Guidelines for Liming Acidified Streams and Rivers

Virginia Water Resources Research Center

Virginia Tech

VIRGINIA POLYTECHNIC INSTITUTE
AND STATE UNIVERSITY

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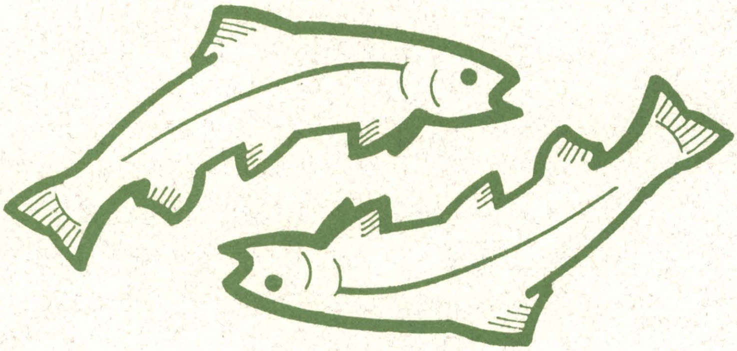

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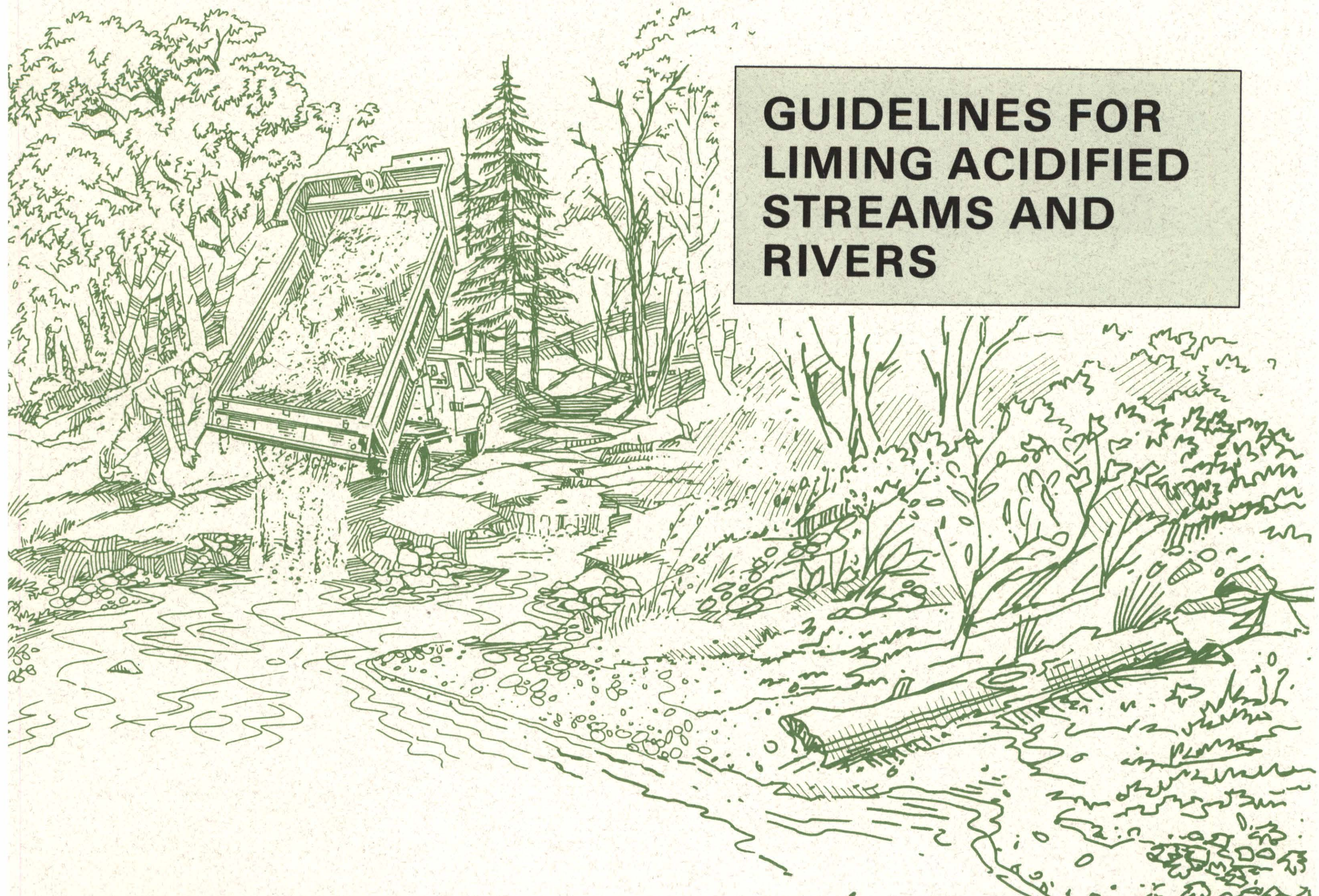


What's in This Publication?

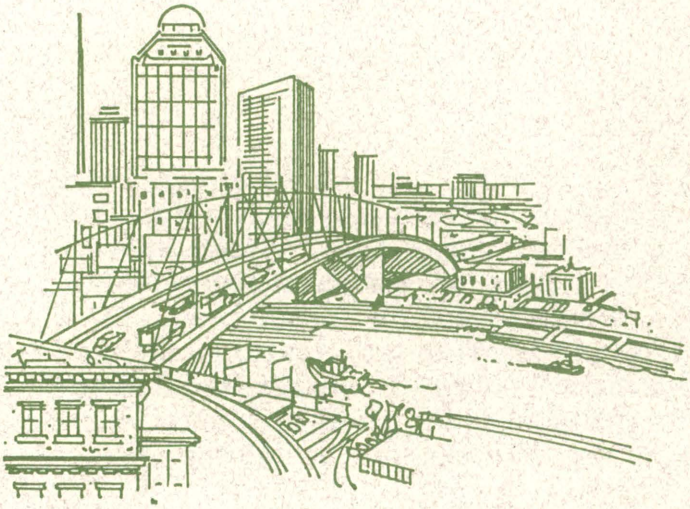
Our companion publication on this topic, *Guidelines for Liming Acidified Lakes and Ponds* covers the addition of limestone, calcium carbonate ($CaCO_3$) to non-flowing surface waters. You may want to order a copy of that publication. The general information on liming lakes and ponds may be of interest and useful if you are considering whether to treat a river or stream.

Limestone can be added to streams whose watersheds are deficient in natural calcium carbonate deposits and, therefore, have limited capacity to neutralize acid loadings. This publication addresses the addition of limestone to flowing water systems, primarily small headwater streams, that are affected by acid deposition or mine acid drainage. Five different methods of applying limestone are presented, and the advantages and disadvantages of using each method are compared. Appendices provide conversion factors for relevant measurements, a simple limestone dosage model used for calculating application rates in streams, examples of experimental limestone application sites, and water quality requirements for selected sport fish.

What Is Liming?

Liming, as the word suggests, is the addition of calcium carbonate, in the form of agricultural limestone, to neutralize acid waters and soils and to buffer them from rapid fluctuations in pH. Limestone typically is added to lawns, gardens, pastures, and croplands to supply calcium, an essential plant nutrient, and to decrease soil acidity. Limestone can be added to surface waters (rivers, streams, ponds, and lakes) to protect and restore fisheries and other forms of aquatic life.

It is important to understand that liming is an artificial, indirect, and temporary approach to dealing with acidification problems. Liming is not the ultimate solution to acid deposition or acid mine runoff. Although acidic surface waters can be neutralized by the addition of limestone, liming a stream does not eliminate the source of the acid, it simply treats the symptoms.



Reduction of sulfur dioxide and nitrous oxide emissions into the atmosphere from industrial smokestacks, auto exhausts, and other sources is necessary to reduce and ultimately eliminate acid rain and other forms of acid deposition. Employing best management practices while actively mining and using wise mine land reclamation practices for closed or abandoned sites are necessary to control and eliminate acid mine runoff.

In the short-term, liming can improve stream conditions and promote restoration until emission controls and reclamation programs remove the sources of acidification to streams and rivers. However, liming may be necessary for restoration and improvement of certain waters. Recent estimates suggest that, even if the sources of acidity were reduced to near zero, half of the waters acidified by acid rain would not improve.

