

**IMPROVING NITROGEN-USE EFFICIENCY BY ALLEVIATING
MICRO-IRRIGATION EMITTER PLUGGING**

Final Report

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Executive Summary

The majority of Florida citrus groves are micro-irrigated (drip emitters or micro-sprinklers). Emitter plugging can be a serious problem, particularly in the southwest and east coast regions. Citrus growers annually spend between \$15 and \$40 per acre to unplug emitters by either hand cleaning them or injecting cleaning chemicals, but remedial treatments often provide unsatisfactory results.

The type of water used for irrigation influences emitter plugging. Surface and shallow well water is aerobic, while deep well water is anaerobic. The main problem with aerobic water is bacterial contamination and slime formation. Anaerobic water is free of biological activity, but can cause chemical scaling because it may be highly mineralized.

Plugging can be caused by biological, physical, or chemical factors. The most important nuisance microbes are iron (Fe) bacteria, which create ochre slime. Other biological factors include sulfur bacteria, algae, and insects. Physical plugging originates from materials that are not dissolved in the irrigation water like soil particles. Chemical plugging is due to scale formation inside the tubing resulting from a chemical response to the changing condition of the irrigation water as it moves through the system.

Water treatment to address a clogging problem can be either preventative or remedial. Prevention is best accomplished by continuous water treatment with chemicals that kill bacteria (e.g. chlorine) or prevent precipitation (e.g. polyphosphates). Remedial treatments require more aggressive chemicals and often relentless effort. Water treatment chemicals vary widely in stability, mode of action, corrosiveness, safety of use, dosage, and cost. Most commercial scaling inhibitors are proprietary mixtures of chemicals that may include acids, chelating or complexing agents, or reducing agents.

Irrigation water used in southwest Florida citrus groves can contain Fe concentrations high enough to present a moderate to severe plugging hazard. Analysis of scale from plugged micro-irrigation emitters indicated that the scale was mostly mineral matter containing about 25% Fe by weight. Scales were most likely composed of oxides and hydroxides of Fe.

Experiments with commercial scale inhibiting chemicals showed that the concentration of an inhibitor had a major influence on its ability to prevent precipitation (the higher the better), and showed that these materials can increase the degree of a scaling problem if not applied at a high enough concentration.

When the water emission uniformity of 23 southwest Florida citrus grove micro-irrigation systems was evaluated, 16 systems tested good or excellent, five systems showed deterioration with time from good or excellent to fair or poor, and two systems had fair or poor initial evaluations and did not show much improvement. Measurements and simulations of injected chemical distribution uniformity clearly showed that the potential for N leaching losses increases as water emission uniformity decreases. In the case of fair and poor systems, some citrus trees could receive twice as much N fertilizer during a growing season than others. In addition, the maximum N recommendation could be exceeded by as much as 35% under some trees, which is where N leaching would most likely occur. Improving water emission uniformity in irrigation systems testing fair or poor will decrease the likelihood of N loss.

IMPROVING NITROGEN-USE EFFICIENCY BY ALLEVIATING MICRO-IRRIGATION EMITTER PLUGGING

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1. Literature review

1.1. Extent of the problem in Florida

Emitter plugging of micro-irrigation (drip or micro-sprinkler) systems used to irrigate Florida citrus orchards is a serious problem in some regions of the state. Plugging can have physical, chemical, or biological origins, or can be a combination of two or more factors. In 1994, citrus production managers were surveyed to determine the magnitude of the problem statewide, the specific problems encountered, and the costs associated with maintenance or remedial action to combat the problems (Boman and Ontermma, 1994). The key findings from this survey are as follows:

- The respondents represented management of more than 130,000 acres of citrus (70,000 acres from the Indian River area, 20,000 acres from southwest Florida, and 40,000 acres from the central Florida ridge).
- The water sources used included canals, artesian wells, lakes, ponds, rivers, reservoirs, and pumped wells.
- About 80% of the respondents' citrus orchards were irrigated with micro-sprinklers, and the remainder was irrigated with drip emitters. Most of the micro-sprinklers had discharges in the 8 to 14 gallons per hour range.
- All irrigation systems had some type of primary filtration, including spin-clean, disc or wafer, media, or screen filters. Automatic back-flushing was indicated on a minority of the primary filters.
- Most of the respondents indicated that emitter plugging was caused by two or more factors:
 - Biological plugging by algae, bacteria, slimes, etc. was indicated by 86% of the respondents.
 - Insects, ants, and spiders caused plugging for 68% of the respondents.
 - Sand and grit caused plugging for 72% of the respondents.
 - Precipitation from chemical reactions resulted in plugging for 42% of the respondents.
- The respondents estimated the annual emitter plugging percentage rate from the various factors as follows:
 - Insects: 22%.
 - Physical particles (sand and grit): 22%.
 - Chemical precipitation: 12%.
 - Biological growths and slimes: 45%.
- 46% of the respondents field checked and cleaned their irrigation systems every 2 to 4 months; 36% checked their systems more frequently, and 18% checked their systems less frequently than 2 to 4 months.

- Average annual cost of emitter maintenance ranged from a few dollars per acre up to \$80 per acre. Most of the reported costs were in the \$15 to \$40 per acre range, with an overall average of \$25 per acre.
- Less than half of those surveyed treated the irrigation water with chemicals to prevent plugging problems. Of the 45% that were using chemicals:
 - 25% used commercial water conditioners.
 - 20% used acid.
 - 35% injected chlorine.
 - 20% used a combination of two or more chemicals.
- Regarding the frequency of chemical injection:
 - 27% used continuous injection.
 - 21% injected at 1 to 3 week intervals.
 - 27% used monthly injections.
 - 15% reported injection intervals of 2 to 3 months.
 - 9% used an injection frequency of greater than 3 months.
- The effectiveness of chemical treatments was rated on a scale of 0 to 10, with 10 indicating a totally effective treatment. The average rating was 7.2, indicating some dissatisfaction with the chemical treatments.

1.2. Water sources and classification

Irrigation water sources are usually classified as either groundwater (well water) or surface water, but from an emitter plugging standpoint it is more advantageous to classify water as either aerobic (containing oxygen) or anaerobic (lack of oxygen) (Boman and Ontermma, 1994). Aerobic water comes from surface or shallow well sources, while anaerobic water originates from deep wells. Aerobic water supports a variety of biological activity and can contain a wide variety of dissolved minerals. Anaerobic water can be rich in dissolved minerals and carbon dioxide, but is relatively free of bacterial contamination.

The main problem associated with the use of aerobic water for micro-irrigation is bacterial contamination and resulting slime formation. Scale formation inside tubing and sprinkler orifices is almost always associated with aerobic organic slime deposits. The main problem that occurs with the use of anaerobic water is the development of mineral scales. The deposition rate of a mineral scale layer depends on the composition and concentrations of minerals in the water. Observation of the source of irrigation water and the resulting classification with regard to oxygen status allows initial prediction of the type of emitter plugging to be expected (Boman and Ontermma, 1994).

The physical, chemical, and biological composition of Florida's irrigation waters is relatively stable with time. Even though surface waters vary seasonally due to changes in rainfall frequency and volume, their characteristics remain similar on an annual basis. Once water is pumped into an irrigation system, it experiences rapid changes in pressure, temperature, exposure to solar radiation, velocity, and composition (filtration) that can upset chemical and biological equilibria within the water. It is this change in the state of the water that can initiate an emitter plugging problem.

1.3. Emitter plugging

The causes of micro-irrigation system emitter plugging can be placed into one of four categories (Pitts et al., 1990; Boman and Ontermma, 1994):

- *Biological plugging*, which results from the growth of microorganisms like bacteria, fungi, and algae within micro-irrigation tubing or on the surface of emitter orifices.
- *Particulate plugging*, which is caused by suspended clay, silt, sand, or plant material carried by the irrigation water. The amount of particulate matter that exists within a micro-irrigation system depends on the water source and the quality of filtration at the pump station.
- *Chemical precipitates*, which usually result from reactions of dissolved inorganic species like calcium (Ca), magnesium (Mg), manganese (Mn), or iron (Fe) with oxygen, sulfates, or phosphates. Precipitates can also form from reactions with dissolved organic compounds often found in surface water due to the degradation of plant or bacterial matter.
- *Insect plugging*, which results from ant or spider activity in the emitter orifices. Another similar pest that can be placed in this category is snails, which can be caught in the emitters.

1.3.1. Biological plugging

Several bacterial species can cause water discoloration, odors, and slime formation. They can reproduce rapidly when the environmental conditions are favorable, and can form resistant dormant structures when they are not. Bacterial plugging develops quickly when there are minerals nutrients available in the water in addition to suspended particles to which they can attach. Bacteria attach to tubing walls by bonding to organic or inorganic compounds that in turn bond to the inner tubing surface.

The most important nuisance microbes are iron bacteria that change the soluble iron species Fe^{2+} to Fe^{3+} , which then precipitates as ferric hydroxide, $\text{Fe}(\text{OH})_3$. The bacteria create a slime called *ochre* that can be colored red, yellow, or tan (Ford and Tucker, 1975). Occasionally small ochre particles separate from the tube wall and can then completely plug an emitter.

