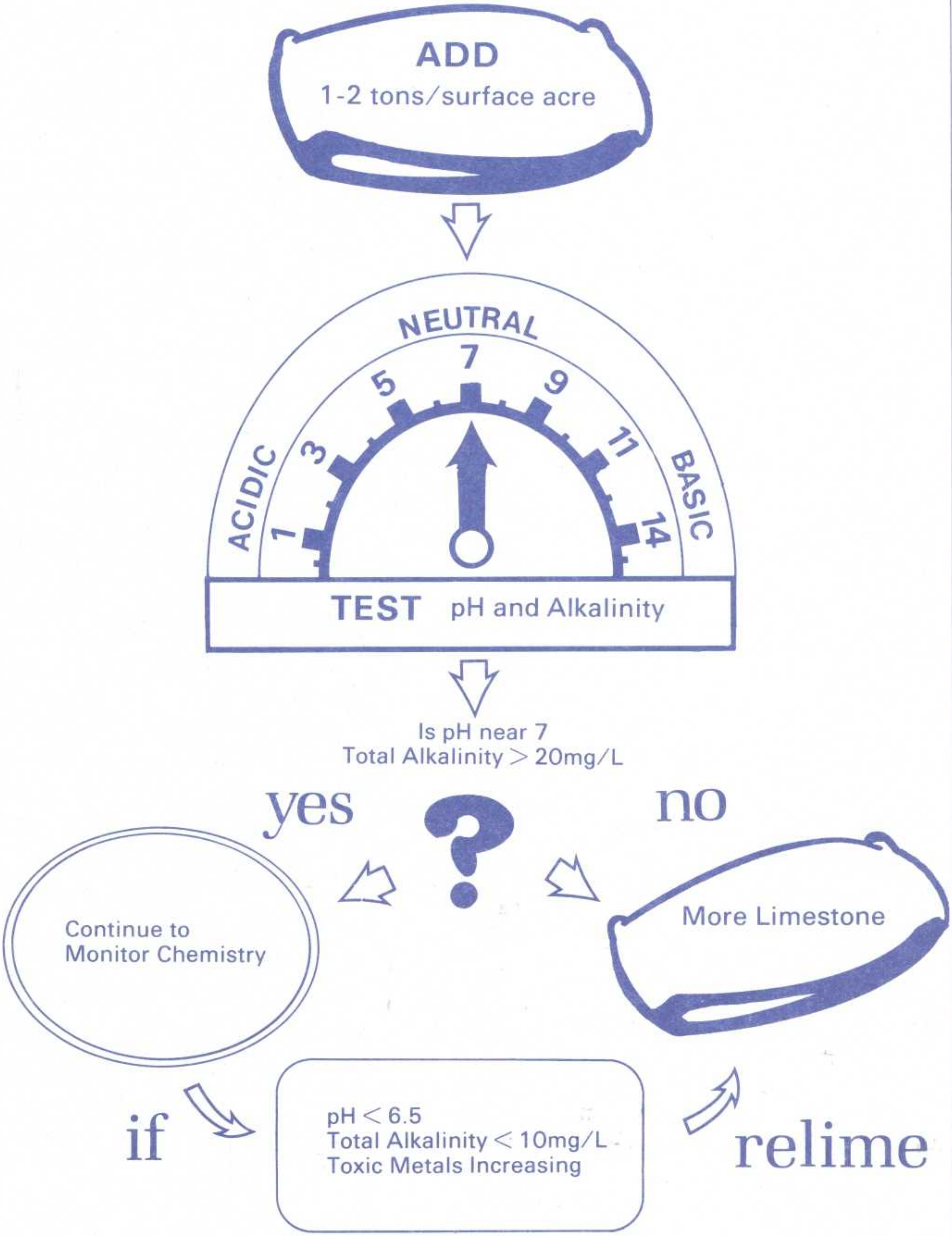
- existing pH, alkalinity, and hardness
- acidity and chemistry of lake bottom mud
- water quality and temperature
- desired pH and target water quality
- density and types of aquatic plants
- type, purity, and particle size of the limestone
- lake volume and flushing rate

Is Reliming Necessary?

One treatment may be sufficient if the lake is small, has a slow flushing rate, and is not very acidic. However, additional treatments may be needed for very acidic lakes or those with fast flushing times that may be quickly reacidified.

HOW MUCH LIMESTONE?