LIMING BENEFITS TO FISH POPULATIONS

- Increased spawning success
- Reduces stress
- Reduced disease & birth defects
- Increased survival
- Increased abundance
- Increased food supply
- Increased growth

Why Lime?

Liming represents a relatively simple, cost-effective method of neutralizing acidic waters, reducing the effects of acidification, and restoring the diversity and productivity of acid-damaged fish populations and other forms of aquatic life. As pH decreases, toxic metals, such as aluminum (Al), copper (Cu), cadmium (Cd), iron (Fe), manganese (Mn), nickel (Ni), lead (Pb), selenium (Se), and zinc (Zn), increase. Liming can reduce these potentially toxic metals, especially Al, Cu, Fe, Pb, Mn, Ni, and Zn, which, in combination with the prevailing acidic conditions, can kill fish and threaten the health and reproductive success of many aquatic animals.

Very acidic streams (pH below 4.5) have few fish, insects, and other animals. Many sport fish, such as trout and bass, prefer stream waters of neutral or alkaline conditions, ranging from pH 7 to 9. In acidic stream waters, fish production and the abundance of aquatic life generally are lower than in alkaline streams. Fish in acidic waters exhibit increased stress, slower growth, reduced disease resistance, and lower reproductive success than those in alkaline waters.

The calcium in limestone is used by aquatic life for bone and shell development and growth. Calcium can reduce the harmful effects of aluminum on fish. The carbonate in the added limestone neutralizes acid and buffers the water against sudden changes in pH. Liming adds nutrients, and can influence the release of nutrients such as phosphorus from the bottom muds. This increased availability of essential nutrients can enhance growth and production through the food chain of aquatic plants-insects-fish.

Any Special Problems in Liming Flowing Waters?

Yes, liming to neutralize acid waters in streams and rivers is more complicated than limestone treatment of lakes and ponds for several reasons. First, flowing systems must be treated on a continual basis, usually over a long period of time, to provide complete and sustained acid neutralization.

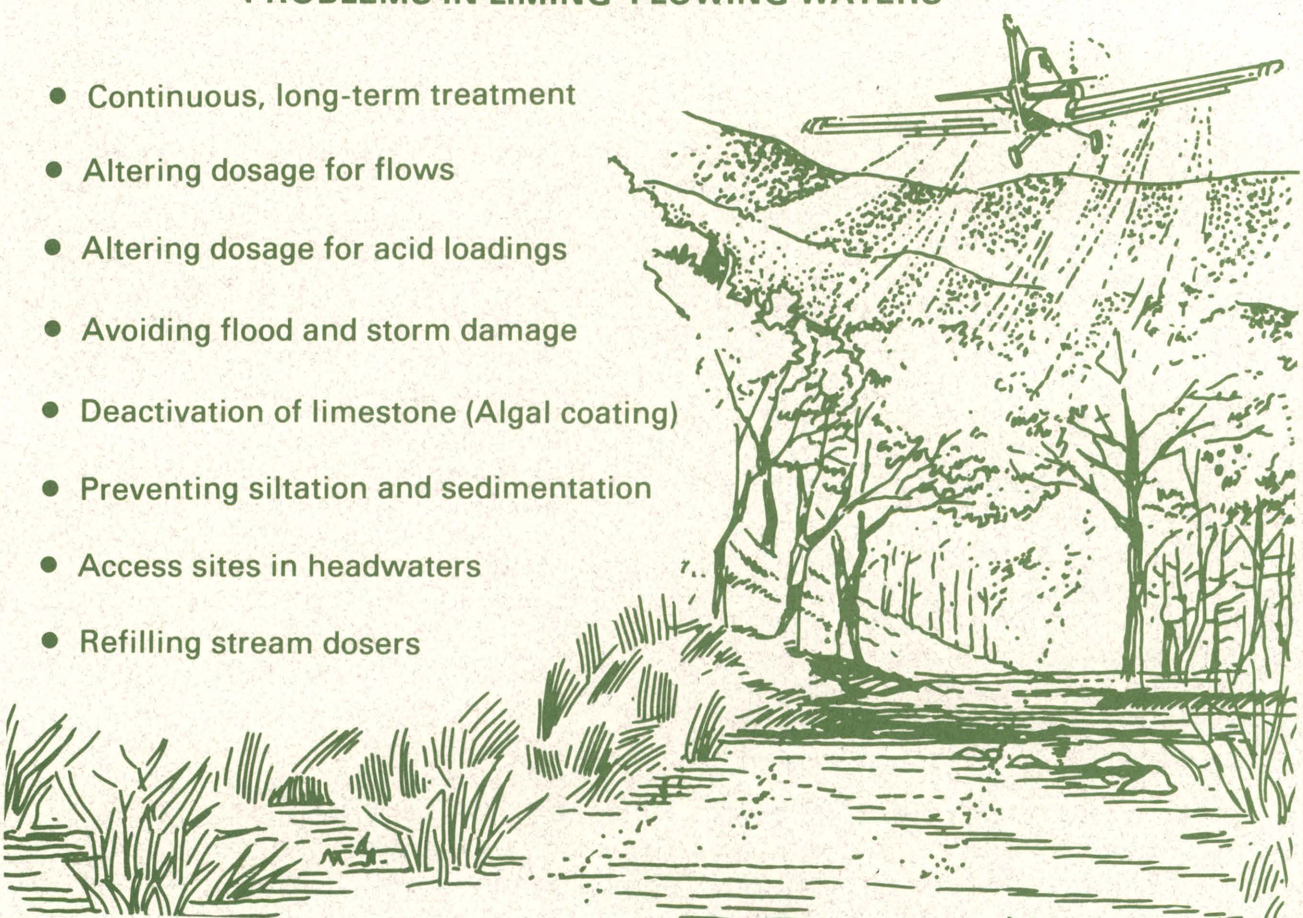
Second, the treatment system must not only deliver limestone to the stream continuously, but the dosage should be variable according to changing water flow and acid conditions. Automatic limestone-dosing devices have been developed to adjust treatments to changing flow and acid levels, but they generally are expensive to buy, install, and maintain.

Third, limestone filters and doser equipment placed in the stream channel or along the streamside are subject to damage from high flows and floods.

Fourth, streambed barriers or filters of limestone may not be effective at neutralizing acid waters over the long term. This is because, over time, the limestone becomes insoluble as it is coated with algae and metal precipitates or covered by sediment. Siltation and sedimentation of in-stream dosers can clog the system and disrupt treatment. A final difficulty is locating a suitable upstream access site for limestone delivery.

PROBLEMS IN LIMING FLOWING WATERS

- Continuous, long-term treatment
- Altering dosage for flows
- Altering dosage for acid loadings
- Avoiding flood and storm damage
- Deactivation of limestone (Algal coating)
- Preventing siltation and sedimentation
- Access sites in headwaters
- Refilling stream dosers

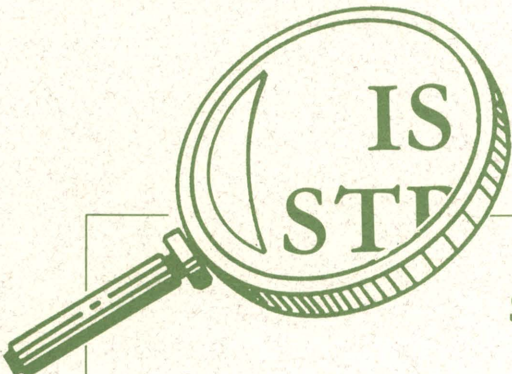


What Should You Consider Before Liming?

Is the stream becoming acidified? Before liming a stream, water quality tests should indicate:

- low pH (lower than 6.5),
- reduced total alkalinities (less than 10 milligrams per liter, mg/L, or 200 microequivalents, μeq/L), and
- increased metal concentrations (especially aluminum) over an extended period of time.

Reduced reproductive success and declining abundance of sport fish, minnows, and other forms of aquatic life are key symptoms of acidification. Monitoring of stream water quality and fish populations by professional biological or environmental consulting firms may be necessary to determine whether the stream actually is receiving acid deposition and whether liming represents an appropriate treatment.



IS THERE EVIDENCE OF STREAM ACIDIFICATION?

YES

IF:

- Acidic stream water (pH below 6.5)
- Soft water stream (alkalinity below 10 mg/L)
- Metals (perhaps Al, Cu, Cd, Fe, Mn, Ni, Pb, Zn) increasing
- Fish populations declining
- Other aquatic life (insects, crayfish, frogs) decreasing

IS LIMING AN APPROPRIATE TREATMENT?