Another group of bacteria that can plug emitters are those that fix sulfur or sulfur derivatives. The bacterial formation in this case is a whitish slime with a strong “rotten egg” smell typical of hydrogen sulfide. Therefore, if this smell is present in an irrigation system, it is likely that emitters may soon become plugged with sulfur slime unless preventative maintenance is undertaken.

Algae are a large group of microorganisms that can photosynthesize in the presence of sunlight. They exist in virtually every location that is continually moist. Algae can contribute to emitter plugging in several ways. Algae cells suspended in the water source increase water turbidity, resulting in intake screen and filter plugging. Dead algae in filters and water lines can serve as a carbon source for the growth of other bacteria. Algae attached to surfaces near emitter orifices can receive enough light to

grow and colonize. As the colony grows, it restricts emitter discharge and eventually plugs the emitter (Boman and Ontermma, 1994).

1.3.2. Physical plugging

Physical plugging originates solely from materials that are not dissolved in the irrigation water. Physical matter that can plug emitter orifices includes soil particles (sand, silt, and clay) and dead or living biological materials like microorganisms. These particles can clog filters as well as emitters. They are also responsible for abrasion on the inside plastic parts of the irrigation system, which creates tiny crevices that invite attachment by microbes or depositing scale. Once these scratches are present, clays and slime can be synergistic as they accumulate, thus deposits can build faster than what would be expected from a water quality analysis. Organic matter like dead plant parts and cell excretions make excellent sites for attachment by bacteria, minerals, and other suspended matter in water and on tubing walls. These materials serve as a carbon source for further organic growths, thus augmenting the problem (Boman and Ontermma, 1994).

The primary method used to eliminate physical materials from the irrigation water stream is filtration. However, good filtration does not come without a price. Expensive irrigation systems with inexpensive filtration will soon fail due to physical plugging if a turbid irrigation water source is used. Filters should be sized according to the emitter manufacturer's recommendations or, in its absence, to remove any particles larger than one-tenth the diameter of the smallest opening in the emitter flow path. High loads of suspended particles in the irrigation water may require pre-filtration treatment. A settling pond may be used where sand and silt size particles are separated by sedimentation. Fine silt and clay particles that pass through the filter may settle out of the water in the lateral tubing or emitters. The irrigation system should be flushed regularly to remove these sediments (Hassan, 2001).

1.3.3. Chemical plugging

Chemical plugging of micro-irrigation systems is due to scale formation inside the tubing as a result of a chemical response to the changing condition of the irrigation water. Precipitate formation depends on several factors including pH, temperature, concentration of ions in solution, time, and aeration (presence or absence of oxygen). Calcium phosphate is a typical substance that can precipitate and cause scaling on the inside surfaces of tubing and emitters. Calcium and phosphate can form seven different combinations depending on the above water characteristics, three of which are non-water soluble. As the system pH increases, the solubility of Ca-P compounds decreases. Phosphates precipitate rapidly under the right conditions, and form stable compounds that are not easy to re-dissolve. Reactions with Ca, Mg, and Fe are important because these elements are typically found in Florida waters.

In the large-scale micro-irrigation systems typically found in commercial Florida citrus groves, flows can range from hundreds to thousands of gallons per minute. Thus, the mass of dissolved elements moving through these systems is high. For example, a system with a 2500 gal/min flow rate pumping water with 1000 ppm total dissolved

solids (TDS) will have more than 20 lbs of solids entering the system each minute (Boman and Ontermma, 1994).

An exercise that examines the theoretical potential for scale formation can be useful to determine if potential clogging problems exist (Table 1). Cations that may exist in Florida waters include calcium (Ca^{2+}), magnesium (Mg^{2+}), iron (Fe^{2+}), and manganese (Mn^{2+}), while anions may include carbonate (CO_3^{2-}), phosphate (PO_4^{3-}), sulfate (SO_4^{2-}), hydroxide (OH^-), and oxide (O^{2-}). This exercise assumes that conditions are right for precipitate formation and that a sufficient supply of anions is present. Assumed water concentrations of each species are: 100 ppm Ca, 100 ppm for Mg, 1 ppm for Fe, and 0.1 ppm for Mn (Boman and Ontermma, 1994).

1.3.3.1. Iron

Iron is ubiquitous in most rocks and soil. Under the proper conditions, Fe will dissolve and leach into groundwater. If water with Fe concentration above 0.3 ppm is used for irrigation, staining and/or scaling can occur. These stains have a yellow, orange, or reddish color, and can affect micro-irrigation system performance. The following types of iron can be found in groundwater (Keller, 2001):

- **Iron bound in organics, or “heme” iron.** This Fe is associated with organic molecules like tannins, which are large molecular weight organic molecules that are a product of decaying vegetation. Tannins cause water to have a yellow to brown color, and have the ability to hold Fe in solution through chelation.
- **Iron bacteria.** This Fe is part of a microorganism that uses ferrous bicarbonate in a metabolic process. In this process the Fe is precipitated and then deposited around the cell wall. *Crenothrix*, *Clonothrix*, *Gallionella*, *Leptothrix*, and *Sphaerotilus* are common Fe bacteria. They can live in a wide range of environmental conditions, and can be controlled with biocides.
- **Ferrous bicarbonate, or “clear water” iron.** Geologic Fe that finds its way into groundwater can react with CO_2 to form ferrous bicarbonate (FeCO_3). This “clear water” Fe is soluble in water and is not visible.
- **Ferric hydroxide, or “red water” iron.** Soluble Fe that is exposed to oxygen will precipitate to the insoluble hydroxide form. This type of Fe has a yellowish to reddish appearance in water, and is a major contributor to scale formation and emitter plugging in micro-irrigation systems that use high-Fe groundwater.

Iron precipitation problems exist in well water areas where the groundwater aquifers are formed mainly of sandy soils or organic soils (very common in Florida), usually with a pH below 7.0, in the absence of dissolved oxygen. *Ferrous* iron (Fe^{2+}) in these waters is chemically reduced and 100% water soluble, and serves as the primary raw material for bacterial slime and chemical scale formation. If present in the water, Fe bacteria react with Fe^{2+} through an oxidation process that changes it to Fe^{3+} , which is insoluble. The insoluble *ferric* iron is surrounded by the filamentous bacteria colonies and creates the sticky Fe slime gel that is responsible for clogging emitters. An Fe^{2+} concentration more than 0.1 ppm is considered a potential hazard to drip irrigation systems (Ford, 1979). Between 0.2 and 1.5 ppm Fe^{2+} , emitter plugging hazard is

moderate. Concentrations above 1.5 ppm are considered severe (Bucks and Nakayama, 1980).

Practically any water that contains Fe^{2+} higher than 0.5 ppm cannot be used in drip irrigation systems unless it is treated chemically or otherwise. Experiments in Florida indicate that chlorination successfully controlled bacterial slime formation when Fe^{2+} concentration was less than 3.5 ppm and pH was below 6.5 (Nakayama and Bucks, 1986). Water containing more than 4 ppm Fe^{2+} cannot be chemically treated in an efficient manner, thus it should be subjected to a pond sedimentation process before pumping it back through a micro-irrigation system (Bar, 1995)

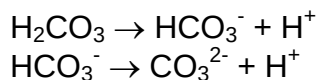
1.3.3.2. Calcium

When irrigation water is low in Fe but high in pH, such as that which originates from a limestone aquifer, calcium carbonate (CaCO_3) is the most common constituent of scale that forms inside a micro-irrigation system. Calcite, aragonite, and vaterite are mineral forms of CaCO_3 that have been found in carbonate scale. Calcite is formed at temperatures common within micro-irrigation systems, and is the most common and stable of the mineral forms.

Calcium minerals occur extensively in the form of limestone and dolomite (calcium-magnesium carbonate). Calcite is the principal constituent of limestone, and occurs in many calcareous metamorphic rocks. Therefore, it is not surprising to encounter CaCO_3 in solution in almost all surface and ground waters, especially in Florida where much of the groundwater is pumped from large underlying limestone formations. As groundwater passes through these limestone formations it dissolves the limestone and carries calcium carbonate with it (Pitts et al., 1990).

The Langelier Saturation index (LSI) is an equilibrium model derived from the theoretical concept of saturation and provides an indicator of the degree of saturation of water with respect to CaCO_3 . The LSI approximates the base 10 logarithm of the calcite saturation concentration. The Langelier index approaches the concept of saturation using pH as a main variable. The LSI can be interpreted as the pH change required to bring water to equilibrium.

Water with an LSI of 1.0 is one pH unit above saturation. Reducing the pH by 1 unit will bring the water into equilibrium because the portion of total alkalinity present as CO_3^{2-} decreases as the pH decreases, according to the equilibriums describing the dissociation of carbonic acid (Corrosion Doctors, 2002):



If LSI is negative, there is no potential CaCO_3 scaling. The water will dissolve CaCO_3 . If LSI is positive, scale can form and CaCO_3 precipitation may occur. If LSI is close to zero, there is borderline scaling potential. Changes in water quality or temperature could change the index.

