Iron precipitation problems in boreholes in the Klein Karoo

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1. INTRODUCTION

Groundwater Consulting Services (GCS) and the CSIR Groundwater Group (GWG) undertook in a joint venture investigation into the iron problems experienced in boreholes in the Klein Karoo Rural Water Supply Scheme. The work was undertaken for the Department of Water Affairs and Forestry. GCS were largely involved with hydrogeological issues while GWG were involved in the chemical and biological evaluations.

The investigation is split into three distinct phases :

Phase 1: *A desk study accumulation of all the available data related to iron precipitation and iron bacterial problems with specific reference to management measures that can be introduced to reduce the problems.*

Phase 2: *Evaluation of historical data from the Klein Karoo scheme related to iron problems and the accumulation of new data on the iron chemistry and bacterial status of the groundwater in all the production boreholes. Samples were collected from 15 boreholes. Detailed chemical and microbiological analyses were undertaken to evaluate the microbial populations present and the conditions influencing their growth as well as the chemical/biological precipitation of iron.*

Phase 3: *Formulation of management procedures or treatment systems to reduce iron problems.*

2. BACKGROUND

Under ideal conditions an expected life time of 15 to 30 years can be achieved for a properly constructed and developed borehole, with a minimum of maintenance. However, if the chemical composition of the groundwater is such that it causes corrosion, incrustations and clogging of the screen, casing, riser pipes and pumping equipment, then the borehole's lifespan can diminish dramatically. Where clogging takes place regular maintenance and rehabilitation becomes a crucial part of the groundwater utilization programme.

Groundwater has long been considered to be of excellent quality because the soil barrier provides effective isolation of this high quality source water from surface pollutants. However, both inorganic and organic chemicals entering the subsurface environment and natural chemical process can be transformed by microbiological processes. The activity of bacteria can affect the chemical environment resulting in a pH change and affect the oxidation-reduction potential of the system , thus increasing clogging and decreasing the permeability of the aquifer material and the borehole screens.

Borehole clogging has been studied for many years. The clogging process can be extremely rapid, reducing the borehole yields to below their recommended capacity within months of installing (Smith, 1982; Hackett, 1987; Cullimore, 1992). Boreholes can however be remediated, although effective remediation requires knowledge on the causes of clogging.

3. CLOGGING

Borehole clogging is a problem that occurs all over the world. It is a complex phenomenon that is caused by a variety of physical, chemical and biological factors (Howsam, 1990), functioning alone or in combination with each other (Mansuy, Nuzman & Cullimore, 1990). Clogging deposits can be attached to the borehole screen or can occur in the aquifer immediately surrounding the screen and treatment of the problem will differ accordingly. The clogging results in reduced groundwater flow to the boreholes, causing a decrease in borehole efficiencies, a decrease in specific capacity, lowering of the borehole yield and eventually, failure of the pump or the borehole

There are differences in the depositional patterns under different environments. Generally, if clogging has affect all the boreholes in a well field, then the clogging is probably caused by geohydrochemical or geomicrobiological processes. If only some of the boreholes in a well field are clogged, the cause will more likely be accidental (Van Beek, 1984). The different depositional environments can result in different rates of clogging, hence the difference in clogging between PVC, iron or stainless steel screens. Deposition over PVC screens seems to be more even, while there tends to be more tuberculation on steel and stainless steel screens. Research has found (Mansuy, 1999) that stainless steel wells plug faster than PVC screens - PVC screens have been found to plug on average 63% slower than stainless steel screens under the same conditions.

3.1. Physical clogging

Clogging of a physical or mechanical nature may originate from either the partial collapse of the screen, infiltration of sand or silt into the interior of the screen, or through particulate matter lodging in the slots of the screen and the gravel pack.

Particulate matter which can cause screen clogging includes :

- drilling fluid invasion damage at construction,
- inter-mixing of aquifer horizons caused by wash-out/caving during drilling and development,
- inter-mixing of aquifer and gravel-pack material during development,
- movement of fines from the aquifer into the gravel-pack,
- movement of aquifer material into the well.

3.2. Chemical clogging

Clogging of a chemical nature may result from the deposition of chemical precipitates that are often initiated by the presence of oxygen, pH shifts to the alkaline range, or increases in the redox potential. Chemical precipitation processes that can affect the aquifer, the well, the pump and pipework include :

- Calcium carbonate precipitation
  The release of carbon dioxide affects the carbonate/bicarbonate equilibrium with the result that calcium carbonate is precipitated.

- Electro-chemical corrosion of components made of iron and steel. The corrosion of casing/screen joints leading to sand ingress and possible total collapse of the screens. Corrosion can also lead to failure of pump components and rising mains.

- Iron oxyhydroxides precipitation
  Occurs when ferrous (Fe $^{+2}$) bearing anaerobic groundwater becomes oxygenated, causing a ferrous to ferric (Fe $^{+3}$) conversion and the precipitation of insoluble ferric oxyhydroxides

3.3 Biochemical clogging (Biofouling).

Biological clogging is the most common form of clogging of water wells and is commonly referred to as biofouling. About 80 % of all wells that are experiencing clogging, have a high level of biological activity (Mansuy, Nuzman & Cullimore, 1990). The production of large amounts of extra cellular polysaccharides as a result of biological activity, acts to cement the chemical precipitates, silt, sand or clay in place, thus clogging the hole and reducing the flow in the pump, borehole or aquifer.

4. IRON DEPOSITION IN GROUNDWATER SYSTEMS

The development of iron-based deposits is a familiar and unwelcome occurrence in groundwater abstraction systems. Iron biofouling in the groundwater environment is a complex process dependent upon the interaction of a number of factors. Iron deposits accumulate on surface and as such form coatings in the boreholes and well structures which may lead to a variety of deleterious effects such as:

- impairment of hydraulic efficiency due to clogging filter packs, screens, pumps and pipework,
- reduction of discharge,
- disintegration of materials due to corrosion,
- changes in water quality.

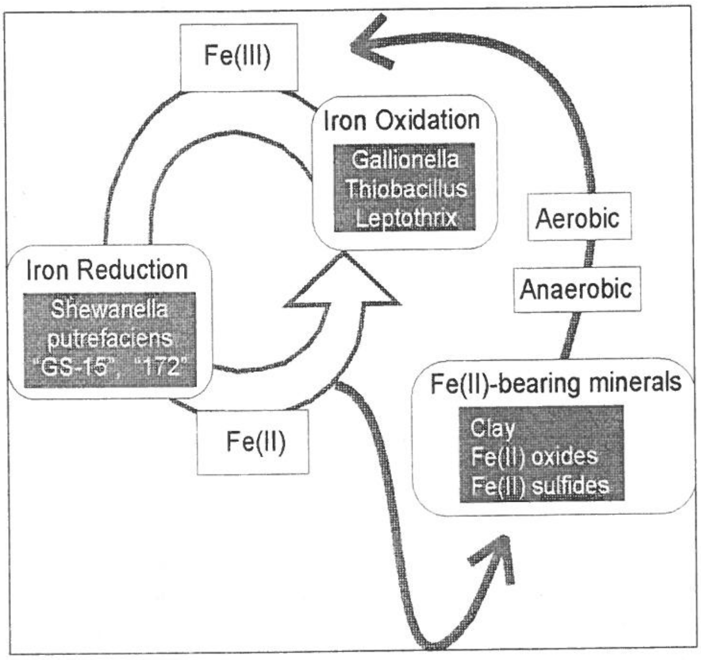
4.1 The Iron Cycle

Iron in the environment exists predominantly in either the reduced ferrous (Fe^{+2}) or oxidized ferric (Fe^{+3}) form. Ferrous iron is relatively soluble in water and is therefore quite mobile. Ferric iron, on the other hand, tends to form insoluble Fe^{+3} oxyhydroxides and is therefore relatively immobile. The iron cycle in most environments involves alternative reduction (mobilisation) of ferric iron followed by oxidation (immobilisation / precipitation) of ferrous iron. Figure 1 is a schematic diagram of the iron cycle. Under anaerobic conditions, Fe(III) oxyhydroxides are reduced by a variety of microorganisms that use Fe(III) as a terminal electron acceptor.

The iron cycle and hence the solubility of iron in water depends upon two main factors, the pH and the redox potential. The redox potential (also known as the Eh) of a water body is an indication of whether the water is in an oxidised state (provide electrons) or reduced state(accept electrons). The redox potential is normally measured in millivolts.

Under oxidative conditions oxygen is present (> 0,05 mg/l DO) while oxygen is absent under a reductive regime (< 0.05 mg/l DO). Monitoring of Eh provides an early warning signal indicating that conditions are changing.

FIGURE 1 : SCHEMATIC DIAGRAM OF THE IRON CYCLE



4.2 Iron reduction / oxidation in groundwater

The degree of iron oxidation or reduction is strongly influenced by a number of physio-chemical factors such as:

- redox potential,
- pH,
- the presence of organic compounds,
- dissolved oxygen and
- microorganisms (which can affect Eh-pH conditions).

Oxidized forms of iron found in groundwater are typically insoluble precipitates of various morphology at moderate pH ranges.

Within the usual pH range of natural water (pH 5 to 9) and within an Eh range of 100 to 200 mV, a considerable Fe^{2+} concentration can be maintained in solution (Hem 1970), although soluble ferric may occur at low pH values. However when oxidation takes place due to the introduction of oxygen or via bacterial activity, the precipitation of insoluble ferric products occurs. The Fe^{+2} form of iron is used in bacterial chemoautotrophic oxidation. When oxidation due to well conditions or bacterial activity occurs, precipitation of insoluble Fe(III) products occurs. As the system becomes more oxidized (higher Eh), the ferric ion (Fe^{3+}) or its mineral or polymeric salts (ie $Fe(OH)_3$) become prevalent. By definition of Glathe and Ottow (1972), strongly oxidizing conditions occur at or above Eh +390 mV at pH 6.

Ferric iron is soluble at low pH values, but above pH 4.8 the solubility of ferric species is below 0.01 mg/L. Only under highly reduced conditions, such as found in coal, for example, will iron occur as pyrite (FeS_2), which is insoluble.

Groundwater that is high in dissolved iron can be associated with the oxidation of reduced iron minerals. Aquifers that contain oxidized iron minerals and organic debris may provide an environment favorable for iron reduction and high concentrations of ferrous ion in solution (Hem 1970). Iron reduction and oxidation in most environments can proceed without the intervention of microorganisms, particularly at near-neutral and alkaline pH values, but bacteria are frequently associated with oxidized iron complexes (Aristovskaya and Zavarzin 1971).

Pumping frequently oxygenates iron-rich water flowing in from the aquifer and iron precipitation can result (Heidel 1964). Boundary layers in redox-stratified environments such as pumping and recharge wells provide the setting for both chemical and microbiological oxidation of iron.

4.3 Iron precipitation

Insoluble iron compounds make up approximately 90% of the dry weight of iron biofouling deposits (Pedersen and Hallbeck, 1985) therefore necessitate an understanding of iron clogging processes when attempting to prevent subsurface clogging. The chemical and biological mechanisms by which iron may be transformed from the soluble to the insoluble state are not easily distinguishable. McCrae, Edwards and Davis (1975) explained the iron precipitation process as follows :

- iron is dissolved from iron-containing formations under anaerobic/acidic conditions
- the iron will remain in the soluble ferrous form until there is a rise in the pH or Eh of the water. An increase in Eh may be encountered because of increased oxygenation as the groundwater approaches a pumping borehole, initiating chemical iron precipitation at the aerobic/anaerobic interface. Some bacteria (like *Gallionella*) can obtain energy from the oxidation of ferrous to ferric iron and tend to grow at the aerobic/anaerobic interface.

Distinguishing between the pure chemical and a biological enhanced process of iron precipitation taking place in this region is very difficult.

4.4 Scale Formation

The mineral content of the scale developed in a borehole dictates the kind of treatment required to remove the scale. The first minerals precipitated are of low crystallinity (amorphous) and thermodynamically unstable. However, with time the minerals recrystallize and become more stable - the process is called "scale aging". Old scale, because it is more stable, is more difficult to remove. The iron precipitation sequence is :

ferrihydrite → lepidocrocite → goethite.

Dissolving iron oxyhydroxides takes place either via proton assisted dissolution or ligand-promoted dissolution or reductive dissolution.

5. BACTERIA IN GROUNDWATER

Bacteria causing borehole clogging occur in complex biofilm communities. The biofilm can range in size and thickness depending on a number of factors which are usually site specific. The analysis and identification of these microbial communities is necessary in order to understand the underlying biological nature of the problem and to be able to design effective borehole maintenance and control procedures.

5.1 Bacterial categories

The dominant micro-organisms observed in boreholes are bacteria and are generally subdivide into a number of interconnected groupings. The identifiable bacterial groups are :

gross aerobic;
heterotrophic;
anaerobic saprophytic;
coliforms;
iron-related (iron oxidizing; iron reducing)
sulphate-reducing
sulphur-reducing
sulphur oxidizing
enteric
slime forming
streptomycetes
pseudomonads

There are three major groups of bacteria which have been generally identified as contributing to clogging problems. These three groups have been identified as Slime Forming Bacteria (SFB), Iron Related Bacteria (IRB) and Sulphate Reducing Bacteria (SRB).

5.1.1 Slime Forming Bacteria

SFB's are the most common group of micro organisms found in aquifers. The majority of slime forming bacteria are also responsible for large deposits of chemical precipitates leading to the overall volume of biomass.

5.1.2 Iron Related Bacteria

The most frequently described bacterial degradation of borehole performance involves the phenomenon known in the groundwater industry as “iron bacteria”. Iron bacteria are described as ‘the most notorious microbiological pests in the borehole industry”. Iron related bacteria consists of many genera and species of bacteria, with varying morphology and physiology. Attempts to predict the occurrence of iron bacteria and to rehabilitate the systems suffering from them often fails. This may be, in part, due to a lack of understanding by microbiologists of the complexity of the subsurface environment and by hydrogeologists of the nature of the mico-organisms involved (Tyrrel and Howsam, 1997). Typically, most iron related bacteria are also slime forming bacteria which are also capable of precipitating and accumulating chemical precipitates.

The following IRB's are some of those listed and described in Bergey's manual of systematic bacteriology (1984) :

Leptothrix spp.

These are the most widely distributed of all the iron bacteria. However, it is difficult to prove that these organisms are able to use the energy liberated during the oxidation of ferrous or manganese ions. The fact that they only grow at pH values of > 6 where rapidly chemical oxidation of ferrous ions takes place, makes the study of the mechanism of the iron oxidation by these bacteria no easy tasks. The bacteria are strict aerobes, but bacteria growth and manganese oxidation may proceed at low oxygen levels. *Leptothrix ochracea* is common in slowly running, iron containing, uncontaminated surface water.

Gallionella spp.

Gallionella are found in ferrous iron-containing waters and in soils. Iron hydroxide can make up 90% of the dry weight of a Gallionella cell mass. The bacteria are micro-aerophilic, developing under oxygen concentrations of about 1 mg/L and under a pH range of 6 - 7. They are often associated with *Lepthothrix ochracea* and together are responsible for considerable iron oxide precipitation. Growth of these organisms causes problems at water works. *Gallionella ferruginea* is widely distributed in iron-bearing waters.

Crenothrix spp.

Crenothrix is found in stagnant and running waters containing organic matter and iron salts. *Crenothrix polyspora* was originally isolated from samples of spring water. It is by far the most dreaded of the iron-bacteria on account of the suddenness of its attacks. It grows as thick brownish masses.

Clonothrix spp

This bacteria is aerobic with the ability to deposit Fe oxides on older parts of the growth filament. Originally this organism was found attached to the iron fittings in a borehole at 14 °C. It was also found in cow troughs and in pond water rich in clay particles.

Thiobacillus spp.

The genus includes obligate aerobes and facultative denitrifying types. Its species exhibit pH optima of 2 - 8 with temperature optima of 20 - 43 ° C. Distribution is seemingly ubiquitous in marine, freshwater and soil environments. Energy is derived from the oxidation of one or more reduced sulfur compounds including sulfides, sulfur, thiosulphate, polythionates, and thiocyanate. However, one specie, *Thiobacillus ferrooxidans*, also derives energy from oxidising ferrous iron to ferric iron. Its optimum pH range is 1.3 to 4.5.

Siderocapsa spp.

These bacteria are found in environments which may be characterised by elevated concentrations of iron and/or manganese. In the presence of iron and manganese the cells become nuclei of metal precipitation, resulting in the formation of insoluble metal oxides which may completely encrust and envelop the cell. Various members have been diagnosed form well-water samples, groundwater, field drainage and effluents as well as from soils.

Sphaerotilus spp.

These sheathed bacteria and are found in aquatic habitats. In the presence of soluble iron compounds the sheaths may turn yellow-brown and become encrusted with ferric oxide. One specie, *Sphaerotilus natans*, can grow at very low concentrations of oxygen (below 0,1 mg/L) with optimum pH of 6.5 - 7.5.

Corynebacterium spp. and *Escherichia coli* are also active in iron adsorption. Many other heterotrophs occur with iron bacteria in situ and in vitro (Cullimore, 1992; Smith and Tuovinen, 1985). All of these groups are associated with poor water quality from a public health standpoint.

Iron precipitation and accumulation are not limited to these iron bacteria only. Several bacteria, including species of *Pseudomonas*, a genus which is found widely in groundwater and is not strictly an IRB, is increasingly implicated in iron slime plugging incidents in boreholes (Cullimore 1982).

5.1.3 Sulphate Reducing Bacteria.

A biofilm developed on a surface can be particularly hardy, having been found to exist in environments of extreme temperature, pressure and chemical condition. Within a biofilm anaerobic conditions can develop - even in a biofilm only a few millimetres thick (Howsam, 1990). The SRB's grow under the anaerobic conditions within the biofilm. SRB's are obligately anaerobic heterotrophic organisms which use organic matter to assist in the reduction of sulphate to sulfide (e.g., *Desulfovibrio* and *Desulfotomaculum*). The products of sulphate reduction are hydrogen sulfide and sulphuric acid - the sulphuric acid can lead to corrosion, while hydrogen sulfide creates problems with water treatment. There is often an association between pseudomonads and sulfate reducing bacteria involved in corrosive biofouling (MIC).

5.2 Biofilm Formation

Biofilm formation is a process whereby micro-organisms attach themselves to the surface and develop a microbial population on the submerged surfaces in the borehole. They are fed by nutrients carried along by fluid movement. A biofilm is typically composed of cells, predominantly bacteria and protozoa in the case of a borehole biofilm. The attached lifestyle is advantageous to the sessile organisms as conditions for nutrient uptake, protection from anti-microbial agents and inter-species co-operation are all enhanced. The attached population (sessile) is significantly more active and greater in size than the free-floating (planktonic) population. As a result of these ecological advantages, the ratio planktonic : sessile population is usually in the order of 1:10 000 (Cloete & Von Holy, 1991).

Biofilm development is initiated by bacteria attaching themselves to the surface of the borehole casing, screen or aquifer material. Once attached, the bacteria reproduce and cover the whole surface with a thin layer (Development stage). This thin layer of slime retains water and nutrients and acts as a protection layer for the individual bacterial cells. Initially the biofilm thickens rapidly (Initial clogging stage) as the nutrients develop to a state of equilibrium with the existing nutrients available. As the biofilm stabilises, the biofilm shrinks in size. Thereafter a more mature pulsing phase of growth takes place during which the biofilm grows, is then sheared away by water pressure and re-grows (Clog maturation stage). With each phase of re-growth mineral precipitation increases until serious plugging takes place (Plugging clog stage) (Drydon Concepts Inc, 1999).

As a biofilm develops the inner zone becomes anaerobic and highly corrosive micro-environments develop resulting in MIC (microbially induced corrosion), also known as bio-corrosion. There are a number of mechanisms involved in biocorrosion (Tyrrel and Howsam, 1997) namely:

- iron dissolution during microbial reduction of insoluble ferric deposits to soluble ferrous compounds.
- cathodic pitting
  The inner anaerobic zone of the biofilm becomes anodic relative to the aerobic edge of the biofilm and localised pitting takes place
- cathodic depolarisation by sulphate reducing bacteria
  Sulphate reducing bacteria develop in the inner anaerobic zone resulting in the removal of cathodic hydrogen, the depolarisation of the metal surface and corrosion of the surface.

5.3 Iron Bacterial Growth Environments

Through the years of scattered research, the various iron bacterial species have been linked to specific Eh-pH ranges for growth. Most of these environmental conditions occur in ground water and wells. Bacteria associated with iron cause its precipitation in the oxidized state by modifying the local redox conditions, either directly or indirectly - ferrous irons are oxidised to the ferric state and the ferric irons so produced form insoluble oxyhydroxides.

$$Fe^{+2} + H^{+} + \tfrac{1}{4}\, O_2 \Rightarrow Fe^{+3} + \tfrac{1}{2}\, H_2O$$

$$Fe^{-3} + 2H_2O \Rightarrow Fe\ OOH + 3H^{+}$$

Most of these reactions are microbially catalysed under natural conditions. The role of microorganisms in iron reduction has only been studied extensively since 1985. Prior to 1985, most geochemists and microbiologists considered Fe^{+3} reduction to be an a biologic reaction initiated by "reducing conditions" (Chapelle, 1992). However, with the isolation and characterisation of Fe^{+3} - reducing microorganisms in the late 1980's, it became clear that this important component of the iron cycle is largely mediated by microbial processes.

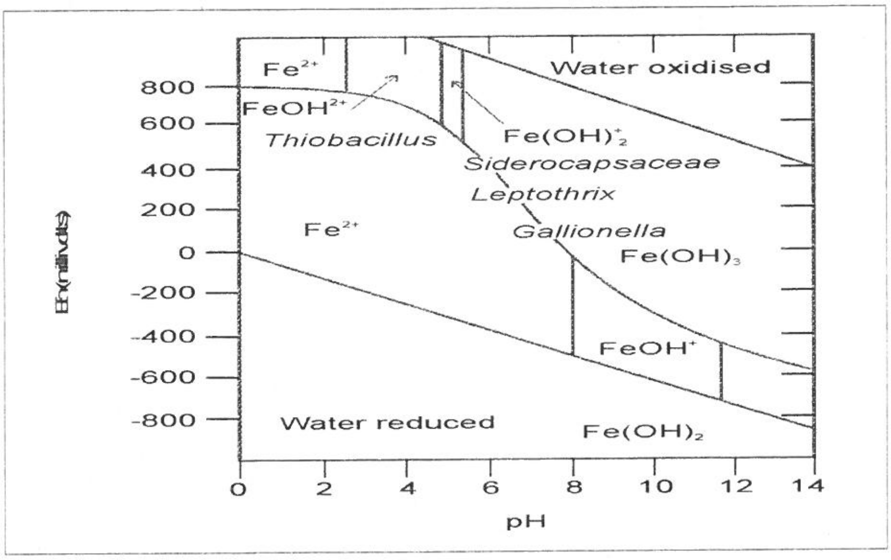
Bacteria growth is enhance under conditions of high flow velocities - the higher velocities increase nutrient uptake and thus the rate of biofilm development. The design of the boreholes and the operation of the pumps should therefore be aimed at reducing flow velocities to the lowest possible levels.

Figure 2 shows the Eh-pH diagram for major iron species in relation to the occurrence of iron bacteria in the environment (after Hem and Cropper 1959; Aristovskaya and Zavarzir 1971). *Thiobacillus* (*T. ferrooxidans*) is an acidophile that uses dissolved Fe^{2+} as an energy substrate and requires an acidic environment. *Siderocapsacae*, *Leptothrix* and *Gallionella* typically thrive at circum-neutral pH, most often at the Eh-pH boundary, which involves the formation of Fe^{+3} precipitates, as the result of their metabolic activities. *Gallionella* is associated with the lowest Eh of the bacteria indicated. Microbial activity normally concentrates around the redox front - the position where water changes form being reductive (from approximately -50mV) to oxidative (greater than 150mV). Positive Eh values support aerobic microbial activity while negative Eh values encourage anaerobic biomass generation - under anaerobic conditions biomass generation is reduced there is a downward shift in pH, a greater potential for gas production i.e. hydrogen sulphide.

A pH of between 7.2 and 8.8 is optimal for the growth of most micro-organisms. At lower and higher pH's the microbial diversity and microbial growth becomes restricted. At pH's of less than 5.5 (as typically seen in the Klein Karoo) the process of biofouling becomes retarded while the only bacteria that grows with any vigour is *Thiobacillus.*

The ideal pH for most bacteria is 8.3 - 8.7. At a pH of less than 4.5 microflaura are restricted, although microbially genertated acidic leaching can occur (assisted by *Thiobacillus*) if oxygen and sulphates exist. At a pH less than 5.5 biofouling is retarded since the microorganisms are generally traumatized by the conditions.

FIGURE 2 : EH-PH DIAGRAM FOR IRON SPECIES VS IRON BACTERIA



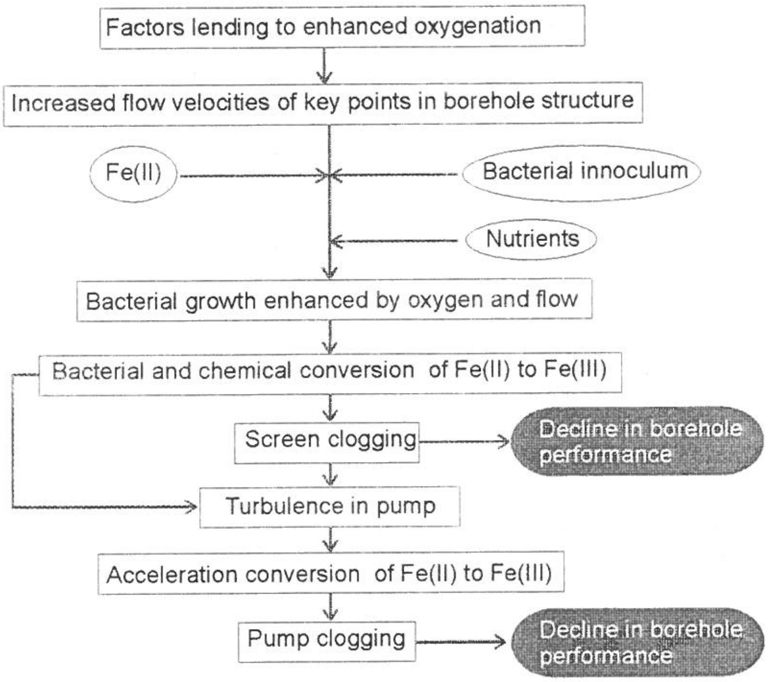
The redox potential also provides an indication of current growth environments :

- under highly oxidized conditions (> 150 mV), the water being abstracted has passed through a redox front, the front being located away from the borehole, deeper in the aquifer.
- Redox values between -50 and +150 mV indicate a redox front in or directly adjacent to the borehole, with potentially serious impacts on the screens and the pump.
- 50 - 150 mV, pseudomonads are often dominant, especially if a source of organic carbon nutrient exists. Most of these pseudomonads will form a slime, often in the upper oxidized zone in a borehole, with SRB's found in the deeper, oxygen poor, reduced environment.
- the zone between -50 and + 50mV constitutes the redox front and is the biozone of greatest microbial activity.
- At redox values of between -50 and -200 mV oxygen is limited, and SRB corrosion is likely.

5.4 Biological Clogging

Although iron oxidation is always a chemical proses, bacterial induced iron precipitation is distinguished from chemical iron oxidation by far more rapid and severe clogging (Smith, 1982). Rates of biologically enhanced iron biofouling can be 100000 greater than rates of chemical clogging. Even under conditions where bacterial levels are low, the bacterial activity increases clogging rates considerably compared to natural chemical clogging (Cullimore, pers com). Tyrrel and Howsam (1990) demonstrated a simple process model, as shown in Figure 3, which identifies those factors considered to govern the initiation and the rate of iron biofouling.

FIGURE 3 : SIMPLE IRON BIOFOULING PROCESS MODEL



Iron biofouling requires a groundwater with a 'significant` dissolved iron content, a microbial inoculum and concentration of nutrients sufficient to support an active biofilm. The assumption of Tyrrel and Howsam's (1990) model is that the nutrient supply and microbial inoculum is always present.

The clogging deposits consist of mainly iron hydroxides, microbial cells, ECPS and water and has a slimy/sludgy texture when relatively fresh (Tyrrel & Howsam, 1990). The characteristics of the biofilm change with age and when the deposit is quite old it tends to become harder, brittle and more compact. Oxygen is considered to be the key factor in iron biofouling as it is responsible for the growth of aerobic iron precipitating bacteria and the oxidation of soluble ferrous to insoluble ferric iron. Flow is required for biofilm development and it has been demonstrated that in certain circumstances, higher flow velocities will increase the rate of biofilm development (Pedersen, 1982, Caldwell, 1986). In addition, turbulence caused by higher flow velocities would enhance nutrient uptake (Cullimore, 1986) and also promote nucleation.

Where the groundwater contains a dissolved iron load, it is proposed that oxygenation and flow are the key controlling factors without which iron biofouling will not proceed irrespective of the other elements of the model.

Under suitable circumstances Fe $^{+3}$ iron precipitation (as ferric hydroxide) can take place without bacterial intervention, specifically under conditions where the groundwater is rich in iron and carbon dioxide.

The effect of biofouling will in some cases be visible, for example, a slimy material can be observed clogging the strainer of a retrieved pump or soft filamentous material can be observed covering the slots of a well screen. In other cases however the clogging material may appear as a brittle encrustation or clay-like sludge - the shape seldom gives a clue that microbial activity is involved. There is growing evidence that incrustations perceived as chemical in origin, probably in fact involved microbial processes. There are many bacteria (eg. *Gallionella*) which can initiate / enhance the formation of commonly encountered iron deposits and others which are associated with precipitation or calcium carbonate in natural environments.