YES

IF:

- Known present or historical fishery
- Slow fish growth and low food production
- Maximum monthly flow $< 50\ m^3$ per sec ($1,765\ ft^3$ per sec)
- No legal, access, or cost problems
- Calcium concentrations low

What Is pH?

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

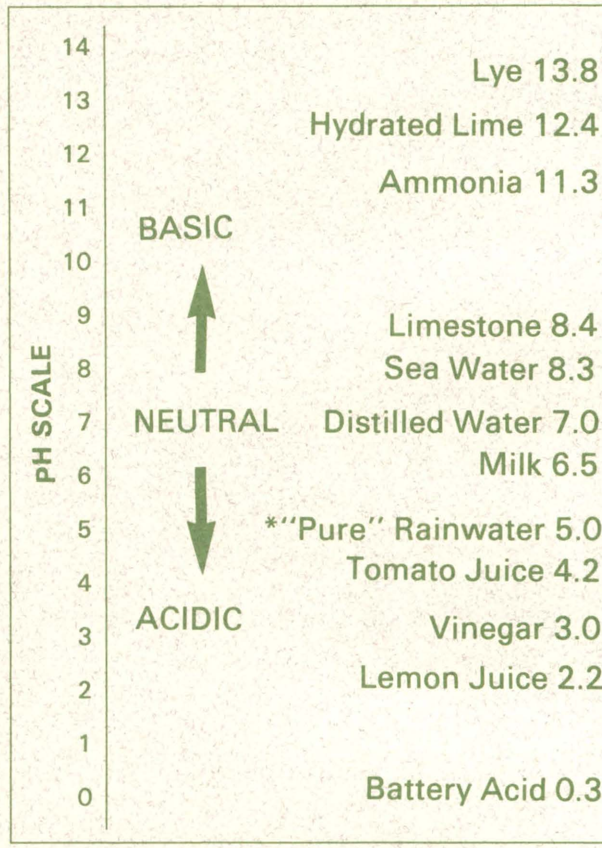
What Is Alkalinity?

The alkalinity of water refers to its capacity to neutralize acids or to resist changes in pH. In the literature, the terms alkalinity and acid neutralizing capacity (ANC) frequently are used interchangeably.

Alkalinity is defined as a measure of the concentrations of three basic ions: carbonates ($CO_3^{=}$), bicarbonates (HCO_3^-), and hydroxides (OH^-) in water expressed as equivalents of calcium carbonate. In certain waters, other buffer systems may contribute in a minor way to alkalinity or ANC. Alkalinity or ANC is commonly expressed as mg/L, meq/L (milliequivalents/liter) or μeq/L, but these can be converted easily. To convert mg/L to meq/L multiply mg/L by 0.02, and to convert mg/L to μeq/L, simply multiply by 20.

In general, soft waters with low alkalinities 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 causes of hardness in natural waters, but other metal ions (Al, Fe, Zn, Mn) also contribute to water hardness. Soft waters 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 concentrations and are less prone to acidification. Dissolved calcium concentrations in excess of 4 mg/L protect fish and other forms of aquatic life from the toxic effects of acidity and aluminum.

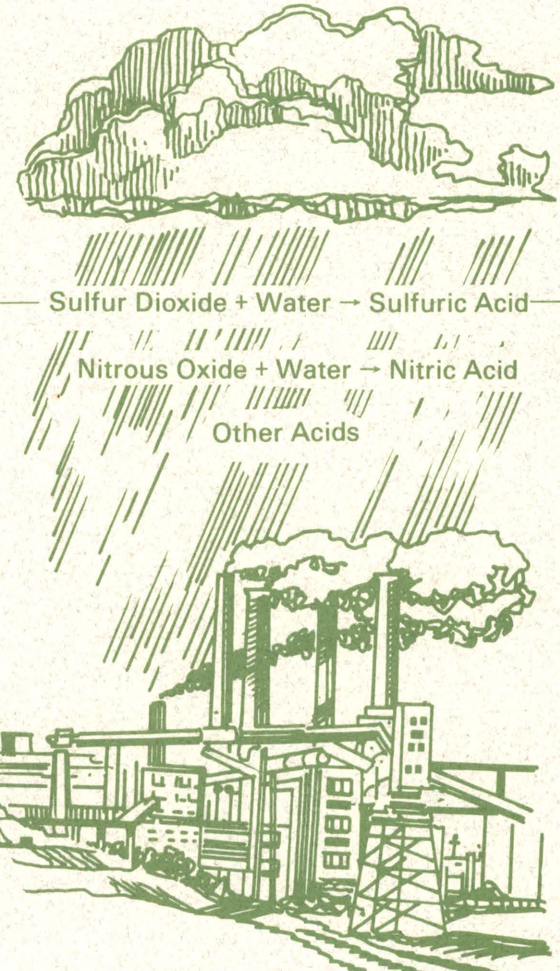
What Are the Sources of Acidity?

Acidification of streams can occur naturally as humic and organic acids from wetlands (bogs, marshes, swamps) drain into streams, and as acids from eroded sulfide minerals combine with groundwater or rainwater and leach into streams. Severe acidification of streams in the eastern United States frequently is the result of acid deposition (acid rain, snow, hail, and other forms of precipitation) or acid mine drainage. In areas downwind of urban and industrial complexes that release sulfur and nitrous oxides into the atmosphere, acid rain and acid runoff result in reduced fish populations, less diversity of aquatic life, and perhaps fish kills and seemingly lifeless streams. In coal country, acid mine drainage resulting from the exposure of sulfur-bearing minerals to air and water, can cause streams to be devoid of fish and most of the other larger and more familiar forms of aquatic life.

Soft-water streams with low alkalinity and a reduced buffering capacity, especially those located in areas of the country receiving acid rain or mining impacts, are particularly susceptible to acidification. Periodic additions of limestone directly to the stream waters or the surrounding watershed can protect streams before they become too acidic. Acidified streams can be restored by liming to manipulate water quality and encourage the recovery of aquatic life. Applications of limestone on a sustained basis may be required to promote the recovery of acidified streams and sport fish populations.

SOME SOURCES OF ACIDITY IN STREAMS

- Acid deposition
- Mine acid drainage
- Bog and swamp waters
- Natural organic acids
- Acidic soil and geologic strata



What About Permits and Public Notices Before Liming?

Permits may or may not be required for liming a private stream, depending on state regulations and site-specific considerations. However, because downstream public waters may be affected by upstream liming, obtaining a permit is often necessary. Moreover, obtaining a permit may afford some legal protection to the property owner. Because liming involves the addition of chemicals and the alteration of water quality, a stream owner who adds limestone may be considered responsible for any changes downstream to private or public waters resulting from the treatment, especially if he or she fails to get a permit.

Permit applications and regulatory information usually are available from the state natural resource or water resource agencies. The permit information required for applications typically includes a description of the treatment site, its location, dosage rates, duration of treatment, limestone material, method of application, existing stream conditions (depth, width, flow rate), water quality (pH, temperature, alkalinity, nutrients, metals), and fish populations. The fisheries biologist at the state natural resource agency and fisheries extension specialist at the state university can help with information on liming, permit applications, and potential treatment effects.

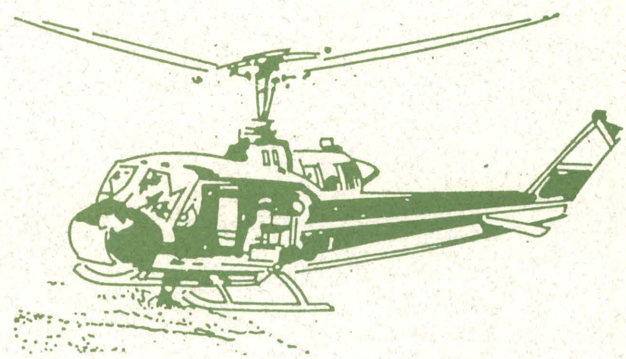
Public notification of the date, time, liming method, and considerations for downstream domestic, livestock, and irrigation water users is recommended. Because liming may discolor the water temporarily, alter the taste and mineral content of water, and stimulate short-term algal blooms, a general public notification and health advisory program is recommended, especially if the target stream feeds downstream water-supply reservoirs. Downstream water users should be notified of the dates of liming and informed of the temporary consequences (cloudy water, increased plant production, flavor alterations) through posters, newsletters, or a personal visit.