The LSI is purely an equilibrium index and deals only with the thermodynamic driving force for CaCO_3 scale formation and growth. It provides no indication of how much scale will actually precipitate to bring water to equilibrium. It simply indicates the

driving force for scale formation in terms of pH as a master variable. In order to calculate the LSI, it is necessary to know the alkalinity (ppm as CaCO_3), the calcium hardness (ppm Ca^{2+} as CaCO_3), the total dissolved solids (ppm TDS), the actual pH, and the temperature of the water ($^{\circ}\text{C}$) (Corrosion Doctors, 2002).

1.4. Water treatment

Most of the technology used to treat water in micro-irrigation systems originated from municipalities or industries that have faced water scaling problems for many years. Water treatment can be categorized as either *preventative* (not allowing clogging to start) or *remedial* (elimination of an existing clogging problem). Prevention is best accomplished by continuous water treatment with organic or inorganic chemicals that are able to either prevent precipitation reactions or dissolve depositing scale on the inside surfaces of tubing and emitters. Water treatment chemicals vary widely in stability, mode of action, corrosiveness, safety of use, dosage, and cost.

Flowing water can be chemically treated either continuously or intermittently (“shock” treatment). The objective of continuous treatment is to prevent the development of clogging symptoms, while shock treatments are intended to attack the symptoms alone. An additional factor to consider when using shock treatments is that the irrigation system must be completely flushed following treatment in order for it to work as intended. Proper preventative treatments greatly reduce the need for system flushing. The major shock treatments used in Florida involve injection of chlorine or acid. These two materials should never be used together because doing so can produce an explosion (Boman and Ontermma, 1994).

1.4.1. Chlorination

Chlorine is used worldwide in water systems to kill unwanted biological organisms including bacteria and algae. In Florida, chlorine is available in liquid or gas form for injection into irrigation systems. Gas chlorine is more effective and less expensive than liquid, but its use requires specially-trained personnel and may subject the property where the gas is used to local, state and/or federal hazardous materials reporting requirements. For these reasons, liquid chlorine (sodium hypochlorite) is the most widely-used chlorine source for injection into irrigation systems.

Liquid chlorine is not without its problems, however. It is only partially effective in penetrating through bacterial layers inside system components, and its strength is affected by the pH and mineral concentration of the water. As water pH increases above neutral (7.0), liquid chlorine begins to lose its activity as a biocide. Thus, chlorination is most effective when the pH is less than about 7.2, and the more acidic the water, the more effective the chlorine. Chlorine demand (the concentration of Cl within the irrigation system that is necessary to be effective) also increases as the dissolved solids concentration of the water increases. The pH and mineral factors can sometimes accumulate to the point where continuous chlorine treatment becomes impractical or uneconomical. Whereas a concentration of 1 to 2 ppm of free (active) chlorine at the last emitter in an irrigation system is all that is required for biocidal action, it may take as much as 50 to 60 ppm at the injection point to compensate for degradation as the

chlorine moves through the system (Boman and Ontermma, 1994).

Another drawback to chlorine use is its oxidizing capability. Chlorine can aid the transformation of the soluble Fe^{2+} ion to the insoluble Fe^{3+} ion, which can lead to a greater (scaling) plugging possibility. The precipitated Fe can then become a nutrient source for further bacterial growth. Liquid chlorine has an additional disadvantage in that its stability in field storage tanks is limited to less than 2 months. Stored sodium hypochlorite (HOCl and OCl^-) solution slowly degrades to elemental chloride (Cl^-) that has no biocidal activity.

1.4.2. Acidification

Acidification of the water that flows into an irrigation system has mainly been used in attempts to dissolve existing scale, not necessarily to serve as a biocide. The primary consideration when using acids is the personal safety of the people involved in handling and injecting the chemical. Acids used in water treatment are extremely corrosive and can cause severe burns upon accidental exposure to the body.

A general rule is that the pH of the water in the irrigation system needs to be lowered to near 2.0 to achieve maximum effectiveness of the acidification (Rible and Meyers, 1986). The idea behind acidification is to use the corrosive power of the acid to loosen and/or solubilize precipitants and scale within system components. The system must be rinsed using flush-out valves or by opening lateral tubing ends following acid injection. If this is not done, there is a chance that emitter plugging could be made worse than before if small particles detached by the acid become caught in emitter orifices.

Low pH solutions can damage irrigation system hardware. Corrosion accelerates rapidly as pH decreases below 5.5. There can also be localized corrosion around the acid injection point in a pipeline if the acid is not injected into the center of the pipe to ensure adequate mixing of acids with water (Burt et al., 1998).

1.4.2.1. Phosphoric and sulfuric acids

Phosphoric acid (H_3PO_4) has been used to treat micro-irrigation systems, but the phosphates from this acid can compound a chemical plugging problem by combining with Ca in the water if the acid is not injected at a high enough concentration. In general, if there is more than 50 ppm Ca in the irrigation water, phosphoric acid should not be injected. This acid is expensive so it can only be economically used in high-value plant production systems.

The other major acid that has been used to clean irrigation lines is sulfuric acid (H_2SO_4). Of the commercial solutions available, the 38% diluted version is the most corrosive, hence it performs the best as a line cleaner. Sulfuric acid is considerably less expensive than phosphoric acid.

Similar to chlorine, acids are subject to degradation between the point of injection and the last emitter in the irrigation system. The “absorption” of acid molecules by the irrigation water is due to dissolved constituents, primarily carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-). The ability of a water source to neutralize acid, or the “acid demand” of the water, can be measured with a laboratory titration. This measurement

indicates the amount of acid that needs to be added per unit of water volume to bring the water to pH 2. A sample acid demand curve for a southwest Florida surface water source is shown in Fig. 1.

It takes a substantial amount of acid to noticeably improve a highly scaled irrigation system. Sometimes multiple treatments are required, with line flushing in between a series of acid injections. Many times the results have not lasted or have been unsatisfactory, especially considering the labor and cost involved. It is usually more cost effective and safer to initiate preventative cleaning treatments with other chemicals before treatment with acid becomes necessary (Boman and Ontermma, 1994).

1.4.2.2. Urea-sulfuric acid

N-pHuric[®] is the trade name of a urea-sulfuric acid mixture manufactured by Unocal that is available in Florida. N-pHuric[®] combines the benefits of adding urea nitrogen to crops with an acidification benefit while eliminating the undesirable characteristics of using sulfuric acid alone (Table 2). N-pHuric[®] is widely used in the western USA for prevention of drip irrigation emitter clogging. Long-term acidic nitrogen fertilizers must be applied with caution because 1) nitrogen should not be applied to some crops near harvest, and 2) the pH of the soil may be adversely affected by excess acid. Besides increasing the availability of several micronutrients, low soil pH in the irrigation wetted pattern will inhibit nitrification (conversion of ammonium-N to nitrate-N) (Burt et al., 1998).

1.4.2.3. Citric acid

Citric acid has both the properties of an acid and a relatively large organic molecule that can complex metal ions. It can prevent iron scale from forming without inhibiting the oxidation of Fe^{2+} to Fe^{3+} .

1.4.3. Water conditioners

Water conditioners can be divided into two categories: 1) chemical treatment, which includes scale inhibitors and anti-bacterial compounds, and 2) physical devices (Boman and Ontermma, 1994). The most common alternative chemicals to chlorine and acids are the scale inhibitors, which lessen scale formation by preventing precipitation reactions from occurring long enough for the irrigation water and its dissolved constituents to exit the micro-irrigation system through the emitters. They are usually composed of a mixture of several synthetic polymers or polyphosphates that have been found to prevent scaling from occurring in laboratory experiments. These mixtures are often combined with surfactants and penetrating chemicals to help break apart biological and crystalline solids that are attached to tubing walls and emitters (Boman and Ontermma, 1994). Water conditioners do not kill bacteria, but merely alter the chemical environment such that the conditions for deposition or attachment are less strong.

Polyphosphates are the most common synthetic scale inhibitors. They have been used to treat municipal waters for more than 60 years. However, there are major

differences between various compounds that are commonly called “polyphosphates.” These compounds usually contain a range of linear chain polyphosphates having different numbers of orthophosphate (PO_4^{3-}) groups that are held together by P-O-P linkages. The average number of P atoms in the chain can range from about 4 to 18 (Holm and Schock, 1991). Polyphosphates vary in their ability to complex metal ions based on their chemical structure. The concentration of a complex formed in solution depends on the concentration of both the metal ion and the polyphosphate as well as the relative stability of the combination, so comparisons of one chemical with another are complicated and depend on specific water chemistry conditions (Burt et al., 1998).

