# Best Management Practices for Irrigation Water Quality Issues in the Limestone Coast Region of South Australia

A report prepared for the Limestone Coast Grape and Wine Council
and the South East Natural Resources Management Board

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by

Nikki M. Harrington and Glenn A. Harrington

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Cover photo: A chlorine dosing system installed down-stream of a pump. Gavin Blacker.

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Innovative Groundwater Solutions Pty Ltd.
3 Cockle Court, Middleton SA 5213
Phone: 0458 636 988
ABN: 17 164 365 495  ACN: 164 365 495
Web: www.innovativegroundwater.com.au
Email: glenn@innovativegroundwater.com.au

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# Introduction

Using groundwater and/or surface water of almost any quality for irrigation can lead to negative and undesirable impacts on infrastructure, soils and crops. Issues range from clogging and failure of irrigation infrastructure and bore screens to soil degradation and salinization and impacts on crop health. A national-scale survey of literature and stakeholders was carried out in 2010 to determine the extent and major causes of bore deterioration in Australia (GHD, 2010). It focused on bore construction as well as water quality issues and found there was limited data on the extent of either of these problems. However, the available case studies and literature review suggested that iron biofouling in particular was causing significant problems across Queensland, South Australia, Western Australia and Victoria. Despite this, it was found that there is an overall lack of detection, monitoring and reporting of bore deterioration and irrigation water quality issues across Australia and the monitoring that is carried out is poorly documented (GHD, 2010).

The Limestone Coast area is an important agricultural region for South Australia, contributing an estimated $790 million in agricultural production to the State’s Gross Domestic Product (PIRSA, 2010). Irrigated agriculture forms a large portion of this, with the most significant irrigated crops being wine grapes, pasture seed, pasture and potatoes. Irrigation water is sourced almost exclusively from underground aquifers, with the most heavily used being an unconfined limestone aquifer. Irrigation water sourced from this aquifer is generally of good quality (salinity less than 1,200 mg/L as Total Dissolved Solids). However, many irrigators face issues with irrigation water quality that affect productivity or increase the costs of infrastructure and/or labour. These include:

- High calcium (Ca) and bicarbonate ($HCO_3$) concentrations that lead to precipitation of calcium carbonate scale ($CaCO_3$) and blockage of irrigation infrastructure components (e.g., drippers).
- Iron and sulphate bacteria that cause clogging and reduced performance of irrigation infrastructure (e.g., pumps and pipes).
- Elevated salinities in some areas that affect crops and increase soil salinities.

Additionally, due to increased pressure on the groundwater resource from agricultural and plantation forestry development, as well as climate effects, irrigators are being called upon to improve their irrigation efficiencies. Low volume irrigation can have adverse impacts on soil salinity (Biswas et al., 2009) and the best approaches for managing this depend on crop type, irrigation water quality, soil type and local climatic conditions.

As they face these challenges, irrigators require accessible, comprehensive and user-friendly information about how to identify, prevent, monitor and manage water quality issues should they affect their businesses. In the case of iron bacteria in particular, early detection is critical in the successful management of the problem (Smith, 2015). There is currently a lack of understanding of the extent of irrigation water quality issues across the Limestone Coast region and no forum for irrigators to share their knowledge and experiences with managing these issues.

The Limestone Coast Irrigation Water Quality project has been funded by the Limestone Coast Grape and Wine Council (LCGWC), the South East Natural Resources Management Board (SENRMB) and Wine Australia. The first step in the project was an online survey designed to capture information about the extents of irrigation water quality issues in the Limestone Coast region and the approaches that are being used to mitigate these (Harrington and Harrington, 2016). Despite being advertised to an estimated 1,600 irrigators, completed surveys covered only 9% of the 3,500 licensed wells in the Limestone Coast region, highlighting the challenges in collecting this sort of information. Nevertheless, the survey results provide insight to the extents of the water quality issues and the techniques being used to manage them. Local information obtained from the survey as well as a review of national and international literature form the basis for these Best Management Practice guidelines for managing irrigation water quality issues in the Limestone Coast region.

## 1.1. Objectives of the Best Management Practice Guidelines

1. Provide an overview of each of the key irrigation water quality issues that have been identified in the Limestone Coast region of SA, including their extents, diagnosis and how and why they occur.
2. Summarise the mitigation strategies that are currently available for these issues, including those that are being used in the Limestone Coast region.
3. Provide recommended best management practices for preventing, identifying and treating these issues.

# Clogging of Irrigation Infrastructure by Calcium Carbonate Scale

## 2.1 Overview of the Problem

A common cause of clogging in irrigation systems using groundwater is the precipitation of minerals such as calcium carbonate ($CaCO_3$) (Ayers and Westcot, 1985). The build7 up of these precipitates, also referred to as 'chemical clogging' or 'mineral scale', is normally gradual and difficult to locate. Irrigation water is most susceptible to calcium carbonate precipitation if it has a pH of 7.5 or higher and a bicarbonate concentration of at least 2 meq/L (approx. 120 mg/L) with comparable levels of calcium. Whilst under natural conditions in the aquifer, these ions remain dissolved in the groundwater. However, for groundwater that is close to 'saturation' with respect to carbonate minerals, any of the following changes can cause it to become "over7 saturated" so that the minerals precipitate out of solution:

- Pumping the water out of the aquifer, which causes a reduction in the pressure of the water as it flows into the well. This reduction in water pressure releases dissolved carbon dioxide gas, causing the pH of the groundwater to increase, followed by calcium carbonate precipitation.
- Mixing with water of a different composition, which changes the water temperature, pressure or overall chemistry, or in particular may increase its overall salinity. One of the most common processes leading to mineral scaling is the mixing of 'incompatible waters', e.g., high carbonate water mixed with high salinity water (McLaughlan, 2002). This sort of mixing can occur in bores screened across more than one geological formation, each with different chemical characteristics. The mixing can also occur when corrosion of bore casing creates a connection between two groundwater types that were not previously connected.
- An increase in temperature, for example, as the water travels through or sits in irrigation lines during the day.
- Evaporation from drippers, which increases the concentration of dissolved salts and causes carbonate minerals to precipitate in the dripper.
- Application of fertilizers through the irrigation system. If the fertilizers include calcium, this may result in precipitation of calcium carbonate. However, the addition of fertilizer also increases the water's overall salinity, which in itself can change the solubility of calcium carbonate and cause it to precipitate.

## 2.2 Extent of the Problem in the Limestone Coast Region

The very name of the 'Limestone Coast region' alludes to the potential for this problem to occur and the formation of calcium carbonate precipitates in irrigation infrastructure is an extensive problem across the region. Most groundwater is pumped from either a Quaternary or Tertiary age limestone ($CaCO_3$) aquifer and the groundwater is therefore likely to be close to saturation with respect to this mineral. Forty-three of the 54 respondents to the recent irrigation water quality survey (80%) reported having problems with calcium precipitates blocking infrastructure (Harrington and Harrington, 2016). This corresponded to 277 of the 313 wells represented in the survey (88%). The problem was identified across all of the 15 unconfined aquifer Management Areas represented in the survey although anecdotal evidence suggested that the problem is most severe in the Padthaway region. The reason for this is unknown. However, the authors of this report note that a search of the SA Government's Obswell database (https://www.waterconnect.sa.gov.au) identified that calcium concentrations in groundwater are generally higher at Padthaway than at Coonawarra for example, whilst bicarbonate concentrations are similar for the two regions. Higher calcium concentrations may contribute to the precipitation of more calcium carbonate in the Padthaway area.

**Calcium carbonate scale build-up in a drip line.**

## 2.3 Predicting the Likelihood of Calcium Carbonate Clogging Problems

Whilst there is no standard method to predict whether chemical clogging will occur in any particular irrigation system, the tendency of water to precipitate calcium carbonate can be identified through knowledge of its basic chemical composition and a calculation of the water's saturation index with respect to calcium carbonate (Ayers and Westcot, 1985). Because temperature and pressure are also factors in mineral precipitation, a water's saturation index is not a definitive indicator of a clogging problem, however. Clogging problems are very likely at measured pHs greater than 8.0, which is the pH of a water close to equilibrium with finely ground limestone ($CaCO_3$). However, clogging can occur at lower pHs depending on the overall water chemistry. High temperatures can also contribute to precipitation of minerals in irrigation infrastructure.

## 2.4 Mitigation Strategies

### 2.4.1 Acid

The most effective method to prevent clogging of irrigation infrastructure by precipitation of calcium carbonate (or similar minerals) is to control the pH of the irrigation water or to clean the system periodically with an acid to prevent deposits building up to levels where clogging might occur (Ayers and Westcot, 1985). A common practice among those with problems is to inject hydrochloric or sulphuric acid into the system periodically. If build-ups occur fairly rapidly, some systems need to be flushed as often as once a week. The acid can be added to a system on a continuous basis if the problem is severe enough but this is expensive and the ongoing storage of acid onsite presents a safety risk. In this case, it is recommended that acid be added at a rate to maintain pH close to but not lower than 6.5.

In the Limestone Coast region, the recent survey showed that mineral scale buildup is a common problem that most irrigators manage as a matter of routine by passing acid through drip / spray system components, usually on an annual basis, but up to three times per year in more severely affected areas such as Padthaway. Most people use local contractors to carry this out.

Note: Anhydrous or liquid ammonia should never be applied through irrigation systems experiencing mineral scaling problems as the ammonia can increase pH of the water to values above 11 and cause rapid precipitation of $CaCO_3$ which clogs the entire system (Ayers and Westcot, 1985).

### 2.4.2 Magnetic Water Conditioners

Several irrigators reported in the recent survey that they have tried magnetic water conditioners to reduce the hardness of their water and hence the occurrence of mineral scale. These magnets are clamped around a pipe through which the water discharged from the pump is flowing. Searching the websites of various manufacturers of these magnetic water conditioners has surprisingly not revealed any theoretical description of how the application of magnets improves the quality of water.

A review of the scientific literature available on the topic of the effectiveness of magnetic water conditioners was carried out by Powell (1998) (see Appendix A). This review suggested that it is physically possible that the application of magnets to water flowing through a pipe may alter the electrical charges of some ions and molecules in the water and hence affect their tendency to form precipitates (scale). Magnets may also affect the form that these precipitates take (i.e. the structure of the precipitating crystals). Hence, it is possible that the application of a magnet may reduce the occurrence of mineral scale in some scenarios. Several studies that actually looked at the effectiveness of magnets in reducing mineral scale produced contradictory results, suggesting that there may be some scenarios where magnets are effective and others where they are not (see Appendix A). At the time of the article by Powell (1998), there were no scenarios identified in which magnets would definitely reduce the occurrence of mineral scale.