Enhanced biofouling is only one of a number of impacts resulting from biological activity. Micro biologically influenced corrosion (MIC) can affect the well screens, the pump and pipework. MIC is caused by various micro-organisms including bacteria, fungi and algae although a group of anaerobic micro-organisms called sulphate-reducing bacteria (SRB) have been cited as the most important cause of MIC (Cloete and Von Holy, 1991).

6. MONITORING AND MEASURING BIOFOULING

One of the greatest problems related to the clogging of boreholes is related to the monitoring of any clogging taking place. It appears inevitable that some form of biofouling will take place in most boreholes with high iron levels and where oxygen is introduced into the hole. However, groundwater chemistry alone will not necessarily reflect the risk or level of biofouling.

The following are other factors which can be monitored to obtain an indication of where the clogging is taking place, and whether this clogging is chemical or biological in nature:

- Turbidity and colour of the water being pumped
- Odour
- Production in specific capacity
- Increase in bacterial activity

6.1 Colour

A clean clear water sample does not necessarily indicate a lack of bacterial growth - if a sample is left to stand and then develops a cloudiness it is likely that some bacterial growth exists. Cloudy water (especially red/yellow or brown/black colouration) is likely as a result of bacterial growth. Use of laser particle sizing systems allows one to count the number of particles and to evaluate the size and shape of the particles in the water. This may allow some form of identification of the structure of the particles and a quantification of the amount of particulate matter.

6.2 Odour

Odours commonly related to micro-biological activity include rotten eggs, earthy/musty and fishy smells. The rotten egg smell is associated with anaerobic conditions, the generation of hydrogen sulphide and the potential for the corrosion of equipment utilised in the borehole.

6.3 Camera Detection

The use of down-the-hole cameras provide direct evidence of the growth of bacteria and the clogging of well screens. Under most circumstances camera investigations are only appropriate in the latter phases of biofilm development and also serve limited purpose in identifying bacterial types or the aggressivity of the bacterial growths. Bacterial growth in a borehole are identified as large nuciod or plate-like structures attached to the side of the casing and extending into the water column. A TV camera only allows identification of problems within the borehole, as a result, biofouling in the gravel pack or aquifer cannot be directly observed.

6.4 Specific Capacity

As a boreholes begins to clog, water has difficulty entering into the borehole through the clogged aquifer and clogged screens, resulting in inefficient flow and a greater drawdown at constant pumping rates. It has however questionable whether monitoring of specific capacity can assist as an early warning monitoring activity, since most boreholes have excess production capacity i.e. they are pumped at a sustainable rate much lower than the maximum yield potential of the borehole. As a result a high amount of deposition can take place before there is any impact on the efficiency of the borehole and hence the specific capacity. It is likely that a decease in the specific capacity will take place once clogging is in an advanced stage.

Difficulties related to monitoring bacterial growth (because of the attachment - detachment phenomena) necessitates alternative methods of monitoring the clogging of boreholes. If a decrease in specific capacity is noticed (usually a 15 - 20% decrease is used as a reaction level), it is likely that clogging is well advanced and rehabilitation will be necessary. Cases where boreholes are being pumped at a fraction of their capacity (as in the Klein Karoo) any loss in specific capacity probably indicates that advanced clogging has taken place.

In monitoring specific capacity it is important that specific capacity is calculated for equivalent conditions i.e. at the same pumping rate once water levels have reached equilibrium.

6.5 Bacterial Activity

Majority of IRB bacteria are slime formers where the monitoring of bacterial levels can be exceptionally difficult because of the attachment - detachment phenomenon. Should sampling co-inside with the period of detachment it would appear that the bacterial growth is exceptionally high. This needs to be taken into account when monitoring takes place

6.5.1 Bacterial Culture

The most common method of evaluating the type and number of bacteria is via spread plate innumeration using a variety of agar media. After culture the visible colonies are counted and usually expressed as colony forming units (CFU) per 100ml. A number of agar media exist for bacteria, but the medium utilised for anaerobic bacteria is considerably more difficult unless the laboratory is specifically equipped to handle anaerobic incubation.

6.5.2 BARTS Test

A range of bio-detectors have been developed by Drydon Concepts Inc to test the aggressivity and type of microbial growth in waters. These tests are known as BARTS tests (Biological Activity Reaction Tests). BART test kits are available for a number of different bacteria including:

- Iron related bacteria (IRB),
- sulphate reducing bacteria (SRB),
- heterotrophic aerobic bacteria (HAB),
- denitrifying bacteria (DN),
- fluorescing pseudonomads,
- slime forming bacteria and nitrifying bacteria.

The BART test kit consists of a test tube which be filled with 15ml of the water sample. In the test tube there is a growth medium specific to the type of bacteria being investigated and a floating intercedent device (FID). The growth medium (at the bottom of the tube) and the FID result in two gradients developing - a gradient of nutrients diffusing upwards and a gradient of oxygen diffusing downwards past the FID. The kind of reaction and the number of days for this reaction to start (dd) allow an interpretation of the kind of bacteria that exists and the aggressivity of these bacteria. During the Clog Formation and Clog Maturation phases, the dd will fluctuate erratically depending on the phase of biofilm detachment.

6.5.3 In-situ Incubation Systems

The number of devices made of sterile glass, plastic or metal surfaces can be introduced into the borehole onto which bacterial growth can attached itself. Once adequate growth has taken place the devices can be removed and electron microscopic examination can take place to identify the bacteria growing in the borehole.

6.5.4 Surface Incubation Tubes

Instead of providing a medium for biofilm cultivation in the borehole it is possible to pump the water to surface and then allow it to move through a device filled with an appropriate medium where bacterial growth can take place at surface. This allows for direct evaluation of biofilm development and the clogging of the medium.

6.5.5. Coliform Tests

Coliform detection methods are well developed and are one of the time methods of indicating the bacterial health of the water. Fortunately, many of the bacteria associated with borehole clogging are not coliform bacteria. As a result the absence of coliform is not necessarily an indication that borehole clogging via bacterial growth will not take place.

6.5.6 Simple Field Tests

There are a number of simple qualitative tests that can be undertaken in the field to evaluate whether any microbial activity is taking place in the borehole. A number of these simple tests are described below:

Rodina Test

Groundwater is poured into a wide necked vessel through which oxygen can easily diffuse into the water, the depth of water been less than 10 cm. The vessel is left at room temperature for bacterial incubation to take place.

Cholodny Test

A cork is used to float a glass slide vertically in the groundwater sample collected. The growth of any "rust spots" or "cotton-like accumulants" on the glass slide is an indication of the presence of IRB's. For more detailed identification of the IRB's the glass slide can be removed for electron microscope examination.

Grainge & Lund Test

A soft steel washer is placed in a conicle flask together with a plastic stirring rod (positioned vertically) and sufficient water is added to the flask to cover the steel washer. After two days the water line around the plastic rod is examined for any bacterial growth. Any translucent string-like growths which develop into a brown tinge are taken as positive identification of IRB.

GAQC Test

A steel washer, 150 ml of water and two drops of Jack Daniels whiskey are poured into a glass which is covered with aluminium foil. Fuzzy growth around the washer or metallic "floaters" in the water are indicators of IRB.

7. REMEDIATION OF CLOGGED BOREHOLES

Experience have shown that there is no one method which can be used as the described formula to effectively rehabilitate all clogged boreholes. Once the biomass is established, several treatments may be required to restore borehole yields to acceptable levels.

Borehole rehabilitation is often made very difficult and ineffective if the problem is not successfully identified. Historically acids have been used extensively in borehole rehabilitation and are often inhibited by extensive blankets of extra cellular polysaccharides . Many organisms living in groundwater aquifers are attached on soil particles. They produce organic sheaths, stalks and slimes, making biofilms around sand grains. These biofilms are often extensive blankets of extra cellular polysaccharides that can form complexes of chelates with certain metals. It has a great significance in the adsorption of different simple molecules on the biofilms. These materials are released when the micro-organisms die-off. Rehabilitation will depend on the nature of the aquifer, the original construction of the borehole together with the problem being experienced. The rehabilitation action should include combinations of physical, mechanical and chemical methods.

It is a worldwide assumption that groundwater and aquifers that are not noticeable polluted are perceived as being bacteriologically clean. It is true that groundwater contains far fewer microorganisms than surface water, but it is by no means sterile. The soil through which much groundwater passes on its way to the aquifer is certainly swarming with microorganisms. Some can adapt to conditions in the aquifer and thus become residents, some can be introduced into the aquifer during drilling (migrants) and some described as ultra-micro cells, with extremely slow rates of metabolism, able to travel long distances through the aquifer.

Borehole clogging is a problem that occurs all over the world, including South Africa. It must be considered very seriously in developing countries where weak economics could well do without the added strain of supporting inefficient systems or where failure can simply lead to going without.

The remediation of a borehole that has been clogged is often misguided in that the majority of the remediation effort is directed at the bacterial problem. However approximately 75 to 80% of the material deposited is of a mineral content, while the remainder of the material is biological (Mansuy, 1998). As a result the most important aspect of rehabilitation is effective deposit removal. In many circumstances the periods between rehabilitation treatments becomes shorter and shorter - this is often thought to be as a result of increasing biological growth and inefficient treatment of the bacteria, while the actual problem is related to ineffectual removal of the mineral scale deposited. A better understanding of the scale deposited is therefore required for effectual removal of the scale blocking the aquifer and screens. It is very important to identify and differentiate the origin and the position of borehole clogging for effective treatment and ultimately borehole rehabilitation

The rehabilitation of a clogged borehole has to be a multifaceted exercise dealing with both the bacterial problem and the scale developed. Normally well rehabilitation will be separated into three distinct steps :

- Pre treatment
- Chemical treatment of the both the bacteria and the scale
- Cleaning and re-development of the borehole

7.1 Pre treatment

The deposit clogging the borehole usually have a soft outside and a harder inside - the softer material should be removed before treatment of the harder scale takes place. Normally pre treatment is of a mechanical nature and can involve :

- Wire brushing to scrape of the softer material
- Jetting to wash off loose deposits
- Surge and purge procedures utilising either water or suitable gasses (i.e. carbon dioxide)
- Sonar jet (a vibratory explosive using an expensive gas)

After pre treatment has taken place chemical treatment of the borehole is utilised to both kill off the bacteria and remove the mineral scale still in place.

7.2 Disinfectants

Disinfectants are normally used to kill off the bacteria in the borehole, the gravel pack and the adjacent aquifer. For any disinfectant to be effective adequate volumes and concentrations of the chemicals applied must be utilised. Commonly a volume equal to 2 or 3 times the well volume has to be introduced to adequately penetrate the surrounding formation with the chemical utilised.

Disinfectants commonly used for killing off bacteria include:

- sodium hypochlorite, calcium hypochlorite, chlorine dioxide, chlorine gas, potassium permanganate.

Of all the disinfectants available sodium hypochlorite is commonly seen as the best available. Some disinfectants are strong oxidising agents - they may be effective at oxidising the bacteria, but oxidation of dissolved iron in the water can lead to additional deposition of iron minerals.

7.3 Scale treatment

Once the bacteria have been treated, it becomes necessary to treat the scale developed, normally achieved by the utilisation of acids. Acids commonly utilised include hydrochloric, hydroxyacetic, citric, acetic, sulfamic, sulphuric and oxalic. The most suitable acid, especially for iron and manganese dissolution, is hydrochloric acid. Hydrochloric acid does however pose a corrosion risk to steel and stainless steel screens and should only be utilised with an inhibitor or surfactant which helps to control corrosion of the steel screens without losing the advantage of the acid dissolving the scale.

A number of commercial organisations have produced treatment chemicals capable of disinfectant and scale removal. These products allow a single treatment of the well reducing both the time and the costs of borehole rehabilitation. One of the most widely used commercial products in the USA is a product called QC-21 well cleaner which is a combination of organic acids, dispersants and surfactants capable of disinfection, slime dispersion and scale dissolution.

There are new technologies capable of both disinfecting and removing the scale which have become widely accepted in the USA lately. One of these techniques involves the injection of both gaseous and liquid forms of carbon dioxide into the borehole and adjacent aquifer. The injection with carbon dioxide results in a coupled effect of freezing and agitation. The freezing of the borehole and the expansion of the carbon dioxide from a liquid to gaseous state results in the killing of the bacteria and the removal of the scale from the surface onto which it had grown.

One irony of the scale removal and biological treatment, is that the bioaccumulation may have been "filtering" iron out of the groundwater - after rehabilitation, iron levels can increase dramatically and water quality can deteriorate.

7.4 Borehole Cleaning / Development

Once the bacteria and the scale have been killed, dissolved or dislodged the material has to be removed from the borehole. Typical procedures to remove the material include :

- Jetting
- Swabbing
- Surging
- Airlifting

Usually a combination of the techniques is used, one of the most effective combination's being airlift swabbing. In most cases material removed from the boreholes is of a potentially hazardous nature and should be disposed of in a suitable facility.

8. MANAGEMENT TO REDUCE BIOFOULING

The development of iron and manganese scales is mostly associated with the introduction of oxygen into the borehole either causing a chemical precipitation or an increase in biological activity which accentuates the chemical scale development. Most measures aimed at reducing scale build up are associated with reducing the inflow of oxygenated water into the borehole. A number of applications to achieve this aim are discussed below.

8.1 Correct screen emplacement

In a situation where screens are emplaced above the pump, water can enter the borehole cascade through the screens to the pump. The pump should therefore be preferably be installed above the screen location. In a situation where multiple fractures (all screened) occur in a borehole it may be necessary to screen the lower fractures only. Screens and casing should only be installed where necessary in a borehole drilled into hard rock. The borehole below the depth at which the pump will be installed should be left open, thus increasing the flow efficiencies in the hole.

8.2 Abstraction Management

Abstraction management should be undertaken in such a way so as to have the least drawdown and therefore the most efficient flow of water to the borehole. Boreholes should rather the pumped continuously at low rates than high pumping rates with a periodic pumping schedule. Intermittent pumping allows for the mixing of anaerobic iron containing waters and aerobic surface waters thus developing a redox front and promoting bacterial growth.

8.3 Introduction of anoxic block systems

Inert gasses can be introduced into a borehole to prevent oxygen from entering the well. By restricting the entry of oxygen the amount of aerobic activity taking place is reduced and plugging is also therefore reduced. Normally nitrogen is the inert gas. There is however a high cost associated with keeping a nitrogen anoxic block in a borehole and these blocks are normally utilised in vitally important production boreholes with severe plugging problems.

8.4 In Situ Chlorination

The South Australia Water Corporation (Forward, 1996) utilizes in situ generation of chlorine by electrolysis of the groundwater being pumped, to control bacterially accentuated clogging. Chlorinator electrodes are placed in a section of the water supply line and energized during a daily one hour period of non pumping. The electrolysis produces 3-4 mg/l free chlorine from the brack water (12 000 mg/l chloride). The chlorinated water is allowed to backflush down the borehole providing effective daily sanitation of the pump, screens and adjacent aquifer. The low chloride levels in the Klein Karoo water limit the application of this treatment method.

8.5 In Situ Iron Precipitation (Vyredox method).

Biofouling tends to be worst in the reduction - oxidation fringe normally within a borehole where oxygen rich waters enters the hole this fringe position is within the borehole. Under suitable conditions it may be possible to extend the position of the oxidation zone into the aquifer by the direct injection of aerated water to specially placed recharge boreholes. The oxygenated water injected mixes with the groundwater in the aquifer, activating bacteria which result in the precipitation of unwanted iron and manganese at a distance away from the borehole. This has the potential of reducing the iron levels in the groundwater reaching the borehole and therefore decreasing the potential for clogging in the production borehole. This technique has been patented under the name of the Vryedox method.

8.6 Monitoring

Any monitoring procedure has to rely upon evidence relating to the particles shearing from the biofilm during pumping, along with the releases of any inorganic of organic product which can be linked to the clogging. The types of bacteria found during the monitoring will indicate the probable form of the clogging. For example, very high populations of IRB's would indicate that a severe clogging is occurring with the bioaccumulation of iron and/or manganese. The presence of large populations of SRB's would indicate that the clogging is anaerobic, sulphate is present in significant concentration and that hydrogen sulphide is being produced which could stimulate electro-chemical corrosion.

Success of remediation treatment (such as disinfections, acids, wetting agents, application of heat) applied to clogged boreholes can be based on an evaluation of the amount of particulate matter removed and the incumbency of different microbial groups. Subsequent monitoring of the boreholes on a routine basis (e.g., monthly) can then be used to determine the speed with which the biofouling is recurring within the well (Cullimore, 1990).

DATA INTERPRETATION AND FIELDWORK RESULTS

The fieldwork and data evaluation undertaken on the Klein Karoo boreholes (see positions marked on the maps in the Map Pocket at the back of the document) was aimed at identifying the cause of the borehole clogging and investigating options for the management of clogging in the future.

Evaluation of the historical data was aimed at assessing whether any data existed which could assist in quantifying the clogging or the bacterial growth. During the fieldwork the main production boreholes were sampled and prevailing chemical and biological conditions were measured. In total 15 boreholes were sampled, some of the holes sampled on two occasions because of inadequate sample purging during the first sample run.

9. HISTORICAL DATA INTERPRETATION

9.1 Borehole yields

The majority of the boreholes in the Table Mountain Sandstones in the Klein Karoo are being pumped at a fraction of the maximum achievable yield potential of the boreholes. This is a result of the low rainfall and limited recharge which results in the borehole's sustainable yield being far lower than the maximum yield achievable. As a result any clogging that may have taken place in the past has had very limited impact (if any) on the ability of the borehole to maintain the pumping rate set.

9.2 Iron Concentrations

A number of the existing production boreholes were utilised by the previous Divisional Council prior to the scheme been taken over by Overberg Water. Unfortunately limited chemical results exist for this early period. Chemical results are available in the reports by Geustyn, Forsyth and Joubert (1989), Mulder (1995) and from existing records held by Overberg Water. The iron levels shown in these results are summarised in Table 1, with the monthly data obtained from Overberg Water having been averaged to obtain a yearly average from 1994 to 1999.

The results do not show any conclusive results of an overall increase in the iron levels - in fact the opposite appears to have occurred. Iron concentrations have dropped since Mulder's sampling in 1992 in all of the holes except for DP12, DP28 and KG1. This may be as a result of oxidation of the ferrous iron in solution, causing precipitation of ferric oxyhydroxides and a lowering of the dissolved iron concentrations. Increases in iron concentration should only be taking place under circumstances where reduction, due to acid generation, results in the disillusion of any iron scale developed. This is a reason why standby boreholes should by operated on a regular basis to stop anaerobic reducing conditions developing.

Iron levels fluctuate wildly in many of the boreholes (see Appendix A), especially those in the Calitzdorp wellfield. These erratic changes are as a result of the sloughing of the biofilm and signifies that bioaccumulation is in an advanced phase. Although comparison between the 1992 and 1994-99 averages, shows that iron concentration appears to have improved in most of the holes, a more detailed assessment of the 1994-99 data does not always support this. In some of the holes (especially DP28, DP29 and KG1) there has been an increase in iron levels since 1994.

TABLE 1 : VARIATIONS IN IRON CHEMISTRY

Borehole	**Sample date**	**Iron level (mg/l)**	**Sample date**	**Iron level (mg/l)**	**Sample date**	**Iron level (mg/l)**	**Sample date**	**Average Iron level (mg/l)**
DP10	1989	3.0	April 1992	3.3	1995	2.5		
DP15	1989	0.7	April 1992	3.0	1995	3	1994-99	2.5
DG110					1995	11-21	1994-99	7.1
DL17			April 1992	8.1	1995	9	1994-99	4.1
DL16			April 1992	6.0			1994-99	3.2
DP29			April 1992	3.8			1994-99	1.7
DP12			April 1992	1.9			1994-99	2.0
DP13			April 1992	6.1			1994-99	2.9
DP28			April 1992	1.1			1993-97 1997-99	0.95 7.9
VG3			April 1992	3.2			1994-99	0.18
VR6			April 1992	0.69			1994-99	<0.05
VR7			April 1992/	0.14			1994-99	<0.05
VR8			April 1992	0.17			1994-99	<0.05
VR11			April 1992	0.6			1994-99	<0.05
KG1			April 1992	3.8			1994-99	3.9

9.2.1 Iron levels - different wellfields

- The iron concentrations are static for those boreholes in the Vermaak's River Valley Boreholes VG1 and VG2 definitely show signs of elevated iron compared to the rest of Vermaaks River holes. It is interesting to note that all of the Vermaaks River holes with the exception of VG1- 3 are drilled into Peninsula Formation (the VG 1 - 3 holes are drilled into Nardouw rocks).
- Borehole DP18 (Olifants river alluvium) has not shown any signs of iron increases, probably because conditions are not suitable for bacteria growth (no oxygenation of the water).
- The Droëkloof (DG110) has consistently shown elevated iron concentrations. The concentration has however not increased with time even though bacterial growth has apparently been exceptionally high in the past.
- The Varkieskloof boreholes have shown a limited rise in iron concentration
- The Bokkraal boreholes have shown dramatic increases in Fe levels, only possible if the iron is being reduced and more iron dissolved into solution.
- The Calitzdorp boreholes have always had an elevated iron content with concentrations increasing from an average of 2.5 in 1994 to 4.0 mg/ℓ in 1998.

9.3 Odour/Turbidity

The number of boreholes have a turbidity problem and have a typical red to orange tinge associated with iron bacteria. This discolouration is normally worst during the initial few minutes when pumping starts, improving with time indicating bacterial growth in and directly adjacent to the hole. The holes with the worst discolouration include:

- DL17, KG1, DG110 and DP28.

Although there is a noticeable odour at a number of the boreholes the aeration and chemical treatment that takes place at the treatment works removes this odour and the final product does not have any unpleasant odours. The boreholes where an odour problem occurs at the abstraction point include:

- DL17 : musty earthy odour
- DP28 : sulphurous rotten egg smell
- DG 110 : earthy musty smell

9.4 Specific Capacity

Comparison of specific capacity in a borehole is only meaningful at a constant pumping rate. Variations in pumping rate result in changes in specific capacity thus making it exceptionally difficult to evaluate whether clogging is causing any decrease in the specific capacity in a borehole. Specific capacity has been monitored in a number of boreholes. Graphs showing rest water level, pumped water level, abstraction rate and specific capacity are shown in Appendix B. The general relationship and trends shown in the various boreholes is summarised in Table 2 below. Unfortunately transducer problems have resulted in difficulties in measuring the pumped water level in the majority of the boreholes during the period 1996 to 1998 and there is limited data for this period. The boreholes where fluctuations in specific capacity have been limited include:

- VR7, VR6, VR3, DP29 and DL16.

Boreholes where borehole fluctuations have been relatively large include:

- DP12, DP15, DP28, KG1 and DL17

TABLE 2 : CHANGE IN SPECIFIC CAPACITIES SINCE 1994

BOREHOLE	CHANGES IN SPECIFIC CAPACITY	INCREASE / DECREASE
VR 11	Dropped as yield dropped - rise in January 1996	Stable
VR 8	General rise. Sharp rise as yield dropped (05/95) sharp drop as yield rose (01/97)	Increase
VR 7	General rise. Fluctuations even though yield and water levels not static	Increase
VR 6	General rise. Sharp rise (05/95) as yield dropped	Increase
VG 3	General rise. As water levels rose (01/95 and 09-10/96), sc rose - recharge?	Increase
DG 110	Drop even though pump rate not constant. Noticeable decline in pumped water level since 04/97	Decrease
DP 12	Drop since 02/95, even though pump rate constant. Sharp decline 08/95 when pumped water level declined	Decrease
DP 29	Unexplained water level changes not related to rainfall or change in pumping rates - stable since 09/96	Stable
DP 15	Wild fluctuations - possible error in measurement of pumped water level	Fluctuating, but stable
DP 28	Rises as pumping rates rise. Dropped with water level rise and pumping rate drop after 10/96 rains. Unexplained lows 9/95 - 1/96	Fluctuating and dropping
KG 1	Unclear relationship, possibly low yields ⇒ higher s.c	Fluctuating and dropping
DL 16	Drops as yield drops, rises as pumping rate rises . Some measurement errors	Fluctuating
DL 15	Drops as yield drops, rises and yield rises	Stable
DL 17	Errors with measurement of pumped water levels confuses trends. Appears that a drop in pumping rate causes drop in sc and visa versa	Fluctuating but rising

The remainder of the holes have had some moderate fluctuations. The only boreholes that show a definite decrease in specific capacity are boreholes DG110and DP12 (only up until 11/95).

Historical monitoring of water levels and yields have not been continuous enough to allow for careful evaluation of specific capacity. Monitoring will have to be upgraded to allow for more careful assessment of changes in specific capacity.

A further assessment of changes in specific capacity could be made by evaluating specific capacity calculated from step tests undertaken during 1995 and further tests undertaken during 1997/98. Table 3 below shows specific capacities for similar pumping rates during the two different periods.

TABLE 3 : SPECIFIC CAPACITY : 1995 TESTS COMPARED TO 1997/98 TESTS.

Borehole #	Test Period	Yield	Drawdown	Specific Capacity	Increase/ Decrease
VG3	1995	10.6	62	0.17	Increase
	1997-1998	10.6	41.4	0.25	
VR6	1995	4.94	12	0.41	Increase
	1997-1998	5	5.9	0.85	
DP28	1995	9.4	3	3.13	Dropping
	1997-1998	9.5	4.2	2.26	
DP18	1995	5.7	1.5	3.8	Increasing
	1997-1998	5.9	1.3	4.54	
DL16	1995	7.2	12	0.6	Dropping
	1997-1998	7.4	15.7	0.47	
KG1	1995	5.91	2.5	2.36	Dropping
	1997-1998	5.9	2.9	2.03	

10. RESULTS FROM 1998/9 FIELDWORK

During 1998 (October and November) and 1999 (January) field trips were undertaken to collect water samples from the more important production boreholes in the Klein Karoo Scheme. Field measurement of electrical conductivity, pH and Eh were undertaken while water samples were collected for chemical and bacteriological analysis.

10.1 Water Chemistry

Twenty samples were collected from the scheme boreholes and some of the adjacent private boreholes. All of the chemistry data is contained in Appendix B, together with the Piper diagram plots .

Two samples were collected from boreholes KG1, VG1, VG2 and DP28, for the following reasons:

KG1:	Initial sample collected by submersible sampling pump after 15 minutes of pumping during a period where the borehole had not been utilised for 3 months previously. The second sample collected with the scheme's production pump after the borehole had been rested for one day but during a period where the borehole was being used daily.
VG1/VG2:	Initial samples collected with a bailer, while latter samples collected with submersible. The second sample was obtained after 20 minutes of purging with a sampling pump.
DP28:	Initial sample collected with a bailer while latter sample, second sample collected while abstraction was taking place utilising the scheme's production borehole.

10.1.1 Cation / Anion Chemistry

The water is typically of a sodium chloride nature although the Piper diagram does show three? distinct groundwaters namely, the Vermaaks River boreholes, the Voorsorg boreholes, the Bokkraal boreholes and the rest of the scheme (Calitzdorp, Varkieskloof and Droëkloof holes). Although different sampling techniques were utilised for some of the holes (as discussed above) the only major difference in chemistry was between the initial and second sampling for DP28. Comments related to the specific cations and anions are contained in Table 4.

TABLE 4 : CATION / ANION CHEMISTRY

Cation/Anions	Comment
K	Calitzdorp levels much higher than other areas
SO4	DP25 and DP28 are exceptionally high - almost unnaturally so VG2 and KB1 are moderately high
Alkalinity	VG2 higher together with Calitzdorp boreholes
Nitrate/Nitrite	Levels all low although some low levels in Vermaaksriver Valley
Fe	Vermaaks holes are low, the Voorsoog holes are moderate, while holes KG1, DG110, DP25 and DP28 are high.
Mn	Holes DG110, VG2, DP25 and DP28 are all high
Hardness	Higher for Bokkraal and Calitzdorp holes.

10.1.2 Field pH

The field pH measured shows the water to be acidic, with the Calitzdorp boreholes being the most neutral (pH variations between 6.42 and 6.2) the remainder of the boreholes (with exception of the Bokkraal holes) have a pH range between 6.3 and 4.8. The two Bokkraal holes (DP28 and DP25) have a pH between 4.2 and 3.4. The pH conditions occurring are not ideal for the growth of bacteria, being too low. Under prevailing pH conditions bacterial growth would be retarded and only specific bacteria would thrive, the conditions suiting *Thiobacillus*.

10.1.3 pH/Eh relationship

The Eh was not measured directly in the field but can be calculated from the dissolved oxygen (DO) measurements which were undertaken in the field. The calculation of the Eh shown in Table 5 below while the Eh and field pH data is shown on the graph in Figure 4.