Simplest Model



The pH and alkalinity of waters should be monitored, especially during the summer, by taking surface samples on a weekly basis and at the same time each day. Inexpensive test kits that use color changes as indicators are useful for pH and alkalinity estimates. If the pH and total alkalinity of the lake water are low a month after the initial liming, the treatment should be repeated.

The addition of 500-3,000 pounds of limestone per surface acre should be sufficient to neutralize most lakes, but those with very acidic soils, low alkalinities, high concentrations of organic matter, and quick flushing rates may require greater dosages and more frequent treatments. Direct injection of treatment material into the lake sediments has been used in a few lakes, and this method may help prolong neutralization of overlying waters.

Reliming should occur whenever pH values drop below 6.5, total alkalinities drop below 10 mg/L, and toxic metal concentrations increase. Maintaining the pH near neutral (pH 7) and total alkalinities above 20 mg/L will minimize stress to fish and prevent the bioaccumulation of toxic metals, such as mercury, in fish tissue.

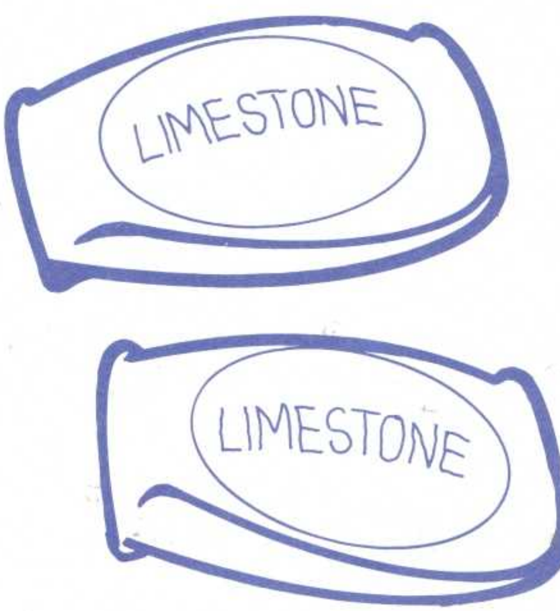
Overliming or applying an excess of the required dosage during the first treatment is generally ineffective and expensive. Generally, the extra limestone is deactivated through time by algae and organic material and does not continue to treat the water. However, in shallow, rocky wind- and wave-swept zones of lakes, limestone may continue to dissolve over a longer time. As a rule, several liming treatments through time are better than one overdose.

Bagged or Bulk Limestone?

Limestone can be purchased in bulk (truckloads) or in bags (50 pound bags) and can be applied as a dry powder or mixed with water as a wet slurry. A well-mixed slurry of lake water and fine-sized particles of limestone is more soluble than a dry powder.

Buy the smallest particle size of limestone available that is cost effective. The smaller the particle size, the better the rate of solution. Large limestone particles dissolve slowly. Finer limestone is more costly per unit of weight, but it generally is more cost-effective because greater amounts go into solution. Pulverized limestone particles that pass through a 200-mesh screen and are about 15-20 microns (0.00059-0.000079 inches) in size are ideal for liming lakes.

Generally, it is easier to handle, transport, and distribute bagged limestone. Volunteers can more easily lift and load bags of limestone from the shoreline staging area (boat dock) onto boats and barges for distribution. Stockpile limestone near the dock area to minimize handling time. Cover bagged limestone with plastic for rain protection if the application period is prolonged. Bulk limestone is much cheaper to buy, but requires special equipment to transport, unload, and distribute quickly and evenly.



APPLICATION METHODS

- Boat or barge
- Surface ice (snowmobile)
- Shoreland (tractor)
- Feeder stream
- Air (helicopter, plane)

How Is the Limestone Applied?

Limestone can be applied to lakes and ponds using four primary methods: (1) broadcast by boat, (2) piled on winter ice, (3) spread by air, and (4) distributed on the watershed or in tributary streams. Each of these has distinct advantages and disadvantages depending on location, access, size, amount of funding, available labor, and water quality.

Application from a boat or barge is the most popular way to treat lakes and ponds. Shoveling limestone into the wake (prop wash) of a moving powerboat is a simple and cheap distribution method. Flushing limestone from a moving barge platform with a high pressure water hose is an alternative broadcast method that promotes dissolution of the limestone.