The most extensive description found of the physical processes that contribute to a reduction in the formation of mineral scale is provided in an article by the manufacturer of the Aqua-Flo magnetic water conditioner (Coke, 2000):

*'Since these reactions are physical rather than chemical, the magnetic water conditioning industry is hard-pressed to satisfy the clamors from the chemical water treatment industry when they ask for proof that the equipment "works." In addition to visual results, physical tests are available to show the positive mechanical changes such as increased water flow and improved heat transfer efficiency in heavily-scaled plumbing systems. The physical energy change factors are described as follows: Calcium carbonate (the major component of scale) exists in two crystal forms: aragonite and calcite. Aragonite has an orthorhombic structure (elongated prism), Brinell hardness of 3.5, and density of 2.947. Calcite has a rhombohedral structure (all sides are equal rhombuses), Brinell hardness of 3, and density of 2.7102. Where*

*the opportunity occurs, ions, atoms, or molecules arrange themselves in positions of least energy and more symmetrical and regular crystal forms. The transformation of aragonite to calcite is much more rapid when in contact with water containing dissolved calcium carbonate. One way to speed up this transformation is to induce a magnetic field which affects the intermolecular forces and, as a result, changes the crystalline structure of scale from aragonite to calcite, which has lower energy, hardness, and density, and has a higher solubility coefficient factor. This effect makes water more capable of dissolving the existing scale build-up encrustations which, in the form of "lime sludge," can be easily rinsed away.'*

In general, those who have tried magnetic water conditioners in the Limestone Coast region are unsure whether they make a real difference, but some report anecdotally that the water seemed better. One irrigator reported that, when it was sprayed onto a glass surface, the treated water left less residue. The magnets that have been tried in the Limestone Coast region have predominantly been supplied by Delta Water Solutions (www.deltawater.com.au). This manufacturer and others report many success stories, and even some results of various in-house trials. However, we found no reference to any independent or externally peer reviewed studies that confirm the claims that these magnetic products reduce the occurrence of mineral scale.

**A magnetic water conditioner applied just downstream of a pump.**

## 2.5 Recommended Best Management Practices for $CaCO_3$ Clogging in the Limestone Coast Region

Groundwater used for irrigation in the Limestone Coast region is drawn from a limestone aquifer and contains high concentrations of calcium and bicarbonate. This groundwater therefore has a high potential to cause clogging by calcium carbonate precipitates. However, the following practices can be used to minimize and manage the problem:

1. Target lower salinity groundwater where possible when drilling new wells – this is likely to have lower calcium and bicarbonate concentrations in general, but a lower salinity also means that the solubility of calcium carbonate will be higher – i.e. the mineral may have less tendency to precipitate in irrigation systems.
2. Avoid screening wells across hydrogeological units containing different water quality.

3. Flush irrigation lines with acid at least annually and more often as necessary to remove scale build up in drippers and dripper lines. A local contractor can be employed to do this to reduce the hazards associated with storing and handling acid.
4. Until the results of a quantitative and independent study into the effectiveness of magnetic water conditioners on reducing mineral scale in the Limestone Coast region are available, irrigators could try this method.

# 3 Clogging of Irrigation Infrastructure by Iron and Sulphate Bacteria

## 3.1 Overview of Iron in Groundwater and Iron Biofouling

Iron (Fe) is present in the rocks and sediments that make up aquifers and is therefore commonly found dissolved in groundwater. Iron concentrations in groundwater are strongly controlled by the chemistry or, more specifically, the redox conditions of the groundwater system. Under oxic conditions (i.e. where oxygen is present) such as occurs close to the water table, iron occurs mainly in its oxidized form, $Fe^{3+}$ (Appelo and Postma, 1999). In the normal pH range of groundwater (pH = 5-8), $Fe^{3+}$ is insoluble and will tend to occur as a solid, meaning that oxic groundwaters usually have low concentrations of dissolved iron. Under anoxic conditions (i.e., low oxygen concentrations) such as occurs deeper below the water table, iron occurs in its reduced and more soluble form, $Fe^{2+}$. Anoxic groundwaters therefore commonly contain significant concentrations of dissolved iron (Appelo and Postma, 1999).

When anoxic groundwater containing dissolved iron ($Fe^{2+}$) comes into contact with oxygen or mixes with more oxygenated groundwater, for example through changes to the groundwater flow regime or mixing in a pumping well, the $Fe^{2+}$ is quickly oxidized to the insoluble form, $Fe^{3+}$, and forms a reddish brown iron-(oxy)hydroxide precipitate. This precipitate can cause clogging problems in wells, pumps and irrigation infrastructure (Appelo and Postma, 1999).

Naturally occurring bacteria in aquifers have a major control over many geochemical reactions that occur in groundwater, including those involving iron (McLaughlan, 2002). Even in the absence of bacteria, iron oxidation and precipitation occurs rapidly in response to a change in redox conditions. However, certain bacteria, collectively known as ‘iron bacteria’, also have the ability to use soluble $Fe^{2+}$ as an energy source for growth and, in the process, oxidise it to its insoluble $Fe^{3+}$ form, causing it to precipitate out as Fe-(oxy)hydroxide (Appelo and Postma, 1999). The resulting iron precipitate becomes incorporated into a biofilm, which also encases living and dead bacteria, their crusts, sheaths, stalks and other particles (Steutz and McLaughlan, 2004). The accumulation of this material can cause serious clogging of groundwater abstraction and irrigation infrastructure. Serious well clogging problems, involving reddish-brown sludgy and slimy precipitates, often associated with high measured concentrations of iron bacteria, are therefore commonly attributed to ‘iron bacteria’ or ‘iron biofouling’ (e.g. Steutz and McLaughlan (2004); Forward (2008); GHD (2010)). Biofouling is any process by which there is an accumulation of material on a solid surface due to the presence of microorganisms including bacteria. Iron biofouling is just one type of biofouling amongst several, including manganese and aluminium biofouling (Smith, 2015). Even in the absence of ‘iron bacteria’, the solid Fe-oxyhydroxide precipitates formed during the inorganic oxidation of $Fe^{2+}$ described above can provide a substrate for the growth of other bacteria (J. Moreau, University of Melbourne, pers. comm. 13th December 2016).

Both inorganic and bacterial iron deposits can cause clogging of wells and infrastructure. However, biofouling deposits are the most common well fouling deposits (McLaughlan, 2002). Bacterial iron deposits can often (but not always) be distinguished from purely mineral iron precipitates by a soft, feathery or slimy appearance, and microscopically by the presence of bacteria and certain mineral structures (Smith, 2015). GHD (2010) concluded that iron biofouling is the most dominant bore failure process across Australia. It is a significant cause of bore deterioration across Queensland, South Australia, Western Australia and Victoria. Victoria's Department of Sustainability and Environment (DSE) has reported a rapid increase in the occurrence of iron bacteria in bores throughout Victoria (DSE, 2004). Approximately 40% of land holders surveyed by the SA Murray Darling Basin NRM Board (2006) were experiencing iron bacteria problems. Iron biofouling is also a widespread issue overseas (e.g. Cullimore and McCann (1977)) and it has been estimated that 70% of groundwater bores in the Canadian prairies experience biofouling problems (approx. 270,000 bores) (GHD, 2010).

**Iron biofouling of a submersible pump. Source: Forward (2008) in GHD (2010).**

The main causes of iron biofouling are the availability of dissolved or complexed iron, the presence of the bacteria themselves, an environment that encourages microbial growth (i.e. nutrients and oxygen) and flow velocities greater than groundwater flow rates (Tyrrell and Howsam, 1994; Smith, 2015). The magnitudes of these factors control the rate of biofouling (McLaughlan, 2002). Steutz and McLaughlan (2004) investigated the factors contributing to iron biofouling of wells in the Wakool saline groundwater interception scheme in the Murray Basin. They found that all wells experiencing iron biofouling problems were associated with (a) groundwater dissolved iron concentrations greater than approximately 1 mg/L, and (b) the presence of the stalked bacteria *Gallionella* sp. These conditions were absent for wells not experiencing iron biofouling at the same site. Cullimore (2000) states that aquifers with any contact with the surface or that are very shallow and with dissolved iron concentrations greater than 0.5 to 1.5 parts per million have a high potential to contain iron bacteria. Therefore, whilst drillers and pump contractors are often accused of transporting iron bacteria from one place to another, the most likely source of iron bacteria in a well is the aquifer around it. However, drilling contractors can take steps to minimize the transport of bacteria from one well to another, recognizing that drilling equipment can never be expected to be sterile.

As described above, a very common scenario for the occurrence of iron biofouling is the mixing of oxygenated groundwater from near the water table with deeper groundwater that has high $Fe^{2+}$ concentrations, for example within a groundwater well (van Beek, 1989). When these shallow and deeper water types mix, the oxygen, aided by bacteria, oxidises the iron to produce iron-(oxy)hydroxide deposits and biomass. Likewise, a drop in water table can bring the upper zone of oxygenated groundwater to within an iron-rich section of the aquifer, allowing bacterially-mediated oxidation of the iron to occur.