What Type of Limestone Should Be Applied?

Agricultural or higher-grade limestone ($CaCO_3$, calcium carbonate) is the best material for treating acidic stream waters. This is the same material that is widely used for liming lawns, gardens, and farm land. Limestone is relatively inexpensive, readily available, easy to handle and distribute, dissolves in water, and is a naturally occurring nontoxic material. Other basic (alkaline) materials, including dolomitic limestone ($CaCO_3$–$MgCO_3$), quicklime (CaO), hydrated lime $Ca(OH)_2$, soda ash (sodium carbonate, Na_2CO_3), lye (sodium hydroxide, $NaOH$) and sodium bicarbonate ($NaHCO_3$), can be used to neutralize acidic waters, but these compounds have fewer advantages than limestone. Agricultural gypsum (calcium sulfate, $CaSO_4 \cdot 2H_2O$) is not a liming material.

Some of these chemicals, such as hydrated lime ($Ca(OH)_2$), quicklime (CaO), and lye ($NaOH$), are not recommended for treating streams. They have been used because less is needed (they have higher neutralizing values than pure limestone), but they are caustic (corrosive) and difficult to control. Hydrated lime increases pH very rapidly and can kill fish at application rates greater than 50 pounds per surface acre. In fact, hydrated lime, quicklime, and lye have all been used to disinfect and sterilize waters prior to fish stocking.

Clean, contaminant-free agricultural limestone is recommended. The calcium content of the limestone is directly related to its acid neutralizing capacity. Pure calcium carbonate has an acid neutralizing capacity of 100%. The calcium content of the limestone used should be at least 70%, and preferably 90-100%, by weight. Dolomitic limestone with high levels (over 5%) of magnesium carbonate ($MgCO_3$) may result in poor dissolution and acid neutralization. A minimum of 70% $CaCO_3$ and a maximum of 5% $MgCO_3$ by weight is recommended.



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

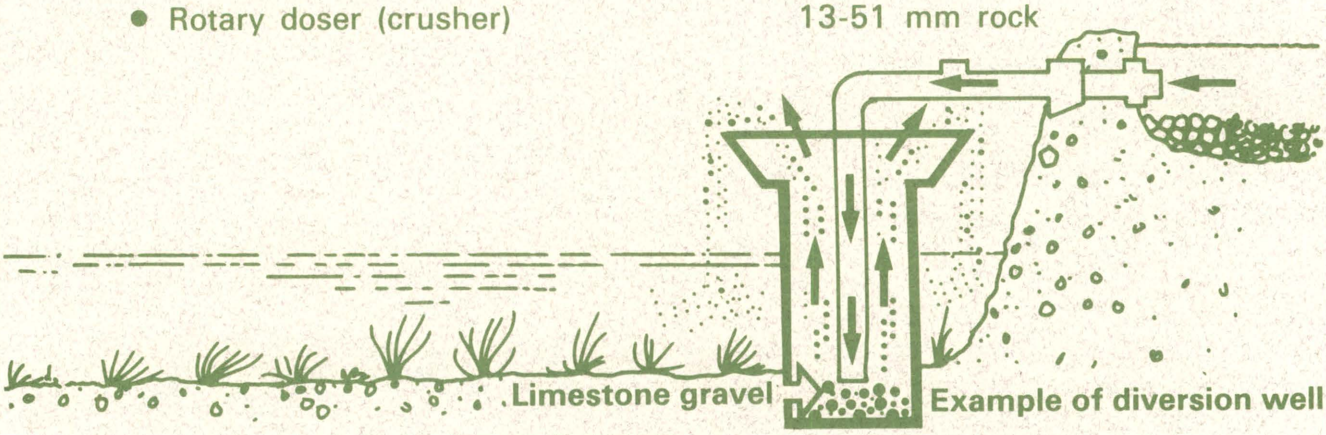
Is the Particle Size of the Limestone Important?

Yes, the effectiveness of agricultural limestone depends on its particle size and chemical composition. Agricultural limestone can be purchased in many particle sizes, ranging from fine dust to large rock—finely ground (pulverized limestone sand, 0.07-4 mm in diameter) to coarser (crushed) limestone gravel (6-51 mm) or rock (51-203 mm). For most stream application methods, grade A, sand-sized limestone, averaging 0.76 mm in diameter (24 mesh) and ranging between 0.07 mm (200 mesh) and 4 mm (5 mesh) is recommended. However, rotary drum dosers that grind limestone on site can use coarse particles of 12.7-51 mm in diameter.

Fine limestone particles are easier to dissolve and distribute uniformly and can effect the necessary change in pH more rapidly than coarse-grade limestone. However, particles that are too small and light can be flushed away too quickly to effect a change in pH in fast-flowing streams. In contrast, coarse limestone (gravel or rocks) dissolves slowly, may be inactivated by a coating of algae or metals and, thereby, provides little treatment. The optimum limestone particle size depends on the particular stream application method selected for treatment.

SUGGESTED PARTICLE SIZES FOR LIMING

METHOD	LIMESTONE PARTICLE SIZE
• Stream barrier/filter (rock baskets)	51-203 mm rock
• Streambed application (dump truck)	0.76 mm sand
• Watershed application (truck, air)	0.76 mm sand
• Diversion well	6-8 mm gravel
• Water and electric-powered doser	0.1-0.5 mm sand
• Rotary doser (crusher)	13-51 mm rock



What Methods Are Used for Applying Limestone?

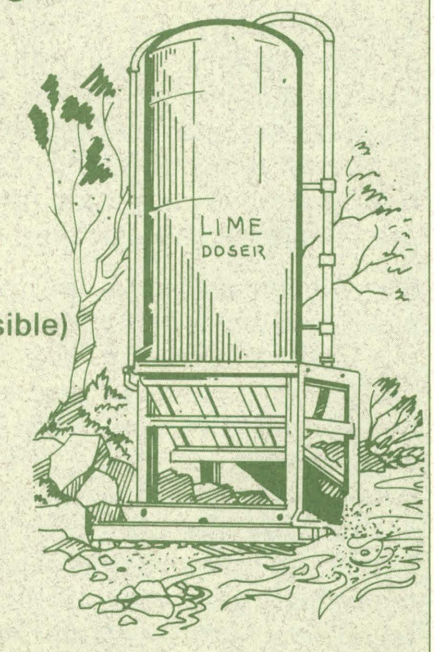
Upstream Lake Liming. If it is possible to neutralize conditions in downstream waters by liming an upstream lake, then lake liming should be seriously considered. Lake liming is generally simpler than most stream liming techniques, and may be less expensive. A detailed description of techniques for liming nonflowing waters is available in the companion publication *A Guide for Liming Acidified Lakes and Ponds.*

Stream and Watershed Liming. Limestone can be applied either directly to a stream or indirectly by spreading limestone sand throughout the watershed. The following basic liming methods are commonly used: (1) a streambed barrier or filter is a collection or wire basket (gabion) of limestone rock that is placed in the stream channel, (2) an in-stream or streambed addition involves limestone sand dumped by truck directly into the stream (usually at a road culvert), (3) a watershed application involves spreading limestone over the surrounding land area by truck, tractor, or aircraft, and depends on storm runoff to dissolve the limestone and wash it into the stream, (4) a diversion well is a limestone-filled tank through which stream water is circulated and neutralized, (5) stream dosers (rotary drums and electric-powered or water-powered dosers) are flow-through systems that use water power to crush coarse limestone, and then divert stream water through crushed the limestone and channel the limestone-water slurry into the stream.

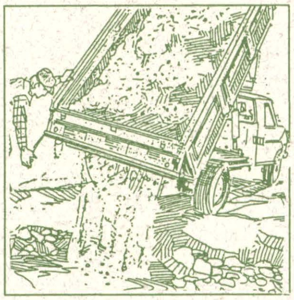
Each application method has advantages and disadvantages, depending on the local conditions, site access, acidity of the stream, and the level of funding and labor available. The simplest and most economical approach is the direct streambed addition of limestone sand. However, effective neutralization of stream acidity may require a combination of these methods.