TABLE 5 : CALCULATION OF EH FROM DO

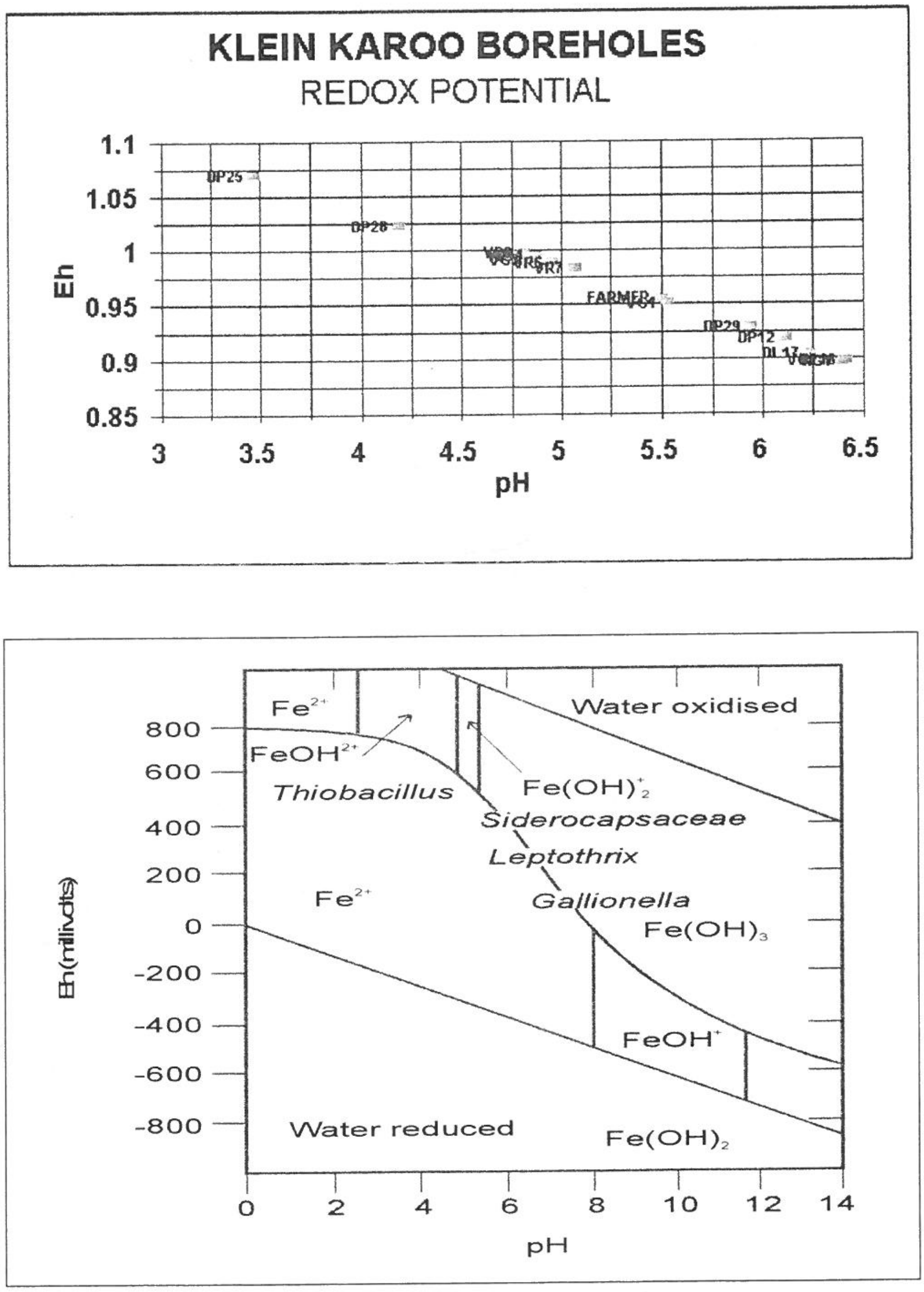
P ox = DO / Kox , where K ox @ 25 C = 1.28 x 10 -3 mol/bar
pE = 20.78 + 0.25 log (P ox) - pH
Eh = 0.05917 pE

BOREHOLE	DO (mg/l)	P ox	pE	Eh	pH
KG1	1.3	1015.63	15.13	0.895	6.4
DL16	2	1562.50	15.16	0.897	6.42
DL17	1.2	937.50	15.28	0.904	6.24
DP28	0.7	546.88	17.27	1.022	4.19
DP25	1.4	1093.75	18.07	1.069	3.47
FARMER	3.8	2968.75	16.15	0.955	5.5
DP12	3.4	2656.25	15.52	0.918	6.12
DP29	3.4	2656.25	15.69	0.928	5.95
VG1	2.6	2031.25	16.08	0.951	5.53
VG2	1	781.25	15.17	0.898	6.33
VG3	2.6	2031.25	16.76	0.992	4.85
VR6	4.8	3750.00	16.71	0.989	4.96
VR7	5.6	4375.00	16.62	0.983	5.07
VR8	4.7	3671.88	16.86	0.998	4.81
VR11	5.6	4375.00	16.82	0.995	4.87

The dissolved oxygen figures show a higher level of dissolved oxygen in the Vermaaksriver Valley with lower DO concentrations in the Calitzdorp area. Dissolved oxygen levels in groundwater are commonly related to the amount of organic material in the soils through which rainfall must infiltrate before entering the groundwater. Where thick soils with high humic concentrations exist DO oxygen levels are commonly low while fractured rock environments with thin soil covers will have higher DO levels. In areas where biological activity in boreholes takes place it is likely that this biological action will reduce the dissolved oxygen content in the groundwater - this explains the low DO levels in D28, VG2, DL17 and KG1 and DP25.

The lower limit of dissolved oxygen necessary for the existence of most aerobic bacteria is considered to be about 0.05 mg/ℓ. Based on the dissolved oxygen levels in the Klein Karoo most of the bacteria existing should be aerobic bacteria .

FIGURE 4 : KLEIN KAROO Eh / pH RELATIONSHIPS.



10.2 BACTERIA

Groundwater samples were collected from 15 of the boreholes in and adjacent to the Klein Karoo Project and were subjected to bacterial tests. Initially the total heterotrophic plate count (NCFU per ml) was measured to get some indication of the total bacterial levels. Thereafter Biological Reaction Test (BARTS) were undertaken to gain an understanding of the iron related bacteria (IRB) and sulphate reducing bacteria (SRB).

10.2.1 Heterotrophic plate count

The heterotrophic plate counts (HPC) were undertaken on the first set of samples collected during September 1998 and some of the December 1998 samples. The majority of the boreholes have exceptionally high HPC with the exception of the Vermaaks river boreholes which showed low levels. It is interesting to note that the HPC in the Vermaaksriver boreholes decreases with distances into the kloof (and thus also with greater depth to groundwater level). The low HPC for borehole DP25 is surprising and is probably related to the anaerobic nature of the bacteria in the borehole. The various HPC for the different boreholes are shown in Table 6.

TABLE 6 : HETEROTROPHIC PLATE COUNT

BOREHOLE NUMBER	**HPC (cfu/ ml)**	
	September 1998	December 1998
FARMER	> 10 000	
DP12	> 5 000	
DP25	320	
DP28	> 5 000	> 5 000
DP29	>5 000	
KG1	>10 000	56 000
VG1	> 5 000	57 600
VG2	>5 000	25 500
VG3	1 600	
DL16	500	
DL17	>5 000	
DG110		72 200
VR6	460	
VR7	158	
VR8	63	
VR11	45	

Dr Cullimore (pers com, 1999) suggested that 50% of all HPC recorded are underestimates, since plate counts do not adequately take into account anaerobic bacteria. As a result the total bacterial populations cannot be accurately gauged.

10.2.2 BARTS Tests

The BARTS biodetectors are test kits developed to determine the aggressivity and forms of biofouling taking place in water. The test vial is so designed that bacteria in the water added to the test vial are provided with a number of different environmental niches, based on the formation of a redox gradient in the vial. Different growth mediums and nutrients are placed in different vials, allowing growth of different microorganisms. The IRB and SRB test vial were used during this investigation. The speed at which the reaction (bacterial growth) takes place and the kind of reaction gives an indication of the bacterial activity in the groundwater. A summary of the typical IRB and SRB reactions is contained in Appendix D. The results from the BARTS tests (the reaction time, the reactions, the aggressivity and the bacteria found in each hole) are shown in Table 7. The results per well field are :

Calitzdorp
(KG1, DL16, DL17) - Moderate to background levels of mixed anaerobic and aerobic bacteria, including pseudomonads and some SRBs.

Bokkraal
(DP25, DP 28 & Farmer) - Moderate levels of pseudomonads & slime forming SRBs

Varkieskloof
(DP12 & DP29) - Moderate levels of mixed anaerobic and aerobic bacteria, including IRBs, SRBs and Pseudomonads

Droëkloof (DG110) - Moderate to high levels of anaerobic & aerobic bacteria, mostly Pseudomonads, plus IRB's and Desulfovibrio.

Vorsorg
(VG1, VG2 & VG3) - Moderate to high levels of mixed anaerobic, enteric, SRB and Pseudomonad bacteria plus slime formers capable of functioning aerobically.

Vermaaks
(VR6, VR7, VR8 & VR11) - Moderate to high levels of mixed anaerobic and aerobic bacteria, dominated by pseudomonads and Desulfovibrio.

The results of the BARTS tests were discussed with Dr Roy Cullimore, one of the leading experts in the biofouling field. GCS was concerned with the variability in the results, especially in the Vermaaks river valley. Dr Cullimore put the variability down to the effect of sloughing of the biofilm - high sloughing would result in high aggressivity readings. Variations between the first and second sampling of the Voorsorg holes (bailed vrs pumped samples) shows IRB and enteric bacteria to exist in the borehole, with pseudomonads dominants in the aquifer. Dr Cullimore also suggested that sulphur oxidizing bacteria may be dominant under the prevailing low pH conditions existing in the Bokkraal wellfield. The difference for the Vermaaks boreholes between the BARTS test results (showing high aggressivity) and the Heterotrophic Plate Counts (showing limited bacteria) was ascribed to the BARTS tests culturing more aggressive and diverse bacteria than the agar speadplate.

TABLE 7 : RESULTS FROM BARTS TESTS

Borehole	IRB				SRB			
	Rxn	**dd**	**Aggressivity**	**Bacteria**	**Rxn**	**dd**	**Aggressivity**	**Bacteria**
Farmer	FO-GC	4	Moderate	Mixed anaerobic & aerobic bacteria dominated by Pseudomonads	BT-BA	9	Background	Aerobic slime formers incorporating SRBs which can colonize anaerobic conditions within the slime.
DP25	No reaction	21	Background	No bacteria	BT-BA	18	Background	Aerobic slime formers incorporating SRBs which can colonize anaerobic conditions within the slime.
DP28	No reaction	13	Background	No bacteria	BT-BA	14	Background	Aerobic slime formers incorporating SRBs which can colonize anaerobic conditions within the slime.
DP28 *	No reaction	> 20	None	None	-	>20	None	None
DP28**	GC	4	Moderate	Mostly Pseudomonads	-	>20	None	None
DP12	FO-GC-BL	4	Moderate	Mixed anaerobes, pseudomonads and enteric bacteria	BT-BA	6	Moderate	Aerobic slime formers incorporating SRBs which can colonize anaerobic conditions within the slime.
DP29	FO-GC	4	Moderate	Mixed anaerobic & aerobic bacteria dominated by Pseudomonads	BT-BA	12	Background	Aerobic slime formers incorporating SRBs which can colonize anaerobic conditions within the slime.
DP29**		4	Moderate	Mixed anaerobic & IRB, plus Pseudomonads				
KG1	FO-GC-BL	7	Background	Mixed anaerobes, pseudomonads and enteric bacteria	BT-BA	7	Moderate	Aerobic slime formers incorporating SRBs which can colonize anaerobic conditions within the slime.
KG1 *	BR-BC	5	Moderate	Mixed anaerobic & IRB with some aerobic slime formers	BT-BA	>21	Background	Aerobic slime formers incorporating SRBs which can colonize anaerobic conditions within the slime.
DL16	FO-GC	4	Moderate	Mixed anaerobic & aerobic bacteria dominated by Pseudomonads	BT-BA	6	Moderate	Aerobic slime formers incorporating SRBs which can colonize anaerobic conditions within the slime.
DL17	FO-GC -BL	4	Moderate	Mixed anaerobes, pseudomonads and enteric bacteria	BT-BA	20	Background	Aerobic slime formers incorporating SRBs which can colonize anaerobic conditions within the slime.
DG110 *	FO-GC	3	High	Mixed anaerobic & aerobic bacteria dominated by Pseudomonads	BB	>21	Background	Deep seated anaerobic bacteria dominated by Desulfovibrio.
DG110***	FO-BR-GC	4	Moderate	Mixed anaerobic & IRB, plus Pseudomonads	-	>20	None	None

Borehole	IRB				SRB			
	Rxn	dd	Aggressivity	Bacteria	Rxn	dd	Aggressivity	Bacteria
VR6	FO-GC	4	Moderate	Mixed anaerobic & aerobic bacteria dominated by Pseudomonads	BB	12	Background	Deep seated anaerobic bacteria dominated by Desulfovibrio.
VR6**	FO-BR-GC	2	High	Mixed anaerobic & IRB, plus Pseudomonads	-	>20	None	None
VR7	FO-GC	7	Background	Mixed anaerobic & aerobic bacteria dominated by Pseudomonads	BB	>21	Background	Deep seated anaerobic bacteria dominated by Desulfovibrio.
VR7**	FO-BR-GC	3	High	Mixed anaerobic & IRB, plus Pseudomonads	BT	15	Background	Dominant aerobic slime (forming heterotrophic including STB's)
VR8	FO-GC	4	Moderate	Mixed anaerobic & aerobic bacteria dominated by Pseudomonads	BB	>21	Background	Deep seated anaerobic bacteria dominated by Desulfovibrio.
VR11	FO-GC	6	Moderate	Mixed anaerobic & aerobic bacteria dominated by Pseudomonads	BT-BA	20	Background	Aerobic slime formers incorporating SRBs , able to colonize anaerobic conditions
VG1	FO-CL -BC -BR	4	Moderate	Mixed anaerobic and enteric bacteria with some slime forming IRB	BT-BA	9	Background	Aerobic slime formers incorporating SRBs which can colonize anaerobic conditions within the slime.
VG1 *	GC	6	Moderate	Mostly Pseudomonads	BT-BA	9	Background	Aerobic slime formers incorporating SRBs which can colonize anaerobic conditions within the slime.
VG2	FO-CC-BC-BR	7	Background	Mixed anaerobic and enteric bacteria with some slime forming IRB	BT	10	Background	Aerobic slime formers incorporating SRBs which can colonize anaerobic conditions within the slime.
VG2 *	RC-GC	6	Moderate	Enteric / IRB bacteria dominate with some Pseudomonads	BT-BA	8	Background	Aerobic slime formers incorporating SRBs which can colonize anaerobic conditions within the slime.
VG3**	FO-BR-GC	3	High	Mixed anaerobic & IRB, plus Pseudomonads	-	>20	None	None
VG3	FO-GC	4	Moderate	Mixed anaerobic & aerobic bacteria dominated by Pseudomonads	BB-BA	22	Background	Anaerobic consortium, including SRB, a fraction of which can operate aerobically.

All samples collected in September 1998 after purging by pumping), except :
* collected in Dec 1998 (Sept sampling of theses holes was by bailer ; December sampling by submersible pump).
** collected in January 1999 (by pumping).

Dr Cullimore evaluated the data from the BARTS tests (Table 7) and found that there were two broad categories to the analyses (Table 8).

TABLE 8 : GROUNDWATER CATEGORIES BASED ON BARTS TESTS.

Group A -	IRB related reaction : BT - BA There are a dominance of aerobic bacteria, probably pseudomonads, that are shielding the SRB.
Group B -	SRB related reaction : BB Indicates a more anaerobic environment with less involvement of aerobic bacteria

Group A (based on the IRB response)

Gro up A.1
GC reaction (without going on to BL) indicates that pseudomonads are very active

- Farmer
- DP29
- KG1
- VG3
- DL16
- VR11

All of these wells had a high plate count, except VR11

GC going onto GC-BL indicates the presence of enterics

- DP12
- KG1
- DL17

All of these wells had a high plate count

Group A.2
IRB not detected. Probably a HAB or SLYM BART should have been used and, in all probability, very aggressive populations would have been detected

- DP25
- DP28

Plate detected moderate to high populations of bacteria

Group A.3
IRB did not detect GC, but gave alternate reactions (BC, BR). Pseudomonad bacteria not dominant but plate showed high bacterial populations. Confirmed by BT and IRB reactions.

- VG1
- VG2

Group B - Based on anaerobic SRB response (BB reaction)

Group B.1
The IRB reaction GC indicates that pseudomonads are present, but do not link up with the SRBs, but form BT reactions or extend to BA reactions

- VR6
- VR7
- VR8

Group B.2
A link up between pseudomonads and SRBs occur, to cause the BB to go to a BA

- VG3

Dr Cullimore suggest the inclusion of SLYM or HAB BART would fill in the gap where there are "high" bacterial populations and relatively low aggressivity in the SRB and/or IRB.

In general, the BARTS test indicate low growth (background levels) of sulphate reducing bacteria in all the holes, with the exception of KG1, DL 16 and DP12 which have moderate levels. GCS has a concern with the SRB levels measured - SRB often grow under the biofilm in the anaerobic zone. Unless sloughing of the biofilm takes place, the SRB are not released into the water and the BARTS tests could well be under-estimated of SRB growth. Moderate to high levels of iron related bacteria exist, with non-IRB pseudomonads being dominant.

10.3 SCALE CHEMISTRY

Four samples of precipitate, as well as analysis of the groundwater chemistry drawn from the boreholes in question, were submitted to the Department of Geological Sciences at the University of Cape Town for analysis. The origin of the samples collected is shown in Table 9.

Table 9 : Sample numbers and origin of precipitates.

Sample Number	Origin
DG110	Scrapings from inside the pump
DP28	Scrapings from inside the PVC casing removed
VG2	Deposit from inside the pump's riser pipes
DL17	Deposit accumulated on the floor of the pump house

The preliminary characterisation of the precipitate samples included :

- Analysis for elemental composition undertaken by Energy Dispersive Spectroscopy, (EDS).
- Morphology and particle size determination by Scanning Electron Microscopy (SEM)
- Phase identification was performed using X-Ray Diffraction (XRD).
- Qualitative tests using hydrogen peroxide (H_2O_2) and hydrochloric acid (HCl) were performed to test for the presence of manganese oxides or calcite respectively.
- Evaluation of the groundwater chemistry using geochemical modelling software (MINTEQA2). In addition, the charge balances were checked using the method defined by Murray and Wade (1996).

The effervescence tests showed a reaction to the addition of hydrogen peroxide on all the samples, except sample DP28, suggesting than manganese oxides and/or organic material exist. There was however, no effervescence observed after the addition of HCl, indicating that no carbonates exist. In view of the absence of Mn and the presence of carbon in some samples (see EDS analysis below), the effervescence observed upon H_2O_2 addition was probably derived from organic carbon and not manganese dioxide. The action of H_2O_2 also had a mildly disruptive effect on the aggregated samples. As H_2O_2 is non-contaminating and has a gentle action, UCT suggested that the addition of H_2O_2 to the boreholes may be a method whereby the fouling deposit could be broken up to reduce the clogging problem, without associated contamination of the borehole water. The results from the EDS, SEM and XRD are shown in Table 10.

Table 10 : Morphology, size, composition and phase identification of precipitates.

Sample	**DL17**	**DG110**	**DP28**	**VG2**
Morphology (SEM)	Aggregated clusters consisting of irregular spherical particles	Irregular large angular and small spherical particles co-mingled with microbes	Aggregated clusters of very small needle like structures	Aggregated clusters consisting of irregular spherical particles
Particle size	~200nm-1µm	Bimodal size 100µm and ~1µm	~50µm and <200nm	~200nm-1µm
Elemental composition * (EDS analysis)				
Dominant components	Fe ; O	Fe ; C ; O	Fe ; C ; O	Fe
Minor	Si ; Ca ; Cl	Si ; P	S	O ; P ; Si
Trace	P		Si	S
XRD Phase identification	Broad peak at ~2.45Å (36.65°2θ)may indicate poorly crystalline ferrihydrite	Largely amorphous	Goethite phase present	Broad peak at ~2.45Å (36.65°2θ) may indicate poorly crystalline ferrihydrite

* Elemental composition by EDS is qualitative because of the small sample size analysed

The major elemental composition of the precipitates are Fe, C and O - it is noticeable that there was no Mn. The mineral is mostly in the form of a poorly crystalline ferrihydrite, although an alteration to goethite has taken place in DP28, suggesting a more advanced stage of precipitation.

The saturation indices provide an indication of the potential of a specific mineral to precipitate out from solution. Increasing (positive values) indicate an increasing potential for the indicated minerals to precipitate from the water. The results (Table 11) show a strong potential for the precipitation of Goethite.

TABLE 11 : SATURATION INDICES OF SELECTED FE AND MN MINERALS IN THE GROUNDWATER SAMPLES

	DL17	DG110	DP28	VG2
Ferrihydrite ($Fe_5HO_8.4H_2O$)	2.9	2.53	-0.172	1.69
Goethite (FeO.OH)	7.29	6.92	4.22	6.08
Natrojarosite $Na\ Fe_3^{+2}\ (SO_4)_2\ (OH)_6)$	4.55	5.46	4.81	1.43
Manganite (MnO.OH)	14.5	12.6	6.51	15

The four borehole waters sampled have acidic to near-neutral pH (see Appendix C for detailed chemistry). All four samples were supersaturated with respect to a variety of iron and manganese oxide and sulphate minerals, indicating a large residual tendency to form precipitates of the kind which is currently causing all the problems.

11. SUMMARY

The fieldwork has show elevated plate counts, moderately aggressive BARTS reactions and conditions conclusive to chemical precipitation of ferrihydrites and goethite. Oxgenation of the water, due to water cascading down the hole from upper water strikes, has resulted in highly oxidized conditions where pseudomonads are growing strongly. All these conditions are condusive to borehole clogging.

PROPOSED MONITORING AND MANAGEMENT ACTIONS

Having undertaken the fieldwork, the results were used to identify actions necessary to reduce clogging in the future.

12. MANAGEMENT ISSUES

12.1 Reduce oxygenation of the groundwater

Oxygenation of the water is directly related to pumping at high rates with too large a drawdown, thus allowing water to cascade down the sides of the borehole. Oxygenation is decreased by limiting the drawdown in the borehole, achieved by reducing pumping rates and extending pumping times to achieve the same daily abstraction volume - this has already been suggested by GCS and is currently being implemented in the Klein Karoo Scheme.

12.2 Pumping Standby Holes

Backup boreholes that are used infrequently can develop an anaerobic condition with the development of smelly sulphurous black water. To stop this happening it is necessary to operate the borehole at regular intervals (1 day per month) to prevent the creation of the anaerobic front in the borehole.

12.3 Monitoring

Rehabilitation of a boreholes should be based on sound monitoring data which would indicate a necessity to undertake expensive rehabilitation. The aim of the monitoring is to assess the bacterial and chemical "health" of the hole, the effect of clogging and the need for borehole rehabilitation. A hierarchical order for the monitoring is recommended :

HPC	-	the plate counts should be undertaken on the utilized production boreholes, on a monthly basis.
Dissolved Oxygen	-	measured in the field (monthly) and converted to Eh so that the redox potential of the water can be assessed. This is important in evaluating the chemical precipitation potential and potential changes from oxidizing to reducing conditions.
Specific Capacity	-	More accurate measurement of drawdown (at a set pumping rate) needs to be undertaken to assess potential decreases in specific capacity. A trend of decreasing specific capacity would signify large scale clogging and rehabilitation will be necessary.

To correctly plan the rehabilitation it is necessary to understand the status of the bacteria, the groundwater chemistry and the scale chemistry.

BARTS tests	-	testing undertaken at the offices of Overberg Water for those holes where the specific capacity is dropping, utilizing tests for IRB, SRB, SLYM and HAB. Four samples collected, a week apart, to average out sloughing effects.

Groundwater chemistry		full chemical analyses are currently being undertaken on a quarterly basis. This should continue. Monitoring of iron levels (undertaken at the treatment works) must continue on a monthly basis.
Scale chemistry	-	results to date show the scale to be predominantly iron, with limited manganese. No further monitoring is suggested.
Video camera	-	holes showing a decrease in specific capacity and aggressive bacteria should be viewed with a video camera to assess the degree of clogging.

13. REHABILITATION

13.1 Regular Bacterial disinfection

HTH ?

Regular disinfection of the wells (every 6 months) should take place, utilizing sodium hypochlorite. The aim of the disinfection is not to restore lost capacity, but merely to retard bacterial growth.

13.2 Scale removal

Some of the holes will continue to clog, although recent changes to the abstraction management and regular disinfection, will reduce the rate of clogging. Holes that show a decline in specific capacity, together with highly aggressive BARTS reactions, should be assessed with a down the hole video camera and rehabilitated if necessary. Rehabilitation should be aimed at breaking down and removing the scale. The exact nature of the rehabilitation treatment depends on the groundwater chemistry and the bacteria growing in the hole.

13.3 Further research / new methodologies

The understanding of clogging of boreholes in the TMG is in it's infancy. Far more research is necessary to understand the controlling conditions and to make more meaningful comments on limiting biofouling. It is strongly urged that further research be funded to allow greater work in the TMG aquifers, with specific emphasis on the Klein Karoo boreholes.

It is also necessary to keep up to date on the latest research and technologies utilized worldwide. For example :

- a newly developed combination of ligands and reducing agents (having a low toxicity, operating at natural pH values without causing bacterial growth)has been documented as being effective in cleaning scale (Houben, Treskatis and Puronpää-Schäfer, 1999).
- Mansuy (pers com, 1999) mentioned that Layne Geosciences, together with Aqua Freed have developed equipment which can be installing in the hole and can mechanically regenerate the hole, without interrupting the supply.

These new technologies need to be investigated to assess their applicability in the Klein Karoo context.

SUMMARY OF MANAGEMENT, MONITORING AND REHABILITATION ISSUES

1. Reduce pumping rates on productions holes and pump for longer.
2. Regular (monthly) pumping of backup holes.
3. Monitor Fe, DO, HPC and specific capacity monthly.
4. Sample boreholes for full chemical analysis quarterly.
5. Sanitization of boreholes six monthly.
6. If specific capacity is decreasing in a borehole, undertake four BARTS tests (each a week apart).
7. If BARTS test show aggressive bacteria, undertake down hole camera assessment and plan scale removal.