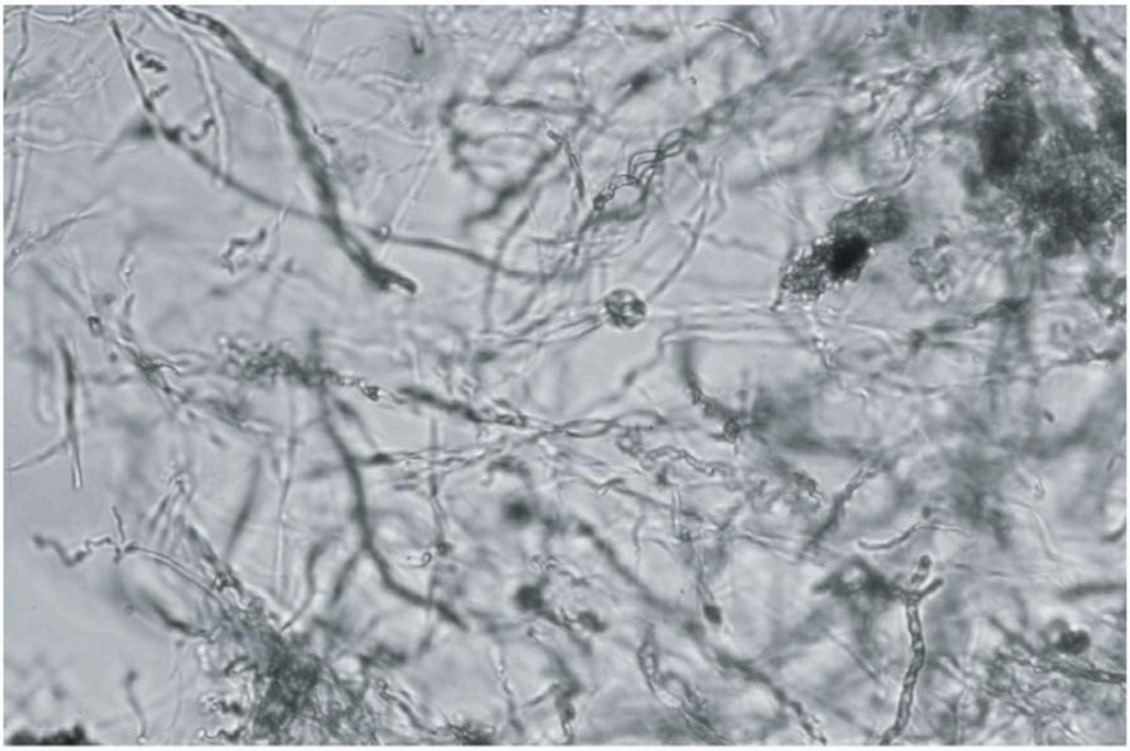
Some potential symptoms of iron biofouling include (GHD, 2010):

- Decreased flow, e.g. clogging of pumps or well screens;
- Decreased well yield due to plugging of voids in the aquifer;
- A decrease in water quality, e.g. taste, colour, staining, odour;
- Increasing acidity and hence corrosion of bore components;
- Encrustation of bore casing, screens, reticulation and irrigation systems;
- Spontaneous slugs of brown, black or red water;
- Short pump life;

**100 mm pipe clogged with an iron bacteria biofilm. Source: SA MDB NRM Board (2006).**

There are numerous different species of iron bacteria, which have three main forms (GHD, 2010):

- Siderocapsa – numerous short rods surrounded by a mucoid capsule. The deposit surrounding the capsule is hydrous ferric oxide, which has a rust-brown appearance.
- Gallionella – twisted bands that resemble a ribbon, with bacterial cells at the end of the ribbon. *Gallionella* sp. were found to occur along with elevated dissolved $Fe^{2+}$ concentrations in biofouled wells in the Wakool subsurface drainage scheme, in the Murray Basin. These bacteria were absent in non-fouled wells at this site (Steutz and McLaughlan, 2004).
- Filamentous Group – cells that are organized into filaments enclosed in a sheath. The sheaths are commonly covered in a layer of slime and become encrusted with ferric hydrate, resulting in large masses of filamentous growth and iron deposits.



**A photomicrograph of the stalked *Gallionella* sp. bacteria (Source: Steutz and McLaughlan (2004)).**

Within groundwater wells, iron bacteria are predominantly found in areas of high water velocity or turbulence, e.g. within the gravel pack of a bore near the pump, in bore screens, pump inlet screens, pump internal components, discharge components and in pipelines (Forward, 2008). Iron bacteria can adhere to the insides of solid risers but flexible riser columns are relatively unaffected as they expand under pressure and flex at pump start up, removing iron bacteria deposits (GHD, 2010).

A common factor in iron biofouling problems is that preventative measures are rarely practiced and rehabilitation measures are generally introduced only once the bore deterioration issue has been identified. GHD (2010) concluded that there is an overall lack of detection, monitoring and reporting of bore deterioration in general across Australia and the monitoring that is carried out is poorly documented. This means that effective risk management cannot be carried out at a national, state or even a local level.

## 3.2 Sulphate Bacteria

'Sulphate bacteria' are a group of naturally occurring bacteria that interact with sulphate ($SO_4$) in the environment and are known to cause clogging of wells and irrigation infrastructure when pumping from anaerobic (anoxic) aquifers (Appelo and Postma, 1999). High flow velocities near abstraction wells provide a larger food supply in the form of dissolved organic carbon and sulphate ($SO_4$) for microorganisms, such as *Desulfovibrio* sp., which live in these conditions (Appelo and Postma, 1999). These organisms are generally not able to remain attached to pipes and other irrigation infrastructure under high flow velocities.

## 3.3 Extent of the Problem in the Limestone Coast

The recent Irrigation Water Quality Survey has indicated that 'iron bacteria' is an issue of great concern to irrigators in certain areas of the Limestone Coast, particularly in the Coonawarra and Naracoorte areas (Harrington and Harrington, 2016). Here, according to anecdotal evidence, the problem has become worse in recent years. For example, irrigators interviewed from the Coonawarra area suggested that the problem was around, affecting a few wells, in the 1960s and 1970s but was not too much of an issue at that time, becoming a lot worse when irrigation development increased in the 1990s. Twenty-one of the 54 survey respondents (39%) indicated that they had 'iron bacteria' in at least one well. Ten of the 15 unconfined aquifer Management Areas covered in the survey had at least one case of 'iron bacteria' reported.

**A pump component from the Limestone Coast region affected by an iron precipitate. Photo: Lawrences Irrigation.**

The survey results and anecdotal evidence suggest that 'iron bacteria' are currently not a problem in the Padthaway area and that, whilst present in the Robe (Waterhouse) area, it is not considered to be a significant problem there. Four respondents, from the Management Areas of Mayurra, Joanna, Wirrega and Zone 3A, reported the presence of sulphate bacteria in their wells. All of these occurred in conjunction with iron bacteria.

Some but not all irrigators who reported 'iron bacteria' problems also reported that groundwater levels in their areas had declined over recent times or that they had needed to deepen their wells in the past 10 years (Harrington and Harrington, 2016). This indicates that groundwater level decline may be a potential driver for the increase in the number of cases of iron clogging in some areas and warrants further investigation. Declining groundwater levels and / or changes to the water levels in wells can cause oxic groundwater to come into contact with anoxic groundwater and sediments containing reduced iron. As described above, this can result in the formation of iron (oxy)hydroxide precipitates that can clog the aquifer, well, pump and other irrigation system components.

The involvement of bacteria in the formation of the reddish brown clogging material described by irrigators in the Limestone Coast region requires confirmation (J. Moreau, University of Melbourne, pers. comm., 13th December, 2016). Whilst a few irrigators have provided analyses of irrigation water samples showing the presence of large numbers of iron bacteria, there have been no reported analyses of the solid clogging material itself. Chemical and microscopic analysis of the clogging material to identify whether there is a significant biological component would help to clarify this. However, it is noted that those who use chlorine dosing to treat relatively severe clogging problems report improvements in the level of clogging. This, along with the numbers of iron bacteria present in some irrigation water samples collected by irrigators, provides an early indication that some of the iron clogging being experienced is iron bacteria related. Some of the milder cases of reddish-brown precipitates observed on pump components and irrigation lines may be simply inorganically oxidized iron, rather than 'iron bacteria' problems. Further research into the drivers of iron precipitation in the Limestone Coast is recommended, including investigation of the redox conditions in the aquifer system, spatial distributions of dissolved iron, the types of bacterial communities present around clogging and non-clogging wells and the mineralogical and bacterial compositions of the clogging precipitates.

The Irrigation Water Quality Survey results indicated that, where 'iron bacteria' and 'sulphate bacteria' have been identified, they always affect infrastructure and always cost money. The costs to businesses vary greatly depending on the severity of the problem but estimates provided were of the order of $100/ha/yr or a total of $1,000 to >$5,000/yr. Follow-up discussions with irrigators indicated that there is a lot of uncertainty about the most appropriate treatment methods to use. There is also a lot of concern about the impacts on businesses should the problem become worse.

The following sections focus on the mitigation strategies available for iron bacteria problems, as early evidence suggests that the severe cases of clogging may be iron bacteria related and this was the most significant biofouling problem identified in the Limestone Coast region

(Harrington and Harrington, 2016). However, many of these mitigation strategies are also applicable to sulphate bacteria.

A dripper line from the Limestone Coast region affected by iron sludge.

## 3.4 Preventative Measures

The underlying message throughout the literature on iron biofouling is that early detection and treatment of an affected well before the problem becomes serious is crucial. In areas where iron biofouling is known to occur, implementation of precautionary methods during bore and pump design and drilling is even better. Canadian research (not sourced; in GHD (2010)) suggests that once a bore has lost more than 40% of its original capacity, it is likely to be difficult to rehabilitate. Part of the reason for this is that, as iron bacteria biofilms build up, it becomes increasingly difficult for treatment chemicals to penetrate these to reach and kill the bacteria.

As iron biofouling is commonly caused by the mixing of chemically different waters, screening of new wells across zones of different groundwater chemistry should be avoided, for example across zones separated by a low permeability layer or zones of different permeability. Different chemical zones in an aquifer can often be identified by differences in colour of the aquifer material. Steutz and McLaughlan (2004) recommend drilling test wells prior to installing large production bores and avoiding zones with high dissolved iron concentrations. Whilst the common situation in unconfined aquifers is for dissolved iron concentrations to increase with depth (van Beek, 1989), Steutz and McLaughlan (2004) found dissolved iron concentrations at their Wakool site to be highly variable over small spatial scales, both laterally and vertically. The spatial distribution of dissolved iron concentrations in the unconfined aquifer in the Limestone Coast region has not been investigated in detail. Further work on this may assist irrigators wanting to drill new wells in avoiding zones of high dissolved iron concentrations.

Once a well is drilled, McLaughlan (2002) recommends the regular monitoring of groundwater quality to observe changes in or the occurrence of elevated iron and/or manganese levels as well as bacteria to anticipate potential problems. Steutz and McLaughlan (2004) state that, as iron biofouling can occur in pipes downstream from the pump, oxygenation of the groundwater during pumping should be minimized, e.g. through ensuring there are no leaking seals or avoiding pumping water from more oxygenated parts of the aquifer.