STREAM LIMESTONE APPLICATION METHODS

METHOD	COMMENT
• Streambed barrier (rock baskets)	Less effective, low dissolution
• Streambed dump (truck)	Simple, inexpensive
• Watershed application (truck, air)	Long-lasting, expensive, if inaccessible)
• Diversion well	Maintenance, construction costly
• Water and electric-powered doser	Maintenance, construction costly
• Rotary doser (limestone crusher)	Complex, expensive



Streambed Barrier. Streambed barriers (filters) of limestone-filled wire baskets (gabions) generally are ineffective. Most attempts at placing limestone rock (large chunks of limestone rather than finer-ground limestone sand and powder) directly into the stream to function as neutralizing filters have been unsuccessful. Limestone rock dissolves slowly, and is quickly inactivated by a coating of silt, algae, and iron hydroxide precipitates. Any effect on water quality is local because little limestone and any accompanying buffering effects are not distributed very far downstream.



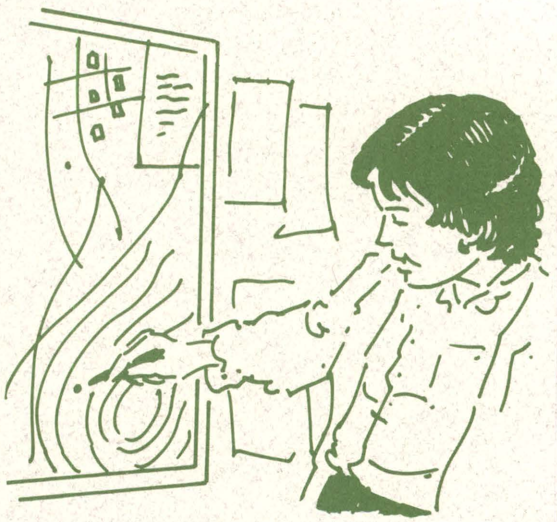
Streambed Dump. Streambed application is the easiest and least complex approach to liming streams. It is accomplished by simply dumping crushed limestone sand from a truck directly into the acidified stream or its tributary. Agricultural limestone can be dumped at one or more convenient access sites along the stream, once or several times annually. Natural stream flow gradually dissolves and distributes the limestone downstream.

Streamside access is an important consideration when using this method. Select the farthest upstream site available that will provide passage and support for a heavily loaded truck to the stream edge with minimal damage. Road culverts, because of their firm support and direct access, are popular sites for dumping limestone into streams. A site with relatively high gradient, fast flows, and turbulent currents that will mix and help dissolve the limestone is desirable.

If stream flows in the extreme headwaters are not sufficient to distribute the limestone, then it may be necessary to select one or more sites for liming farther downstream. Limestone dissolution rates depend on stream flow, water temperature, turbulence, and other factors at the site where the limestone treatment occurs. These dictate how far downstream the limestone will disperse. Studies indicate that agricultural limestone in relatively small, less than 3,000 gallons per minute (gpm) flow, headwater streams generally will spread about 1,000 yards downstream, farther in large streams with stronger flows and steep gradients.

SITE SELECTION CONSIDERATIONS FOR STREAMBED APPLICATION

- Farthest upstream access
- Sufficient flow for limestone sand distribution
- Stable vehicle support
- Turbulent mixing zone
- Non-spawning site



Avoid liming biologically sensitive stream areas because, where limestone and water combine, conditions harmful to aquatic life can occur as a result of quick shifts in water chemistry, precipitation or dissolution of metals, and loss of habitat. Toxic effects can extend from the mixing zone to immediately downstream of the liming point. Special care is needed to avoid fish nesting, nursery, and feeding areas when selecting a treatment site.

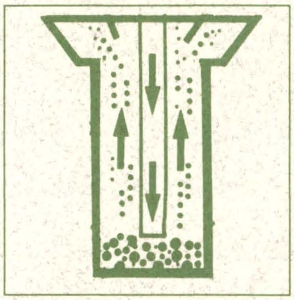
Watershed Application. Watershed application is the addition of limestone to soils in the drainage basin, rather than directly into the stream itself. The methods for watershed liming are identical to those used in agricultural liming. Liming riparian (streamside) areas, forests, or fields in the drainage basin of the stream is done using trucks or tractors equipped with blowers to disperse and spread crushed or pelletized agricultural limestone. Where access is good, this is a relatively simple and economical procedure. Aerial limestone application also can be used in remote or roadless areas, but this method is three or four times more expensive than land application.

Watershed liming does not necessarily require the even distribution of limestone over the entire stream drainage basin. In fact, watershed treatment is most effective when the limestone is targeted at the major water runoff pathways, such as gullies, ditches, dry channels, intermittent streams, seeps, small tributaries, and lowlands. Treatment of the major water pathways in the watershed is especially economical, reducing the amount of limestone required and

maximizing its neutralizing impact. Low-lying drainage areas within the watershed that flow during rainstorm events and snowmelt should receive a heavier dose of limestone. In relatively flat watersheds that lack identifiable runoff channels, it may be necessary to distribute the limestone uniformly throughout the basin.

One advantage of watershed liming over direct stream additions is the sustained, longer-term treatment that occurs as the limestone is slowly released and gradually dissolved with rainfall and snowmelt over a number of years. Another is that limestone spread over the watershed is available to neutralize acidic rainfall and snowmelt whenever and wherever it occurs. Liming watershed soils also may slow the dissolution and leaching of aluminum from upland soils into streams, where it is toxic to aquatic life.

Treatment rates for watershed liming have not been fully developed. They depend primarily on the acid-base reactions in the watershed soils and the pH of the target stream. The Cooperative Extension Service or the Soil Conservation Service in most states has soil-testing laboratories that can determine soil pH and provide recommendations. Drainage areas, channels, seeps, and other pathways of water runoff within the watershed that flow during rainstorm events and snowmelt should receive a heavier dose of limestone than upland areas. Generally, 2-4 tons/acre of limestone should be applied to dry watershed soils, and 5-10 tons/acre to drainage and discharge areas.

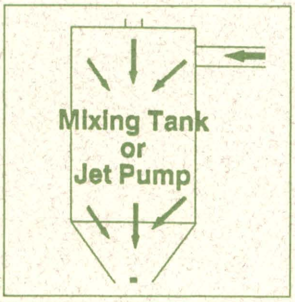


Diversion Well. A diversion well is a relatively simple, flow-through method that can be used to neutralize acidic stream water, although it is somewhat costly to construct and maintain. It consists of a large tank (5-6 feet in diameter and 6-7 feet in height) made of metal, concrete (manhole sections), or plastic. The tank is set upright in the stream bed or along the stream side. It can be sunk into the ground as a well or erected above ground level. The tank is half-filled with a bed of limestone gravel (½ - ¾ inches in diameter). As the supply of crushed limestone in the diversion well is depleted, it is periodically refilled. Flowing water is diverted from an upstream pool or dam, through supply pipes, and into a 9-10-inch diameter polyvinylchloride (PVC) pipe fitted with rubber-gasket joints. The pipe is about 5-6 feet in length (slightly shorter than the well height), and feeds stream water vertically down into the bottom-center of the tank. The movement of the upwelling stream water mixes, grinds, and partially dissolves and suspends the limestone particles in the well into an acid-neutralizing limestone slurry, which flows out of the well and into the stream. Acid neutralization occurs in the well and as the limestone slurry flows downstream.

A diversion well gets its operating energy from stream water. It requires adequate stream flow and stream head (waterfall, or difference in elevation between two points) for power. Stream head and flow provide the energy necessary to move, grind, dissolve, and distribute the limestone slurry. A stream head of 8 feet, an average flow rate of 2,000 gpm, and a maximum flow greater than 15,000 gpm are needed for a diversion well to operate effectively.

Adequate stream head can be generated by creating a dam or piping water from a higher elevation upstream to the diversion well site. Sizing the well diameter and pipes to match the flow rate is especially important to maintain sufficient water velocity and energy to dissolve and mobilize the limestone. Some diversion wells are flared at the top to reduce water velocity and allow undissolved limestone particles to sink back into the well.

Diversion wells do not require electric power, and have no moving parts. They are capable of increasing stream pH values from 1-2 pH units, and of using up to 90% of the added limestone, but they may not provide good results during high-flow and low-flow conditions. A reverse T fitting at the upstream intake helps prevent leaves and woody debris from clogging the system, but some maintenance (weekly) is required.