MJolly

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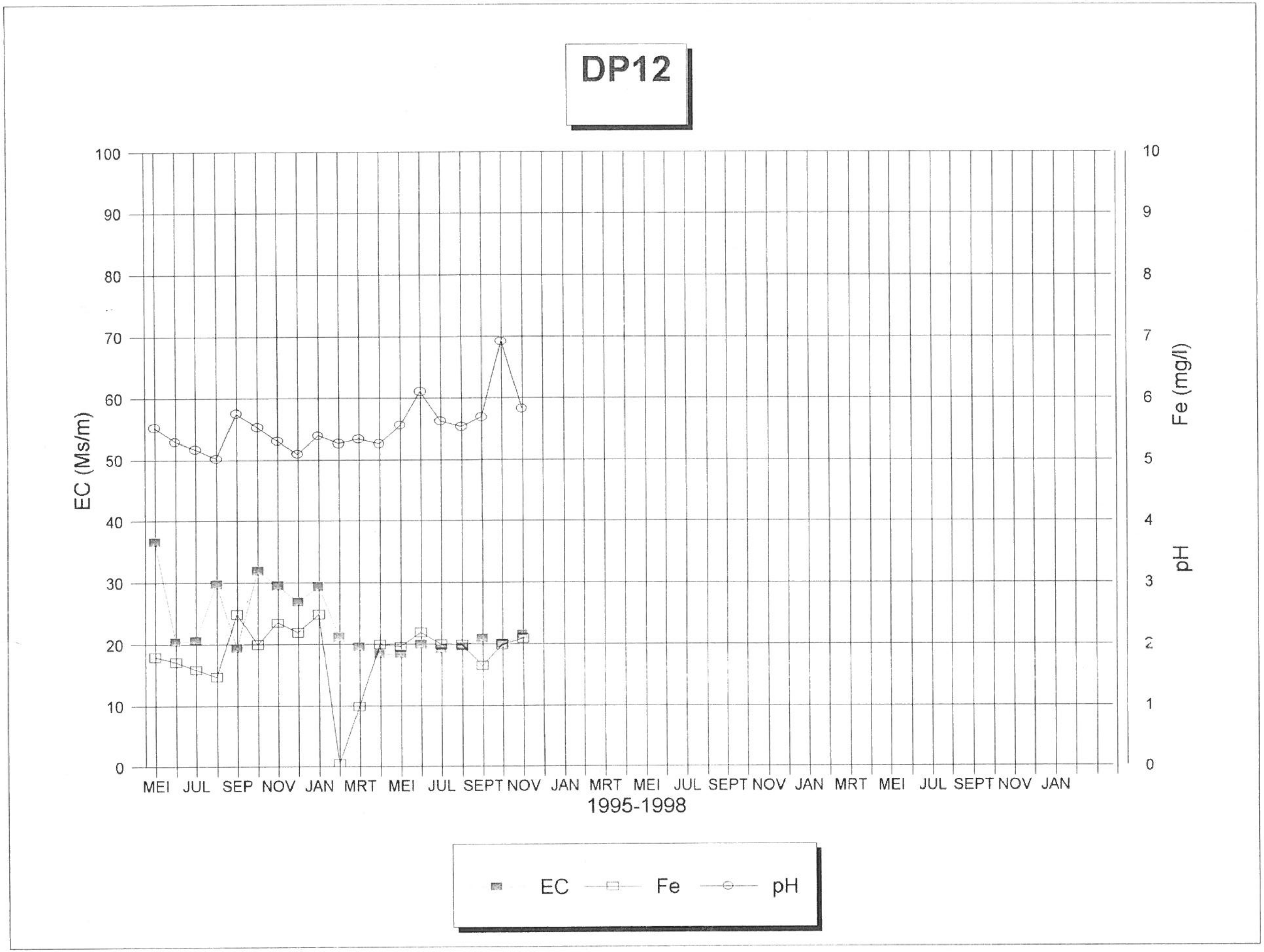
APPENDIX A

FLUCTUATIONS IN IRON CONCENTRATIONS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1995-1998
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7
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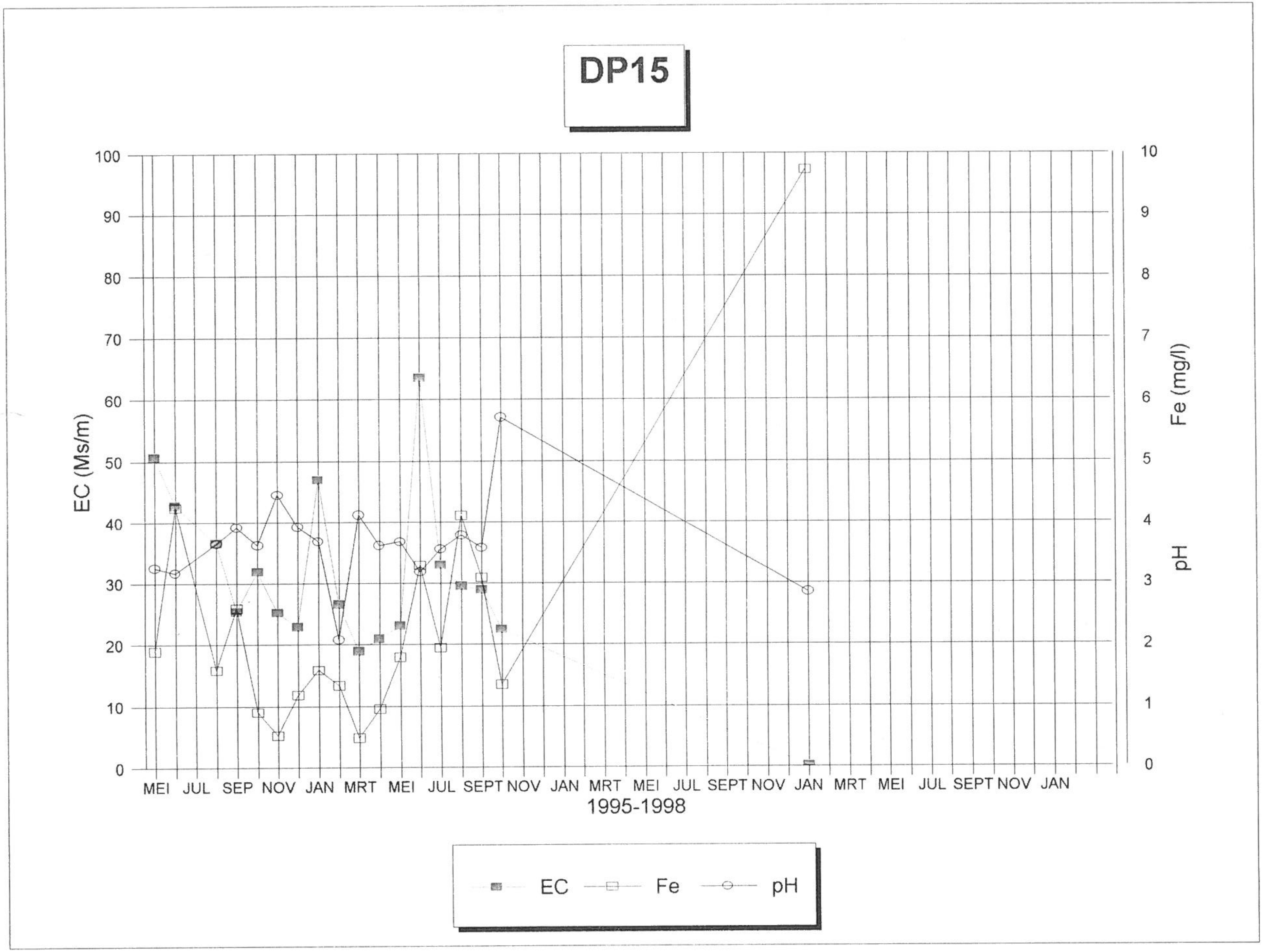
Fe (mg/l)
pH
EC
Fe
pH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Fe (mg/l)
pH
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8
7
6
5
4
3
2
1
0
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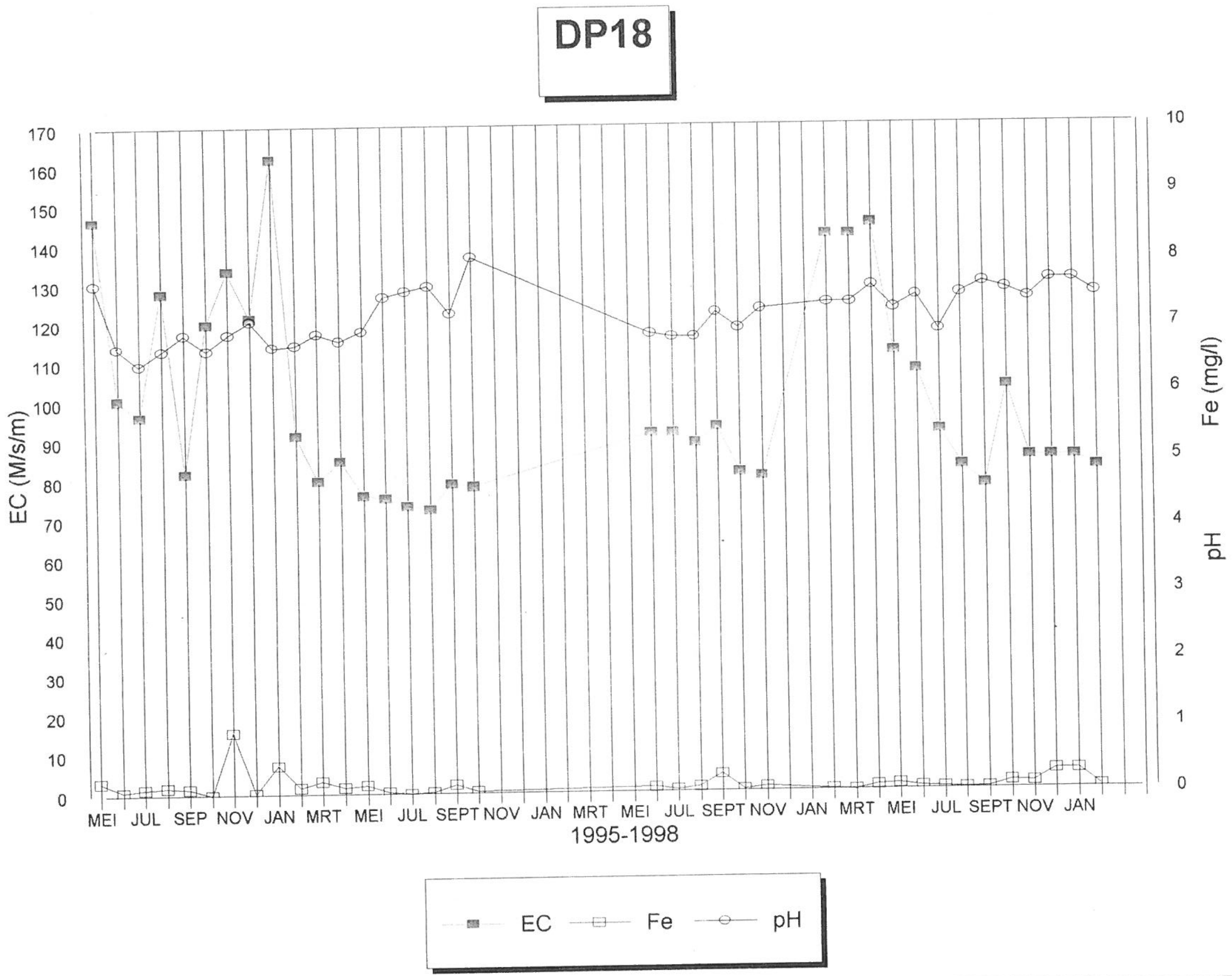
1995-1998
EC
Fe
pH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20
10
0
Fe (mg/l)
pH
10
9
8
7
6
5
4
3
2
1
0
MEI
JUL
SEP
NOV
JAN
MRT
MEI
JUL
SEPT
NOV
JAN
MRT
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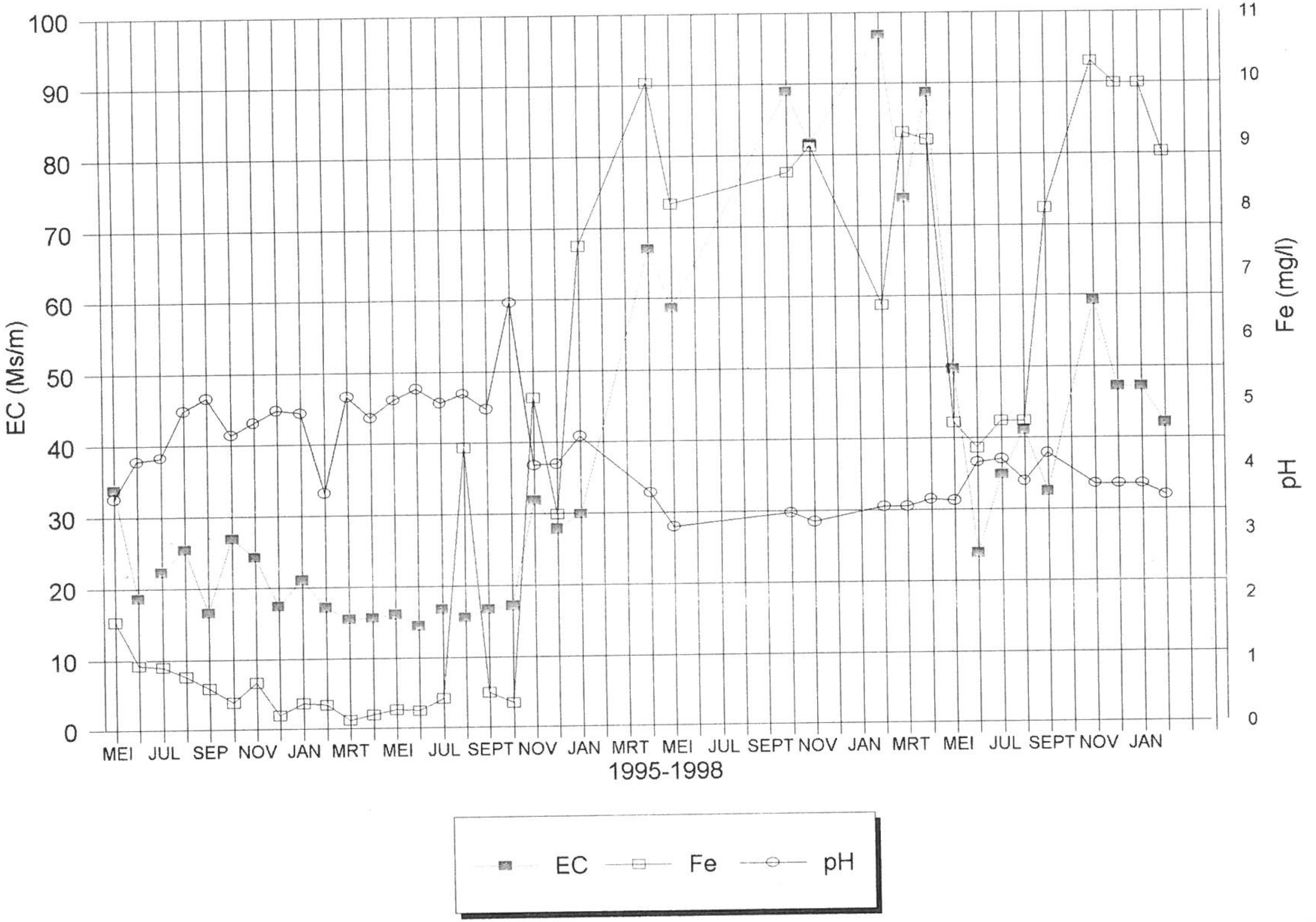
JAN
1995-1998
EC
Fe
pH

DP28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3
2
1
0
Fe (mg/l)
pH
MEI
JUL
SEP
NOV
JAN
MRT
MEI
JUL
SEPT
NOV
JAN
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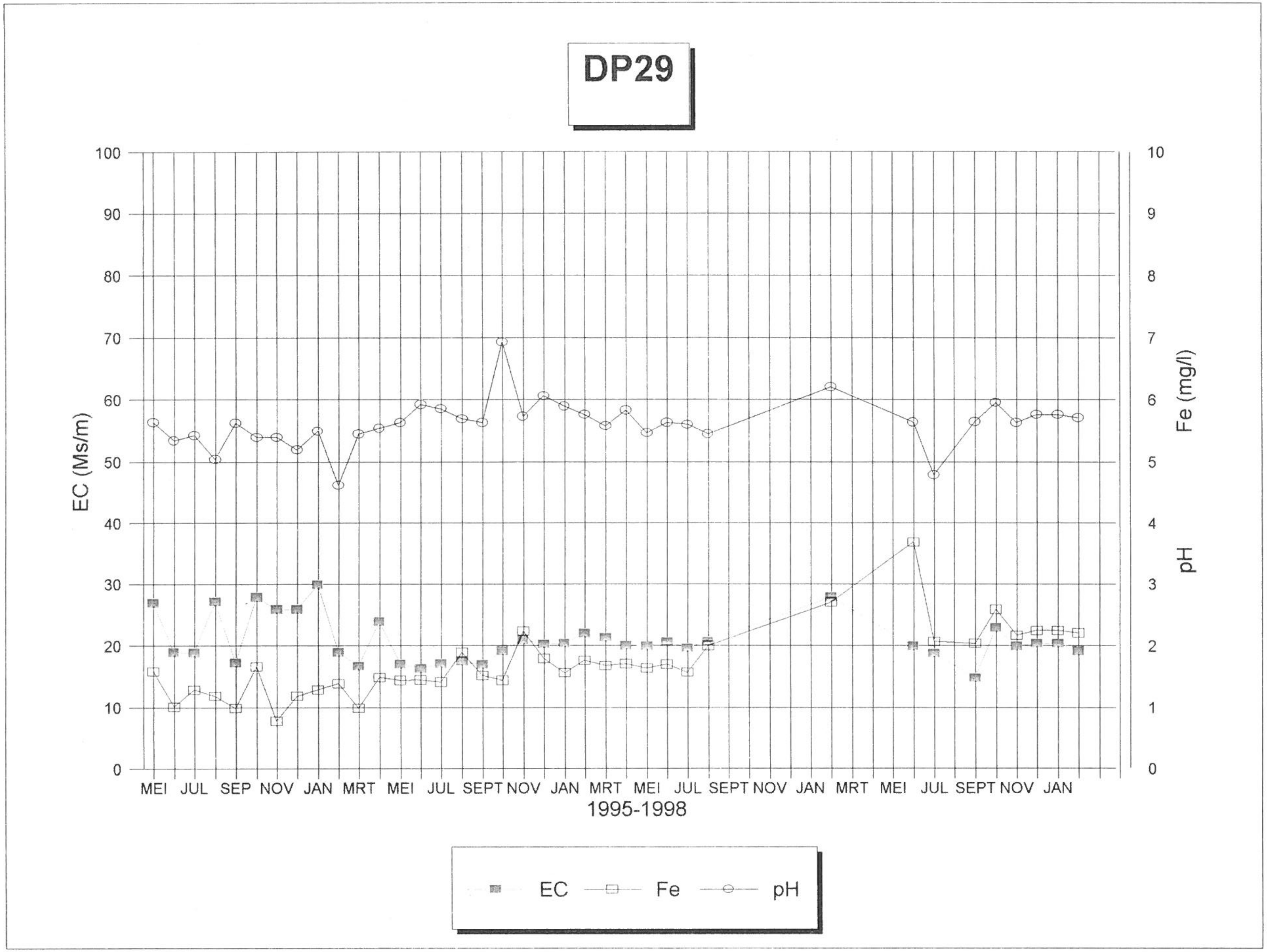
1995-1998
EC
Fe
pH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8
7
6
5
4
3
2
1
0
MEI
JUL
SEP
NOV
JAN
MRT
MEI
JUL
SEPT
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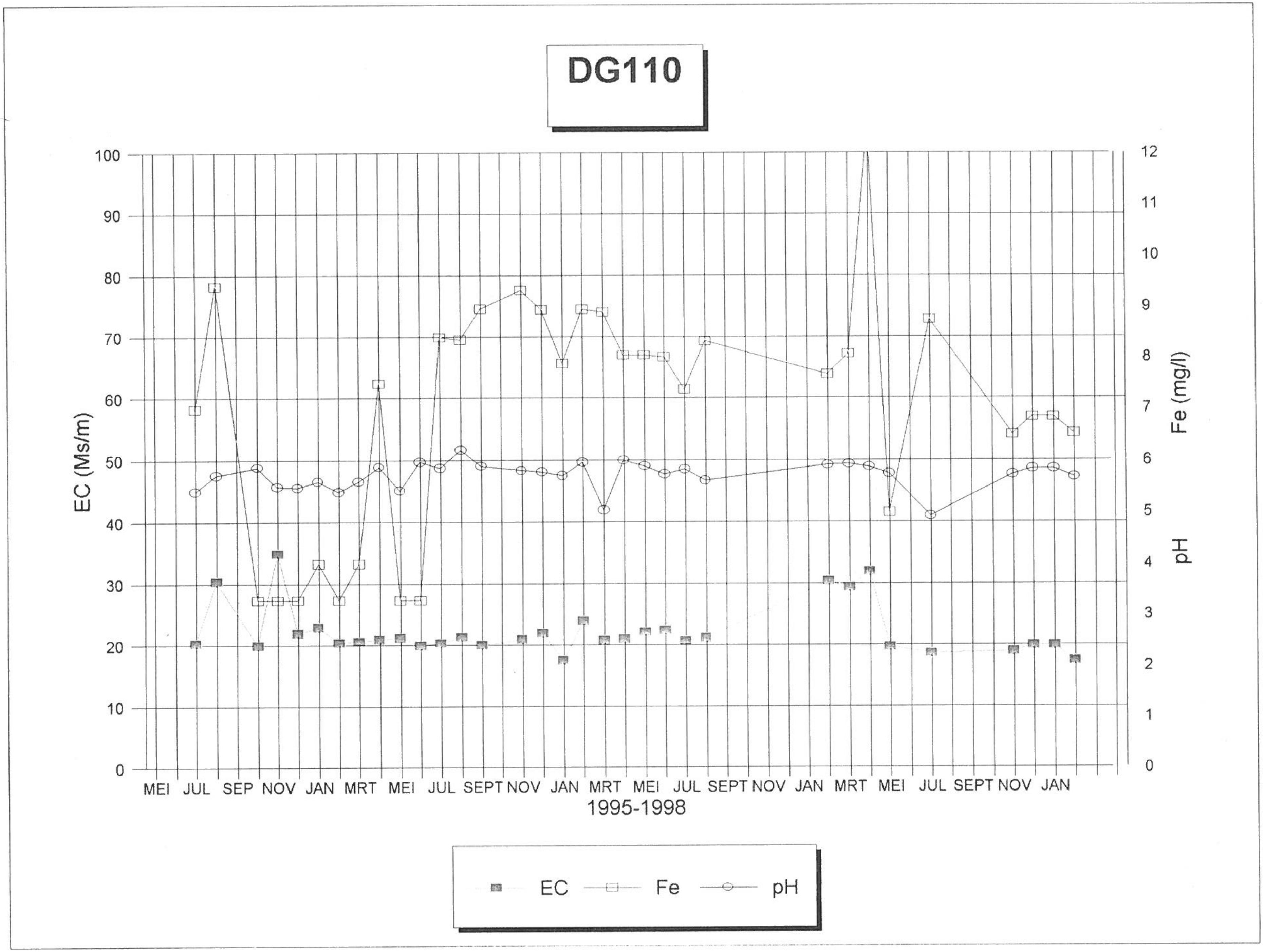
JAN
1995-1998
EC
Fe
pH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50
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30
20
10
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Fe (mg/l)
pH
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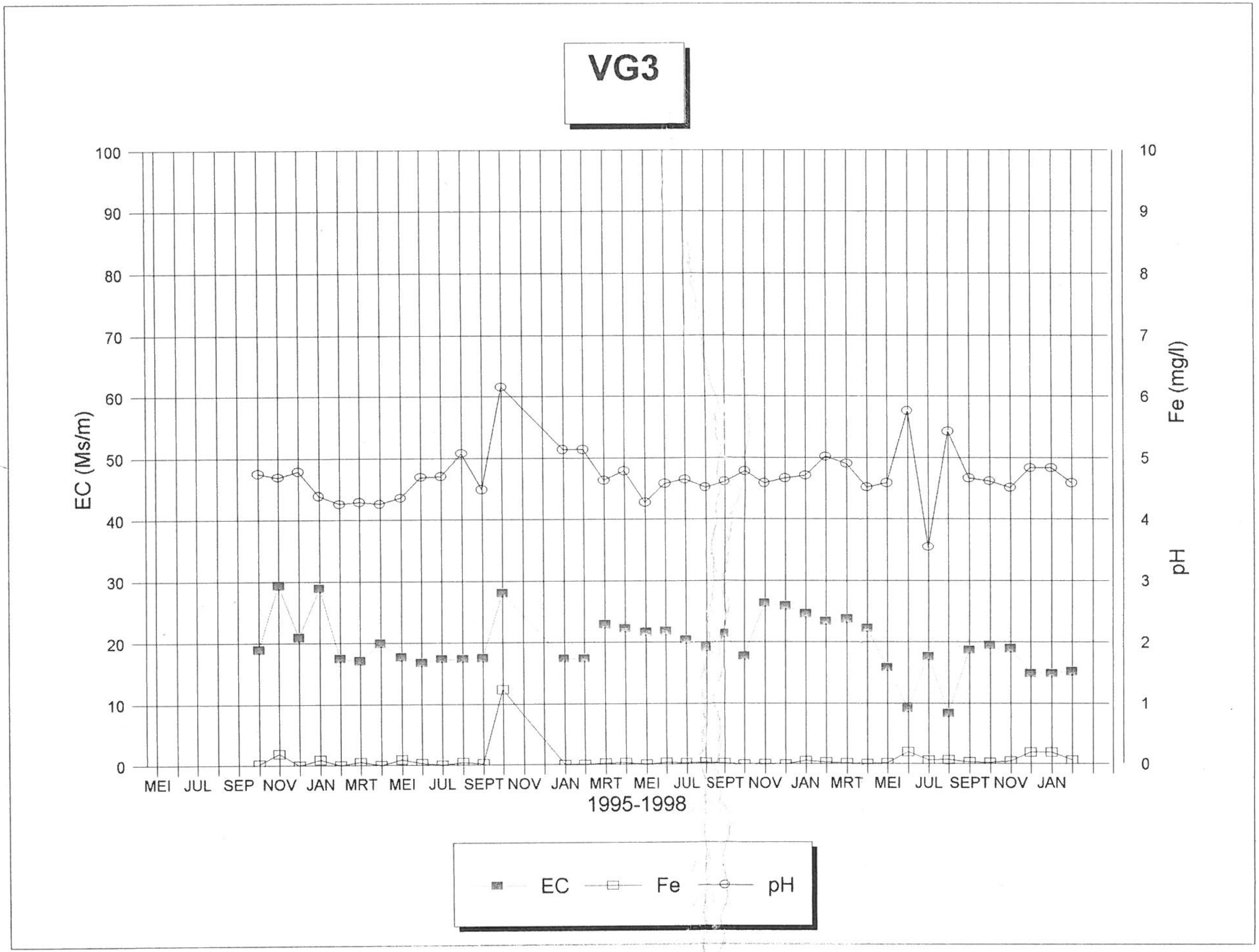
11
10
9
8
7
6
5
4
3
2
1
0
MEI JUL SEP NOV JAN MRT MEI JUL SEPT NOV JAN MRT MEI JUL SEPT NOV JAN MRT MEI JUL SEPT NOV JAN
1995-1998
EC
Fe
pH



VG3

EC (Ms/m)
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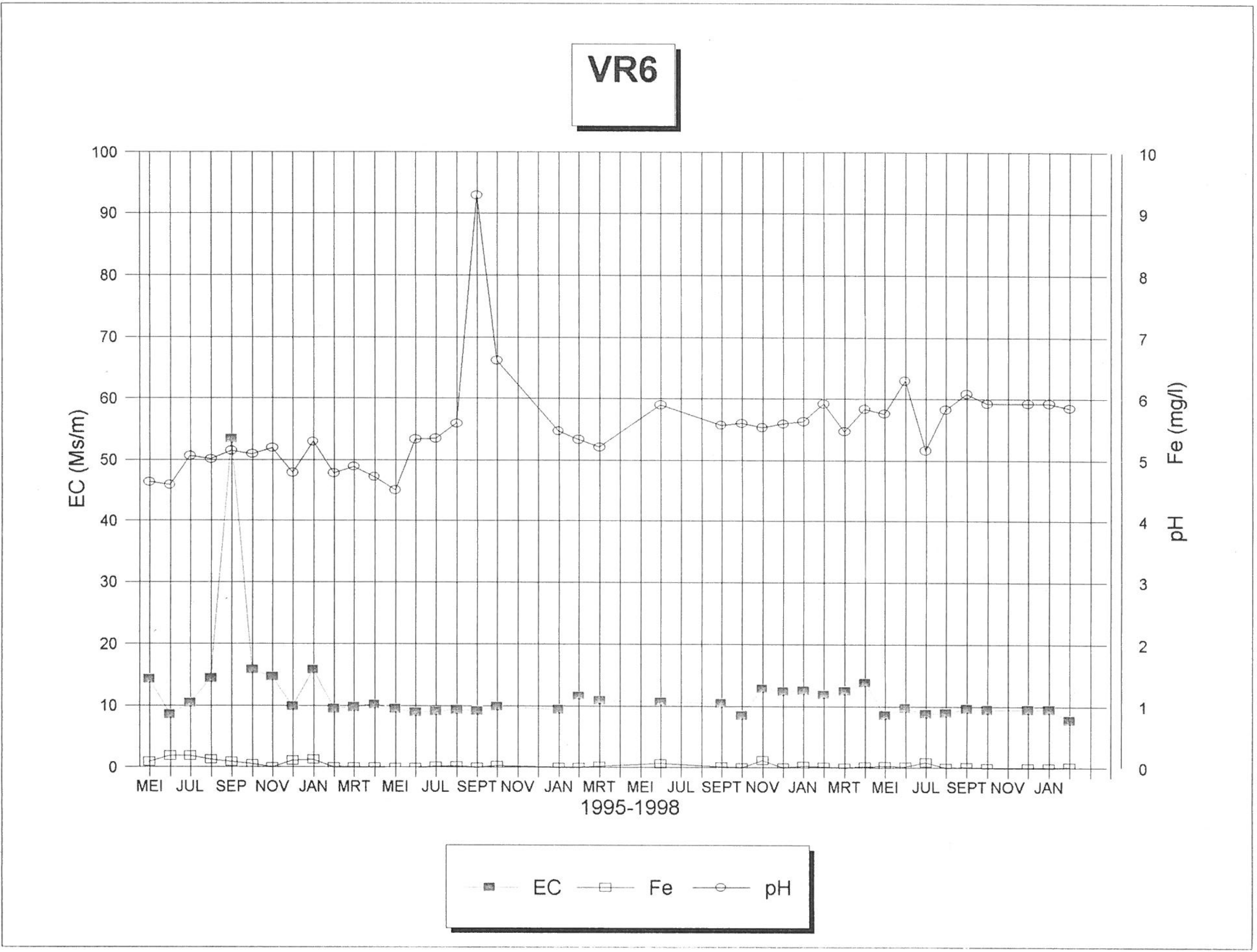
60
50
40
30
20
10
0
10
9
8
7
6
5
4
3
2
1
0
Fe (mg/l)
pH
MEI JUL SEP NOV JAN MRT MEI JUL SEPT NOV JAN MRT MEI JUL SEPT NOV JAN MRT MEI JUL SEPT NOV JAN
1995-1998
EC
Fe
pH