Scaling inhibitors can be costly because they are usually proprietary materials. They are injected into irrigation systems at rates normally less than 10 ppm to keep their use affordable. A water analysis can help determine the most favorable combination of chemicals in a particular mixture. Some water conditioner manufacturing companies will not sell a product to a customer until water sample test results are known. In this way, scaling inhibitors can be custom blended for particular water sources. Initial applications of scale inhibiting chemicals to poorly maintained micro-irrigation systems might require higher rates than normally used for routine maintenance. The increased rate may be required for several applications until system cleanliness has improved to the point that only maintenance rates are required (Boman and Ontermma, 1994).

There has been very little in-depth independent research or confirmation of the claims made by the manufacturers of scaling inhibitors (Burt et al., 1998). Robinson et al. (1990) studied polyphosphates with respect to their use in municipal water systems to sequester iron and manganese. Their conclusions pertaining to treatment of drinking water and rehabilitation of clogged city water pipes were as follows:

- Polyphosphates prevent the oxidation of manganese by chlorine. No significant differences were seen between several polyphosphates tested in their performance for sequestering Mn.
- Calcium interfered with treatment by polyphosphates due to calcium phosphate precipitation.
- Polyphosphates sequester Fe. Chlorine should not be added ahead of polyphosphates, because the Fe would oxidize and precipitate. Significant differences were found between the sequestering ability of polyphosphates for Fe.
- When treating a water system, chlorine must be added at least 30 seconds after the polyphosphates have been added.
- Some polyphosphates lose their potency with long storage times.
- Different municipal water suppliers report quite different successes of polyphosphate use.
- Iron is oxidized from ferrous to ferric during sequestration, but manganese is not oxidized by the polyphosphates.

Attempting to control scale with physical devices has been only marginally successful. Various magnetic treatment systems and ion exchange resins have been tried, but the magnetic treatment has not worked well because its effect diminishes rapidly away from the treatment area, and the resin systems have proved to be too

costly for agricultural use, although they work well to remove unwanted dissolved ions (Boman and Ontermma, 1994).

1.5. Specific plugging problems and their solutions

The following summary of problems and solutions was suggested by Burt et al. (1998):

Problem	Possible solution
Small slimy bacteria	1. Continuously apply chlorine at low dosage. Free chlorine at the far end of the system should measure 1 ppm. 2. Superchlorinate to 200-500 ppm free chlorine at the far end of the system: Thoroughly flush system, inject chlorine, allow to sit overnight, flush system the next day.
Iron and manganese bacteria	1. If the bacteria inhabit the well, injecting acid or chlorine directly into it may minimize the problem. Check for legality of this procedure in the local area. 2. Pump well water into a reservoir and aerate it before pumping it to the irrigation system. The oxidation will cause precipitation of iron and manganese. 3. Inject a long chain linear polyphosphate or polymaleic acid into the irrigation water to sequester iron and manganese, keeping them suspended while they move through the irrigation system. 4. Inject chlorine gas (1.4 parts chlorine for each 1.0 part iron in the water) prior to a fine media or disc filter to precipitate the iron from the water and trap it in the filter. This technique will not work for manganese.
Calcium and magnesium carbonate precipitation	1. Neutralize the carbonates by injecting phosphoric or sulfuric acid into the irrigation water such that the pH decreases below 6.5. 2. Inject a very long chain linear polyphosphate into the irrigation water at a rate of 1 to 2 ppm to sequester calcium and magnesium, keeping them suspended while they move through the irrigation system.

2. Survey of the chemical properties of scaling inhibitors and removers

2.1. Scaling inhibitors

Most commercial products sold for scaling inhibition are proprietary mixtures of chemicals discussed in the previous section. Examples include materials called “Di-Solv,” “Aqua-Solv,” and “Turbo-Clean.” According to product literature, they are “formulated from compounds which are negatively charged.” The claim is that “when added to the irrigation water, these compounds attract and bond with positively-charged

minerals such as calcium carbonate, magnesium carbonate and iron preventing them from accumulating in the irrigation system. Since bonded minerals cannot precipitate, they pass right through the system without harmful effects.”

2.2. Scale removers

General chemical properties of scale removers were determined by searching national and international patents. Commercial products sold as scale removers may contain one or more of the following:

Inorganic acids	Chelating or complexing agents	Reducing agents
Hydrochloric acid	Citric acid	Sodium sulfite
Phosphoric acid	Glycolic acid	Sodium hydrosulfate
Sulfuric acid	Maleic acid	
Nitric acid	Gluconic acid	
	Oxalic acid	
	Erythorbic acid	
	Ascorbic acid	
	Phosphonate	
	Sodium EDTA	
	Ammonium, potassium, or sodium citrate	

3. Survey of the chemical properties of irrigation water and emitter plugging substances

Chemical properties of groundwater used for irrigation in southwest Florida were obtained from the United States Environmental Protection Agency Office of Water Storage and Retrieval website, often referred to as “STORET” (USEPA, 2002). The iron concentration (Fig. 2) in the majority of interior wells was high enough to present a moderate to severe plugging hazard (Table 3). Coastal wells were less affected by iron. Calcium (Fig. 3) and hardness (Fig. 4) concentrations present moderate plugging potential, while pH (Fig. 5) presents slight to moderate potential. It is apparent from these data that iron is the most likely cause of micro-irrigation plugging in the region since most systems are connected to interior wells.

Chemical properties of emitter plugging substances were determined by removing scale from clogged emitters taken from three southwest Florida citrus groves, dissolving it in strong acid, and measuring total carbon (C), nitrogen (N), carbonate (CO_3^{2-}), calcium (Ca), magnesium (Mg), manganese (Mn), and iron (Fe). It was assumed that the inorganic C in the materials was primarily in the carbonate form, so organic C was calculated by subtracting carbonate C from total C.

Carbon made up less than 12% of the weight of the analyzed scales, indicating that they were primarily of chemical origin (Table 4). Most of the C present was organic, indicating that some biological activity was present in the irrigation lines. The C:N ratios of the organic fraction ranged from 5 to 48. The mineral portion of the scales was dominated by Fe, which made up about one-quarter of the total weight (Table 5). It

appears that calcium carbonate formation was minimal. The scales were most likely composed of oxides and hydroxides of iron.

4. Effects of scaling inhibitors on water with high scaling potential

One commercial (Di-Solv) and one experimental (FFF 201M) scale inhibitor were investigated for their potential to prevent precipitation of iron in well water. Iron solutions containing 3, 10, or 30 ppm Fe^{2+} were prepared by dissolving FeSO_4 in a beaker of SW Florida well water. The scale-inhibiting chemical was added to these solutions to achieve final concentrations of 50, 100, or 200% of the iron concentration in the beaker. For example, beakers of 3 ppm Fe^{2+} solution contained 1.5, 3, or 6 ppm of scale inhibitor. The solutions were left standing for 24 hours, followed by filtration. The mass of precipitate trapped by the filter was then determined.

The results were expressed as the relative (percentage) amount of precipitant that formed in beakers where scale-inhibiting chemicals were added compared with the amount that formed in control beakers without a scale inhibitor. The FFF 201M material inhibited precipitation when it was equal to or double the Fe concentration (Fig. 6). However, precipitation was greatly enhanced when the inhibitor was half the Fe concentration. Di-Solv did not consistently inhibit precipitate formation, and in several cases increased it slightly (Fig. 6). The results illustrate that the concentration of an inhibitor had a major influence on its ability to prevent precipitation, and showed that these materials can actually increase the degree of a scaling problem if not applied at a high enough concentration.

5. Water emission uniformity of commercial micro-irrigation systems

Measuring the water emission uniformity (EU) of a micro-irrigation system is a way to estimate how evenly water is distributed throughout a citrus grove. The standard USDA-Natural Resource Conservation Service Mobile Irrigation Laboratory (NRCS-MIL) method involves measuring the discharge rate of 16 emitters within the coverage area of one sub-main. EU is defined as the average flow rate of the lower quarter of observations divided by the average flow rate of all 16 observations. The higher the EU, the more uniform the system. Uniformity is important especially when the irrigation system is used for fertilizer delivery (fertigation).

The EU of 23 southwest Florida citrus grove irrigation systems was evaluated by the Southwest Florida MIL (Table 6). Several evaluations were made with time in individual groves to measure performance change. For evaluation purposes, 90% or greater EU is considered “excellent,” 80 to 89% is considered “good,” 70 to 79% is considered “fair,” and less than 70% is considered “poor.” Sixteen of the 23 systems tested good or excellent throughout their evaluation. Five systems showed deterioration with time from good or excellent to fair or poor. Two systems (one drip system and a micro-sprinkler system using surface water) had fair or poor initial evaluations and did not show much improvement.

Following the initial evaluation of a system, the NRCS provided maintenance recommendations to the irrigation manager. The acceptable performance of the majority of systems was probably due to plugging prevention and/or remediation practices

adopted by the manager. Plugging remediation is often costly and requires considerable hand labor, especially if unplugging clogged emitters is required.