Limestone Dosers. A doser is a device used to release powdered or slurried limestone into an acidified stream. A variety of automated stream dosers, including water-powered, electric-powered, and rotary-drum dosers, have been used for treating streams. However, most dosers generally are not commercially available, and they may have to be manufactured to fit site-specific requirements.

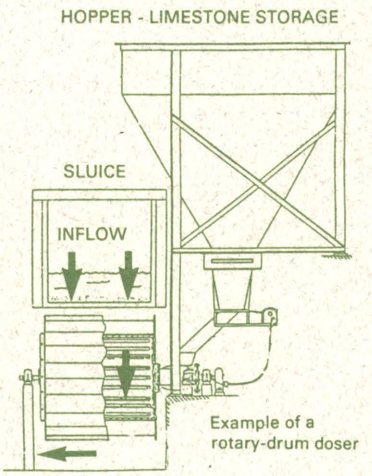
Electric-powered and Water-powered Dosers. Electric-powered and water-powered dosers distribute either dry or slurried limestone directly into the stream. A doser consists of a large limestone storage bin from which dry or slurried limestone is fed by an auger (screw-type) feeder or a circulating pump through a conveyer belt or pipe into a mixing tank with stream water and, finally, back into the stream as a neutralized slurry. Limestone feed is regulated automatically via water-level controls.

Electric-powered dosers require 120/240 line voltage and are, of course, subject to power failures. In remote locations where line power is unavailable, 12-volt battery-powered dosers can be used, but they require expensive recharging and maintenance and are subject to failure during freezing (-5°C) weather conditions. Tapered storage bins help prevent adsorption of limestone powder on the walls, or a vibrating device can be incorporated to loosen compacted limestone.

Water-powered dosers are less costly to construct and maintain than electric-powered dosers. As the name implies, they use energy derived from the stream flow to mechanically feed, grind, and mix the limestone and stream water, and to distribute the slurry into the stream. They operate by diverting a regulated amount of streamflow through a pipe or sluiceway channel to operate a tipping-bucket feed or paddlewheel feed mechanism. Powdered limestone from a large storage bin is gravity-fed into a mixing chamber filled with stream water, and the resulting limestone slurry is directed back into the stream.

Rotary-drum Dosers. Rotary-drum dosers are round cylinders used to crush limestone; they are rotated using water power. Water diverted from the stream and directed down a sluiceway rotates the drums in a water-wheel fashion. A storage hopper feeds limestone rock directly into the rotary drums, which grind and powder the limestone as they revolve. The finely ground limestone is mixed with stream water, and the slurry is directed into the stream.

Rotary-drum dosers are more effective in neutralizing larger streamflows than other techniques, but they are expensive to build and to maintain. Even with a 10-ton storage hopper, weekly refilling may be required. Bulk limestone, available at a lower cost, can be delivered and stockpiled at the site to reduce the cost of frequent deliveries and long-term cost of treatments.



Example of a rotary-drum doser

How Much Limestone Should Be Used?

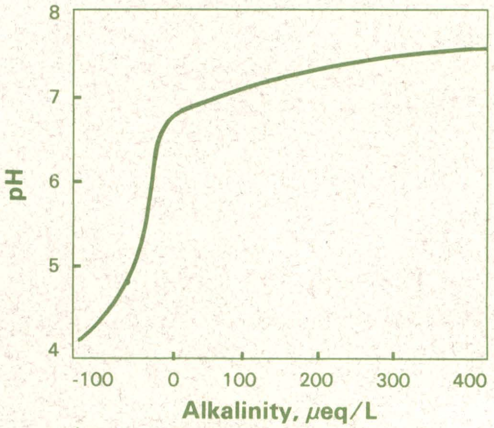
Exact Calculations Are Difficult. Calculations to determine the amounts of limestone to apply to acidic streams are complex. Dosage rates vary seasonally with rainfall, stream pH, stream length, flow rates, and limestone quality and dissolution rates. Single, multiple, or continuous applications of limestone may be necessary, depending on stream acid levels.

Dosage rates for limestone applied to watershed soils range from 2-10 tons per acre (2-4 tons per acre to dry soils and 5-10 tons per acre to low-lying and discharge areas). The total amount of limestone applied to streams varies considerably, from less than 10 to more than 2,000 tons per year, depending on the acid loading rates and local conditions. Continuous application by automatic stream dosers ranges from 0.5 pounds to 1 ton per hour, and streams with persistent acid loadings may require such continuous treatment.

Extra Limestone Is Not Harmful. Precise calculations of dosage rates may be unnecessary. Because limestone is a naturally occurring, nontoxic material, over-liming is not a major problem for aquatic stream life. Excess limestone in the stream will provide some long-term protection against continuing acidification and will eventually dissolve. Moreover, because bulk limestone is relatively inexpensive, a few extra tons dumped in the stream will not be costly.

General Relationship Between Alkalinity and pH. Fisheries biologists or water resource specialists can conduct water quality tests to determine when and how much limestone to add. The alkalinity or acid neutralizing capacity (ANC), a chemical measurement of the buffering capacity of stream water expressed as microequivalents per liter (μeq/L) of carbonate, and pH are the most important measurements needed. The general relationship between ANC and pH, shown below, indicates that only a small increase in ANC can significantly increase the stream pH to the recommended level—6.5 or greater for stream life—as long as the stream is not too acidic.

Relationship Between pH and ANC[1]



[1]National Surface Water Survey, from the National Acid Precipitation Assessment Program.

Trial Dosage Approach. One trial approach to determine the correct stream limestone dosage rate for small streams is to add one truckload (10-20 tons) of limestone sand to the streambed and monitor the pH on a weekly basis at selected sites downstream. By testing the stream pH through time and space, you should be able to determine the length of stream effectively treated and the duration of effective treatment.

Stream Limestone Dosage Model. Appendix B provides a relatively simple stream limestone dosage model for use in estimating how much limestone should be applied. This model is based on the relationship between the acid neutralizing capacity of the limestone and the pH of stream water. It requires only that you know the stream pH in your targeted stream section and the watershed size (area in acres).

DOSAGE RATES VARY WITH:

- Stream water quality
- Stream pH, ANC, alkalinity
- Stream flow rates
- Stream length
- Stream gradient

- Water temperature
- Rainfall
- Mixing zone
- Limestone particle size
- Limestone quality (% $CaCO_3$)

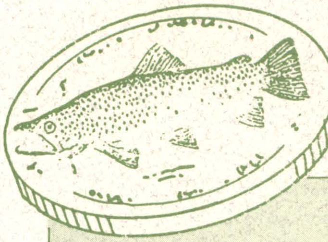
The model provides a dosage estimate for the stream in tons of limestone per year, and is based on a typical small, mountain stream. A more accurate (but more complicated) estimate of dosage rate can be calculated if the acid loading (sulfate deposition), watershed sulfate retention levels, and total annual stream discharge values are known. However, these quantities seldom are known and are difficult to determine.

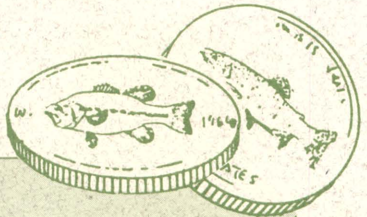
Is Continuous Treatment Necessary?

One treatment at one site may be sufficient on a small stream that is not very acidic. However, if a single liming treatment is inadequate and reliming is necessary, the treatment frequency can be increased, additional downstream treatment sites can be added, or larger quantities of limestone can be used at one or more sites.

The duration of the treatment depends primarily on the amount of limestone used, dissolution rate of the limestone, contact time with the stream water, and stream discharge. Studies suggest that limestone sand dissolves at a steady rate, and treatment should last one year if a sufficient amount of limestone is distributed. For those streams experiencing periodic acidic episodes only during snow melt or storm events, it may be adequate to apply a high dosage of limestone during snow melt and the spring rainy season, when acidic conditions are prevalent. Small streams with relatively minor acidic loads may require only one dose per year.

However, continuous liming may be necessary to maintain pH levels, alkalinities, and calcium concentrations at the appropriate levels for water quality and for minimizing stress and preventing metal toxicity to fish populations and other forms of stream life.