VR6
EC (Ms/m)
100
90
80
70
60
50
40
30
20
10
0
MEI
JUL
SEP
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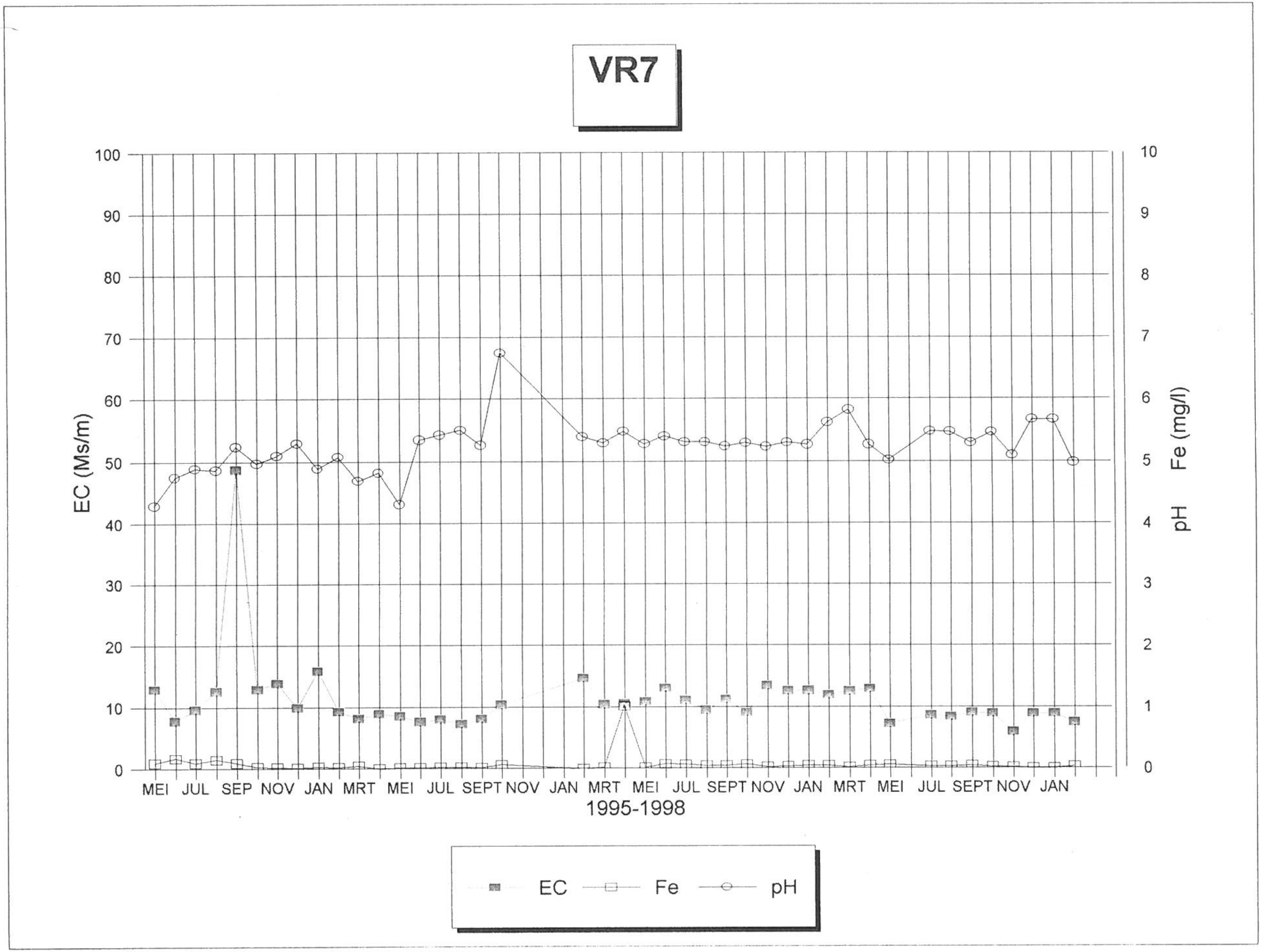
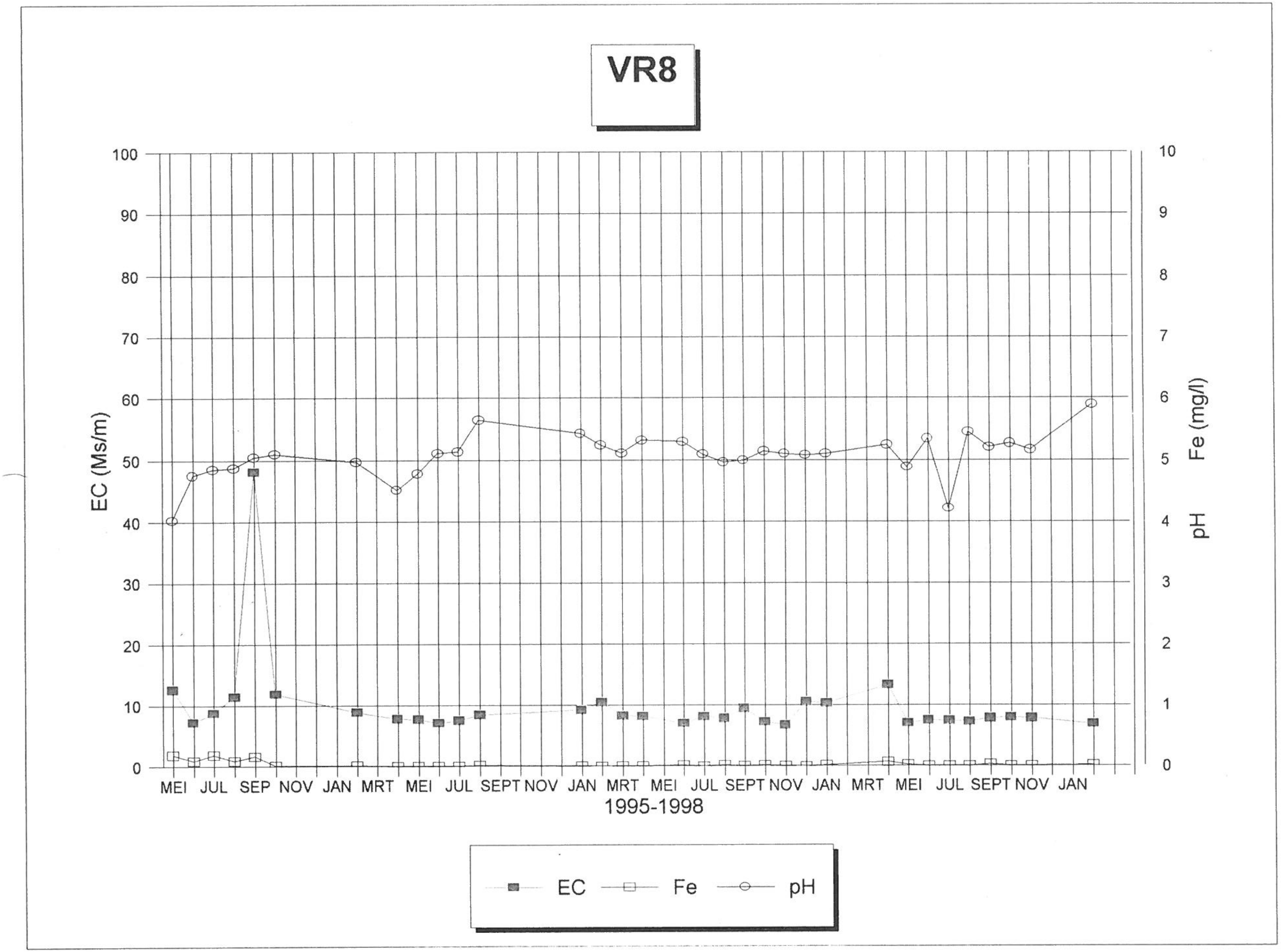
JAN
MRT
MEI
JUL
SEPT
NOV
JAN
MRT
MEI
JUL
SEPT
NOV
JAN
MRT
MEI
JUL
SEPT
NOV
JAN
1995-1998
10
9
8
7
6
5
4
3
2
1
0
Fe (mg/l)
pH
EC
Fe
pH


VR7
EC (Ms/m)
100
90
80
70
60
50
40
30
20
10
0
10
9
8
7
6
5
4
3
2
1
0
pH Fe (mg/l)
MEI JUL SEP NOV JAN MRT MEI JUL SEPT NOV JAN MRT MEI JUL SEPT NOV JAN MRT MEI JUL SEPT NOV JAN
1995-1998
EC
Fe
pH


VR8
EC (Ms/m)
100
90
80
70
60
50
40
30
20
10
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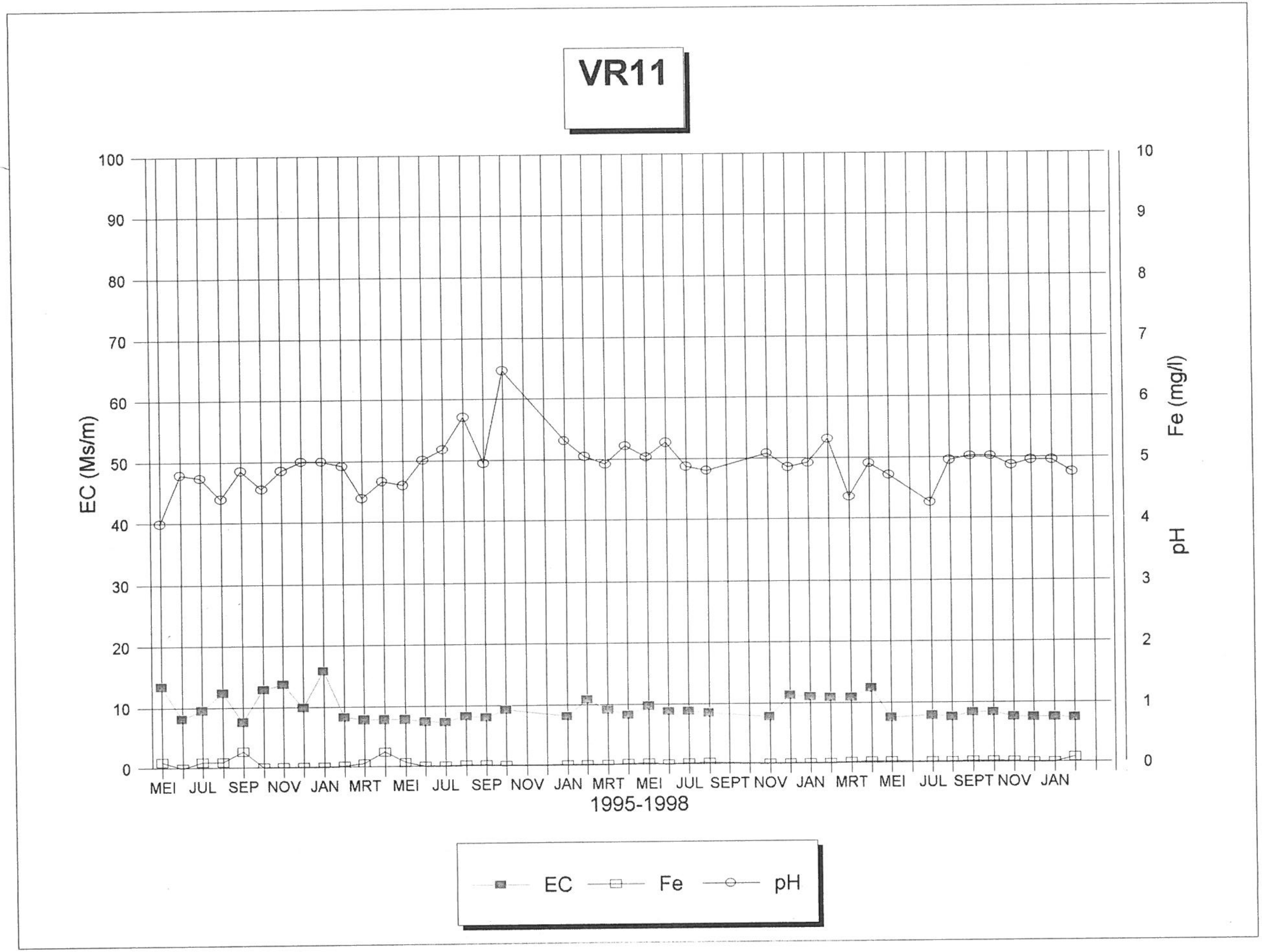
10
9
8
7
6
5
4
3
2
1
0
Fe (mg/l)
pH
MEI
JUL
SEP
NOV
JAN
MRT
MEI
JUL
SEPT
NOV
JAN
MRT
MEI
JUL
SEPT
NOV
JAN
MRT
MEI
JUL
SEPT
NOV
JAN
1995-1998
EC
Fe
pH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EC (Ms/m)
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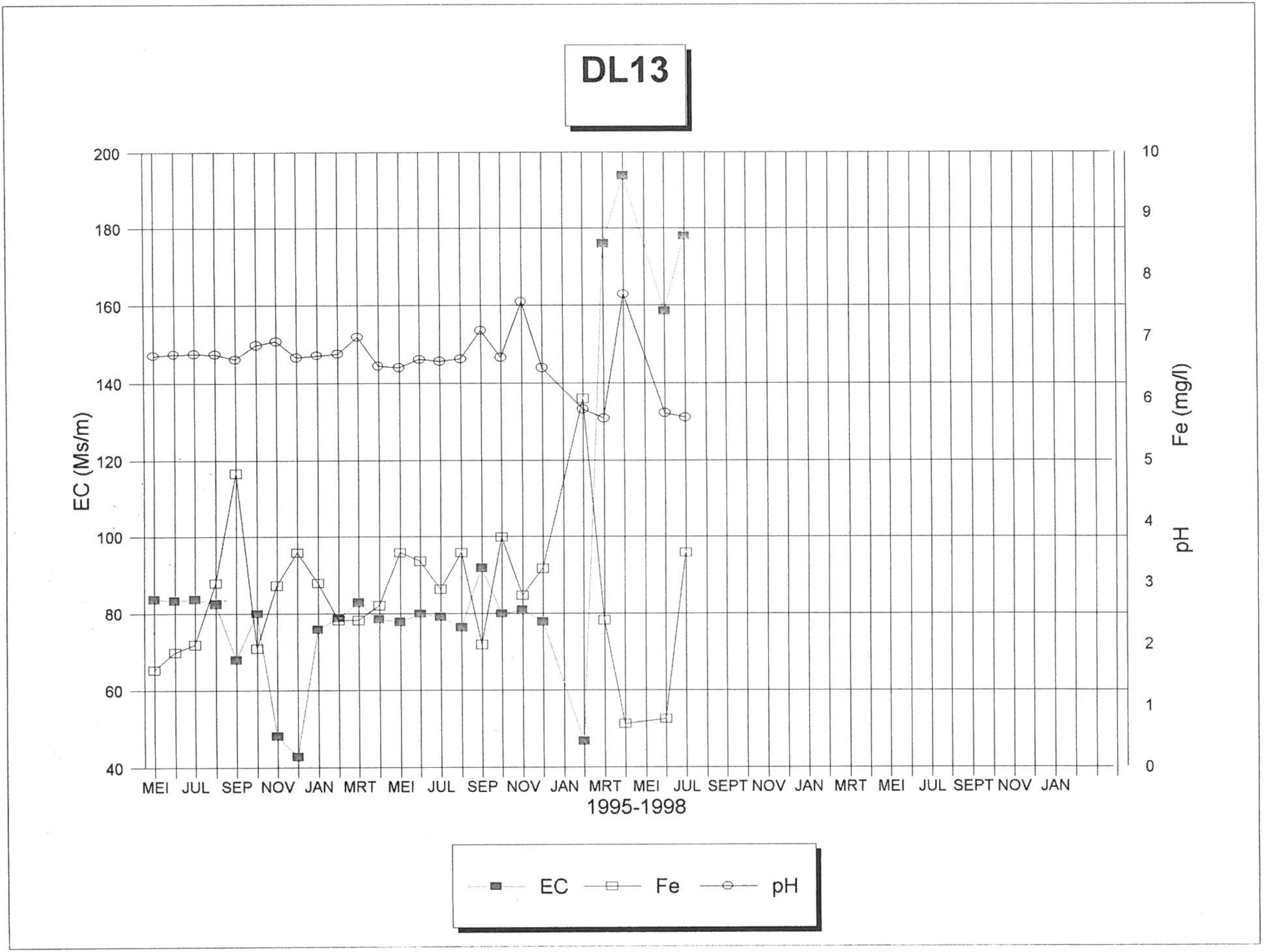
70
60
50
40
30
20
10
0
10
9
8
7
6
5
4
3
2
1
0
Fe (mg/l)
pH
MEI JUL SEP NOV JAN MRT MEI JUL SEP NOV JAN MRT MEI JUL SEPT NOV JAN MRT MEI JUL SEPT NOV JAN
1995-1998
EC
Fe
pH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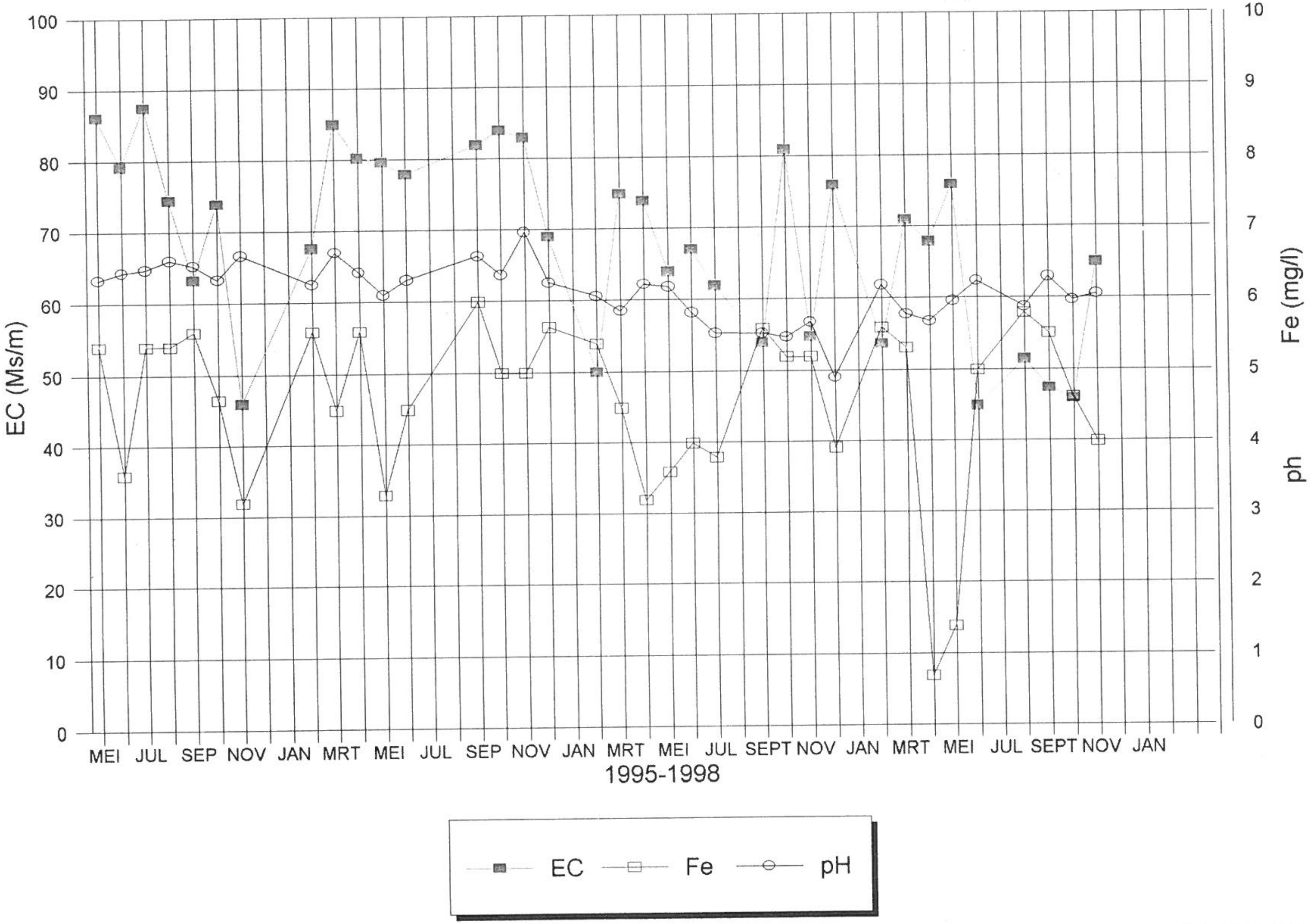
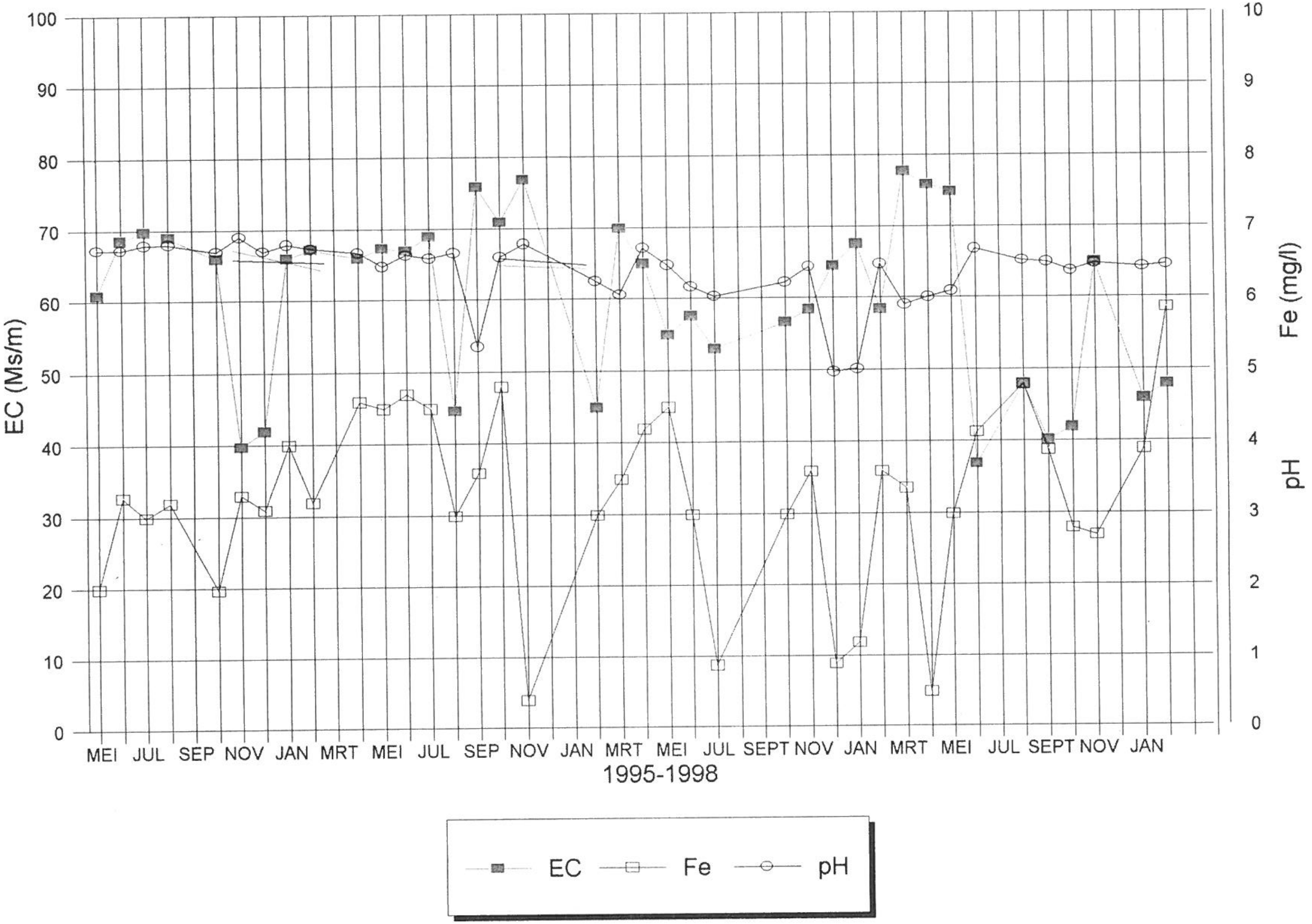
180
160
140
120
100
80
60
40
Fe (mg/l)
pH
10
9
8
7
6
5
4
3
2
1
0
MEI
JUL
SEP
NOV
JAN
MRT
MEI
JUL
SEP
NOV
JAN
MRT
MEI
JUL
SEPT
NOV
JAN
MRT
MEI
JUL
SEPT
NOV
JAN
1995-1998
EC
Fe
pH

DL15



EC (Ms/m)
100
90
80
70
60
50
40
30
20
10
0
Fe (mg/l)
ph
10
9
8
7
6
5
4
3
2
1
0
MEI
JUL
SEP
NOV
JAN
MRT
MEI
JUL
SEP
NOV
JAN
MRT
MEI
JUL
SEPT
NOV
JAN
MRT
MEI
JUL
SEPT
NOV
JAN
1995-1998
EC
Fe
pH