Using an on-board slurry box to mix the limestone and water solution before pumping the mixture into the lake helps ensure better solution and circulation. Applying limestone as a wet slurry increases its dissolution efficiency by 25% when compared to its application as a dry dust on the water or on surface ice in winter.

The efficiency of boat applications is limited by the carrying capacity of the boat. Use of a large boat or barge to directly distribute or to transport the material from a staging area to a target area is less costly and more efficient than using small boats. A 300-acre lake can be treated in two to four days by a large barge (5-ton capacity).

Spreading limestone by snowmobile, tractor/spreader, or truck directly on ice-covered lakes is a relatively easy and economical method to use in the northern U.S. where surface ice is prevalent in winter and thick enough to support heavy, loaded vehicles. At spring ice-melt, the limestone dissolves with the surface ice and is evenly distributed into the lake waters. Sometimes heavy spring rains and snow melts flush a lake and reduce the effectiveness of liming.

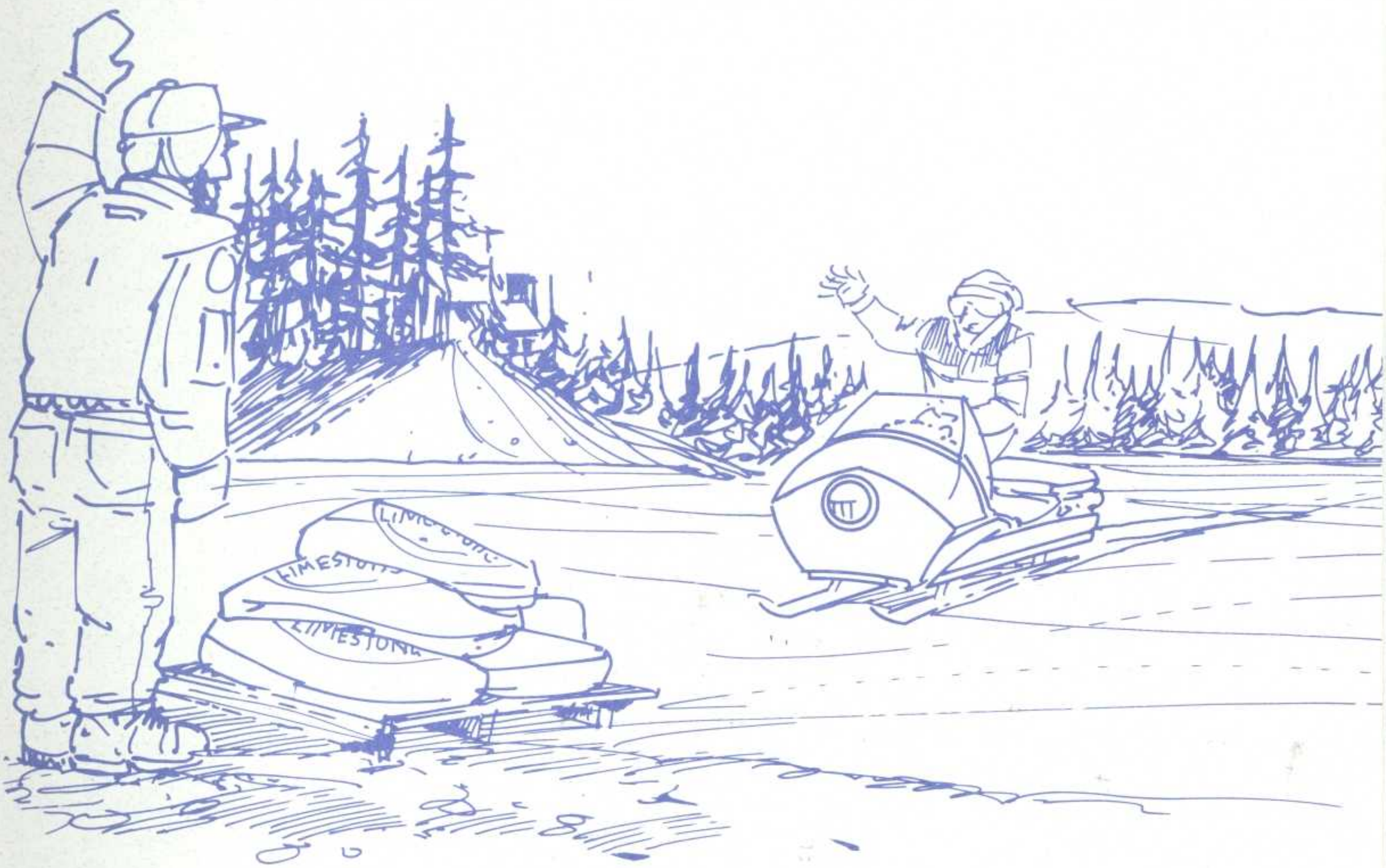
Limestone applied by helicopter, truck, or hand to the lake watershed (lawns, fields, and forests) will eventually wash into the lake. Rather than broad-scale application across the surface of the watershed, treatment should be restricted to water pathways such as wetlands, headwater springs, tributaries, and other sources of water discharge.