Physically removing plugging material from an emitter can often increase the orifice diameter. Occasionally internal parts (like diaphragms) within emitters of complex design are removed to augment flow (NRCS-MIL, personal communication). This procedure is not recommended because it substantially affects emitter flow rates. If cleaning of emitters or removal of system parts causes an emitter flow increase above the design capacity, it becomes more likely that emission uniformity will decrease (Fig. 7). The most straightforward cleaning methods are sometimes not the best ones to use, but often there is no other alternative besides replacing clogged emitters with new ones.

6. Nitrogen distribution uniformity and potential N leaching losses from irrigation systems with poor water distribution uniformity.

The Southwest Florida Research and Education Center's foundation citrus grove was used for this demonstration. The grove was planted in 1989, so the irrigation system was about 10 years old when evaluated. System design and components were typical of commercial southwest Florida citrus groves. The system had one micro-sprinkler per tree designed to discharge 14.5 gal/hr.

The demonstration consisted of the following steps:

- One irrigation sub-main was selected and the EU within it was measured using the standard NRCS method.
- A tracer dye was injected at the pump station to simulate injected fertilizer.
- The tracer concentration and total water volume discharged during the test were measured at each of the 16 emitters evaluated within the sub-main.
- The mass of tracer discharged was calculated for each test emitter.
- Tracer concentration and mass uniformity were calculated for the system.
- Additional mass uniformities were calculated using simulated EU values.
- Estimates of nitrogen distribution uniformity and potential leaching losses from irrigation systems with poor water distribution uniformity were made.

The SWFREC foundation grove irrigation system performed exceptionally, with an EU of 98% (Fig. 8). The tracer concentration uniformity was excellent as well (93%), indicating good mixing and distribution throughout the pipes and tubing. The mass distribution uniformity of the tracer was 92%, which is an estimate of how well fertigated N would be spread throughout the grove. Soluble N distributed by each of the 16 emitters was estimated assuming that 200 lbs/acre would be applied by an emitter that was discharging at the average rate (Fig. 8). The range for the system was 156–220 lbs N/acre, which is within the typical N rate range that is applied to Florida citrus.

Similar calculations were made for irrigation systems that had “good,” “fair,” and “poor” EU (Figs. 9-11). These calculations were made using the measured tracer concentration uniformity of 93%. As system performance declined, the range of N rates distributed by the emitters widened. Fertigated N varied between 169–240 lbs/acre for the “good” system, 138–252 lbs/acre for the “fair” system, and 115–269 lbs/acre for the “poor” system. The upper end of the latter two ranges goes beyond the maximum recommended N rate for citrus, which represents over-fertilization for the “fair” and

“poor” EU systems.

The potential for N leaching losses caused by non-uniform micro-irrigation is clear. In the case of the “fair” and “poor” systems, some citrus trees could receive twice as much N fertilizer during a growing season than others. In addition, the N recommendation could be exceeded by as much as 35% under some trees, which is where N leaching would most likely occur. Improving EU in poorly-uniform groves will decrease the likelihood of N loss.

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Table 1. Calculated precipitate formation rates and characteristics for various cation and anion combinations (from Boman and Ontermma, 1994).

Cations	Anions				
	CO ₃	PO ₄	SO ₄	OH	O
Ca (100 ppm)					
Precipitate (lb/1000 gal) ¹	2.6	2.2	2.8	1.5	1.2
Precipitate formula	CaCO ₃	Ca ₃ (PO ₄) ₂	CaSO ₄	Ca(OH) ₂	CaO
Anion requirement (ppm) ²	210	158	160	85	40
Color of precipitate	colorless	colorless white	colorless white	colorless	white
Mg (100 ppm)					
Precipitate (lb/1000 gal)	3.7	3.0	8.4	2.0	1.4
Precipitate formula	MgCO ₃	Mg ₃ (PO ₄) ₂	MgSO ₄	Mg(OH) ₂	MgO
Anion requirement (ppm)	346	260	396	140	66
Color of precipitate	colorless white	colorless white	colorless	colorless	colorless
Fe (1 ppm)					
Precipitate (lb/1000 gal)	0.02	0.03	0.02	0.01	0.01
Precipitate formula	FeCO ₃	FePO ₄	FeSO ₄	Fe(OH) ₂	Fe ₂ O ₃
Anion requirement (ppm)	1.5	1.7	1.7	0.6	0.4
Color of precipitate	gray amorphous	white/black yel./white pink	yellow white black/grn.	green white	black red/brown
Mn (0.1 ppm)					
Precipitate (lb/1000 gal)	0.002	0.002	0.002	0.001	0.001
Precipitate formula	MnCO ₃	Mn ₃ (PO ₄) ₂	MnSO ₄	Mn(OH) ₂	Mn ₂ O ₃
Anion requirement (ppm)	0.2	0.1	0.2	0.06	0.04
Color of precipitate	rose light brown	rose gray	pink rose	white/pink brn./black	black dark red

¹Calculated mass of precipitate that could potentially be deposited in an irrigation system assuming a sufficient supply of anion is present.

²The minimum anion concentration that is required for the reaction to proceed to completion.

Table 2. Quantities of N-pHuric required to neutralize 90% of the bicarbonate in an acre-foot of irrigation water (Unocal, 1993).

Bicarbonates in water	N-pHuric 28/27	N-pHuric 15/49	N-pHuric 10/55
ppm	Gallons	gallons	gallons
50	31	16	14
100	61	32	28
200	122	63	56
400	244	126	112

Table 3. Chemical criteria for plugging potential of micro-irrigation water sources (Pitts et al., 1990).

Factor	Plugging hazard based on concentration		
	Slight	Moderate	Severe
pH	< 7.0	7.0 to 7.5	> 7.5
Iron (ppm)	< 0.1	0.1 to 1.5	> 1.5
Hardness as ppm CaCO ₃	< 150	150 to 300	> 300

Table 4. C and N concentrations in scale from three SW Florida citrus micro-irrigation systems.

Scale ID	Total C	Inorganic C*	Organic C	Total N
	----- % of scale weight -----			
1	6.6	0.8	5.8	0.12
2	11.5	1.1	10.4	0.55
3	5.0	1.9	3.1	0.60

*Carbon present as carbonate

Table 5. Metals concentrations in scale from three SW Florida citrus micro-irrigation systems.

Scale ID	Ca	Mg	Mn	Fe
	----- % of scale weight -----			
1	2.7	0.1	0.0	26.6
2	2.8	0.1	0.0	23.1
3	2.2	0.2	0.0	30.6

Table 6. Emission uniformity of micro-irrigation systems in SW Florida citrus groves. Data were obtained from the NRCS mobile irrigation laboratory, Collier County, FL.

Grove	Date	System type	Age	Design output	Meas. output	Fraction of output design	Emission uniformity	Water source	pH	Cond.	Fe	Ca
			yrs	gal/hr	gal/hr	%	%			dS/m	ppm	ppm
1	10/10/96	Micro-sprinkler	7	23	22	96	85	Well	7.5	260	0.5	180
	11/25/98		9	23	24	105	80					
	11/7/01		12	16	16	100	96					
2	11/10/99	Drip	20+	0.62	0.22	35	7	Well				
	3/1/00		20+	0.62	0.66	106	76					
3	2/9/00	Micro-sprinkler	13	14.1	13.8	98	89	Well	7.5	250	0.0	260
	3/2/00		13	14.1	13.8	98	89					
	9/26/01		14	14.1	12.3	87	83					
4	2/9/00	Micro-sprinkler	13	14.1	14.1	100	90	Well				
	9/26/01		14	14.1	12.4	88	84					
5	11/8/93	Micro-sprinkler	6	10.5	13.3	127	81	Well	7.5	442	0.5	300
	2/11/00		13	10.5	12.2	116	51		7.1	260	0.0	200
6	11/30/90	Micro-sprinkler	3	10.5	12.3	117	87	Well	7.5	480	0.5	260
	11/10/93		6	10.5	13.8	131	84		7.0	493	0.5	320
7	11/30/90	Micro-sprinkler	3	10.5	12.8	122	80	Well	7.5	1664	0.5	560
	11/10/93		6	10.5	13.8	131	78		6.8	2112	0.5	880
8	8/26/93	Micro-sprinkler	2	10.5	11.0	105	93	Well				
	6/12/97		6	10.1	12.1	120	62					