ESTIMATED COSTS OF STREAM LIMING

DISTRIBUTION METHOD*	ANNUAL DOSAGE (TONS)	AVERAGE CONSTRUCTION COSTS	AVERAGE ANNUAL MAINTENANCE COSTS
Streambed dump	20	----	----
Watershed (500 acres)	2,500	----	----
Diversion well	88	$23,000	$8,500
Water-powered doser	99	10,000	7,000
Electric-powered doser	2,206	50,000	11,000
Rotary-drum crusher	496	120,000	15,000

* Costs for limestone and transport average $25-100 per ton; application costs average $50-500 per ton for truck or tractor and $200-500 per ton for fixed-wing aircraft (modified from Brockson et al. 1992).

How Much Will Stream Liming Cost?

Liming can be a relatively inexpensive method of restoring acidified streams, and the material, agricultural limestone, is the least expensive part of the operation. Limestone costs range from $10-50 per ton (about $25-100 per ton including transportation costs), depending on the amount needed and the available supply. Bulk purchases (truckloads) are cheaper than bagged limestone. Pulverized limestone sand is more expensive than coarse limestone gravel or rock, but the smaller particle sizes are more cost-effective because they dissolve faster and more completely than larger ones.

Costs for stream liming vary considerably, depending on accessibility, the method selected, and the application equipment needed. The least expensive methods of neutralizing acidified streams are applying limestone to an upstream lake, if possible, and direct streambed application. For areas readily accessible by road, conventional trucks, tractors, and farm equipment can be used to distribute limestone across streams and drainage areas. Most of the costs can be attributed to the limestone material, its transport to the target site, and labor. Liming less accessible sites and forested watersheds is more costly, requiring helicopters or fixed-wing aircraft for limestone distribution.

For continuous limestone treatments using stream dosers and diversion wells, specialized equipment and costly construction and maintenance are necessary. For example, the typical cost of a limestone rotary drum, delivering almost 500 tons annually is, on the average, about $132,000 to construct, $16,500 to maintain, and $25,000 for limestone and transportation. In comparison, an electric powered doser, delivering about 2,200 tons of limestone annually, would cost, on the average, about $55,000 to construct, $12,100 to maintain, and $110,000 for limestone and transportation.

What Are the Effects of Liming?

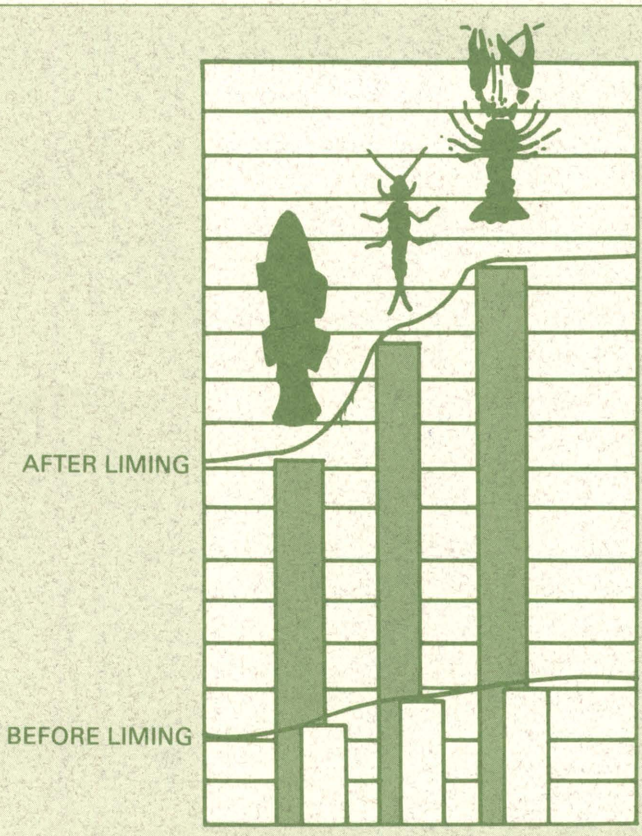
Aquatic ecosystems exhibit some of the most apparent and harmful effects of acid rain because they serve as collection basins for runoff from rain and snowmelt. If the surface waters and the surrounding watershed have a poor capacity to neutralize the acid and buffer the system against pH fluctuations and the release of toxic metals, the abundance and diversity of fish and other forms of aquatic life decreases and toxic metals increase, which can threaten both fish and human health.

Liming has resulted in improvements in fish populations, other forms of aquatic life, and water quality; however, because of the difficulty of treatment, fewer streams and rivers have been restored through liming in comparison to lakes and ponds. But, liming flowing waters and the surrounding watershed has resulted in higher pH levels and increases in buffering capacity and calcium concentrations. Concentrations of metals that may be toxic to aquatic life have been lowered, and nutrient cycling, decomposition, and overall productivity have increased.

Historically, the purpose of liming was the maintenance or restoration of water quality suitable for the support of fish populations. Liming has been favorable to fish populations — permitting the restocking of lost fish species, the introduction of new species, and the recovery of existing, but stressed, populations. However, as long as the source of the acidification exists, waters probably will reacidify over time. Ultimately, large-scale reductions and control of sulfur dioxide and nitrous oxide emissions and releases will be necessary for long-term control of acid rain and its effects.

BENEFITS OF LIMING

- Acid neutralization
- Increased pH
- Increased alkalinity
- Increased calcium
- Improved fish production
- Increased biodiversity
- Decreased toxic metals



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Appendix A. Useful Conversion Factors

To convert	Into	Multiply by
a		
acre	hectare	0.4047
acres	square feet	43,560.0
acres	square meters	4,047.0
acre-feet	cubic feet	43,560.0
acre-feet	gallons	3.259×10^{5}
c		
centimeters	feet	3.281×10^{-2}
centimeters	inches	0.3937
cubic centimeters	cubic feet	3.531×10^{-5}
cubic centimeters	cubic inches	0.06102
cubic centimeters	cubic meters	1.0×10^{-4}
cubic centimeters	gallons (U.S. liquid)	2.642×10^{-4}
cubic feet	cubic meters	0.02832
cubic feet	gallons (U.S. liquid)	7.48052
cubic feet	liters	28.32
cubic inches	cubic centimeters	16.39
cubic inches	cubic meters	1.639×10^{-5}
cubic inches	liters	0.01639
cubic meters	cubic feet	35.31
cubic meters	cubic yards	1.308
cubic meters	gallons (U.S. liquid)	264.2
f		
fathom	meter	1.828804
fathoms	feet	6.0
feet	centimeters	30.48
feet	kilometers	3.048×10^{-4}
feet	meters	0.3048
g		
gallons	cubic centimeters	3,785.0
gallons	cubic feet	0.1337
gallons	cubic meters	3.785×10^{-3}
gallons	liters	3.785
gallons/minute	cubic feet/second	2.228×10^{-3}
gallons/minute	liters/second	0.06308
grams	grains	15.43
grams	ounces (avoirdupois)	0.03527
grams	ounces (troy)	0.03215
grams	pounds	2.205×10^{-3}
grams/centimeter	pounds/inch	5.6×10^{-3}
grams/liter	parts/million	1,000.0
grams/square centimeter	pounds/square foot	2.0481

Appendix A. Useful Conversion Factors - Continued

To convert	Into	Multiply by
h		
hectares	acres	2.471
hectares	square feet	1.076×10^5
i		
inches	centimeters	2.54
inches	meters	2.54×10^2
k		
kilograms	pounds	2.205
kilograms/cubic meter	pounds/cubic foot	0.06243
kilograms/meter	pounds/foot	0.672
kilograms/square meter	pounds/square foot	0.2048
kilometers	centimeters	1.0×10^5
kilometers	feet	3,281.0
kilometers	miles	0.6214
kilometers/hour	feet/second	0.9113
l		
liters	cubic feet	0.03531
liters	gallons (U.S. liquid)	0.2642
liters	quarts (U.S. liquid)	1.057
liters/minute	cubic feet/second	5.886×10^4
m		
meters	feet	3.281
meters	inches	39.37
meters	miles (statute)	6.214×10^4
meters	yards	1.094
meters/minute	feet/second	0.05468
microns	meters	1.0×10^6
miles (statute)	kilometers	1.609
miles (statute)	meters	1,609.0
miles (statute)	miles (nautical)	0.8684
milligrams/liter	parts/million	1.0
millimeters	feet	3.281×10^{-3}
millimeters	inches	0.03937
millimicrons	meters	1.0×10^{-9}
million gallons/day	cubic feet/second	1.54723
o		
ounces	grams	28.349527
ounces	pounds	0.02957