The following preventative methods have also been recommended by Smith (2015):

- Never put surface water down a well.
- Do not use organic polymer muds in drilling wells or phosphorous containing mud breakers.
- Develop wells thoroughly after drilling and always chlorinate after development or pump servicing (chlorination chemicals and concentrations are recommended in Smith, 2015).
- Chlorinate any equipment used on wells.
- Never re-install any parts that are encrusted or covered in biofilm of any kind without thorough cleaning and chlorination.
- Test water quality and total coliforms on new wells (after evacuating 3 bore volumes).
- Use specific tests for iron and/or sulphate bacteria.
- If iron bacteria are identified in a new well, it is recommended to redevelop and shock chlorinate the well.

Through experience in dealing with serious biofouling problems in saline interception schemes around the River Murray, Forward (2008) has also developed the following recommendations:

- (In areas where iron bacteria problems are known to occur) anticipate potential problems during well design and design conservatively in terms of well construction, pump size and capacity, pump selection and iron bacteria control techniques.
- Implement a performance monitoring and maintenance strategy.
- Measure bore performance indicators every three months to identify, monitor and mitigate potential effects of bore deterioration processes at an early stage, i.e.:
    - Pump discharge pressure
    - Flow (using a flow meter)
    - Bore water level
    - Pipeline flows and pressures in larger systems.

## 3.5 Testing for Iron Bacteria

According to Smith (2015), tests for total coliforms, biofouling bacteria and key chemical indicators (total and ferric iron) should be carried out soon after a well is drilled or serviced in any way, and also at regular intervals, usually annually or when there is any noticeable change in the water or well performance. However, it should be noted that testing of a water sample may not detect iron bacteria, as they adhere to surfaces, so testing of water is not always definitive or reliably quantitative. Discussions with irrigators from the Limestone Coast region highlighted this; those wells that appear to be the worst affected do not always have the highest iron bacterial counts when test results are available for comparison. However, the presence of iron bacteria can be used as an indicator of a potential problem. It is possible to install a special collector surface within a well, which is designed to be removed and analysed and this should produce more quantitative results (Smith, 2015). However, this is not currently standard practice.

Several irrigators from the Limestone Coast have had their water tested for iron bacteria by the Australian Water Quality Centre. Testing can be organised by calling 1300 653 366 or emailing awqc@sawater.com.au. Table 1 provides the details of some of the relevant tests for iron bacteria that can be performed by Australian Water Quality Centre. Tests for total and dissolved iron should also be requested. Ideally, full chemical analyses (i.e. Total Dissolved Solids, major cations and anions and nutrients) should also be carried out with measurements of temperature, pH and alkalinity made at the time of sample collection to better understand the chemical conditions contributing to the clogging problem. A geochemist would be required to interpret the results of such analyses.

**Table 1. Details of water quality and bacteriological tests performed by The Australian Water Quality Centre relevant to identifying a potential or actual iron bacteria problem. Information current at the time of preparation of this report.**

| Test Description | Cost per sample | Sampling procedure | Sample turnaround time | Detection Limit |
|---|---|---|---|---|
| **Microscopic identification and spread plate count to identify iron bacteria. AWQC Codes: IRON_SP and IRON_MF** | $105 + GST | Collect sample in a sterilized bottle provided by AWQC. Store on ice and return to lab within 24 hrs of sample collection. | 11 days | 10 organisms per millilitre |
| **Bacterial DNA analysis. Provides bacterial makeup – results are semi quantitative expressed as a % of each organism against the total DNA present.** | $280 + GST However, the cost is reduced with multiple samples. A microscopic examination is also required with this to determine the fungal or algal component ($95 + GST) | As above. | 60 days | NA |

ALS Global also perform a range of water quality tests including tests for iron bacteria (Table 2). Contact Kieren Burns on 8162 5130 (kieren.burns@alsglobal.com) to arrange for sample bottles, sample transfer and testing. Samples can be collected in the afternoon and taken to Mount Gambier where ALS will arrange for them to be transferred overnight to Melbourne via courier. Small batch and courier fees apply in addition to the prices shown below.

Table 2. Details of total iron and iron bacteria analyses carried out by ALS Global.

| MATRIX | TEST PARAMETER | ALS Code | TECHNIQUE / METHOD REFERENCE | LIMIT OF REPORTING | PRICE PER SAMPLE ($) Ex. GST |
|---|---|---|---|---|---|
| WATER | ICP/MS: 1st metal (Inc. digestion) (e.g. Fe) | EG020T | USEPA 6020 ICP/MS | 0.0001-0.01 mg/L | 18.00 |
| WATER | Iron reducing bacteria (NN) | MW016 | BART Kit | <25 cfu/ml | 75.00 |

As described in Section 3.1 above, iron bacteria tend to collect around well screens and filter packs. A downhole camera can be used to confirm the presence of iron bacteria biofilms in a well, their location and also the severity of the problem.

Confirmation of the role of bacteria in the formation of clogging material, as opposed to simple inorganic oxidation of iron, is important in selecting the most effective treatment method (J. Moreau, University of Melbourne, pers. comm., 13th December 2016). Microscopic and chemical analysis of the clogging material to identify mineralogy and confirm the presence of an iron bacteria biofilm is the most definitive way to do this and can be carried out by a range of laboratories, including the Australian Water Quality Centre and ALS Global (see contact details above).

## 3.6 Available Treatments

Results of the recent Irrigation Water Quality Survey suggested that the location at which iron bacteria problems occur in an irrigation system can vary from within the well screen (restricting well yields) and the pump (causing reductions in flow rates and pump failure) to within dripper lines and drippers (affecting dripper outputs and hence crop health). A review of the available literature and treatment products advertised on the internet suggests that the most appropriate treatment for an iron bacteria problem depends on the location of the problem. In all cases, iron bacteria originate in the aquifer and hence iron bacteria, where they are causing apparent problems, will always occur in the well and around the pump. However, they may not be causing a problem here. In some cases, however, this may be the main location of the problem and downstream irrigation infrastructure (e.g. dripper lines) are unaffected.

### 3.6.1 Treatment of Affected Groundwater Wells and Pumps

Of those irrigators captured by the survey who were experiencing iron bacteria problems at the well, only two identified a reduction in bore yield. The remainder had problems with clogging and damage to pump components. A national-scale review of bore deterioration issues by GHD (2010) found that a range of preventative and rehabilitation methods have been used to manage iron biofouling issues in Australia. Unfortunately, none of the treatments appear to completely cure an iron bacteria problem and most rehabilitation attempts result in short-term solutions (SA MDB NRM Board, 2006 in GHD, 2010).

#### *Physical Methods*

The simplest treatment for clogged pumps is to remove the pump periodically and clean and replace components where necessary. Some irrigators find that doing this once every five years is sufficient to keep the problem under control and that the expense is manageable. Likewise, in mild cases where well yields are affected, well contractors can be employed to clean well screens using brushes and air surging / redevelopment.

Forward (2008) (in GHD (2010)) suggests the use of an alternative pump. For example, the MonoTM Pump has been found by SA Water to reduce the effects of the clogging process as it is a positive displacement pump and is less prone to losing flow as clogging increases and is inherently self-cleaning.

### *Chemical Treatments*

For other irrigators in the Limestone Coast, the degree of clogging or deterioration of pumps is so great that the pump must be removed and cleaned or replaced every one to two years, which is a very costly exercise. Additional treatment is required in these cases. The most successful treatment method for iron bacteria problems identified by GHD (2010) was chemical treatment.

There are numerous other chemical treatments for iron bacteria advertised on the internet. Some of those listed in GHD (2010) and their pros and cons are summarized below. In many cases, there is little information readily available about the active ingredients in these commercial products. However, as much information as possible has been provided below.

- 'Clearbore' ( www.clearbore.com.au). The results from a survey conducted in the Malle PWA of SA suggested that this was the most effective treatment product on the market at that time (SA MDB NRM Board, 2006). The manufacturers state that this product dissolves and clears iron bacteria crusts or sludge, that it is biodegradable and non-toxic.

- Acids. Sulphamic acid ($NH_3SO_3$) is commonly used worldwide in well cleaning chemicals. The acid generally comes as a soluble white crystalline powder, which is poured down a well. The acid dissolves as it is allowed to slowly (at approx. 0.5-1.0 L/minute) flow through the pump for approximately 12 hours. The pump is then restarted to flush the bore. Methane sulfonic acid (MSA) liquid can be used as an alternative to sulphamic acid (GHD, 2010). Acid dosing is a simple and cost-effective method. However, GHD (2010) suggest that it is effective against carbonate scales but not against biofouling on its own. However, acid may be effective in clearing iron deposits contains significant amounts of carbonate material, which may be the case in the Limestone Coast region. A mineralogical analysis of the clogging material would identify whether this is the case. Sulfamic acid is not as aggressive as hydrochloric or sulphuric acid, which can be very harmful. As it is available as a powder, it is easier to transport and handle. Inhibiting agents, which limit the acid's attack on casing, pump and screen metallic parts are often mixed with sulfamic acid.

- Biocides. Chlorine is the most commonly used biocide in well maintenance. Several irrigators who responded to the Irrigation Water Quality Survey reported that they use a chlorine-based biocide to control iron bacteria problems, generally administered as pellets through an automatic dosing system. These products are discussed further below. Electrolytic chlorination is a biocidal method that can be cost-effective in saline environments, as a chlorine solution is produced by electrolysis of the saline water being pumped. Glycolic acid is also considered to be a good biocide and biofilm dispersing agent (GHD, 2010). Biocides are only effective in treating iron clogging problems that are bacteria related.

- 'Pumpmate' (http://www.biostatengineering.com/pumpmate.htm) is a product developed by Biostat Engineering consisting of copper electrodes that are dissolved by an electric current to act as a biocide (Forward, 2008).
- 'Boresaver' range of products (http://boresaver.com.au). Boresaver is manufactured by Aquabiotics Industrial Pty, and is a range of cleaning solutions for systems that are contaminated with iron oxide, manganese oxide and iron related bacteria. Boresaver Ultra C and Boresaver Liquid are approved by the US Secretary of State under regulation 31 of the Water Supply (Water Quality) Regulations 1989 for use in potable water applications. The Boresaver Ultra C product is described on the manufacturers website as a blend of monohydrates and organic acids, with one of the key components being oxalic acid. The manufacturers of this product state that it is environmentally friendly and that oxalic acid is a naturally occurring, biodegradable organic acid, however we have not independently verified this. According to the website, on application of Boresaver Ultra C to iron deposits, an oxidation-reduction reaction occurs: the acid is oxidised to water and carbon dioxide and the iron oxides/hydroxides converted to soluble iron. While this process is underway the slimes that form the large proportion of the clogging problem are disrupted and dissolved. With the clogging and iron oxides dissolved it becomes a simple matter to remove them from the bore by either airlifting or pumping. Boresaver Liquid Enhancer is a copper salt solution that acts as a biocide for severe iron biofouling cases (Forward, 2008).
- Some of the products available on the market are not suitable for saline or hard water, however the product Sokolan® is reported to be suitable under these conditions (GHD, 2010). Our research into the details of the product suggests that it is simply a dispersing agent.