Generally, watershed treatment is much more expensive than direct lake application in cases where both are biologically feasible. The average cost of direct lake application is only about 20% of the cost of one average watershed treatment. However, watershed treatment may provide sustained neutralization and reduce the movement of aluminum from soils into the lake.

Watershed liming has been effective on small lakes with small tributaries, and in those systems where target species spawn in feeder streams. Reliable, easily implemented procedures for treating watersheds are not yet widely available in the U.S.

Limestone application by aircraft may be necessary on very large or remote lakes where road access and ground transportation are not available. However, this technique generally is unnecessary and very expensive (often four times the cost of boat delivery methods).

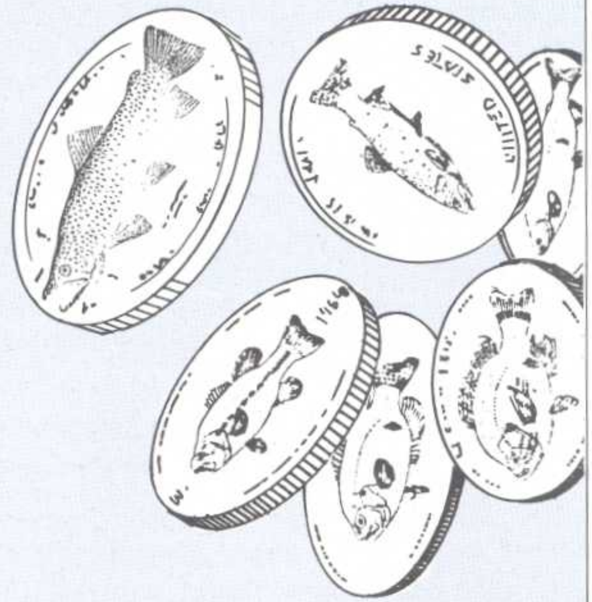
Limestone should be spread over (blanketing) the entire lake surface. Areas of deep water have greater volumes and will require proportionally greater amounts of limestone. Consult a hydrographic (depth) map to determine dosage rates and limestone placement within the lake.



ESTIMATED COST OF LAKE LIMING
(Includes Materials and Application)

DISTRIBUTION	$/SURFACE ACRE	$/TON
Boat or Barge	20-141	45-320
Truck or Tractor	30-242	68-544
Airplane or Helicopter	80-263	181-590

Costs vary with labor charges, accessibility of lake, etc. Modified from Brocksen et al. 1992.



What Will It Cost?

Generally, liming is a relatively inexpensive lake restoration technique and the material itself is the cheapest component. Agricultural limestone costs, for example, range from $10-50 per ton, depending on the quantity needed and the available supply. Bulk purchases are cheaper than bagged limestone, and finely ground limestone is more expensive than coarse limestone.

Much of the total cost of liming a lake or pond is attributed to transport, labor, and the application equipment. Of course, the more acidic the lake, the greater the amount of limestone required and the greater the cost of treatment. Moreover, complete restoration to the original pH and the maintenance of self-reproducing (rather than stocked) fish populations may require repeated treatments.

Annual treatments are more expensive than a single treatment, but the costs can be spread over many years. Annual treatments allow smaller dosages than the recommended rate of 1-2 tons/acre to be applied. For example, after the initial dose, smaller doses, usually 25% of the initial application rate, can applied over four years.

When Should Lakes and Ponds Be Limed?

Lakes and ponds can be limed at any season of the year, but fall turnover (the time of complete water circulation, top to bottom; the end of thermal stratification) in October or November generally is recommended. If the limestone is to be applied on surface ice, then January or February are the optimal months. Fall and winter liming will buffer the lake from extreme acid inflows that frequently occur in the March and April at ice melt and high spring rains.