Grove	Date	System type	Age	Design output	Meas. output	Fraction of output design	Emission uniformity	Water source	pH	Cond.	Fe	Ca
			ys	gal/hr	gal/hr	%	%			dS/m	ppm	ppm
9	9/1/93	Micro-sprinkler	2	10.5	11.6	110	90	Well	6.8	365	8.0	290
	9/14/95		4	10.5	11.8	112	85		6.9	326	8.0	230
10	8/11/93	Micro-sprinkler	2	10.5	11.2	106	87	Well	7.3	346	5.0	260
	9/14/95		4	10.5	10.4	99	65		7.5	335	8.0	260
11	10/18/93	Micro-sprinkler	2	10.5	11.3	107	85	Well	6.8	423	7.0	320
	6/11/97		6	10.1	14.2	140	68		6.8	384	8.0	260
12	11/27/95	Micro-sprinkler	2	10.5	10.0	95	84	Well	7.6	365	0.5	240
	10/7/96		3	10.5	10.4	99	87		7.1	378	0.0	240
13	10/30/89	Micro-sprinkler	3	12.0	10.4	87	96	Well	7.4	1261	0.0	180
	12/29/98		13	12.0	11.8	99	93		7.4	800	0.0	180
14	10/30/89	Micro-sprinkler	3	12.0	11.5	96	90	Well	7.5	1184	0.0	280
	1/14/99		13	12.0	12.2	102	93		7.1	940	0.0	300
15	12/4/89	Micro-sprinkler	6	12.0	11.9	99	88	Well	7.7	1171	0.0	260
	1/15/99		13	12.0	11.4	95	85		7.4	1110	0.0	300
16	3/20/90	Micro-sprinkler	4	12.0	12.3	103	97	Well	7.3	800	0.0	240
	12/8/98		13	12.0	11.5	96	92		7.6	440	0.0	240
17	3/20/90	Micro-sprinkler	4	12.0	10.8	90	94	Well	7.4	704	0.0	220
	12/10/98		13	12.0	11.6	97	88					
18	10/30/89	Micro-sprinkler	3	12.0	10.2	85	96	Well	7.4	717	0.0	260
	12/22/98		13	12.0	11.7	98	93		7.3	540	0.0	340

Grove	Date	System type	Age	Design output	Meas. output	Fraction of output design	Emission uniformity	Water source	pH	Cond.	Fe	Ca
			ys	gal/hr	gal/hr	%	%			dS/m	ppm	ppm
19	10/30/89	Micro-sprinkler	4	12.0	11.5	96	91	Well	7.4	544	0.0	220
	1/12/99		13	12.0	12.1	100	94		7.5	560	0.0	240
20	10/30/89	Micro-sprinkler	3	12.0	10.0	83	94	Well	7.2	864	0.0	230
	1/5/98		13	12.0	12.0	100	92		7.3	920	0.0	240
21	10/30/89	Micro-sprinkler	4	12.0	10.1	84	81	Well	7.2	832	0.0	260
	12/28/98		13	12.0	10.8	90	82		7.3	560	0.0	220
22	10/30/89	Micro-sprinkler	3	12.0	10.7	90	95	Well	7.3	512	0.0	220
	12/23/98		13	12.0	11.9	99	91		7.3	430	0.0	220
23	12/18/96	Micro-sprinkler	2	16.7	13.2	79	78	Canal				
	3/20/00		6	16.7	16.2	97	75					

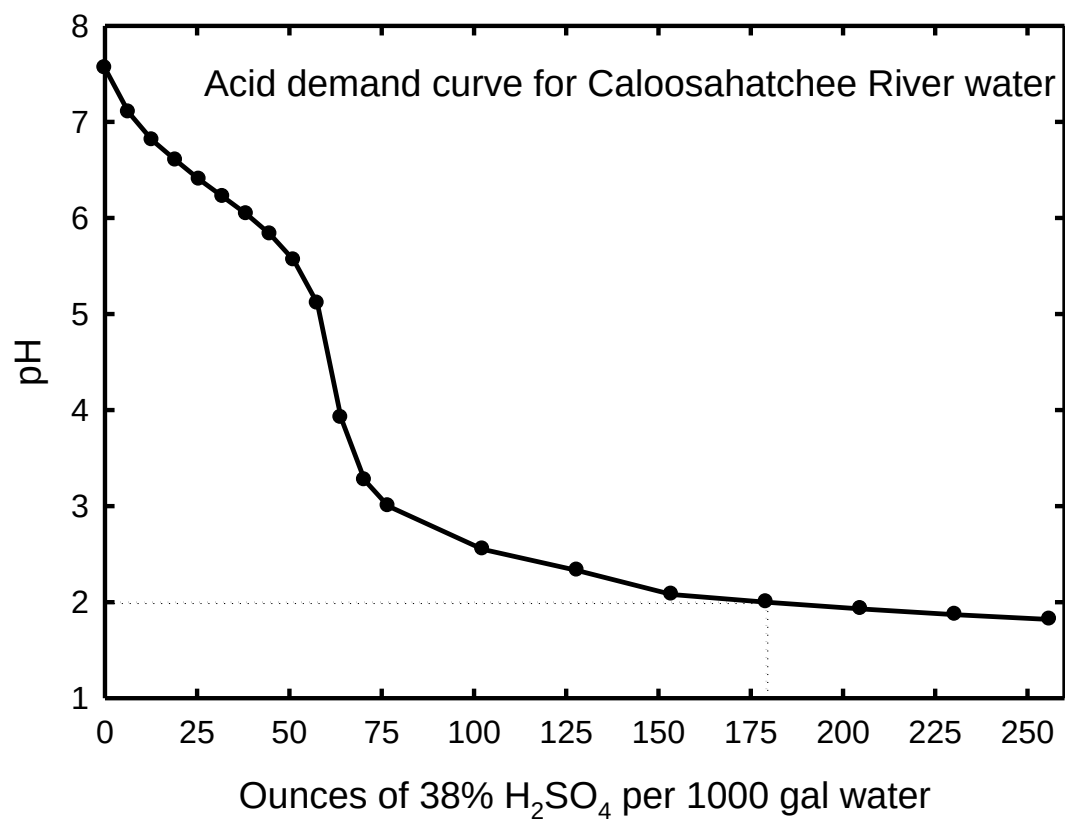


Fig. 1. Typical acid-irrigation water titration curve for south Florida surface water.

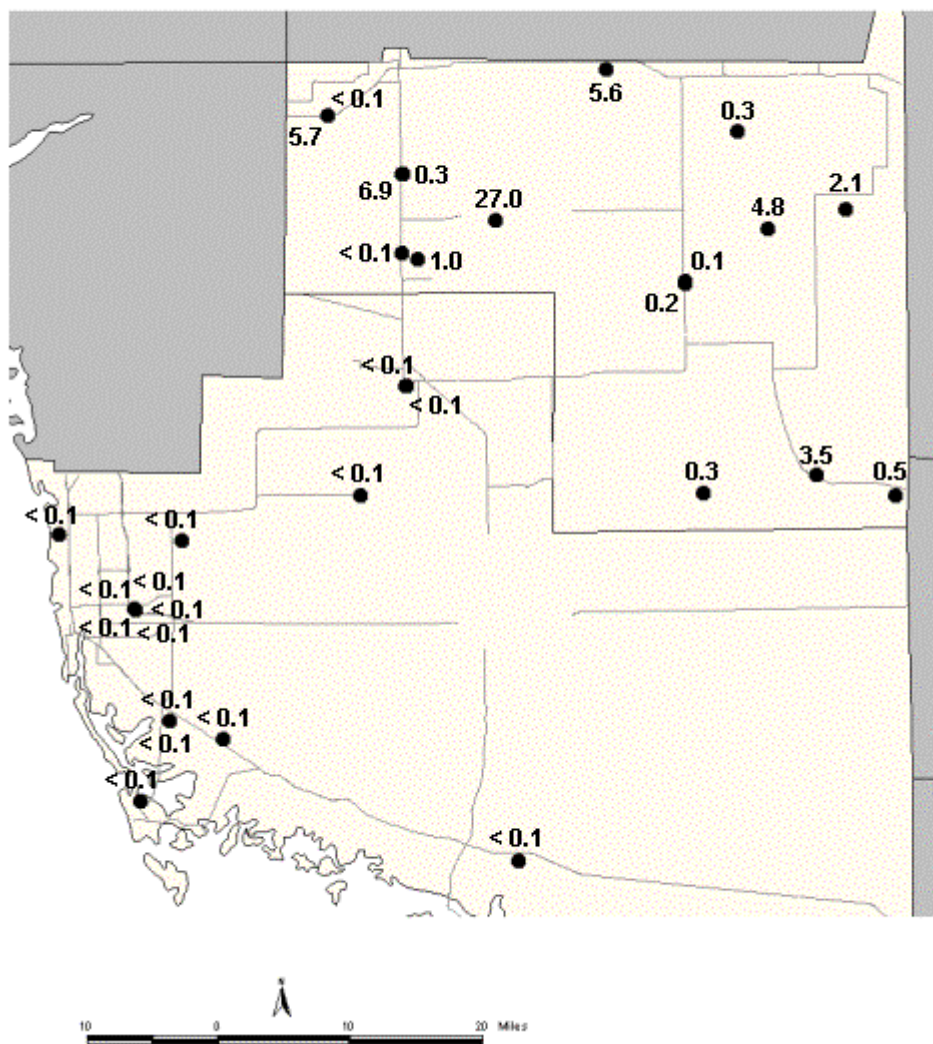


Fig. 2. Iron concentrations (ppm) in Hendry and Collier county well water.