The most common treatment method currently being used by irrigators in the Limestone Coast region is chlorine dosing. This is reported to maintain iron bacteria clogging problems at a manageable level. Chlorine is a biocide and will therefore only be effective if clogging is biologically mediated. Therefore, if there is some doubt that clogging is being caused by iron bacteria, analyses of water and samples of the solid clogging material should be carried out as described in Section 3.5 to confirm the presence of iron bacteria before investing in a chlorine dosing system.

**A chlorination system used in the Limestone Coast region, showing the automatic dosing unit and chlorination pellets. Photo: Gavin Blacker.**

The chlorine dosing systems listed in the recent Irrigation Water Quality survey were Goldclean, Halosan and Halovac, which our research suggests are essentially the same chemical. Most of the following information has been obtained from the GoldTec Website (www.goldtecsystems.com.au):

GoldClean / Halosan / Halovac are all pelleted BCDMH (1-Bromo-3-chloro-5,5-dimethylhydantoin) chemicals. According to Wikipedia, BCDMH is an excellent source of both chlorine and bromine as it reacts slowly with water releasing hypochlorous acid and hypobromous acid. BCDMH is used as a chemical disinfectant for recreational water and drinking water purification. For well treatment, the Goldclean / Halosan / HaloVac is applied at 5 ppm to the well after each irrigation event, (depending on the bacteria level in the bore). The water can then be introduced back into the irrigation system.

To treat heavy build-ups in irrigation systems, the manufacturers suggest a shock treatment where the product is injected at higher concentrations. A strong 20-30 ppm solution of chemical is injected into the mainline, left for approximately 1 hour before flushing to waste.

Ongoing maintenance of driplines is then recommended to prevent the re-blocking of the system. They suggest treating on daily, weekly, fortnightly or monthly basis with increasing quantities respectively from 1 ppm in constant applications to 3 ppm on a fortnightly or monthly basis. This application is done either by applying GoldClean through a GoldClean Canister on a bypass to the system, and monitoring the downstream concentration with GoldCleanTest, or by crushing the pellets to powder and injecting a GoldClean brew into the line through existing fertigation systems. The chemical must remain in the line for 1-2 hrs before flushing it out.

Limitations of some chemical treatments include:

- Products that contain phosphates as surfactants or dispersants can exacerbate bacterial growth (GHD, 2010).

- Oxalic acid should not be used if calcium concentrations are greater than 50 mg/L (common in the Limestone Coast region) as oxalic acid can form an insoluble precipitate under these conditions (Smith, 2015).
- Some of these products can be expensive (GHD, 2010).
- Chlorine and other chemical solutions are strong oxidants and can cause skin irritation and burns, and damage plants and clothing. Disposal of chlorine solutions and other treatment chemicals should be carried out carefully and following environmental regulations.

If an iron bacteria problem is caught early, Smith (2015) suggests that regular treatment using chlorination (in the case of simple coliform contamination) or chelating organic acids (in the case of severe iron biofouling) and vigilant monitoring can keep it under control. Chelating agents reduce the occurrence of iron biofouling by bonding with the iron and making it unavailable for bacteria to metabolize. If the biofouling is light, shock chlorination alone may be effective. The suggested methodology for shock chlorination is to recirculate chlorine within the well using a hose to allow proper mixing of the chlorine throughout the well. As this is done, the residual chlorine concentration should be measured and adjusted to 50 mg/L. Smith (2015) suggests that it is more effective to measure the actual chlorine concentration of the circulating the water (the residual) than to rely on a calculated dose. A simple pool chlorine test kit can be used for this. The water should also be acidified with vinegar, acetic or glycolic acid to a pH of 5.5 to 6.5, which can be tested using pH test strips.

The need to reapply a chemical treatment is bore specific and also depends on the severity of the problem and the growth rate and source of the bacteria. Smith (2015) also suggests that water analyses should be carried out before and after any treatment to test its effect.

#### *Combined Methods*

Smith (2015) states that, for entrenched cases of iron biofouling, combined approaches including physical agitation such as surging and combinations of chelating agents and acids are necessary. He emphasizes that chemicals, hot water, and surging can be dangerous and, in many cases, is best done by professionals. After any cleaning treatment, a well should be pumped until the water is clear, and then chlorinated and allow to stand for twenty-four hours. It should be noted that cleaning can produce significant solids that can clog filters or damage pumps.

Another combined approach has been developed by SA Water and is a variation to the Canadian Ultra Acid Base (UAB) Technique, which involves a sequence of air surging to dislodge bacteria and deposits, with alternating treatments with acid and alkaline surfactants. This method is described in detail in GHD (2010).

### 3.6.2 Downstream Treatments (for Impacted Irrigation Delivery Systems)

In some of the iron bacteria cases reported in the Irrigation Water Quality Survey, there was minimal impact at the well or pump but clogging of drippers was a serious issue. In these cases, it may be preferable to treat the water downstream of the pump. Chlorine solutions as described above can also be applied through irrigation systems. The following additional treatment methods are suitable for treating pumped water prior to distribution through an irrigation system.

**Iron precipitate ejected from a dripper line during flushing in the Limestone Coast. Photos: Gavin Blacker.**

### *Aeration Systems*

The survey results identified one irrigator in the Limestone Coast region using an aeration system to remove iron and iron bacteria deposits from water pumped from groundwater wells before it is distributed through a drip irrigation system. In this case, water pumped from two wells is pumped into sub-surface mains, approximately 200 m long, aerated and then passed through filters. The filter material requires changing approximately every two years. The systems cost approximately $60,000 and have been in place for approximately 12-13 years (i.e. installed around 2004). It is believed that they were installed at the time that all dripper lines were replaced on the vineyard blocks that these bores supply. Occasional tests suggest that dripper outputs on these vineyard blocks are relatively even. Analyses of both total iron and iron reducing bacteria suggest that both of these parameters are decreased significantly by the aeration and filtration systems. Iron bacteria numbers, measured using the BART test (Droycon Bioconcepts, Inc., http://www.dbi.ca/BARTs/FAQ.html), are reduced from 35,000 to 9,000 and total iron is reduced from approximately 1 mg/L to approximately 0.2 mg/L.

Aeration causes dissolved ferrous iron to be oxidized to insoluble ferric oxides, forcing it to precipitate out in settling tanks or pipelines to be removed by filtration before it can cause a problem in downstream infrastructure. This also removes the food source for iron bacteria, restricting the proliferation of bacterial populations.

### *Magnetic Water Conditioners*

Several irrigators in the South East report having tried magnetic water conditioners in treating iron bacteria problems (Harrington and Harrington, 2016). Others have used them predominantly in treating calcium precipitation issues, as described in Section 2.4.2. The dominant supplier of these is Delta Water Systems (www.deltawater.com.au). The magnets are applied downstream of the pump and cost approximately $12,000 - $15,000 each. In general, there was little success reported for iron bacteria problems, although one irrigator reported that there was definitely more "muck" being discharged when flushing the system and less settling in filters, hydrocyclones and drippers. This irrigator is considering investing in more magnets.

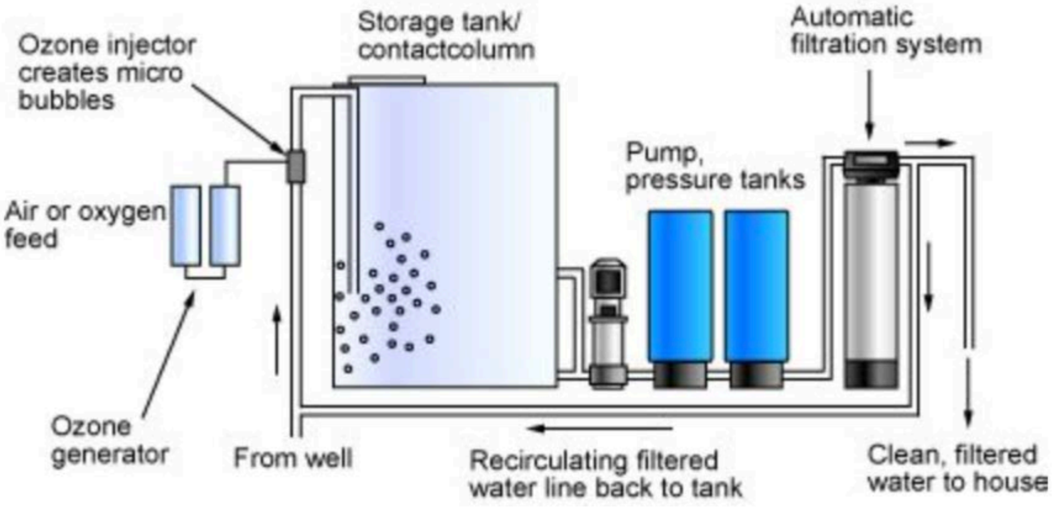
### *Ozonation*

Oram (2016) and US EPA (1999) explain the ozonation process and its application to water treatment. The following is derived from these sources. Ozone is an unstable gas comprising three oxygen atoms ($O_3$). Once formed, the gas readily converts back to oxygen, and during this transition a free oxygen atom, or free radical forms. The free oxygen radical is highly reactive and short-lived, degrading over time ranging from a few seconds to 30 minutes. The rate of degradation is a function of water chemistry, pH and water temperature.

Ozone has been used in water treatment since the late 1800s predominantly in Europe and Asia. It is a more effective disinfection agent than chlorine. Disinfection is thought to occur through oxidation / destruction of cell walls, causing leakage of cellular constituents outside of the cell. In addition, the oxidizing properties of ozone can reduce the concentrations of iron and manganese by oxidising them to form insoluble metal oxides. These insoluble particles are then removed by post-filtration.