Liming during the summer months may disrupt recreational activities and temporarily diminish water clarity, resulting in public inconvenience and displeasure. Additionally, the limestone may not be evenly mixed throughout the water column in a stratified lake during the summer.

What Are the Effects of Liming?

Short-term effects of liming may include increased cloudiness or turbidity and reduced water clarity resulting from suspension of the limestone particles in the water column, and a gradual increase in aquatic plant production as more phosphorous is released from the bottom muds. Lake property owners and recreational users should be notified of the dates of liming treatments and informed of these short-term consequences through posters and newsletters.

The immediate effects of liming on fish populations and aquatic life usually are slow and subtle. If an adequate number of adult spawning fish remain in an acidified lake, natural reproductive success may restore the fish populations. Liming improves the survival of fish eggs and developing embryos, which are particularly sensitive to acidification. By stimulating the growth of plankton populations, liming provides prey items for young sport and forage fish.

Liming has been successfully used for over a century to enable acidified and naturally acidic surface waters to support more productive fisheries. The objectives of protection and restoration of recreational fisheries can be achieved with a higher degree of certainty and rapidity by liming than by relying solely on emission controls—limiting the release of sulfur dioxide (SO_2) and nitrogen oxides (NO_x). Even when emission controls are in place, liming achieves short-term fishery improvements until the controls are effective in reversing acidification processes in surface waters.

RESTORE LAKE AND POND VALUES

- Water Supply
- Lakeshore Real Estate
- Swimming & Boating
- Fish & Wildlife Habitat
- Scenic Beauty
- Crop Irrigation
- Livestock Watering

HELPFUL REFERENCES

Brocksen, R. W., M. D. Marcus, and H. Olem. 1992. *Practical Guide to Managing Acidic Surface Waters and Their Fisheries.* Lewis Publishers, Chelsea, MI.

Gloss, S. P., C. L. Schofield, and M. D. Marcus. 1989. Liming and Fisheries Management Guidelines for Acidified Lakes in the Adirondack Region. Rep 80(40.27). U.S. Fish and Wildlife Service, Kearneysville, WV.

Olem, H. 1991. *Liming Acidic Surface Waters.* Lewis Publishers, Chelsea, MI.

Olem, H., R. Kent Schreider, R.W. Brocksen, and D.B. Porcella. 1991. *International Lake and Watershed Liming Practices.* Terrene Institute, Washington, D.C.

Weigmann, D.L., L.A. Helfrich, and D.M. Downey. 1993. *Guidelines for Liming Acidified Streams and Rivers.* Virginia Water Resources Research Center, Virginia Tech, Blacksburg, VA.

The U.S. National Acid Precipitation Assessment Program: 1990 Integrated Assessment Report. 1991. The NAPAP Office of the Director, 722 Jackson Place, NW, Washington, D.C.

Appendix A. Units and Conversion Factors of Length, Area, Volume and Weight

Length, meter, m

1 inch, in = 25.4 mm = 0.0254 m
1 foot, ft = 12 in = 304.8 mm = 0.3048 m
1 yard, yd = 36 in = 0.9144 m
1 mile = 1760 yd = 1.60934 km

Area, m^2

1 in^2 = 6.4516 cm^2 = 6.4516×10^{-4} m^2
1 ft^2 = 929.0304 cm^2 = 9.290304×10^{-2} m^2
1 yd^2 = 8361.2736 cm^2 = 0.83612736 m^2
1 acre = 4046.86 m^2 = 0.40486 ha

Volume, m^3 (1 liter = 1 dm^3 = 10^{-3} m^3 and 1.0 ml = 1 cm^3)

1 in^3 = 16.3871 cm^3 = 1.63871×10^{-5} m^3
1 ft^3 = 28.3168 dm^3 = 0.0283168 m^3
1 gallon (US), US gal = 3.78541 dm^3 = 3.78541×10^{-3} m^3

Mass, kg

1 ounce (av), oz = 28.3495 g = 0.0283495 kg
1 ounce (US), fluid, fl oz = 29.57 cm^3
1 pound, lb = 453.59239 g = 0.45359239 kg
1 quarter (UK, long) = 12.7006 kg
1 hundred weight (long), cwt = 50.8023 kg
1 ton (long), = 1016.05 kg

	Multiplying factors	
	to kg/m^2	from kg/m^2
mt/ha (metric tons or tonnes)	0.1000	10.00
mt/acre (metric tons)	0.2471	4.047
lt/acre (long or British (UK) tons)	0.2511	3.983
st/acre (short or United States (US) tons)	0.2242	4.460
lb/yd^2	0.5429	1.842

Pounds per acre are best converted to short tons by dividing by 2000.