DL16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70
60
50
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30
20
10
0
Fe (mg/l)
pH
10
9
8
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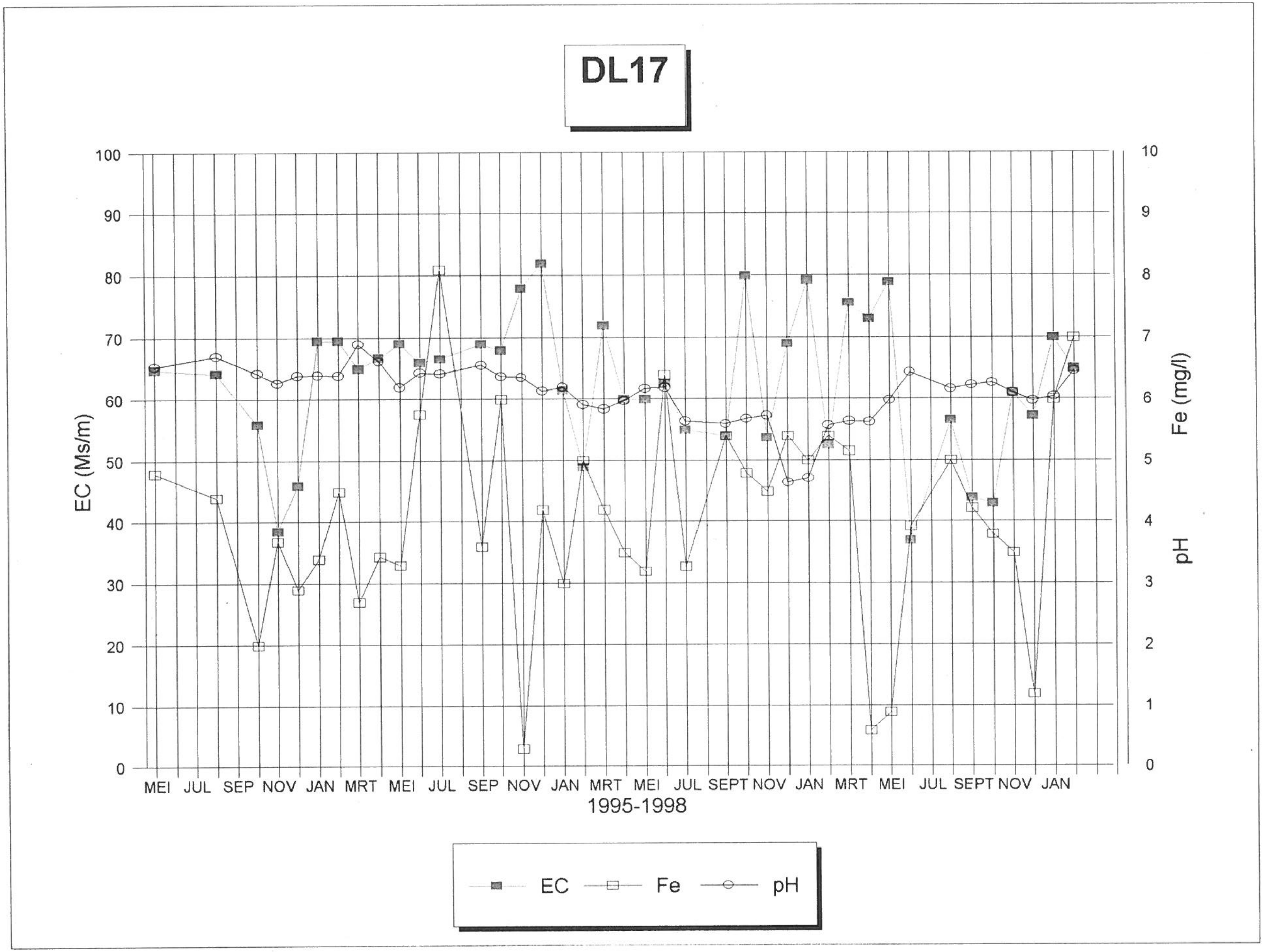
6
5
4
3
2
1
0
MEI JUL SEP NOV JAN MRT MEI JUL SEP NOV JAN MRT MEI JUL SEPT NOV JAN MRT MEI JUL SEPT NOV JAN
1995-1998
EC
Fe
pH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EC (Ms/m)
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70
60
50
40
30
20
10
0
Fe (mg/l)
pH
10
9
8
7
6
5
4
3
2
1
0
MEI
JUL
SEP
NOV
JAN
MRT
MEI
JUL
SEP
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MRT
MEI
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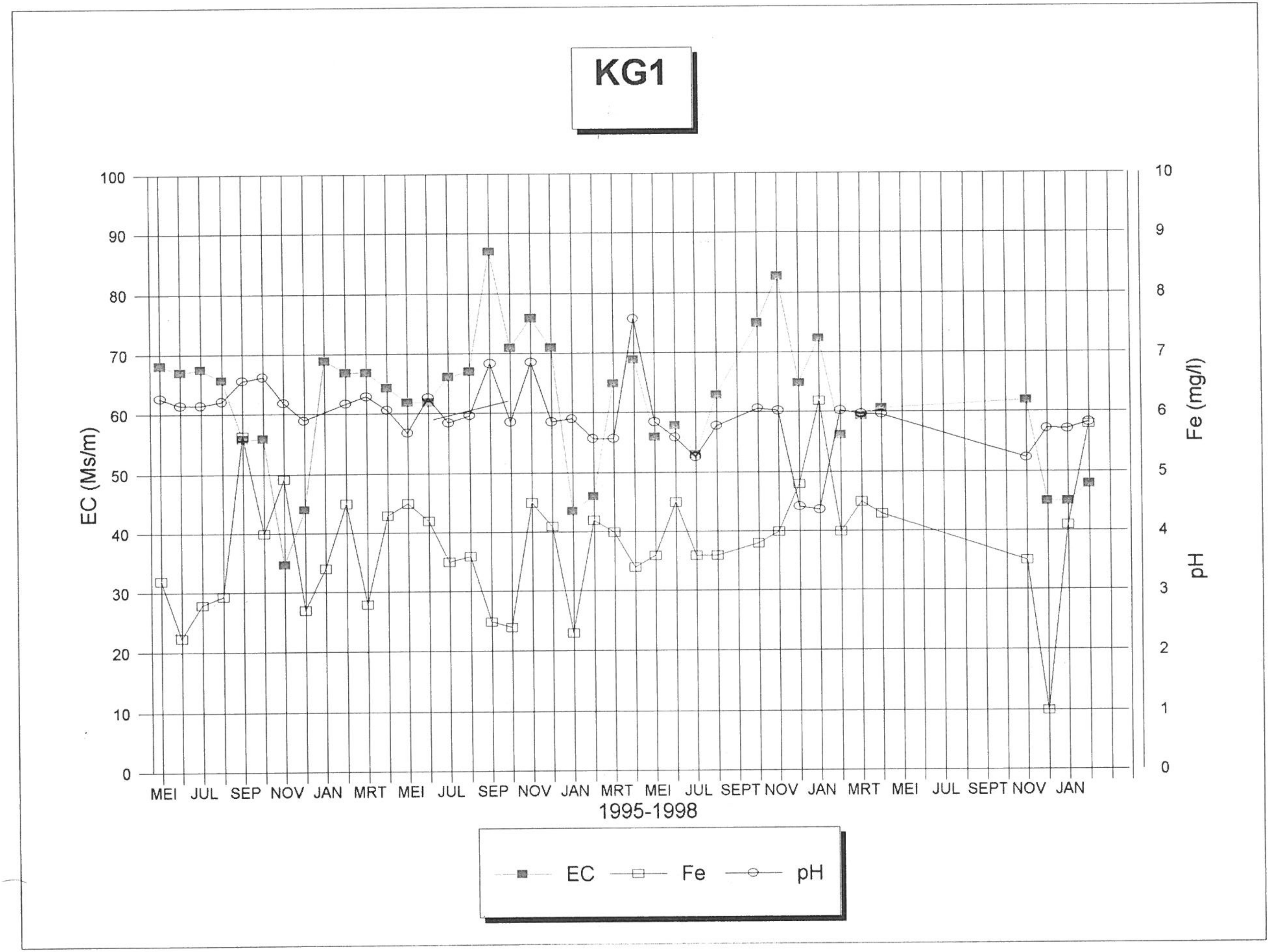
MRT
MEI
JUL
SEPT
NOV
JAN
1995-1998
EC
Fe
pH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50
40
30
20
10
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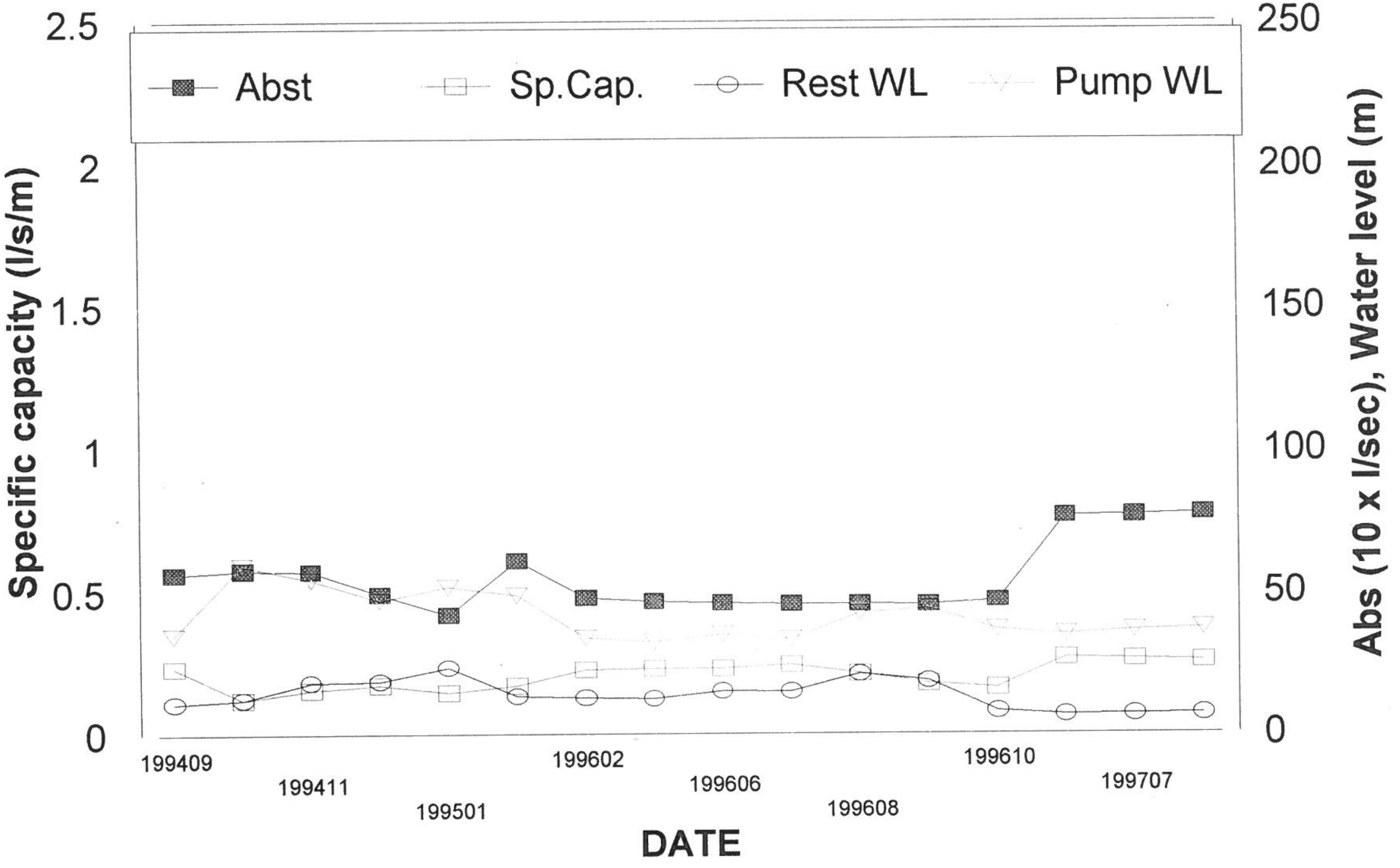
10
9
8
7
6
5
4
3
2
1
0
Fe (mg/l)
pH
MEI
JUL
SEP
NOV
JAN
MRT
MEI
JUL
SEP
NOV
JAN
MRT
MEI
JUL
SEPT
NOV
JAN
MRT
MEI
JUL
SEPT
NOV
JAN
1995-1998
EC
Fe
pH