Oxygen is transformed into ozone with the use of energy. This process is carried out by an electric discharge field in CD-type ozone generators (corona discharge is similar to the effects of lightning), or by ultraviolet radiation in UV-type ozone generators (similar to the ultraviolet rays from the sun). In addition to these commercial methods, ozone can also be produced through electrolytic and chemical reactions. In general, ozonation systems include passing dry, clean air through a high voltage electric discharge. In treating small quantities of waste, UV ozonation is the most common while large-scale systems use either corona discharge or other bulk ozone-producing methods.

The raw water is passed through a venturi throat which creates a vacuum and pulls the ozone gas into the water or the ozone is bubbled up through the water being treated. Since ozone reacts with metals to create insoluble metal oxides, post filtration is required.



**Conceptual diagram of an automatic ozone injection, filtration and recirculation system for iron and manganese.**

**Advantages**

- Ozone is more effective than chlorine in destroying bacteria.
- The ozonation process utilizes a short contact time (approximately 10 to 30 minutes).
- There are no harmful residuals that need to be removed after ozonation because ozone decomposes rapidly.
- After ozonation, there is no regrowth of microorganisms, except for those protected by particulates.
- Ozone is generated onsite, and thus, there are fewer safety problems associated with shipping and handling.

**Disadvantages**

- Ozonation is a more complex technology than chlorine or UV disinfection, requiring complicated equipment and efficient contacting systems.
- Ozone is very reactive and corrosive, requiring corrosion-resistant material such as stainless steel.
- Ozone is extremely irritating and possibly toxic, so off-gases from the contactor must be destroyed to prevent worker exposure.
- The cost of treatment can be relatively high in capital and in power intensiveness.

IGS contacted a supplier of ozone generation systems in Australia, Oxyzone. The size of the system required depends on the iron concentration of the water being treated and the flow rate required. The ozone requirement is 1 g ozone per 1 ppm iron per 1,000 L water per hour. As an indication, treatment of 2 ppm iron with a 20 L/sec flow rate would require a 130 g/hour system, with a capital cost of approximately $60,000 including the necessary oxygen generator, injector and pump. A 40 g/hr system with the necessary 8 L/min oxygen generator, injector and pump would cost approximately $18,000. This company has supplied trailer-mounted 120 g/hour ozonation systems to Sydney Water with excellent results.

### 3.6.3 Targeted Approaches

Targeted treatment approaches to Iron Bacteria problems are advocated by some specialists, e.g. Droycon Bioconcepts Inc. (DBI; http://www.dbi.ca/BARTs/FAQ.html). The reason for this is that there are many types of Iron Related Bacteria (IRBs) and the most effective approach in treating a clogging problem depends on the type of bacteria present. Specific testing can be carried out using the BART test system (see DBI website) to determine the composition of the bacterial community and this can then be used to design an effective treatment approach.

## 3.7 Recommended Best Management Practices for Managing Iron Bacteria Problems in the Limestone Coast Region

**Drilling New Wells:**

5. When drilling new wells, ensure that drilling equipment has been cleaned to minimize contamination.
6. Never put surface water down a well and do not use organic polymer muds in drilling wells or phosphorous containing mud breakers.
7. Avoid screening wells across hydrogeological units containing different water quality, particularly across oxic and anoxic zones.
8. If possible, avoid screening wells across zones in the aquifer with high dissolved iron concentrations.
9. Test for water quality and iron bacteria on new wells (after evacuating 3 bore volumes).
10. If iron bacteria are identified in a new well, redevelop and shock chlorinate the well.
11. Develop wells thoroughly after drilling and always chlorinate after development (chlorination chemicals and concentrations are recommended in Smith, 2015).

**Well Maintenance:**

12. Chlorinate any equipment used on wells.
13. Never re-install any parts that are encrusted or covered in biofilm of any kind without thorough cleaning and chlorination.
14. When pumping water from anoxic parts of an aquifer or containing high dissolved iron concentrations, avoid introducing oxygen into the pumped water, e.g. repair leaking seals and avoid mixing with water from near the water table.

**Monitoring:**

15. If your well is located in identified iron bacteria problem areas (i.e. the Management Areas of Bool, Comaum, Glenroy, Joanna, Zone 5A, Zone 3A, Lucindale, Mayurra, Waterhouse, Wirrega and Tatiara), regularly test water (total and dissolved iron, iron bacteria) and monitor well performance. Any changes in water quality, iron bacteria numbers or well performance may indicate a developing iron bacteria problem and early detection is critical to effective treatment.

**Treatment:**

16. If clogging with a reddish-brown precipitate occurs, test the water and the clogging material as described in Section 3.5 to determine whether the problem is inorganic or bacterially mediated.
17. If iron bacteria are identified, implement an iron bacteria treatment program as soon as possible. Early intervention is critical to effective treatment.

Treatments for iron bacteria depend on the main location and severity of the problem. If iron bacteria are identified in the well, affecting well and pump performance:

18. Regular maintenance and servicing of pump may be sufficient. Chlorinate before re-installing. Monitor the severity of the problem and water quality, including iron bacteria numbers.
19. If the problem becomes worse, shock chlorination or regular chlorine dosing of well using protocols as described above may be required. Acid may be effective if there is a significant carbonate component to the clogging material.

If iron bacteria are mainly affecting irrigation distribution systems:

20. Chlorination, aeration or ozonation systems plus settling and filtration downstream of the pump may be required.

# 4 Irrigation Water Salinity and Salt Build Up in Vineyard Soils

## 4.1 Overview of the Problem

Groundwater is the predominant source of irrigation water in the Limestone Coast region. Groundwater salinity across the region ranges from very fresh at approximately 600 mg/L total dissolved solids (TDS) to brackish at more than 1,400 mg/L TDS. Application of this water to the soil during irrigation, and subsequent uptake of the water by crops, can cause salt to build up within the root zone (Biswas et al., 2009). This occurs because plants exclude most salt when they take water from the soil. As water resources become more tightly managed, irrigators seek to achieve higher water use efficiency and now apply water to accurately meet crop needs. These irrigation volumes are often insufficient to flush the salt through the root zone to the water table during an irrigation season, and soil salinity levels are rising in many horticultural areas (Biswas et al., 2009).

## 4.2 Extent of the Problem in the Limestone Coast

The recent Irrigation Water Quality Survey indicated that some irrigators (ten of the 54 survey respondents; 19%) are finding that irrigation water salinity is causing problems with their crops. These are located in the Unconfined Aquifer Management Areas of Joanna, Padthaway Flats, Waterhouse, Zone 3A, Zone 5A and Bool. However, many more irrigators (57%) are already implementing methods to manage irrigation water salinity and in doing so preventing impacts on their crops. The methods applied include using longer irrigations, planting salt tolerant rootstocks, casing-off saline sections of wells, deepening wells or ceasing to use saline wells.

Anecdotal evidence from two vineyard managers in very different parts of the Limestone Coast region indicated that winter rains can generally be relied upon to flush salt accumulated during the irrigation season from the root zone. However, impacts of soil salinity on vine health have been observed recently following a dry winter, suggesting that, in years when winter rainfall is low, it may be necessary to apply extra flushing irrigation volumes during the subsequent growing season to manage root zone salinity.

DeGaris et al. (2015) also found that, when applying deficit irrigation at Padthaway using relatively saline irrigation water, annual variations in winter rainfall had the largest impact on chloride concentrations in grape juice and outweighed the effects of the irrigation management technique applied, including Partial Rootzone Drying (PRD). In that study, the chloride concentration in juice did not vary between irrigation practices within each season but did vary between seasons due to the large range in rainfall that occurred across the three seasons studied. This highlighted the impact that annual variations in winter rainfall can have on soil salinity.

The Irrigation Water Quality Survey indicated that 39 of the 54 respondents (72%) test their soil for salinity. The majority of these reported that they use the results of the soil tests to influence management practices, indicating that irrigators are largely aware of the need to manage root zone salinity.

## 4.3 Mitigation Strategies

### 4.3.1 Applying Knowledge of Soils, Crop Water Use and Irrigation System to Irrigation Scheduling

The results of the Irrigation Water Quality survey suggested that many irrigators in the Limestone Coast region already consider irrigation water salinity in their irrigation scheduling. For those irrigators wanting to base their irrigation scheduling more precisely on crop water needs and also incorporate knowledge of their soil and irrigation system, the Mackillop Farm Management Group has developed an excellent Irrigation Best Practice Glovebox Guide. This provides the necessary basic information and methodologies to calculate the irrigation volumes needed for different crop and soil types, to facilitate leaching if necessary, and to evaluate the efficiency of irrigation systems. This guide can be found at www.mackillopgroup.com.au.

### 4.3.2 Monitoring Root Zone Salinity

Soil samples can be collected in the field and sent to the laboratory so that soil salinity can be measured by either a saturated soil paste or a 1:5 soil to water suspension. These methods are useful for checking soil salinity on an annual basis, where salinity has not become a significant problem. However, the technique is time-consuming and costly and not practical for regular monitoring. In order to manage root-zone salinity issues, irrigators need to be able to accurately measure salt levels in the root-zone and monitor salinity trends over time. There is now a range of effective tools available to irrigators to assist with monitoring root-zone salinity over time, including suction cups (e.g. the SoluSampler, marketed by Sentek Technologies Australia; www.sentek.com.au) and wetting front detectors (www.fullstop.com.au) (Biswas et al., 2009). It should be noted that suction cups cannot be used when soil tensions are greater than approximately 60 kPa, so these are most useful for measuring soil water salinity at the end of winter or following winter or spring leaching irrigations (K. DeGaris, pers. comm., 7th Dec 2016).

### 4.3.3 Winter Leaching

Leaching of salts from the root-zone continues to be the most effective technique for root-zone salinity management (Biswas et al., 2009). However, research has shown that the leaching process is complex and is not always completely effective, due to the presence of preferred pathways through which water moves resulting in salt building up in other parts of the soil. The build-up of salt in soil can also affect soil structure. Application of leaching practices therefore requires an understanding of soil structure. Biswas et al. (2009) provide excellent guidelines for managing root-zone salinity in irrigated horticulture in winter rainfall zones of Australia. They suggest that winter leaching to complement rainfall is the most practical way to reduce root-zone salinity. Some reasons for applying winter irrigations to enhance leaching include lower evapotranspiration of the water applied during winter and the fact that the soil is wet and any potential preferred pathways may have “closed up”.

View of the side of a soil trench dug through the root zone of a vine, showing differences in soil structure that affect the leaching of salt from the soil profile.