Appendix A. Useful Conversion Factors - Continued

To convert	Into	Multiply by
p		
parts/mullion	grains/U.S. gallon	0.0584
pounds	grains	7,000.0
pounds	grams	453.5924
pounds	kilograms	0.4536
pounds	ounces	16.0
pounds of water	cubic feet	0.01602
pounds of water	cubic inches	27.68
pounds of water	gallons	0.1198
pounds/foot	kilograms/meter	1.488
pounds/inch	grams/centimeter	178.6
pounds/square foot	inches of mercury	0.01414
q		
quarts (liquid)	cubic centimeters	946.4
quarts (liquid)	cubic feet	0.03342
quarts (liquid)	cubic meters	9.464×10^{-4}
quarts (liquid)	liters	0.9463
s		
square centimeters	square feet	1.076×10^{-3}
square centimeters	square inches	0.155
square centimeters	square meters	0.0001
square feet	acres	2.296×10^{-3}
square feet	square centimeters	929.0
square feet	square meters	0.0929
square inches	square centimeters	6.452
square kilometers	acres	247.1
square kilometers	square feet	10.76×10^{6}
square kilometers	square miles	0.3861
square meters	acres	2.471×10^{-4}
square meters	square centimeters	1.0×10^{4}
square meters	square feet	10.76
square meters	square miles	3.861×10^{-7}
square meters	square yards	1.196
square miles	square kilometers	2.59
square miles	square meters	2.59×10^{-6}
square yards	square meters	0.8361
y		
yards	centimeters	91.44
yards	kilometers	9.144×10^{-4}
yards	meters	0.9144

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

DOWNEY LIMESTONE DOSE MODEL

Data required

- stream pH before liming
- watershed size (acres)

The model is based on the interrelationship of springtime stream pH values and the acid neutralizing capacity of limestone. It is based on an average mountain stream in Virginia and assumes an annual rainfall rate of 39 inches per year with a 50% runoff rate and a target pH of 6.5.

Calculation steps

STEP 1: Estimate watershed size (acres)

Use a U.S. Geological Survey topographic map or another map to outline the stream watershed and estimate the size of the watershed (acres) above the treatment site.

STEP 2: Estimate stream pH

Measure the stream pH under normal flow conditions (more than 3 days after a rain event or snow melt) in the spring (March or April).

STEP 3: Estimate D_1 (dosage multiplier factor)

Using Figure A, locate the stream pH on the X axis, interpolate (read up to the pH-curve intersection and across to the Y or vertical axis) to find D_1

STEP 4: Calculate D (the limestone dosage rate in tons/year)

Multiply D_1 times the watershed size in acres to determine D, the required dose for limestone in tons per year.

Example = *Given a watershed size of 2,000 acres and a stream pH of 5.1, the multiplier factor or D_1 would = 0.0035 and D, the estimated dosage rate, would be 7 tons of limestone per year (0.0035 x 2,000 = 7). The 7 tons can be distributed at one or many sites, once or several times per year.*

Appendix B. Examples of a Model (Continued)

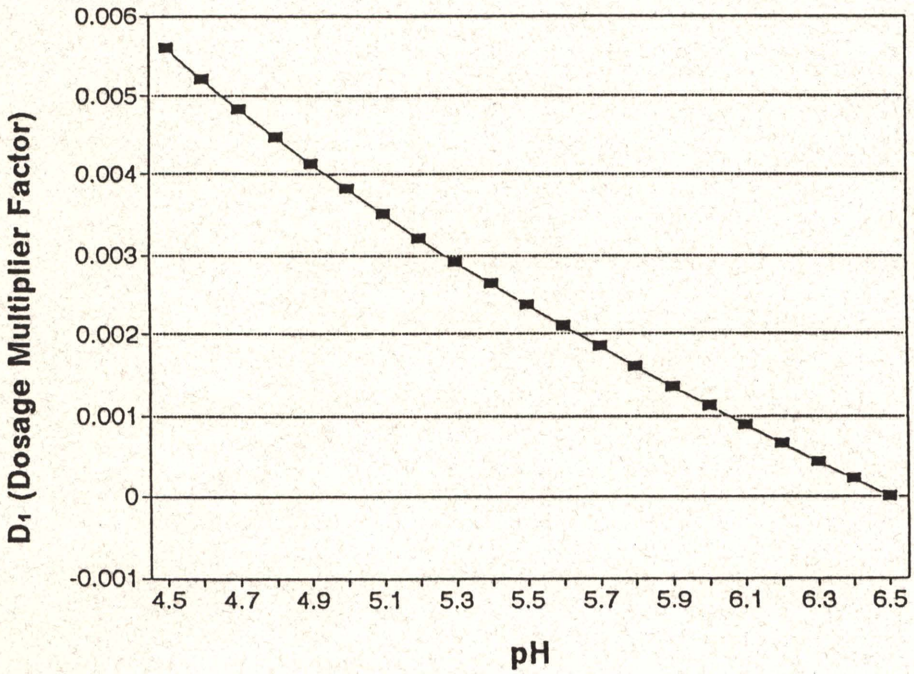

Figure A. Estimation of the Dosage Multiplier Factor (D_1)

Appendix C. Stream, Location, and Method of Experimental Limestone Application for Treating Acidic Stream Waters[1]

Stream	State	Application Method (Annual dosage)
Stocketts Run	Maryland	Gas-powered doser
Bacon Ridge Branch	Maryland	Electric-powered doser
Mattawoman Creek	Maryland	Electric-powered doser
Rock Branch	Maryland	Limestone barrier
Whetstone Brook	Massachusetts	Water-powered doser (35 tons)
Otter Creek	West Virginia	Rotary-drum doser (200 tons)
Crouch Run	West Virginia	Stream-bed dump (71 tons)
Yocum Run	West Virginia	Stream-bed dump (68 tons)
Dogway Fork	West Virginia	Rotary drum doser (310 tons)
Granny F. Branch	Pennsylvania	Limestone barrier
Gifford Run	Pennsylvania	Doser (24 tons)
Stony Creek	Pennsylvania	Diversion well (36 tons)
Lick Creek	Pennsylvania	Diversion well
McNerney Run	Pennsylvania	Doser (24 tons)
Wolf Run	Pennsylvania	Doser (56 tons)
Powell Creek	Pennsylvania	Briquettes (48 tons)
Constable Creek	New York	Limestone barrier
Little Stony Creek	Virginia	Stream-bed dump (38 tons)
Mill Creek	Virginia	Stream-bed dump (8 tons)
Cedar Creek	Virginia	Stream-bed dump (12 tons)

[1]Adapted from a number of sources in the References section.

Appendix D. Temperature, pH and Calcium Requirements for Selected Sport Fish[1]

Common Name	Scientific Name	Water Temperature Requirements	pH Requirements (Eggs - Adults)	Calcium Requirements
Atlantic salmon, landlocked	*Salmo salar*	Below 21°C (70°F)	Above 6.0	Above 2.5 mg/L
Brown trout	*Salmo trutta*	Tolerant from 0°C-27°C (32°F-80°F)	Above 6.0	Above 2.5 mg/L
Lake trout	*Salvelinus namaycush*	Prefer temps. below 13°C (55°F)	Above 6.0	Above 2.5 mg/L
Brook trout	*Salvelinus fontinalis*	Tolerant from 0°C-24°C (32°F-75°F)	Above 6.0-9.5	Above 2.5 mg/L
Rainbow trout	*Oncorhynchus mykiss*	Tolerant from 0°C-27°C (32°F-80°F)	Above 6.0; tolerant from 5.8-9.5	Above 2.5 mg/L
Striped bass, landlocked	*Morone saxatilis*	Tolerant from -1°C-32.5°C (30°F-90°F)	Above 6.0	Above 2.5 mg/L
Largemouth bass	*Micropterus salmoides*	Above 27°C (80°F)	Above 6.0	Above 2.5 mg/L
Smallmouth bass	*Micropterus dolomieu*	21°C-27°C (70°F-80°F)	Above 6.0	Above 2.5 mg/L
Walleye	*Stizostedion vitreum*	Tolerant from 0°C-32.5°C (32°F-90°F)	Above 6.0	Above 2.5 mg/L
Yellow perch	*Perca flavescens*	Tolerant from 0°C-32.5°C (32°F-90°F)	Above 6.0	Above 2.5 mg/L

[1]Modified from Brockson et al. 1992.

ACKNOWLEDGEMENTS

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