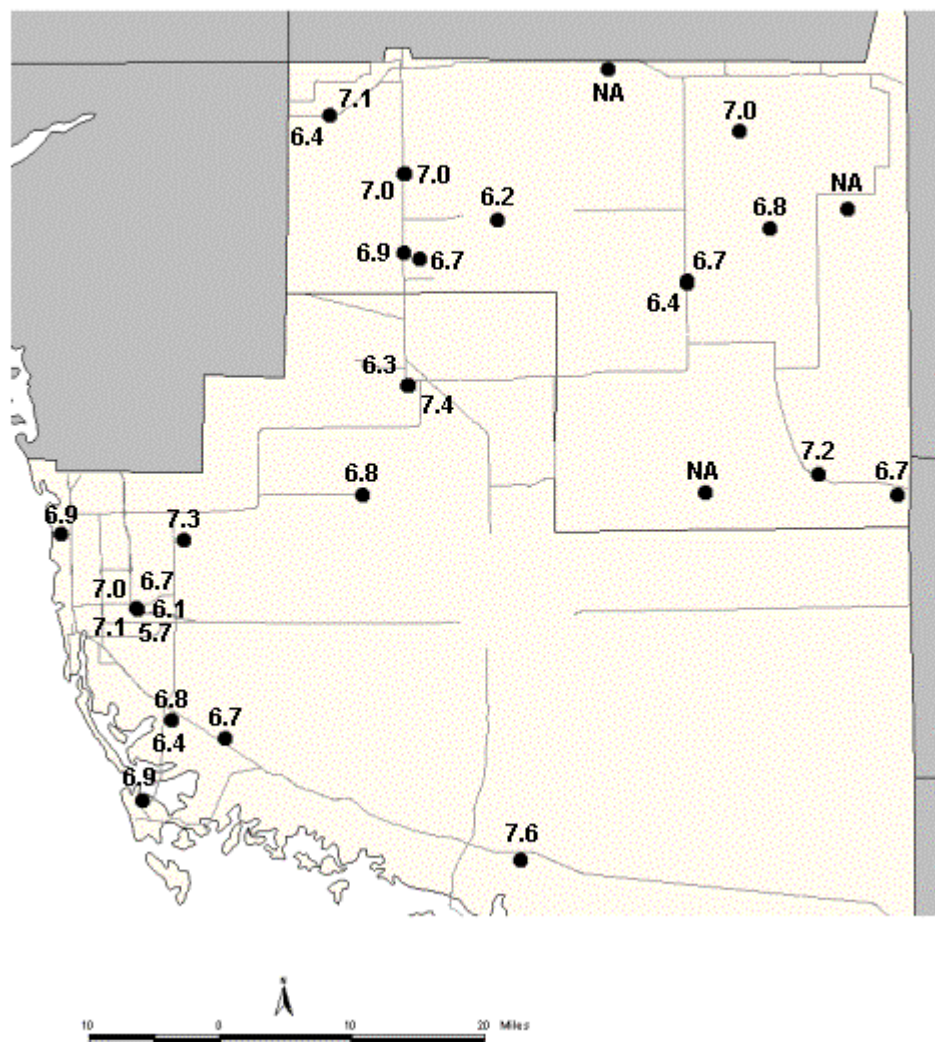


Fig. 5. pH of Hendry and Collier county well water.

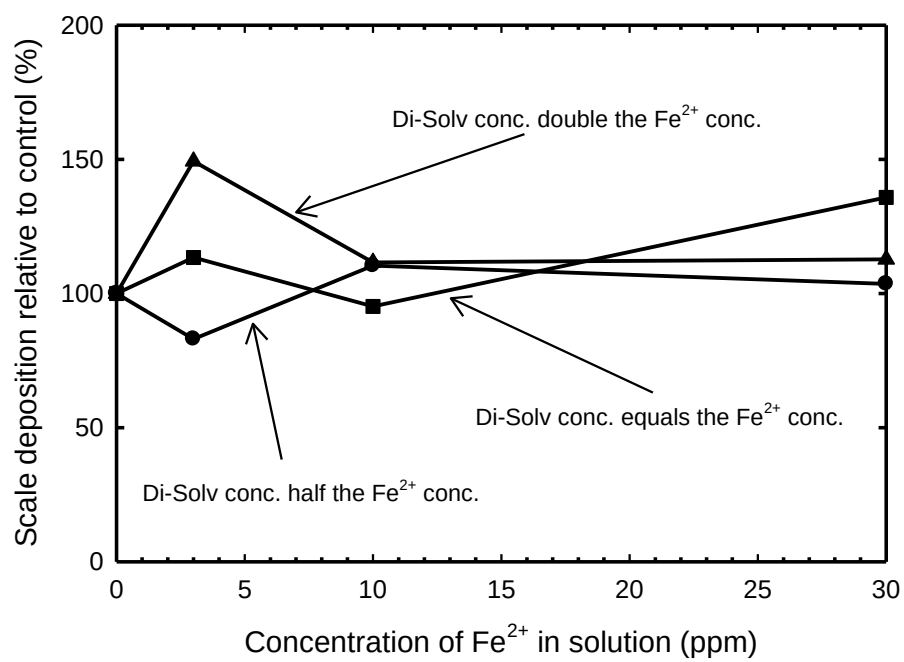
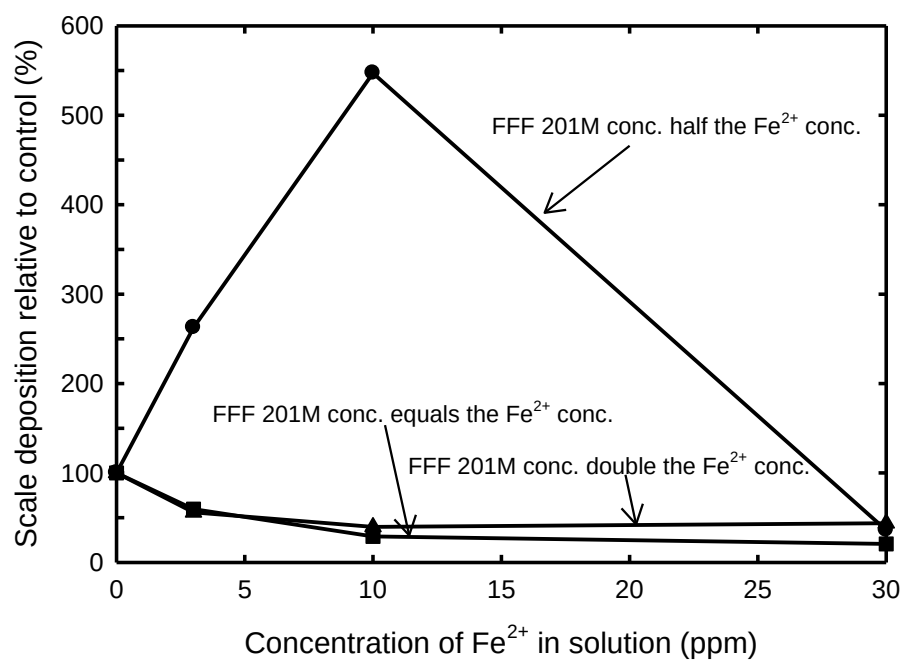


Fig. 6. Effect of scaling inhibitors on water with high scaling potential.

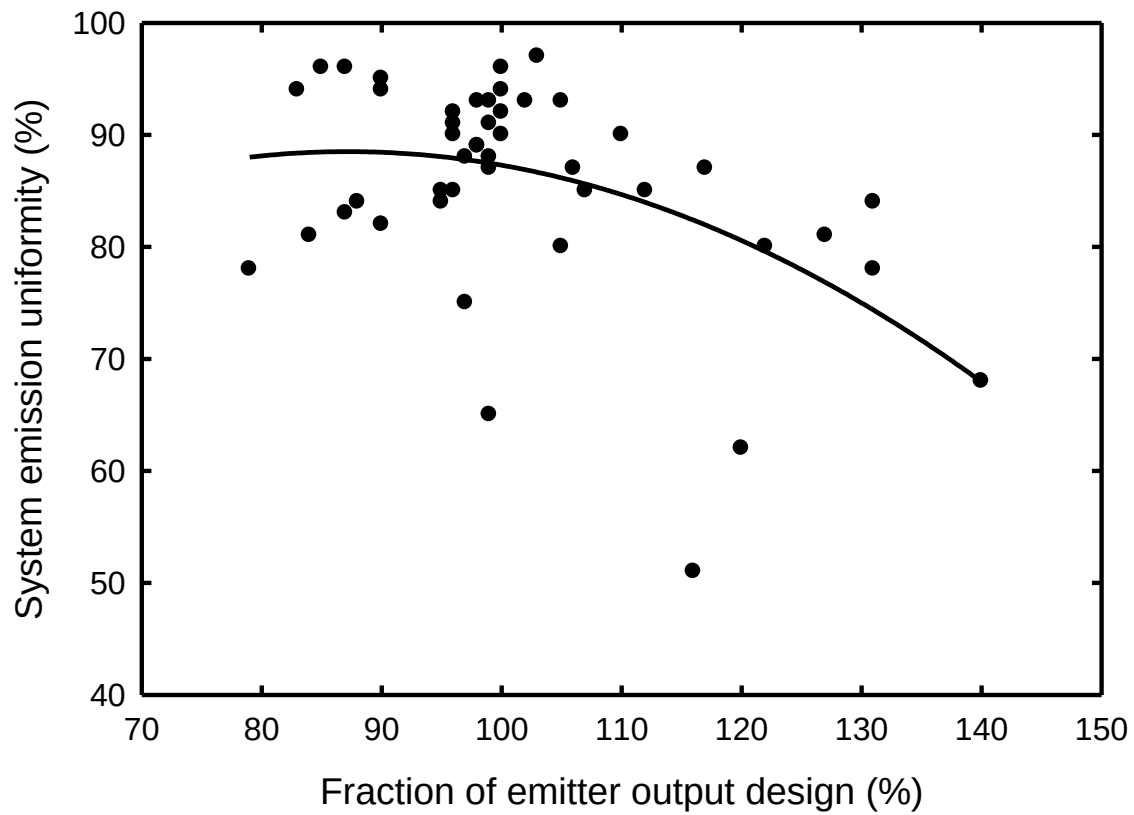


Fig. 7. If cleaning of emitters or removal of system parts causes an emitter flow increase above the design capacity, it becomes more likely that emission uniformity will decrease.