### 4.3.4 Enhanced Leaching in Vineyards by Mounding in the Mid-Row

One of the solutions to vineyard root zone salinity problems that has been investigated extensively is mounding of soil in the mid-row and covering it with plastic to focus winter recharge in the vine row (Stevens et al., 2012). This was found to reduce soil salinity by 38% and the concentrations of sodium and chloride in juice by 35%. This study also found that, where soils had become saline and sodic as a result of below average winter rainfall, subsequent above average winter rainfall events were able to reclaim these soils.

Mid-row mounding and lining with black plastic to focus recharge towards vine roots. Source: Stevens et al. (2012).

## 4.4 Recommended Best Management Practices for Managing Root Zone Salinity in the Limestone Coast Region

If there is potential for crop issues associated with irrigation water salinity (i.e. where irrigation water salinity is greater than approximately 1,200 mg/L), but a problem has not yet been identified, irrigators should be proactive and:

21. Monitor irrigation water salinity to detect changes over time.
22. Get to know the characteristics of the soils on their properties and familiarize themselves with the factors influencing their irrigation system efficiencies (see Section 4.3.1 above).
23. Measure root zone salinity at the end of each winter at locations that cover the ranges of soil and crop types on the property.
24. Monitor foliage for visual symptoms of salt damage; test the chemical composition of leaf/fruit tissue on a regular basis.

Biswas et al. (2009) recommend the following protocol for managing root-zone salinity, where the problem has been identified:

25. Measure root-zone salinity two to three days after at least 15-20 mm of rainfall in one week. Check this measured value against the crop threshold, or a target threshold that is acceptable (e.g. see Biswas et al., 2009 for examples of crop thresholds for maximum production and for reduced yields). In measuring root zone salinity, disregard any spikes that occur soon after fertilizers are applied.
26. Apply one or several small leaching irrigations, and re-check root-zone salinity. The aim is to reduce root-zone salinity to (or slightly below) the threshold by the beginning of each irrigation season.
27. Record all soil salinities measured and leaching volumes applied to identify the optimum leaching volumes for your crop and soil over time.
28. Where there is a shallow or saline water table, install sub-surface drainage below the water-table to remove the saline water.
29. Apply a surface cover (e.g. mulch or perennial grass) of at least 30% to reduce salt accumulation by reducing evaporation.
30. Take care of soil structure by building up soil organic matter. This will improve the efficiency of leaching irrigations.

# 5 References

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# APPENDIX A.

# Magnetic Water and Fuel Treatment: Myth, Magic, or Mainstream Science?

**Feature**

***Mike R. Powell***

**Skeptical Inquirer Volume 22.1, January / February 1998**

*Magnetic treatment has been claimed to soften water and improve the combustibility of fuels. A literature review reveals that these claims are not well supported by data.*

Magnets are not just for refrigerators any more. In fact, according to some magnet vendors, magnets can be used to improve blood circulation, cure and prevent diseases, increase automobile mileage, improve plant growth, soften water, prevent tooth decay, and even increase the strength of concrete. Some of these claims are backed by experimental evidence. Many are not. This article focuses specifically on the claimed benefits of magnetically treated fuel and water.

Most magnetic water and fuel treatment systems appear to be marketed through independent distributors who sell out of their homes. An Internet search using the keywords magnetic treatment reveals dozens of independent distributor home pages. Very few such devices are offered by national chain stores or advertised in mail-order catalogs. Possibly, the magnetic-device manufacturers sell through independent distributors to insulate themselves from some of the more exotic claimed benefits of magnetic treatment, or perhaps consumer and wholesaler skepticism has kept magnetic treatment out of mainstream retail. Regardless of the reasons, magnetic water and fuel treatment devices are not usually available at the local hardware or automobile parts supply store. This lack of wide availability has given magnetic water and fuel treatment a sort of fringe-science status in the minds of many consumers. Whether this label is deserved is the subject of this article.

## Claimed Benefits and Effects

The claimed benefits of magnetic water treatment vary depending on the manufacturer. Some claim only that magnetic treatment will prevent and eliminate lime scale in pipe and heating elements; others make additional, more extravagant claims. Some of the additional claims include water softening, improved plant growth, and the prevention of some diseases in people who consume magnetically treated water. Magnetic water treatment devices consist of one or more magnets, which are clamped onto or installed inside the incoming residential water supply line. Typical costs for a residential installation range from about $100 to $600 or more.

Magnetic fuel treatment devices are constructed similarly. One or more magnets are clamped around or installed inside an automobile's engine fuel line between the gas tank and the carburetor (or fuel injectors). Claims for these devices include decreased hazardous gas emissions, more complete combustion, improved engine power, longer-lasting engine components, and a 10 percent to 20 percent increase in gas mileage. Prices for automotive fuel treatment magnets range from about $50 to $300.

The distributors of these devices rarely can cite any documented test results that validate these claims. Instead, they rely on numerous testimonials, lists of corporations and municipalities that purportedly use the devices, and scientific-sounding explanations of magnetic water and fuel treatment. However, just because distributors do not cite the literature does not mean that no relevant literature exists. Published test reports and journal articles that investigate magnetic treatment are available. This article reviews the available experimental evidence for magnetic water and fuel treatment.

## Magnets and Magnetism

To many people, magnets are a complete mystery. Vendors of magnet-based scams often use this ignorance to their own advantage, so a familiarity with the basics of magnetism can aid in the detection of dubious claims.

Magnetic fields are produced by the motion of charged particles. For example, electrons flowing in a wire will produce a magnetic field surrounding the wire. The magnetic fields generated by moving electrons are used in many household appliances, automobiles, and industrial machines. One basic example is the electromagnet, which is constructed from many coils of wire wrapped around a central iron core. The magnetic field is present only when electrical current is passed through the wire coils.

Permanent magnets do not use an applied electrical current. Instead, the magnetic field of a permanent magnet results from the mutual alignment of the very small magnetic fields produced by each of the atoms in the magnet. These atomic-level magnetic fields result mostly from the spin and orbital movements of electrons. While many substances undergo alignment of the atomic-level fields in response to an applied magnetic field, only ferromagnetic materials retain the atomic-level alignment when the applied field is removed. Thus, all permanent magnets are composed of ferromagnetic materials. The most commonly used ferromagnetic elements are iron, cobalt, and nickel.

The strength of a magnet is given by its magnetic flux density, which is measured in units of gauss. The earth's magnetic field is on the order of 0.5 gauss (Marshall and Skitek 1987). Typical household refrigerator magnets have field strengths of about 1,000 gauss. According to the distributors, the magnets sold for water and fuel treatment have magnetic flux densities in the 2,000 to 4,000 gauss range, which is not unusually strong. Permanent magnets with flux densities in the 8,000 gauss range are readily available. The magnets sold for magnetic fuel and water treatment are nothing special; they are just ordinary magnets.

## Water Hardness

The phrase hard water originated when it was observed that water from some sources requires more laundry soap to produce suds than water from other sources. Waters that required more soap were considered "harder" to use for laundering.

Water "hardness" is a measure of dissolved mineral content. As water seeps through soil and aquifers, it often contacts minerals such as limestone and dolomite. Under the right conditions, small amounts of these minerals will dissolve in the ground water and the water will become "hard." Water hardness is quantified by the concentration of dissolved hardness minerals. The most common hardness minerals are carbonates and sulfates of magnesium and calcium. Water with a total hardness mineral concentration of less than about 17 parts per million (ppm) is categorized as "soft" by the Water Quality Association (Harrison 1993). "Moderately hard" water has a concentration of 60 to 120 ppm. "Very hard" water exceeds 180 ppm.

Hard water is often undesirable because the dissolved minerals can form scale. Scale is simply the solid phase of the dissolved minerals. Some hardness minerals become less soluble in water as temperature is increased. These minerals tend to form deposits on the surfaces of water heating elements, bathtubs, and inside hot water pipes. Scale deposits can shorten the useful life of appliances such as dishwashers. Hard water also increases soap consumption and the amount of "soap scum" formed on dishes.

Many homeowners and businesses use water softeners to avoid the problems that result from hard water. Most water softeners remove problematic dissolved magnesium and calcium by passing water through a bed of "ion-exchange" beads. The beads are initially contacted with a concentrated salt (sodium chloride) solution to saturate the bead exchange sites with sodium ions. These ion-exchange sites have a greater affinity for calcium and magnesium, so when hard water is passed through the beads the calcium and magnesium ions are captured and sodium is released. The end result is that the calcium and magnesium ions in the hard water are replaced by sodium ions. Sodium salts do not readily form scale or soap scum, so the problems associated with hard water are avoided.

A 1960 survey of municipal water supplies in one hundred U.S. cities revealed that water hardness ranged from 0 to 738 ppm with a median of 90 ppm (see Singley 1984). Ion-exchange water softeners are capable of reducing the hardness of the incoming water supply to between 0 and 2 ppm, which is well below the levels where scale and soap precipitation are significant.

One of the principal drawbacks of ion-exchange water softeners is the need to periodically recharge the ion exchange beads with sodium ions. Rock salt is added to a reservoir in the softener for this purpose.

## Magnetic Water Treatment

A wide variety of magnetic water treatment devices are available, but most consist of one or more permanent magnets affixed either inside or to the exterior surface of the incoming water pipe. The water is exposed to the magnetic field as it flows through the pipe between the magnets. An alternative approach is to use electrical current flowing through coils of wire wrapped around the water pipe to generate the magnetic field.

Purveyors of magnetic water treatment devices claim that exposing water to a magnetic field will decrease the water's "effective" hardness. Typical claims include the elimination of scale deposits, lower water-heating bills, extended life of water heaters and household appliances, and more efficient use of soaps and detergents. Thus, it is claimed, magnetic water treatment gives all the benefits of water softened by ion-exchange without the expense and hassle of rock-salt additions.

Note that only the "effective" or "subjective" hardness is claimed to be reduced through magnetic treatment. No magnesium or calcium is removed from the water by magnetic treatment. Instead, the claim is that the magnetic field decreases the tendency of the dissolved minerals to form scale. Even though the dissolved mineral concentration indicates the water is still hard, magnetically treated water supposedly behaves like soft water.