Appendix A. Units and Conversion Factors for Length (continued)

To Convert Units in the Top Line into Those in the Left Hand Column,
Multiply by the Appropriate Tabled Value
(Move Down from the Top Line and Across from the Left Hand Column)

	Angstroms	Nanometers (millimicrons)	Micrometers (microns)	Millimeters	Centimeters	Kilometers	Meters	Inches	Feet	Miles
Angstroms	1	10	10^{4}	10^{7}	10^{8}	10^{13}	10^{10}	2.540×10^{8}	3.048×10^{9}	1.609×10^{13}
Nanometers (millimicrons)	10^{-1}	1	10^{3}	10^{6}	10^{7}	10^{12}	10^{9}	2.540×10^{7}	3.048×10^{8}	1.609×10^{12}
Micrometers (microns)	10^{-4}	10^{-3}	1	10^{3}	10^{4}	10^{9}	10^{6}	2.540×10^{4}	3.048×10^{5}	1.609×10^{9}
Millimeters	10^{-7}	10^{-6}	10^{-3}	1	10	10^{6}	10^{3}	2.540×10	3.048×10^{2}	1.609×10^{6}
Centimeters	10^{-8}	10^{-7}	10^{-4}	0.1	1	10^{5}	10^{2}	2.540	3.048×10	1.609×10^{5}
Kilometers	10^{-13}	10^{-12}	10^{-9}	10^{-6}	10^{-5}	1	10^{3}	2.540×10^{-5}	3.048×10^{-4}	1.609
Meters	10^{-10}	10^{-9}	10^{-6}	10^{-3}	10^{-2}	10^{3}	1	2.540×10^{-2}	3.048×10^{-1}	1.609×10^{3}
Inches	3.937×10^{-9}	3.937×10^{-8}	3.937×10^{-5}	3.937×10^{-2}	3.937×10^{-1}	3.937×10^{4}	3.937×10	1	12	6.336×10^{4}
Feet	3.281×10^{-10}	3.281×10^{-9}	3.281×10^{-6}	3.281×10^{-3}	3.281×10^{-2}	3.281×10^{3}	3.281	8.333×10^{-2}	1	5.280×10^{3}
Miles	6.214×10^{-14}	6.214×10^{-13}	6.214×10^{-10}	6.214×10^{-7}	6.214×10^{-6}	6.214×10^{-1}	6.214×10^{-4}	1.578×10^{-5}	1.894×10^{-4}	1

Example: To convert from meters to inches, multiply by the tabled value of 3.937 x 10. Therefore 5 meters would equal (5 x 39.37) = 196.85 inches.

Appendix B. Example of a Model Used for Calculating Application Rates

OLEM LIME DOSE MODEL

Data required

- pH before liming
- lake retention time (yr)
- lake volume (m^3)
- average limestone particle size (μm)
- calcium content of limestone (in percent CaO)

The model assumes water quality targets of pH 6.5 and ANC 5 mg/L as $CaCO_3$ (100 μeq/L).

Calculation steps

STEP 1: Estimate D_1

Using the lake water pH before liming and the water retention time, D_1 is estimated using Figure A.

STEP 2: Modify the dose for limestone calcium content

The calcium content of the limestone, C (expressed as percent CaO), is entered into Equation 1.

$$D_2 = D_1 \times 60/C \qquad \textbf{Equation 1}$$

where D_2 is the dose factor adjusted for calcium content,
D_1 is the dose factor with no adjustments for limestone characteristics estimated in Step 1 (Figure A), and
C is the percent calcium as CaO.

STEP 3: Modify the dose for limestone particle size

The average particle size of the limestone is used in Figure B to determine the dissolution factor, F. This factor is entered into Equation 2.

$$D_3 = D_2/F. \qquad \textbf{Equation 2}$$

where D_3 is the dose adjusted for the limestone particle size and calcium content in g/m^3,
D^2 is the dose factor adjusted for calcium content, and
F is the dissolution factor estimated from Figure B.