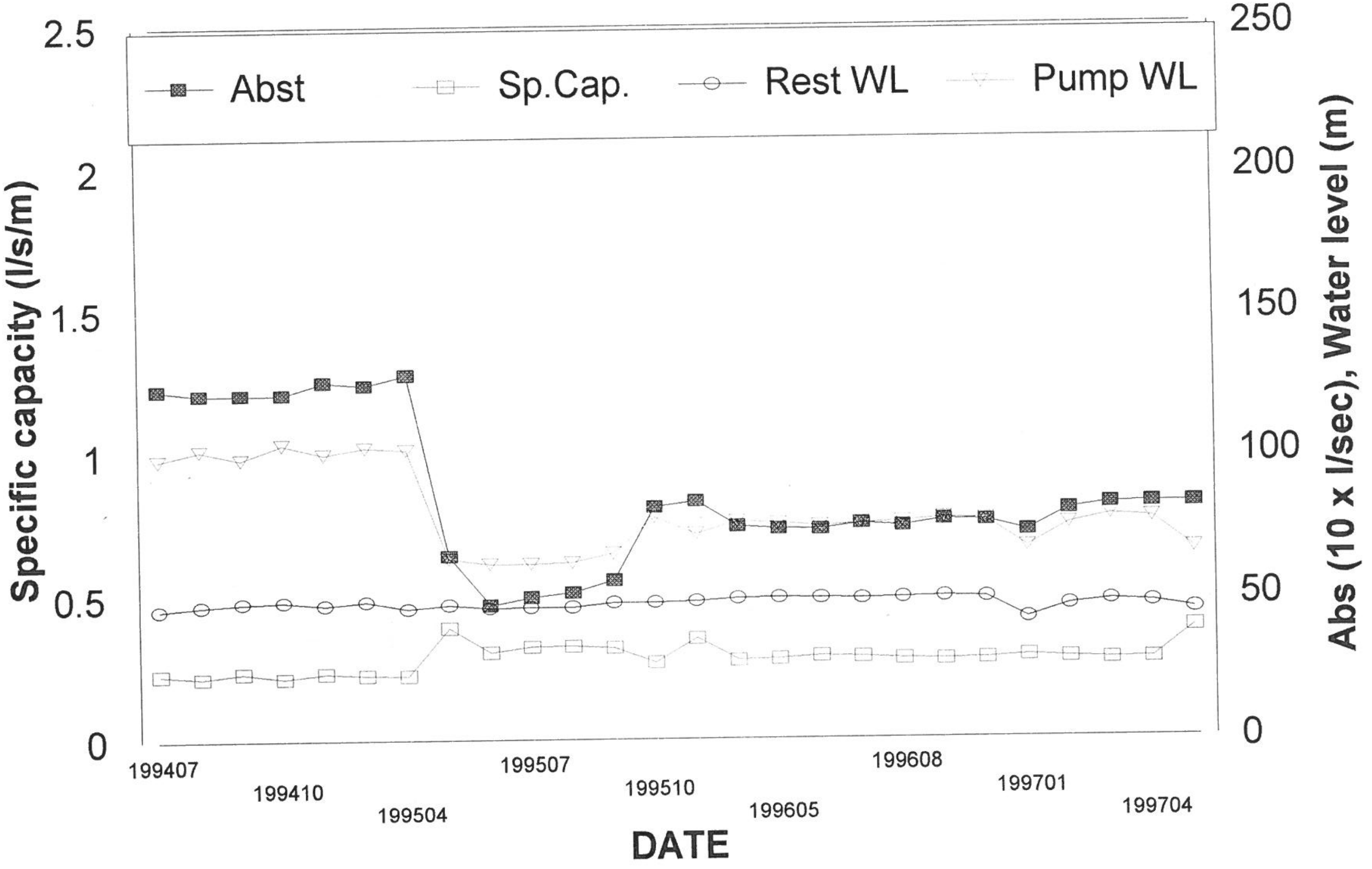
APPENDIX B

GRAPHS OF STATIC WATER LEVELS, ABSTRACTION RATES AND CHANGES IN SPECIFIC CAPACITY

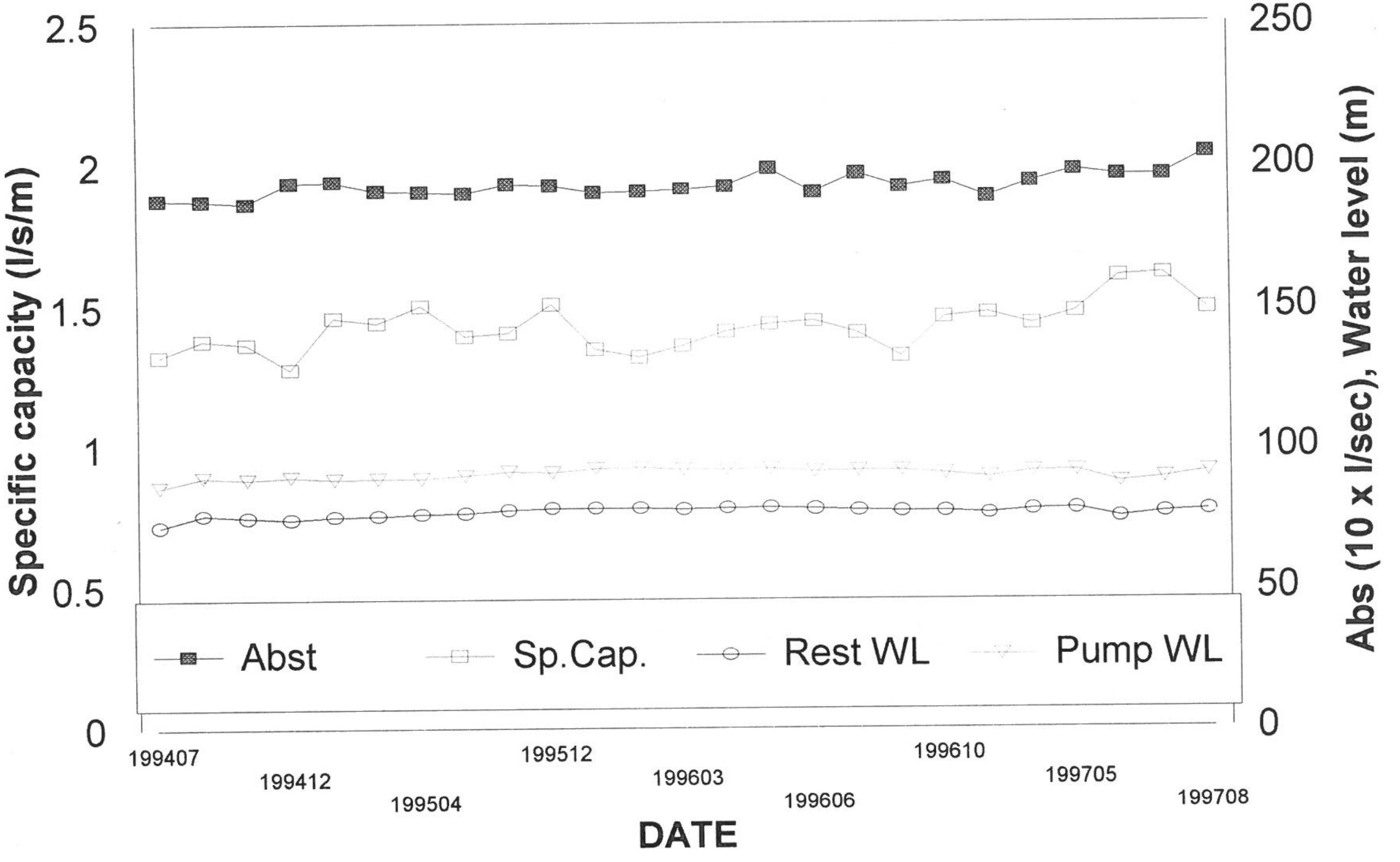
KLEIN KAROO BOREHOLES
VG3



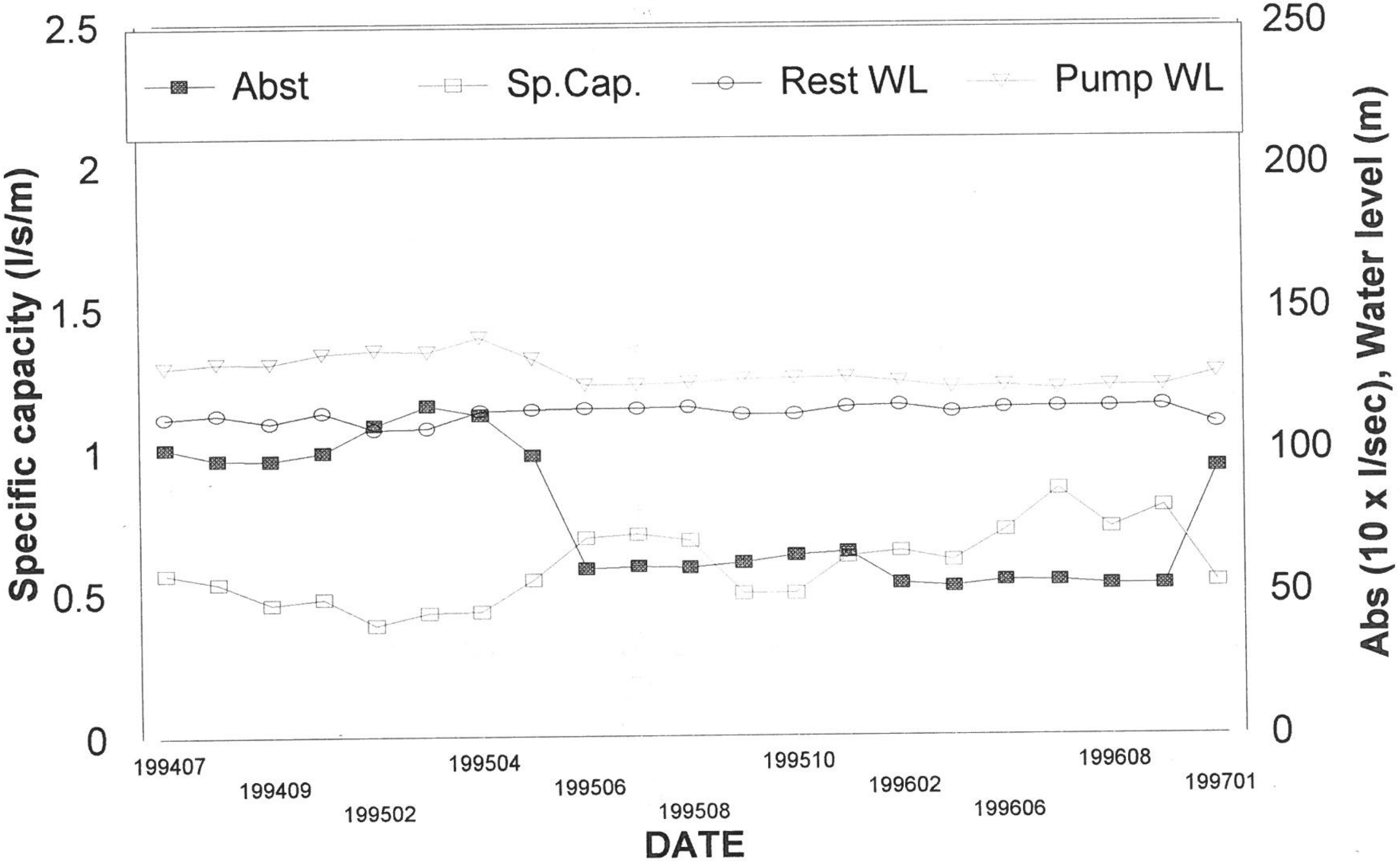
KLEIN KAROO BOREHOLES
VR6



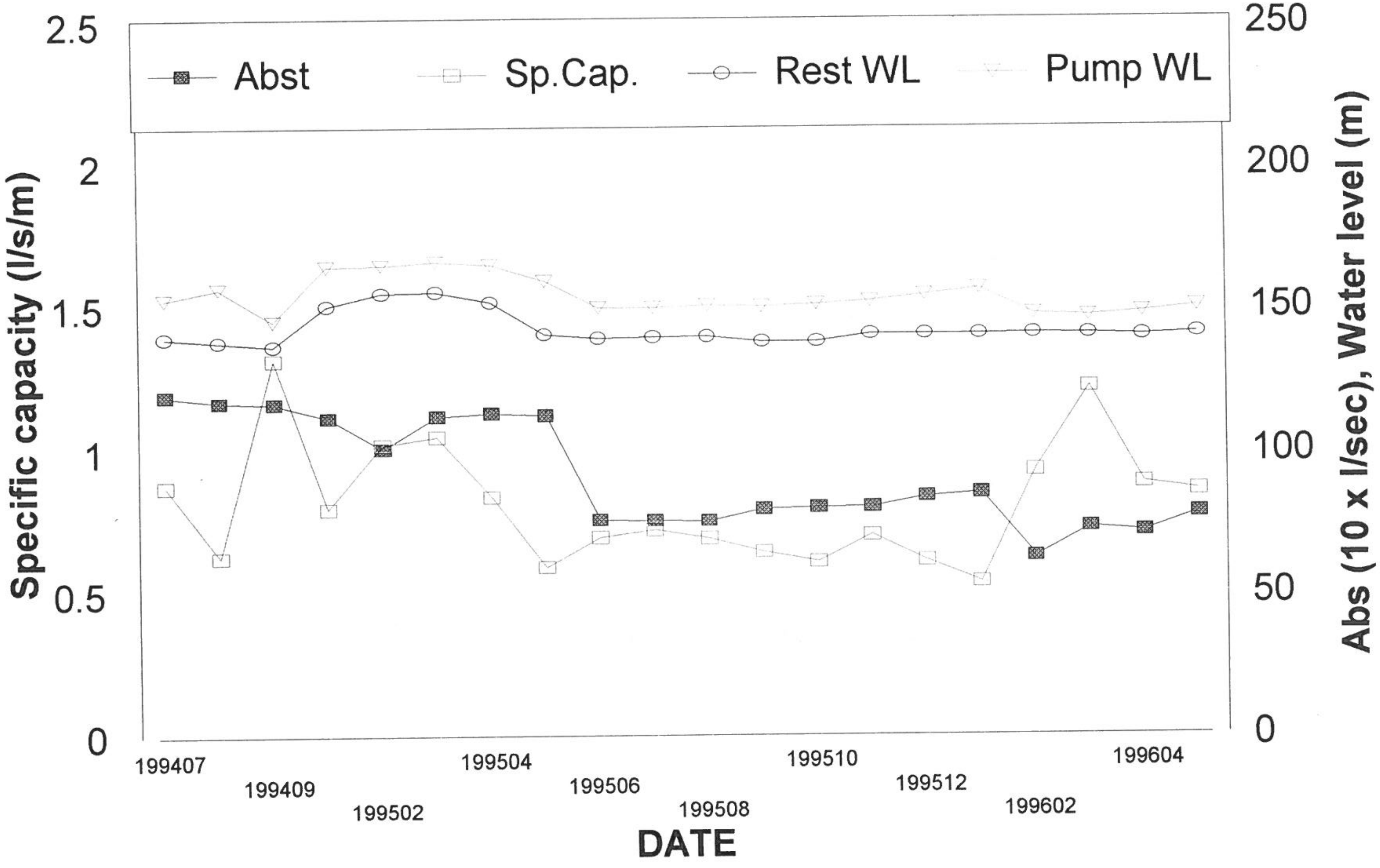
KLEIN KAROO BOREHOLES
VR7



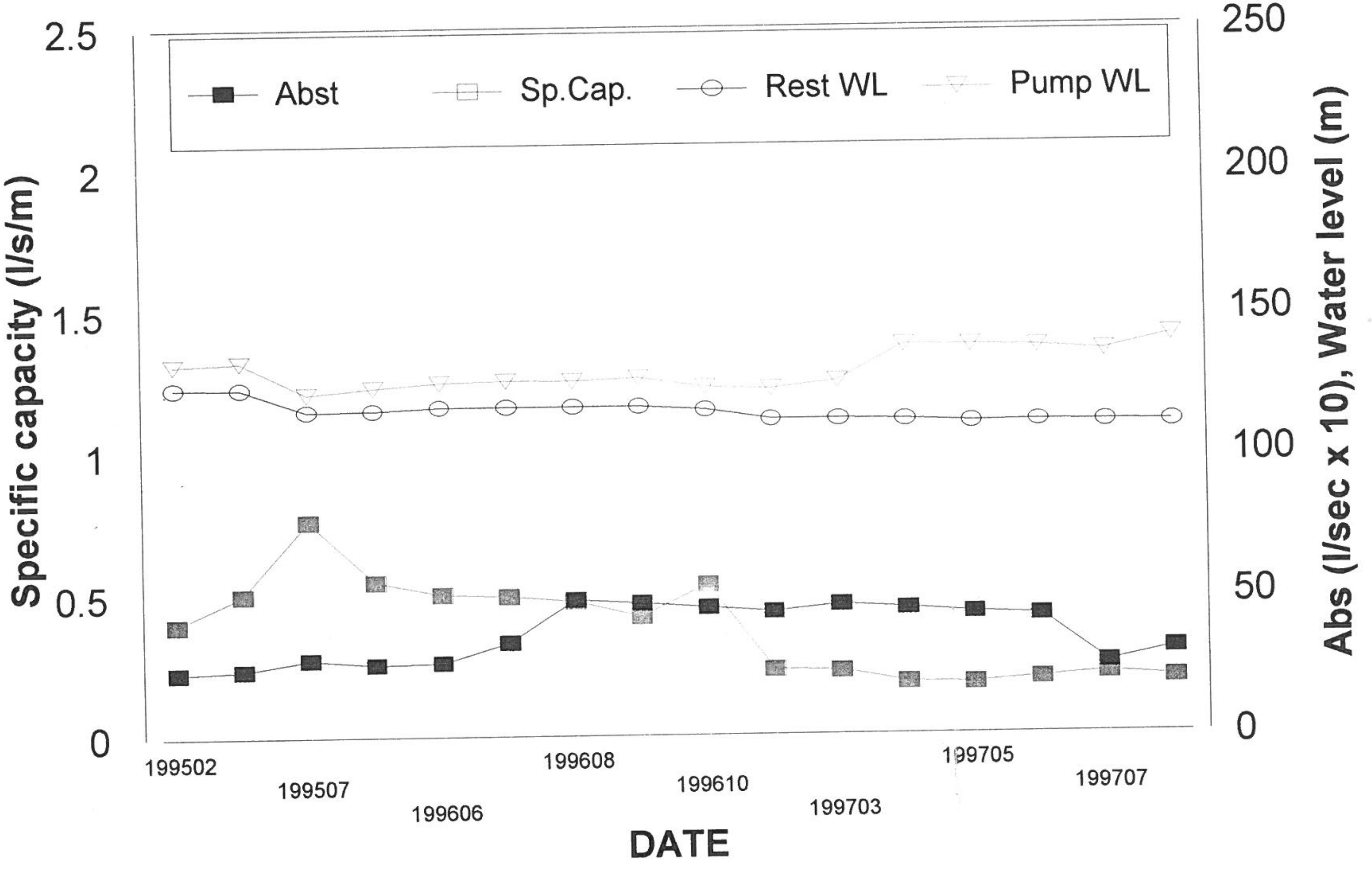
KLEIN KAROO BOREHOLES
VR8



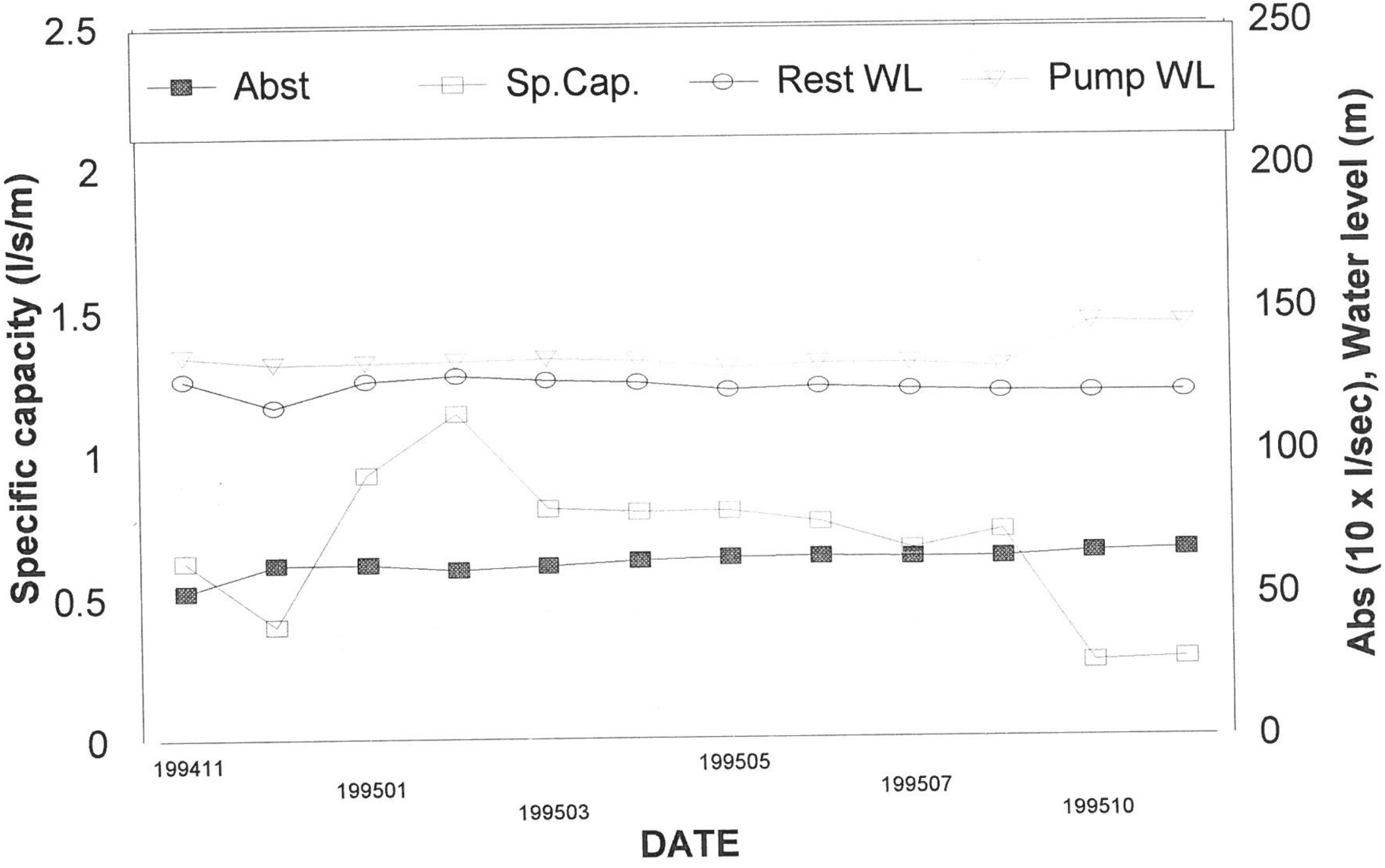
KLEIN KAROO BOREHOLES
VR11



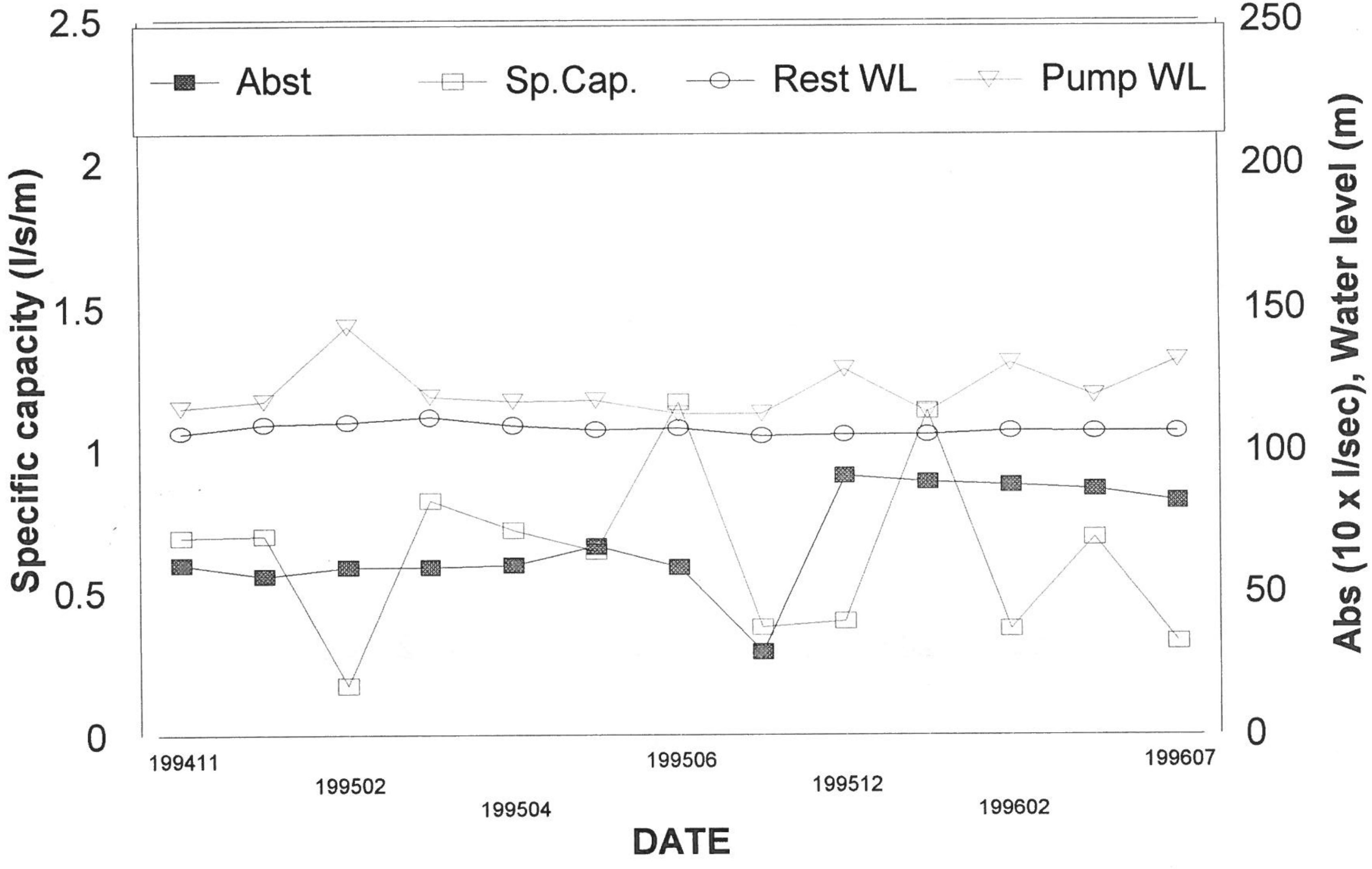
KLEIN KAROO BOREHOLES
DG110



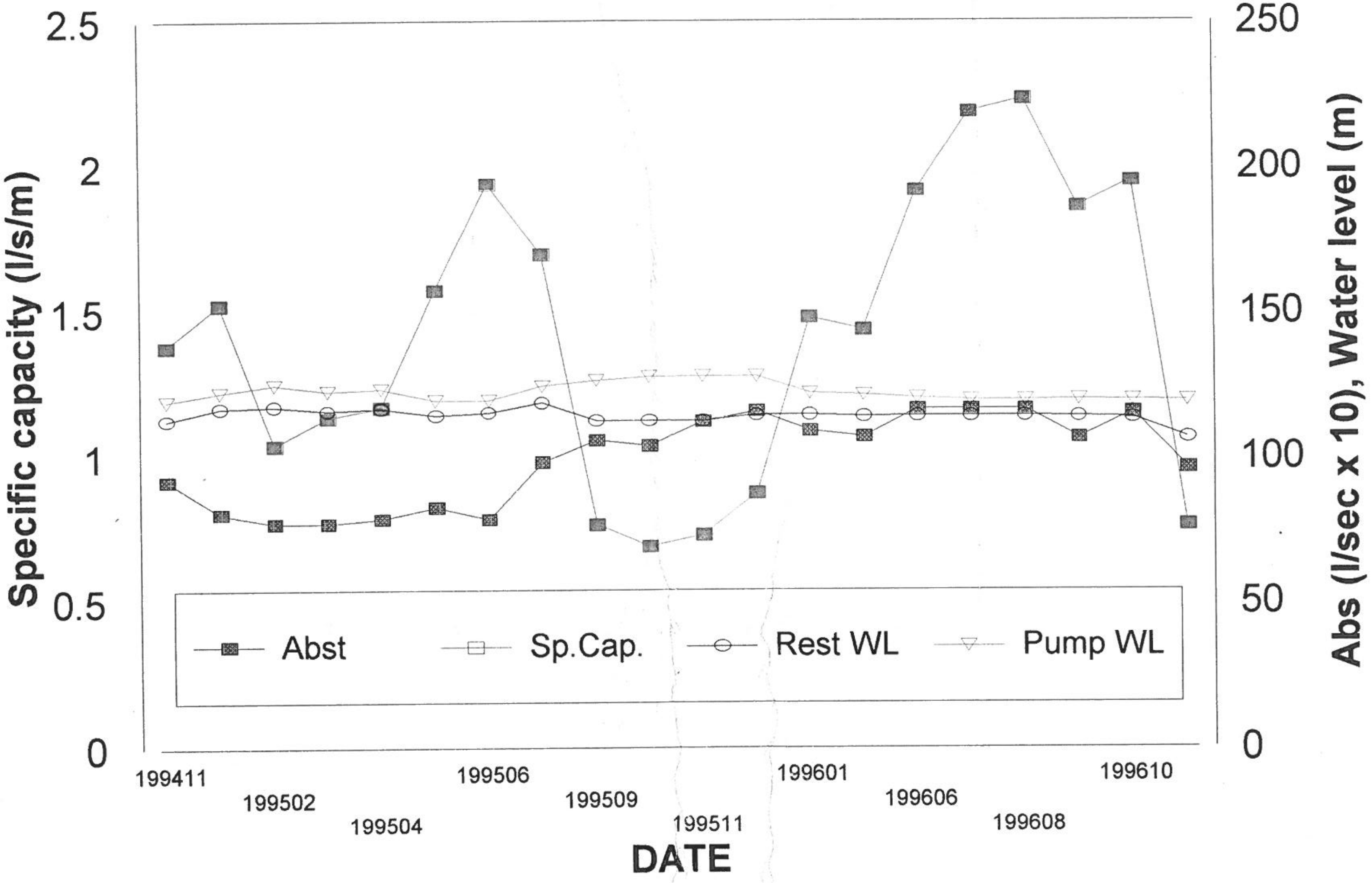
KLEIN KAROO BOREHOLES
DP12



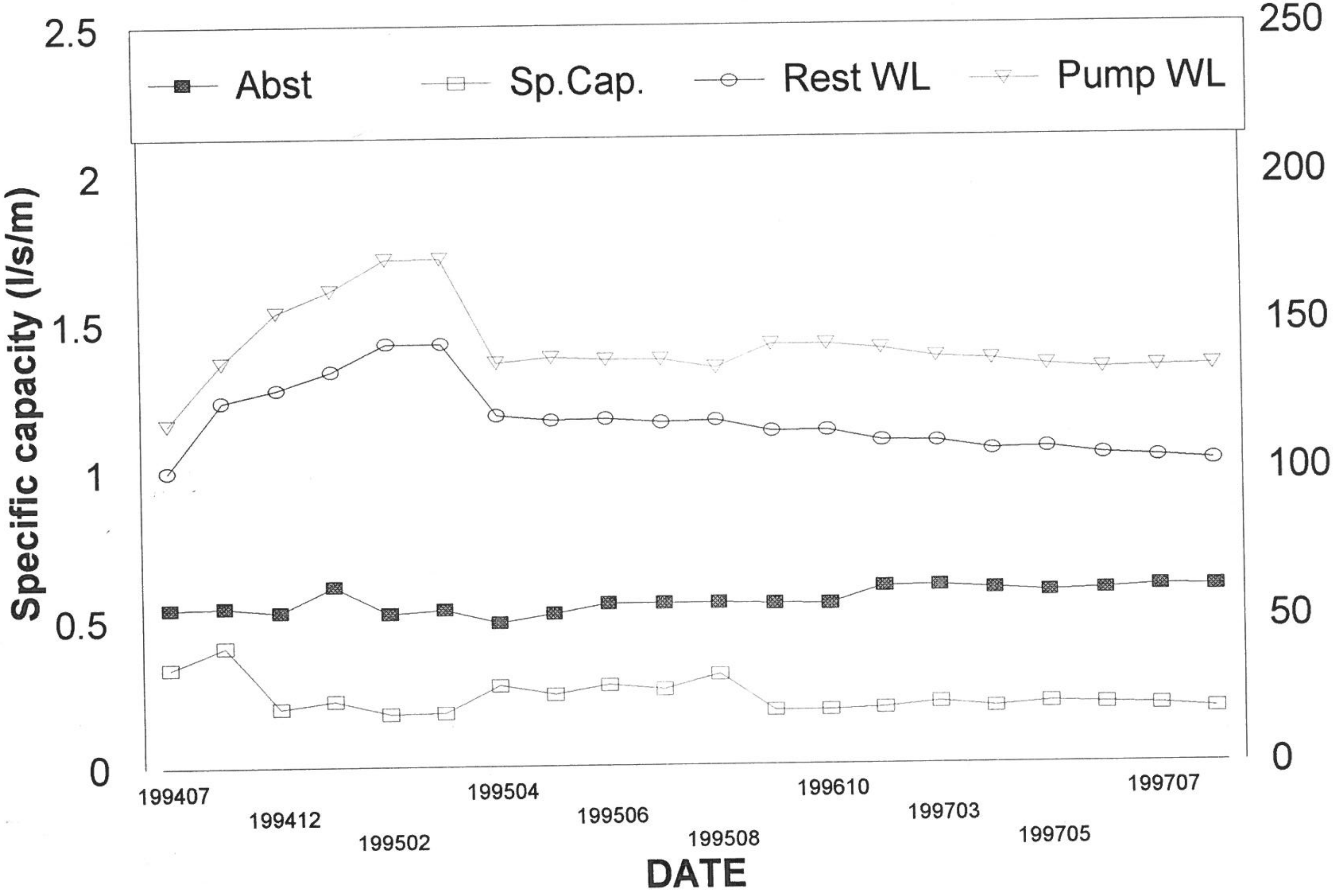
KLEIN KAROO BOREHOLES
DP15



KLEIN KAROO BOREHOLES
DP28

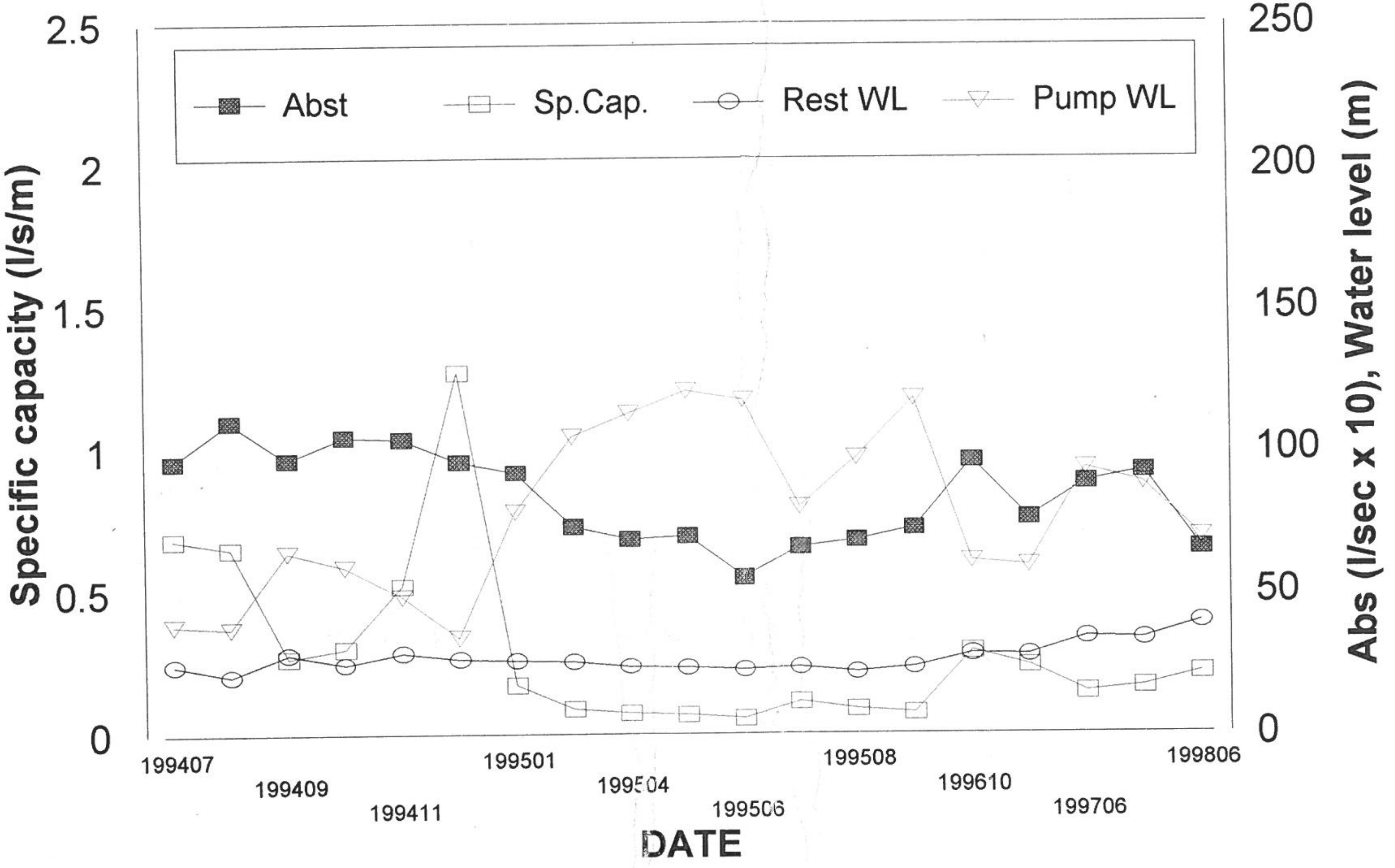


KLEIN KAROO BOREHOLES
DP29

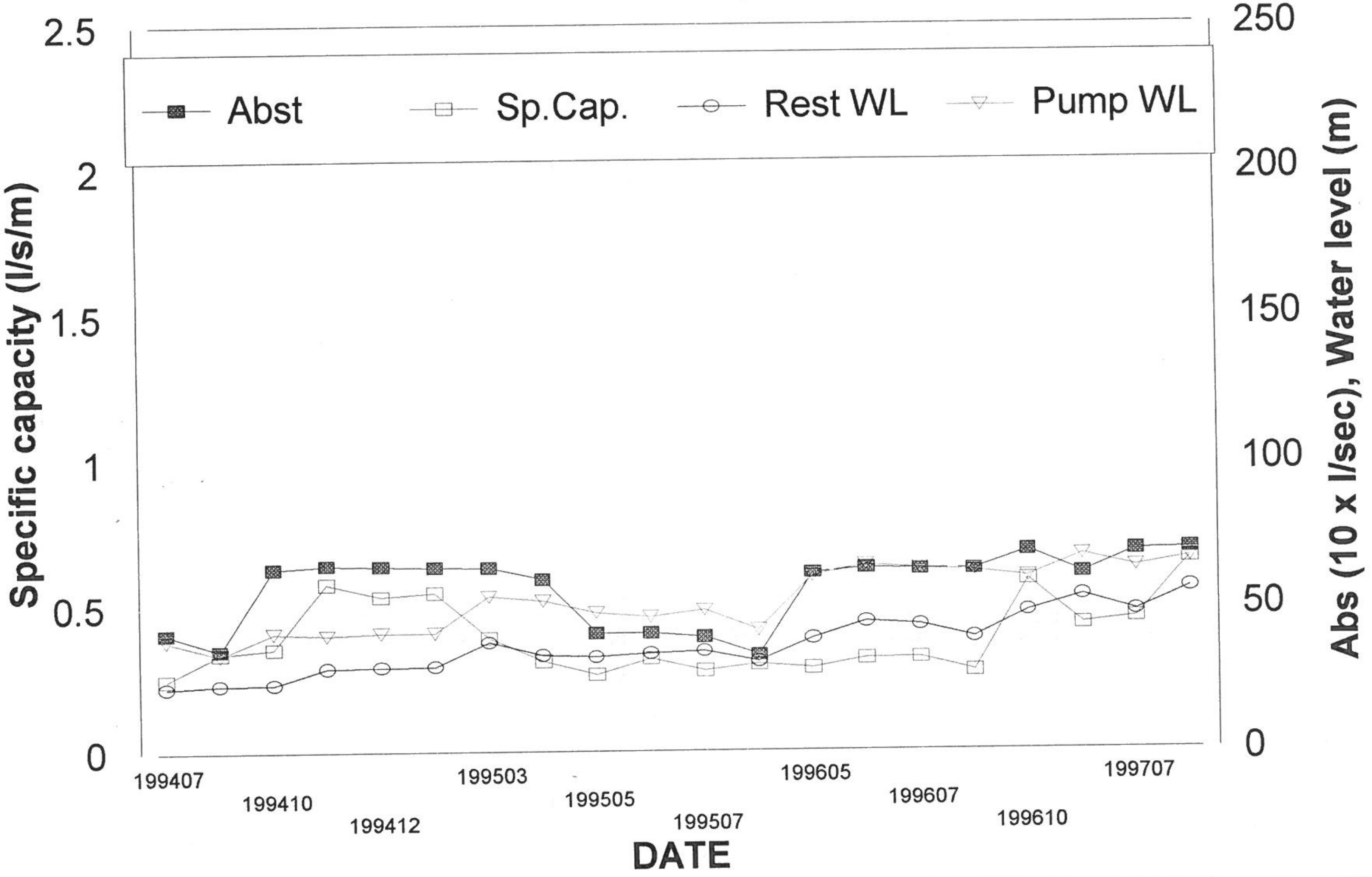


KLEIN KAROO BOREHOLES

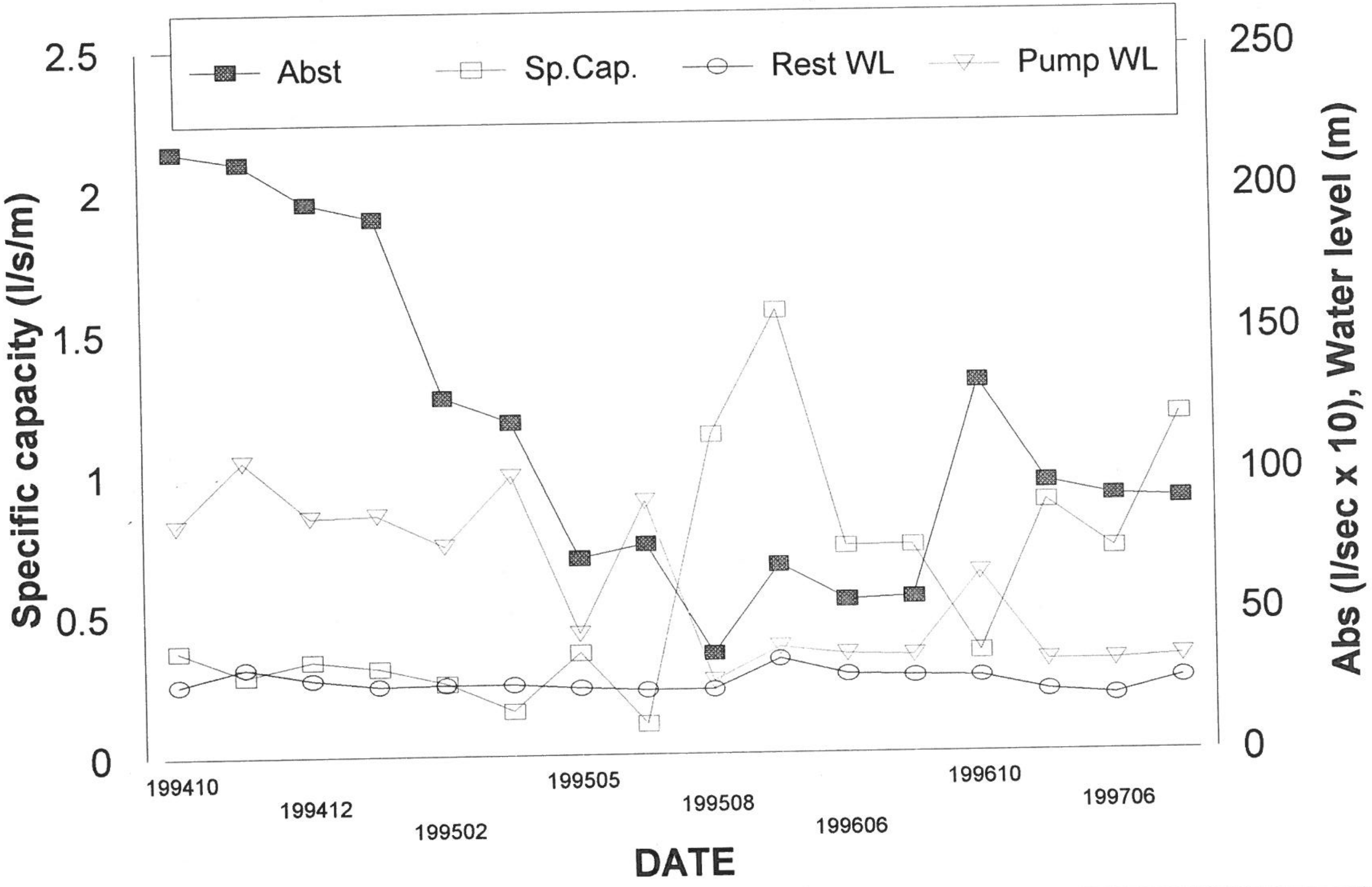
DL15



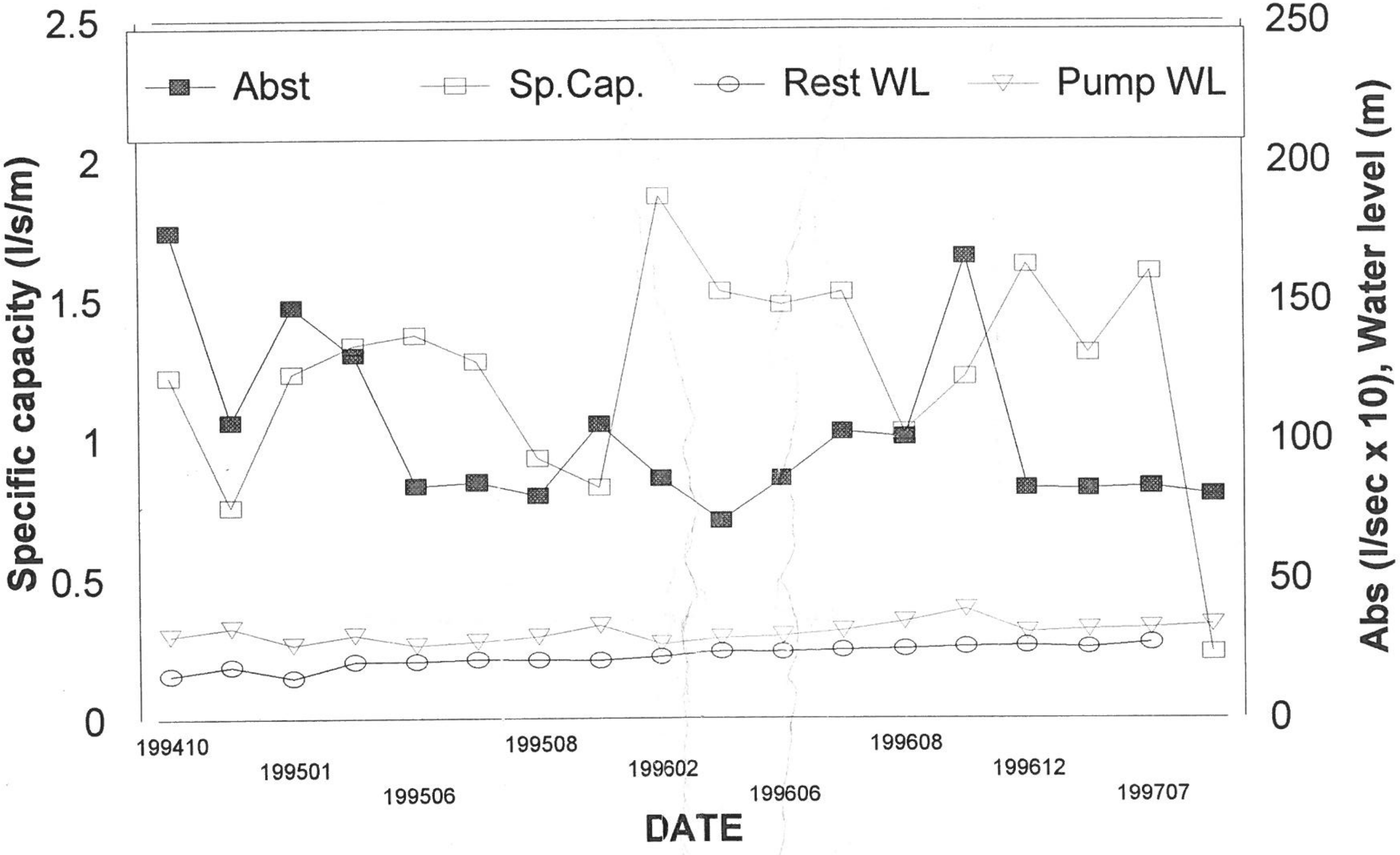
KLEIN KAROO BOREHOLES
DL16



KLEIN KAROO BOREHOLES
DL17



KLEIN KAROO BOREHOLES
KG1



APPENDIX C

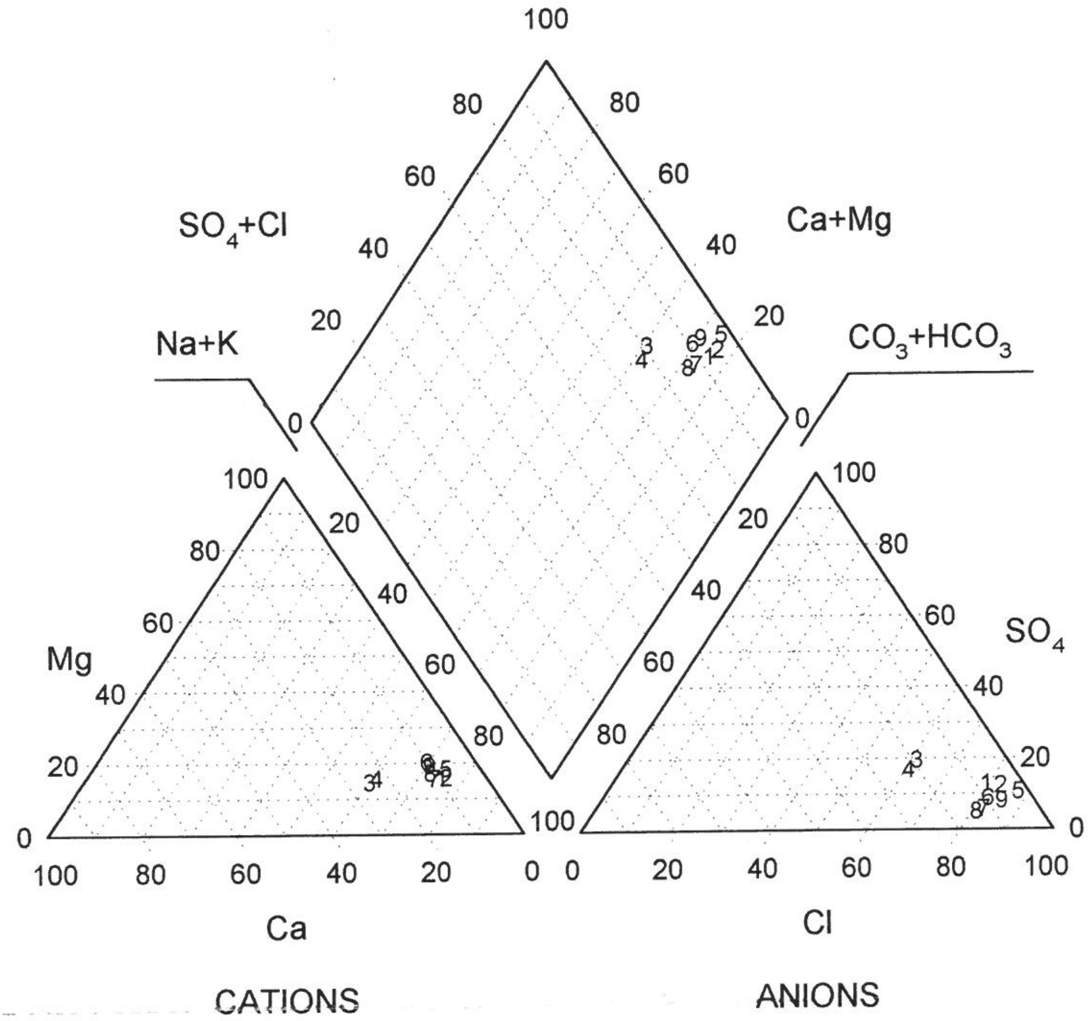
WATER QUALITY ANALYSIS
AND PIPER DIAGRAMS