According to some vendors, magnetically softened water is healthier than water softened by ion exchange. Ion-exchange softeners increase the water's sodium concentration, and this, they claim, is unhealthy for people with high blood pressure. While it is true that ion-exchange softening increases the sodium concentration, the amount of sodium typically found even in softened water is too low to be of significance for the majority of people with high blood pressure. Only those who are on a severely sodium-restricted diet should be concerned about the amount of sodium in water, regardless of whether it is softened (Yarows et al. 1997). Such individuals are often advised to consume demineralized water along with low-salt foods.

There is apparently no consensus among magnet vendors regarding the mechanisms by which magnetic water treatment occurs. A variety of explanations are offered, most of which involve plenty of jargon but little substance. Few vendors, if any, offer reasonable technical explanations of how magnetic water treatment is supposed to work.

The important question here, though, is whether magnetic water treatment works. In an effort to find the answer, I conducted a search for relevant scientific and engineering journal articles. I describe the results of this search below.

More than one hundred relevant articles and reports are available in the open literature, so clearly magnetic water treatment has received some attention from the scientific community (e.g., see reference list in Duffy 1977). The reported effects of magnetic water treatment, however, are varied and often contradictory. In many cases, researchers report finding no significant magnetic treatment effect. In other cases, however, reasonable evidence for an effect is provided.

Liburkin et al. (1986) found that magnetic treatment affected the structure of gypsum (calcium sulfate). Gypsum particles formed in magnetically treated water were found to be larger and "more regularly oriented" than those formed in ordinary water. Similarly, Kronenberg (1985) reported that magnetic treatment changed the mode of calcium carbonate precipitation such that circular disc-shaped particles are formed rather than the dendritic (branching or tree-like) particles observed in nontreated water. Others (e.g., Chechel and Annenkova 1972; Martynova et al. 1967) also have found that magnetic treatment affects the structure of subsequently precipitated solids. Because scale formation involves precipitation and crystallization, these studies imply that magnetic water treatment is likely to have an effect on the formation of scale.

Some researchers hypothesize that magnetic treatment affects the nature of hydrogen bonds between water molecules. They report changes in water properties such as light absorbance, surface tension, and pH (e.g., Joshi and Kamat 1966; Bruns et al. 1966; Klassen 1981). However, these effects have not always been found by later investigators (Mirumyants et al. 1972). Further, the characteristic relaxation time of hydrogen bonds between water molecules is estimated to be much too fast and the applied magnetic field strengths much too small for any such lasting effects, so it is unlikely that magnetic water treatment affects water molecules (Lipus et al. 1994).

Duffy (1977) provides experimental evidence that scale suppression in magnetic water treatment devices is due not to magnetic effects on the fluid, but to the dissolution of small amounts of iron from the magnet or surrounding pipe into the fluid. Iron ions can suppress the rate of scale formation and encourage the growth of a softer scale deposit. Busch et al. (1986) measured the voltages produced by fluids flowing through a commercial magnetic treatment device. Their data support the hypothesis that a chemical reaction driven by the induced electrical currents may be responsible for generating the iron ions shown by Duffy to affect scale formation.

Among those who report some type of direct magnetic-water-treatment effect, a consensus seems to be emerging that the effect results from the interaction of the applied magnetic field with surface charges of suspended particles (Donaldson 1988; Lipus et al. 1994). Krylov et al. (1985) found that the electrical charges on calcium carbonate particles are significantly affected by the application of a magnetic field. Further, the magnitude of the change in particle charge increased as the strength of the applied magnetic field increased.

Gehr et al. (1995) found that magnetic treatment affects the quantity of suspended and dissolved calcium sulfate. A very strong magnetic field (47,500 gauss) generated by a nuclear magnetic resonance spectrometer was used to test identical calcium sulfate suspensions with very high hardness (1,700 ppm on a $CaCO_3$ basis). Two minutes of magnetic treatment decreased the dissolved calcium concentration by about 10 percent. The magnetic field also decreased the average particle charge by about 23 percent. These results, along with those of many others (e.g., Parsons et al. 1997; Higashitani and Oshitani 1997), imply that application of a magnetic field can affect the dissolution and crystallization of at least some compounds.

Whether or not some magnetic water treatment effect actually exists, the further question, and the most important for consumers, is whether the magnetic water treatment devices perform as advertised.

Numerous anecdotal accounts of the successes and failures of magnetic water treatment devices can be found in the literature (Lin and Yotvat 1989; Raisen 1984; Wilkes and Baum 1979; Welder and Partridge 1954). However, because of the varied conditions under which these field trials are conducted it is unclear whether the positive reports are due solely to magnetic treatment or to other conditions that were not controlled during the trial.

Some commercial devices have been subjected to tests under controlled conditions. Unfortunately, the results are mixed. Duffy (1977) tested a commercial device with an internal magnet and found that it had no significant effect on the precipitation of calcium carbonate scale in a heat exchanger. According to Lipus et al. (1994), however, the scale prevention capability of their ELMAG device is proven, although they do not supply much supporting test data.

Busch et al. (1997) measured the scale formed by the distillation of hard water with and without magnetic treatment. Using laboratory-prepared hard water, a 22 percent reduction in scale formation was observed when the magnetic treatment device was used instead of a straight pipe section. However, a 17 percent reduction in scaling was found when an unmagnetized, but otherwise identical, device was installed. Busch et al. (1997) speculate that fluid turbulence inside the device may be the cause of the 17 percent reduction, with the magnetic field effect responsible for the additional 5 percent. River water was subjected to similar tests, but no difference in scale formation was found with and without the magnetic treatment device installed. An explanation for this negative result was not found.

Another study of a commercial magnetic water treatment device was conducted by Hasson and Bramson (1985). Under the technical supervision of the device supplier, they tested the device to determine its ability to prevent the accumulation of calcium carbonate scale in a pipe. Very hard water (300 to 340 ppm) was pumped through a cast-iron pipe, and the rate of scale accumulation inside the pipe was determined by periodically inspecting the pipe's interior. Magnetic exposure was found to have no effect on either the rate of scale accumulation or on the adhesive nature of the scale deposits.

*Consumer Reports* magazine (Denver 1996) tested a $535 magnetic water treatment device from Descal-A-Matic Corporation. Two electric water heaters were installed in the home of one of the *Consumer Reports* staffers. The hard water (200 ppm) entering one of the heaters was first passed through the magnetic treatment device. The second water heater received untreated water. The water heaters were cut open after more than two years and after more than 10,000 gallons of water were heated by each heater. The tanks were found to contain the same quantity and texture of scale. *Consumer Reports* concluded that the Descal-A-Matic unit was ineffective.

Much of the available laboratory test data imply that magnetic water treatment devices are largely ineffective, yet reports of positive results in industrial settings persist (e.g., Spear 1992; Donaldson 1988). The contradictory reports imply that if a magnetic water treatment effect for scale prevention exists, then it only is effective under some of the conditions encountered in industry. At present, there does not seem to be a defensible guideline for determining when the desired effect can be expected and when it cannot.

One of the claims made for residential magnetic treatment devices is that less soap and detergent will be required for washing. Compared to the claim to suppress scale formation, this claim has received little direct attention in the literature. To decrease soap and detergent consumption, the concentration of dissolved hardness minerals must be decreased. The tests by Gehr et al. (1995), described earlier, demonstrated a decrease in dissolved mineral concentration of about 10 percent. If this fractional decrease in dissolved mineral concentration is representative of that obtained by magnetic treatment, then it is unlikely that soap and detergent use will be significantly reduced. For example, given a water supply with 100 ppm dissolved hardness, magnetic treatment would only be expected to reduce the hardness to 90 ppm, assuming the results of Gehr et al. can be applied at this hardness concentration.

Is there a beneficial effect of magnetic water treatment? Perhaps.

Is there sufficient evidence of a beneficial effect to warrant spending hundreds of dollars on a residential magnetic water treatment unit? Unlikely. The understanding of magnetic water treatment must first be developed to the point where the effects of magnetic treatment can be reliably predicted and shown to be economically attractive.

Does magnetic water treatment perform as well as ion-exchange treatment? Definitely not. At present, the conventional water softening technologies are clearly much more reliable and effective. Further, the initial cost of an ion-exchange water softener (around $500) is comparable to that of many magnetic treatment systems.

## Magnetic Fuel Treatment

Magnetic fuel treatment devices installed in automobiles are similar in design to magnetic water treatment devices. Hydrocarbon fuel is pumped through a canister containing one or more magnets or a magnetic device is clamped to the external surface of the fuel line. Magnetic treatment of fuel, it is claimed, results in increased horsepower, increased mileage, reduced hazardous gas emissions, and longer engine life.

Typically, vendors claim that either mileage or horsepower will be improved by about 10 to 20 percent. They also claim that if no improvement in mileage is noted, then the improvement must have come in the form of more horsepower. This, of course, makes it difficult for consumers to determine whether their magnetic fuel treatment devices really are working.

A literature search for magnetic fuel treatment studies revealed that such studies are practically nonexistent. I found a total of three references. Two of these (Daly 1995; McNeely 1994) were anecdotal accounts describing the use of a magnetic treatment device to kill microorganisms in diesel fuel, a fuel treatment application not usually mentioned by magnetic fuel treatment vendors.

The third reference (Tretyakov et al. 1985) describes tests conducted in which the electrical resistance and dielectric properties of a hydrocarbon fuel were found to change in response to an applied magnetic field. This report does not address whether the observed physical property changes might affect fuel performance in an engine, but it references two research reports that may contain performance data (Skripka et al. 1975; Tretyakov et al. 1975). Unfortunately, I could obtain neither report, and both are written in Russian.

My literature search search found no other credible research reports pertaining to magnetic fuel treatment.

The utter lack of published test data is revealing. According to the vendors, magnetic fuel treatment has been around for at least fifty years. If it actually worked as claimed, it seems likely that it would by now be commonplace. It is not.

Vendors of magnetic fuel treatment sometimes respond to this reasoning with hints that the automobile manufacturers and big oil companies are conspiring to suppress magnetic fuel treatment to maintain demand for gasoline. Such a conspiracy seems quite improbable. This supposed conspiracy has not managed to suppress other fuel-saving innovations such as fuel injection and computerized control.

In summary, I found no test data that support the claims for improved engine performance made by vendors of magnetic fuel treatment devices. Until such data become available, considerable skepticism is justified. At present, it seems quite unlikely that any of the claimed benefits of magnetic fuel treatment are real.

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## *Mike R. Powell*

Mike R. Powell, P.E., is a chemical engineer for a research and development laboratory in Richland, Washington.

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