STEP 4: Calculate the dose in tonnes

The required dose for limestone with a calcium content, C, a mean particle size, P, is calculated using Equation 3.

$$D = D_3 \times V/1{,}000{,}000 \qquad \textbf{Equation 3}$$

where D is the dose in tonnes,
D_3 is the dose in g/m^3, and
V is the lake volume in m^3

Adapted from Brocksen, R.W., M.D. Marcus, and H. Olem. 1992. *Practical Guide to Managing Acidic Surface Waters and Their Fisheries.* Lewis Publishers, Ann Arbor, MI.

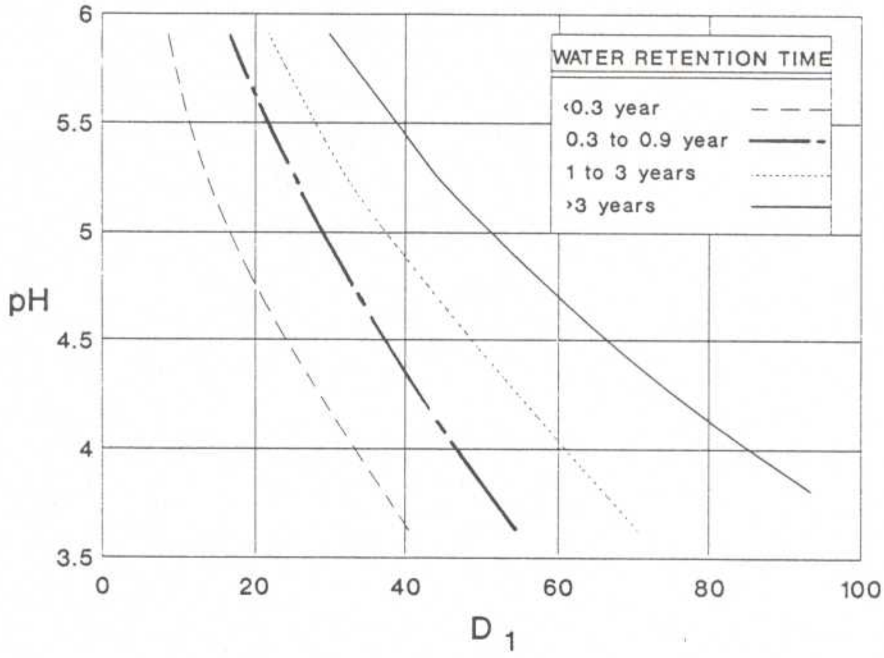


Figure A.—Step 1 of lime dose model: calculation of D_1, unadjusted dose factor.

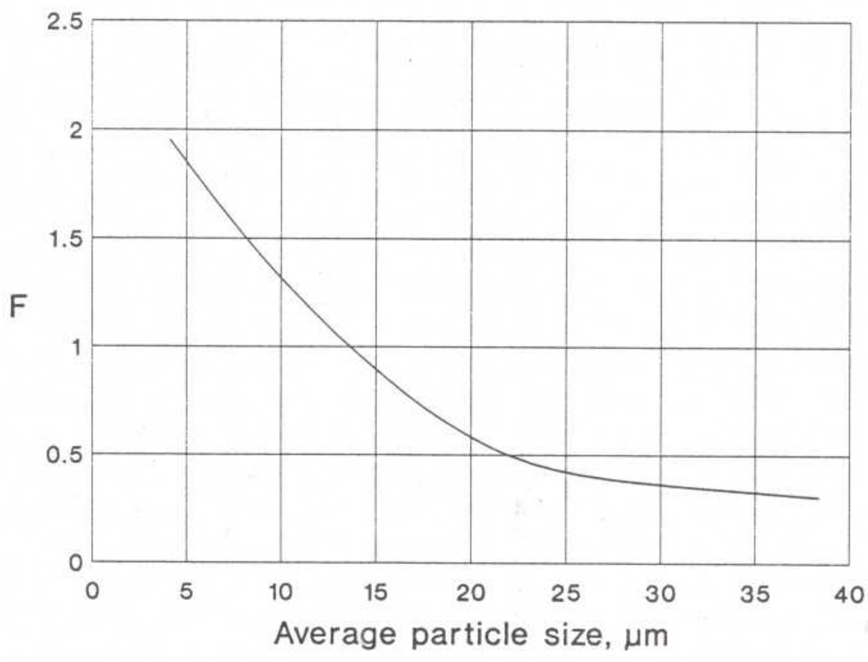


Figure B.—Step 3 of lime dose model: calculation of F.