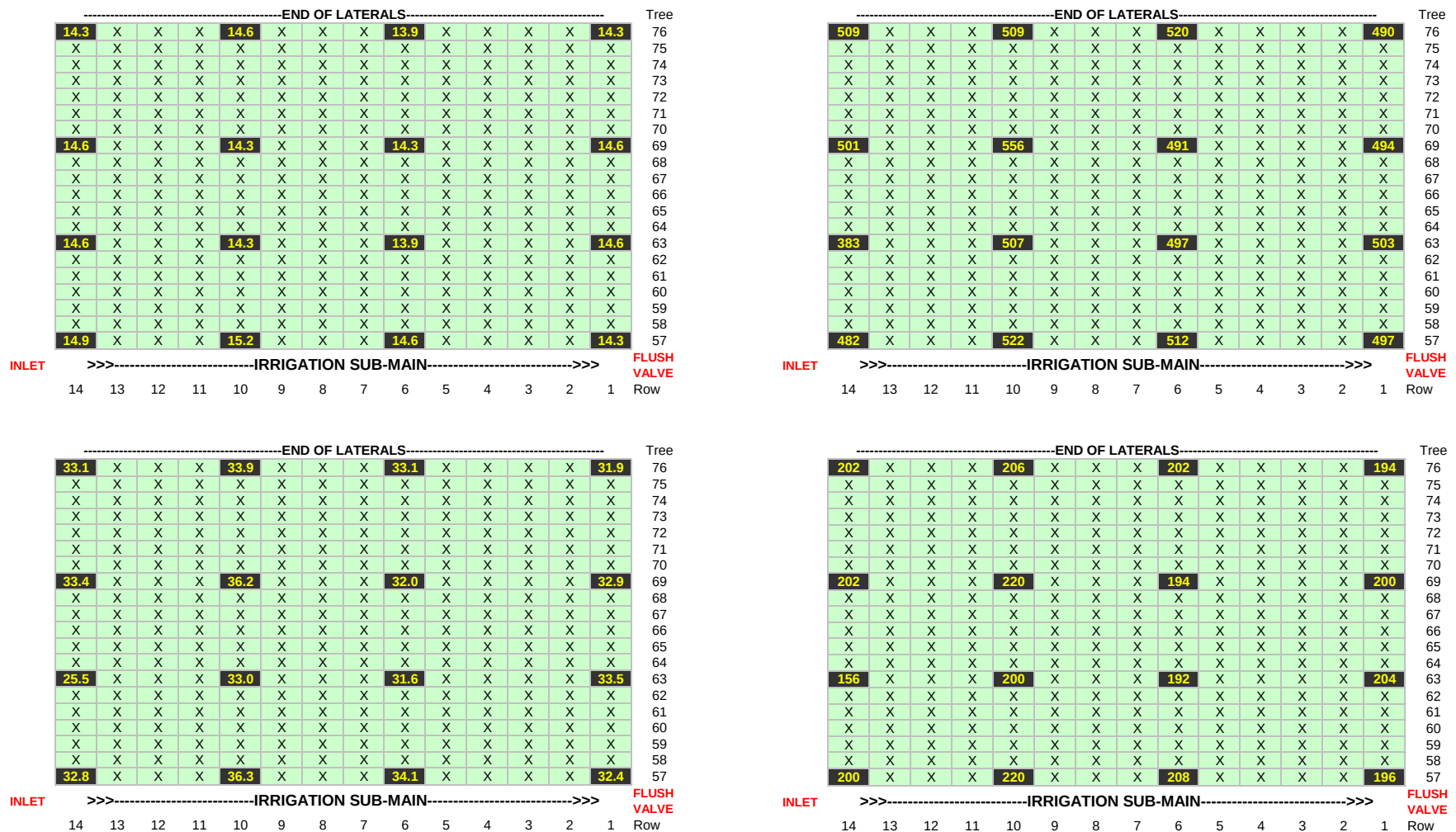


Fig. 8. Diagram of the micro-irrigation system (14.5 gal/hr emitters) used for the evaluation described in Section 6.

Top left: Emitter flow rates in gal/hr (average flow rate = 14.4 gal/hr). Water EU was 98% ("excellent").

Top right: Tracer concentration (ppb) discharged during simulated fertigation. Concentration uniformity was 93%.

Bottom left: Cumulative tracer mass (mg) discharged during simulated fertigation. Mass discharge uniformity was 92%.

Bottom right: Simulated N fertilization rate (lbs/acre) applied to selected trees if the equivalent of 200 lbs N/acre was fertigated through an emitter of average flow rate.

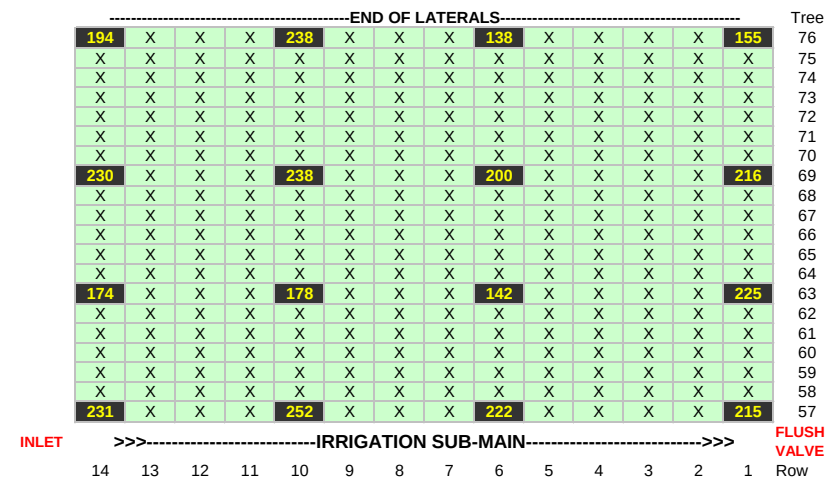
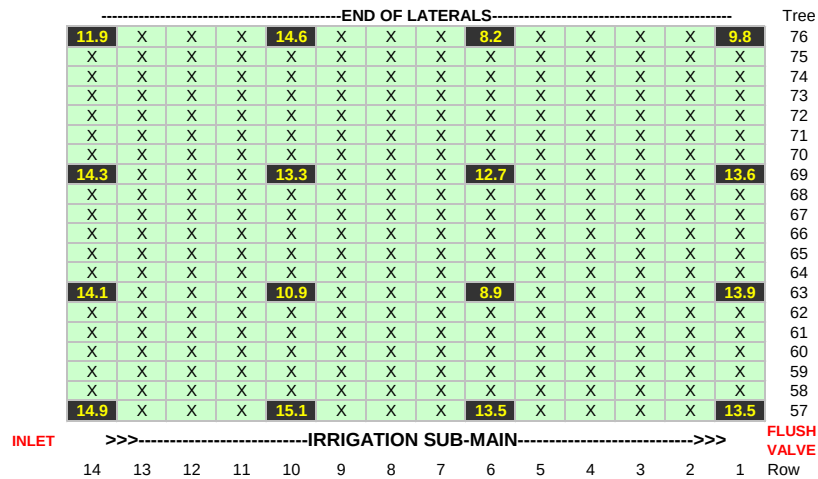


Fig. 10. Example of a micro-irrigation system with a “fair” EU rating. The designed emitter flow rate was 14.5 gal/hr.

Average emitter flow rate = 12.7 gal/hr. Water EU = 75%; Chemical (fertigation) EU = 83%

Left: Actual emitter flow rates (gal/hr).

Right: Simulated N fertilization rate (lbs/acre) applied to selected trees if the equivalent of 200 lbs N/acre was fertigated through an emitter of average flow rate.