Well Ident	DateSample	K	Na	<SAR>	Ca	Mg	SO4	Cl	Alkalinity	Nitrate + nitrite	Fe	Mn
VG1	26/10/1998	6.30	28.00	2.5327	3.50	3.50	12.00	53.00	7.20	0.70	3.20	0.39
VG2	26/10/1998	10.10	31.00	1.8564	13.40	4.70	26.00	60.00	26.00	<0.1	0.20	3.7
VG3	26/10/1998	0.90	27.00	2.5912	2.30	3.60	8.10	48.00	4.30	0.80	0.30	0.42
VR6	26/10/1998	0.40	13.00	1.7526	1.70	1.50	2.20	22.00	4.30	0.20	0.10	0.05
VR7	26/10/1998	0.30	11.00	1.5524	1.50	1.40	1.60	19.00	4.50	0.20	0.10	<0.05
VR8	26/10/1998	0.60	10.00	1.4178	1.30	1.50	2.40	18.00	2.00	0.50	0.10	<0.05
VR11	26/10/1998	0.60	10.00	1.3878	1.30	1.60	2.80	19.00	3.00	0.10	0.10	<0.05
BOER	26/10/1998	2.00	24.00	2.3310	2.60	3.30	7.50	44.00	5.30	0.20	0.20	0.44
DP12	26/10/1998	6.10	28.00	1.9327	8.50	4.50	40.00	42.00	6.80	<0.1	4.00	1.06
DP25	26/10/1998	3.90	24.00	0.9875	20.40	14.80	548.00	37.00	0.00	<0.1	89.10	4.6
DP28b	26/10/1998	2.80	23.00	1.3187	8.40	8.90	84.00	35.00	0.00	<0.1	2.50	1.5
DP29	26/10/1998	3.10	25.00	1.9328	5.60	4.30	19.00	40.00	12.00	<0.1	2.00	0.7
DL16	26/10/1998	15.70	46.00	2.4983	11.70	8.50	14.00	81.00	54.00	<0.1	4.70	0.42
DL17	26/10/1998	14.70	42.00	2.0301	14.00	11.20	19.00	93.00	40.00	<0.1	2.60	0.68
KG1	26/10/1998	11.10	33.00	1.6466	14.80	9.50	8.10	79.00	40.00	1	6.10	1.6
KG1b	08/12/98	10.00	37.00	1.8765	13.00	10.00	22.00	80.00	31.00	<0.1	7.40	1.3
VG1b	08/12/98	5.90	29.00	2.6570	3.10	3.60	11.00	54.00	4.30	0.60	5.30	0.38
VG2b	08/12/98	9.10	28.00	1.7968	11.00	4.50	20.00	53.00	27.00	<0.1	13.10	3.1
DP28b	08/12/98	1.10	28.00	1.1168	18.00	18.00	210.00	34.00	0.00	<0.1	20.60	3
DG110	08/12/98	1.40	23.00	2.0998	3.00	3.70	10.00	47.00	4.00	<0.1	8.40	3.3

Well Ident	DateSample	EC (mS/m)	Lab pH	Field pH	Saturated pH	DO (field)	TDS	Hardness	<Cations>	<Anions>	Difference	Hetrotrophic
VG1	26/10/1998	24.00	5.70	5.53	10.2	2.6	152.00	23.00	2.01	1.89	3.22	>5000
VG2	26/10/1998	32.00	6.40	6.33	9	1.0	206.00	53.00	2.67	2.75	1.81	>5000
VG3	26/10/1998	21.00	5.00	4.85	11	2.6	131.00	21.00	1.62	1.55	1.21	>1600
VR6	26/10/1998	10.00	5.30	4.96	10.7	4.8	63.00	10.00	0.79	0.75	0.71	460
VR7	26/10/1998	8.00	5.40	5.07	10.7	5.6	52.00	9.00	0.68	0.66	1.39	158
VR8	26/10/1998	8.00	5.00	4.81	11.1	4.7	53.00	9.00	0.64	0.60	0.74	63
VR11	26/10/1998	9.00	5.10	4.87	10.9	5.6	54.00	10.00	0.65	0.65	1.31	45
BOER	26/10/1998	19.00	5.30	5.50	10.4	3.8	121.00	20.00	1.51	1.50	0.09	>10000
DP12	26/10/1998	26.00	5.70	6.12	9.8	3.4	168.00	40.00	2.38	2.15	2.39	>5000
DP25	26/10/1998	128.00	3.10	3.47	-	1.4	819.00	112.00	8.17	12.45	13.65	320
DP28b	26/10/1998	38.00	3.70	4.19	-	0.7	240.00	58.00	2.36	2.74	6.81	
DP29	26/10/1998	21.00	5.80	5.95	9.7	3.4	136.00	32.00	1.91	1.76	1.97	>5000
DL16	26/10/1998	41.00	6.70	6.42	8.8	2.0	264.00	64.00	3.94	3.66	0.28	500
DL17	26/10/1998	44.00	6.50	6.24	8.8	1.2	280.00	81.00	3.96	3.82	0.09	>5000
KG1	26/10/1998	38.00	6.50	6.40	8.8	1.4	240.00	76.00	3.57	3.20	1.02	>10000
KG1b	08/12/98	40.00	6.40		9		256.00	74.00	3.73	3.33	1.35	
VG1b	08/12/98	24.00	5.70		10.4		154.00	23.00	2.15	1.84	0.30	
VG2b	08/12/98	30.00	6.60		9.1		192.00	46.00	3.07	2.45	1.29	
DP28b	08/12/98	74.00	3.20		-		474.00	119.00	4.73	5.33	3.62	
DG110	08/12/98	21.00	5.60		10.5		134.00	23.00	1.94	1.61	0.91	72 200

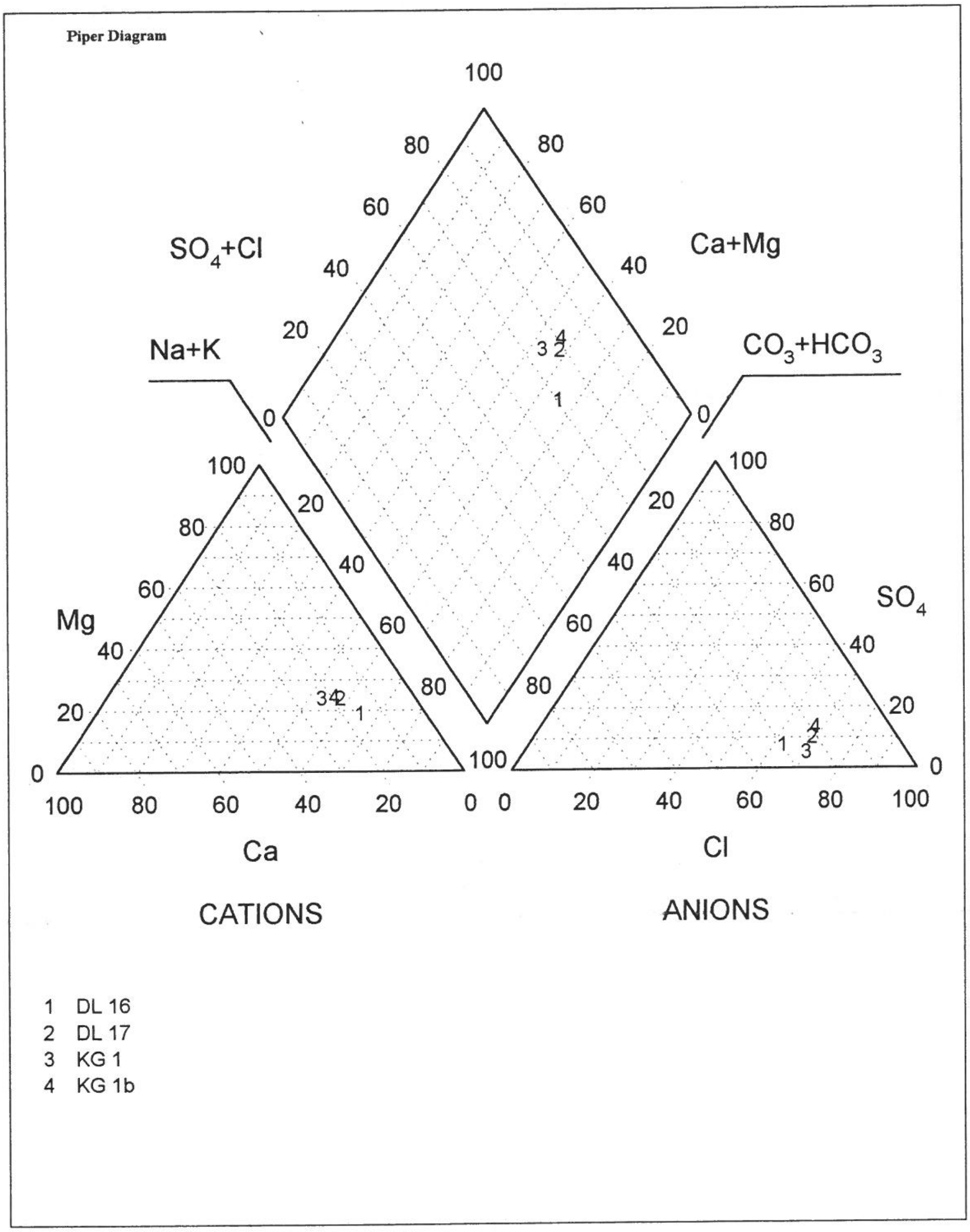
Piper Diagram

Piper Diagram

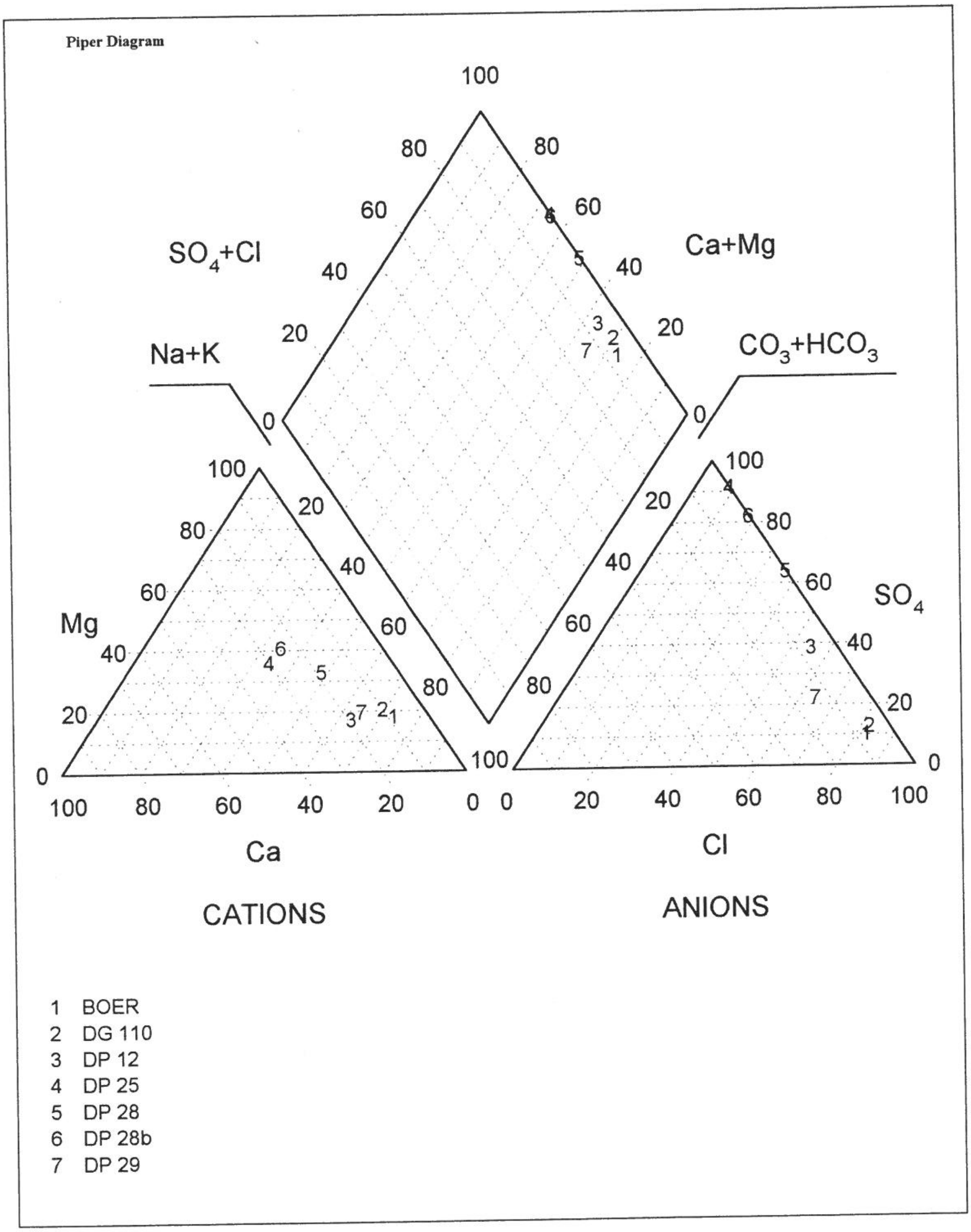


1	VG 1
2	VG 1b
3	VG 2
4	VG 2b
5	VG 3
6	VR 11
7	VR 6
8	VR 7
9	VR 8

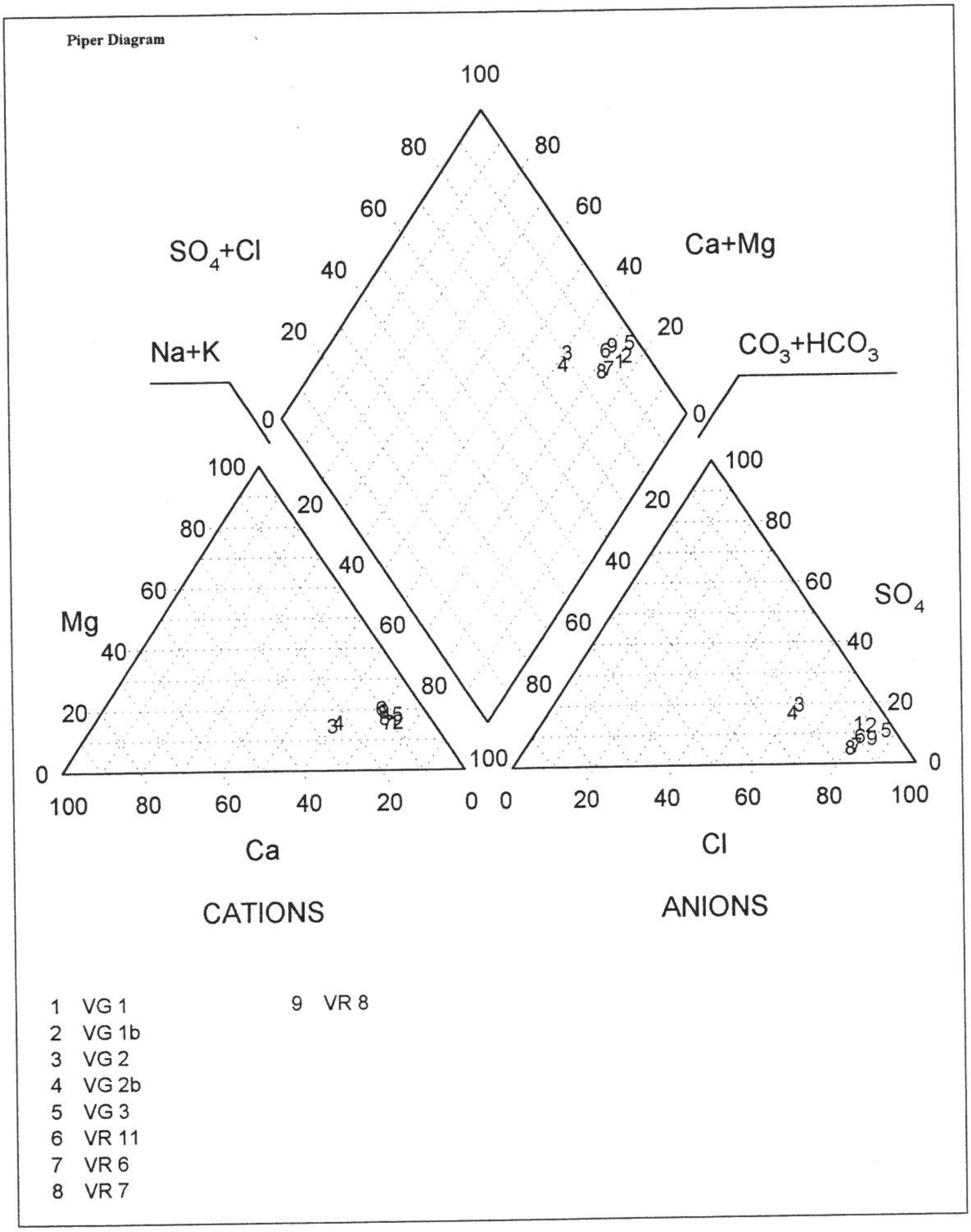
Piper Diagram



Piper Diagram



Piper Diagram



APPENDIX D

BARTS REACTIONS FOR IRBs AND SRBs

IRON RELATED BACTERIA

OLD REACTIONS

1 Deep set slime forms in base of biodetector
2 Cloudy zones form with or without a slime ring
3 Brown thick basal gel and brown slime ring
4 Brown turbid growth with or without brown slime ring
5 Bubbles form foam under and around the FID ball
6 Tight brown slime ring, clear yellow or green liquid
7 Loose brown slime ring, red clouded liquid
8 Light green slightly cloudy liquid, usually darkens
9 Dark green cloudy liquid, almost opaque
10 Blackened lower zone extending upwards

NEW REACTIONS

CL – GC -	Mixed heterotrophic IRB dominated by Pseudomonads
CL – BG -	Mixed heterotrophic IRB with some Enteric bacteria (possibly Enterobacter)
CL – BC -	Mixed heterotrophic IRB
CL – BC – BR	Mixed heterotrophic IRB with some slime formers
CL – FO -	IRB with mixed aerobes and some anaerobic activity
FO – CL -	Anaerobic bacteria with some aerobic heterotrophic IRB
FO – CL – RC -	Anaerobic bacteria with some aerobic heterotrophic IRB and Enteric bacteria (possibly Enterobacter, Citrobacter or Serratia)
FO – CL – BC – BR	Mixed anaerobic and Enteric bacteria with some slime forming IRB
FO – BR – BC -	Mixed anaerobic and IRB with some aerobic slime forming bacteria
FO – GC -	Mixed anaerobic and aerobic bacteria dominated by Pseudomonads *
FO – GC – BL -	Mixed anaerobes, Pseudomonads and Enteric bacteria
GC -	Most of the bacteria present are Pseudomonads *
GC – BL -	Pseudomonads dominate with some IRB and Enteric bacteria present
RC – CL – BR	Enteric/IRB bacteria dominate

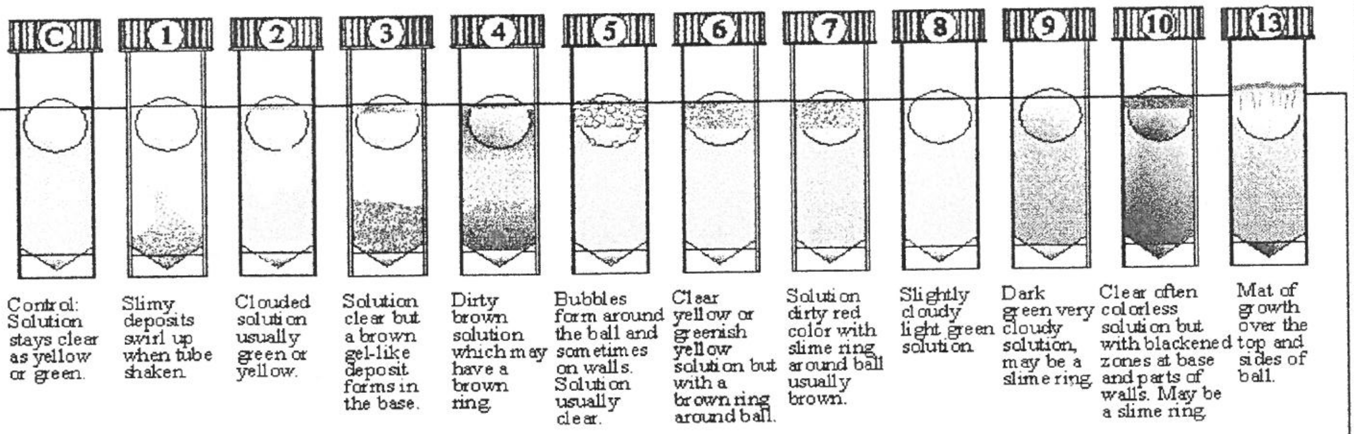
COMPARISON BETWEEN NEW & OLD REACTIONS

BC - Brown Cloudy (Reaction 4)
BG - Brown Gel (Reaction 3)
BL - Blackened Liquid (Reaction 10)
BR - Brown Ring
CL - Cloudy Growth (Reaction 2)
FO - Foam (Reaction 5)
GC - Green Cloudy (Reaction 8 & 9)
RC - Red Cloudy (Reaction 7)

AGGRESSIVITY

dd	Aggressivity	Population (log cfu/mL)
1	Very High	6.2+1.4
2	High	5.4+0.9
3	High	4.5+1.2
4	Moderate	4.1+1.2
5	Moderate	3.8+1.4
6	Moderate	3.3+1.4
7	Background	3.1+1.5
10	Background	2.5+1.2
15	Very Low	<2.0

Iron-Related Bacteria (IRB)



SULFATE REDUCING BACTERIA

REACTION

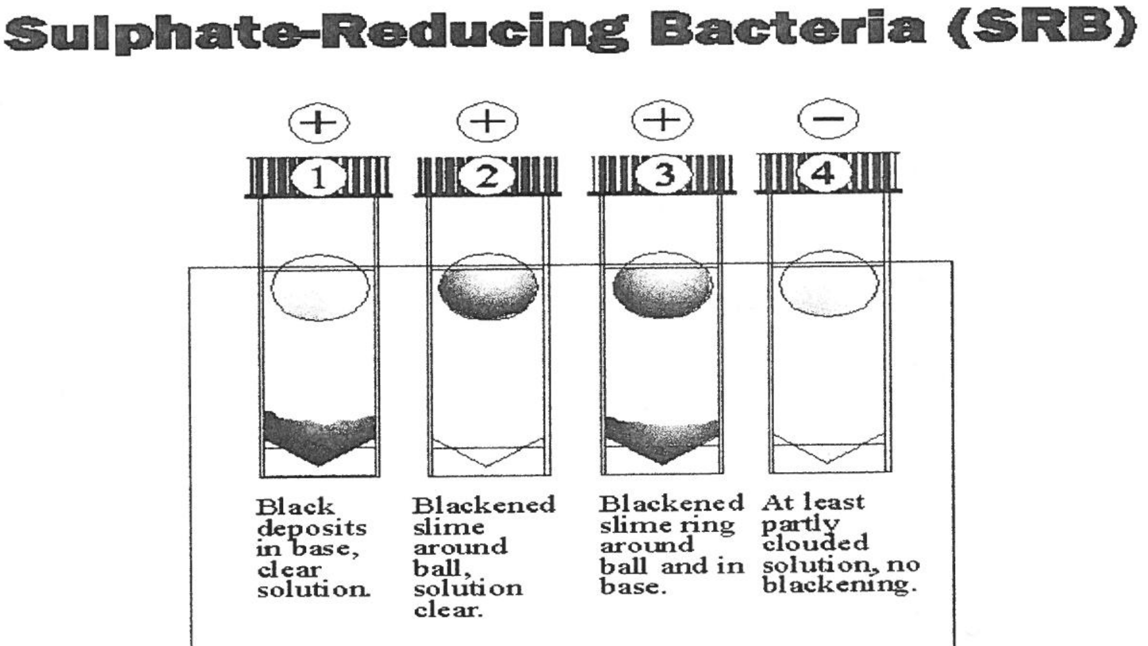
BB - Blackened Base (Reaction 1)
BT - Blackening around Ball (Reaction 2)
BA - Blackening in Base and around Ball (Reaction 3)

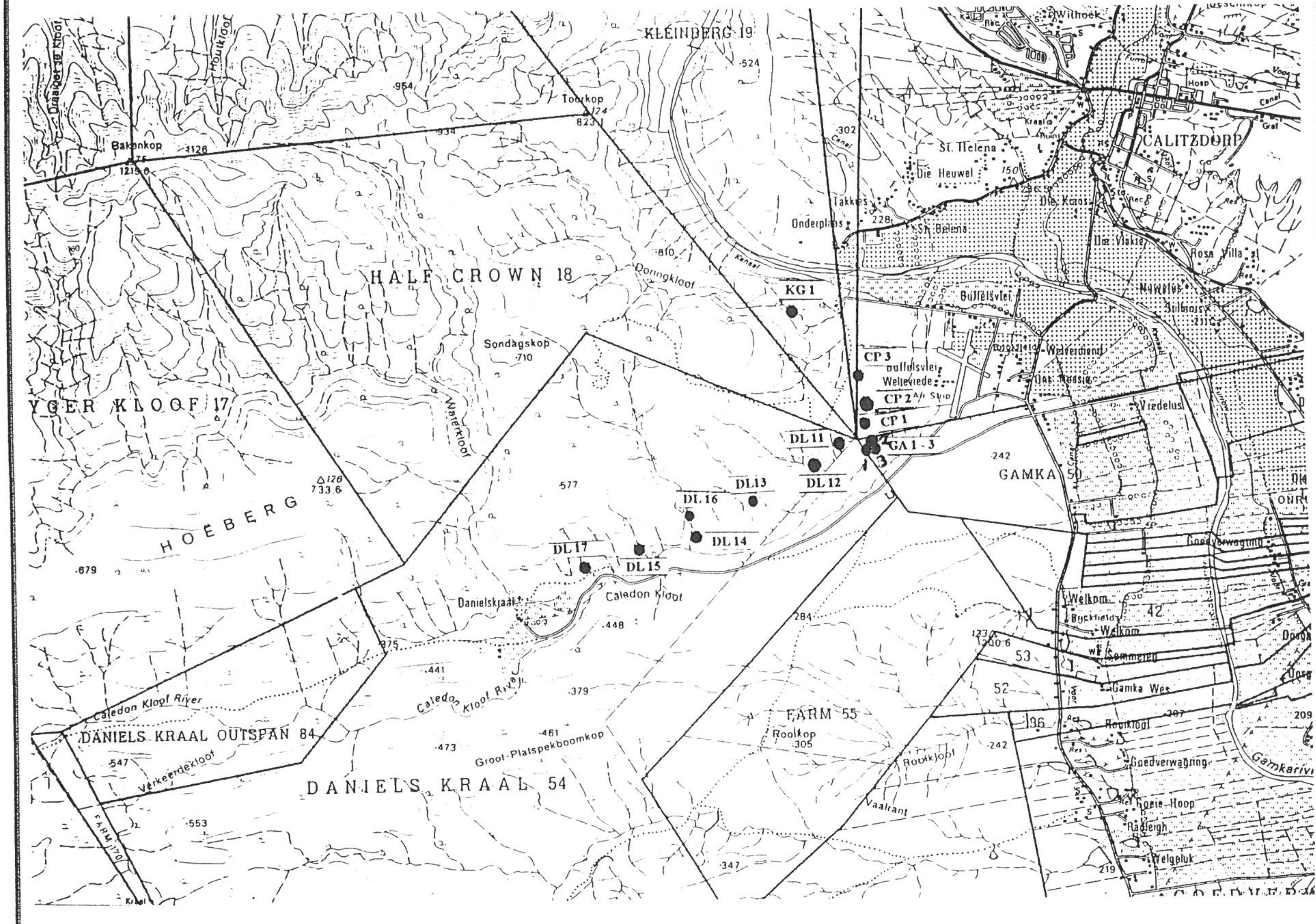
BACTERIA

BB -	Deep-seated anaerobic bacteria dominated by Desulfovibrio
BT -	Dominant aerobic slime forming heterotrophs include SRB in the consortium
BB – BA -	Dominant anaerobic consortium including SRB with a fraction able to function aerobically as slime formers incorporating the SRB
BT – BA -	Aerobic slime formers incorporate SRB and are able to also colonize anaerobic conditions

AGGRESSIVITY

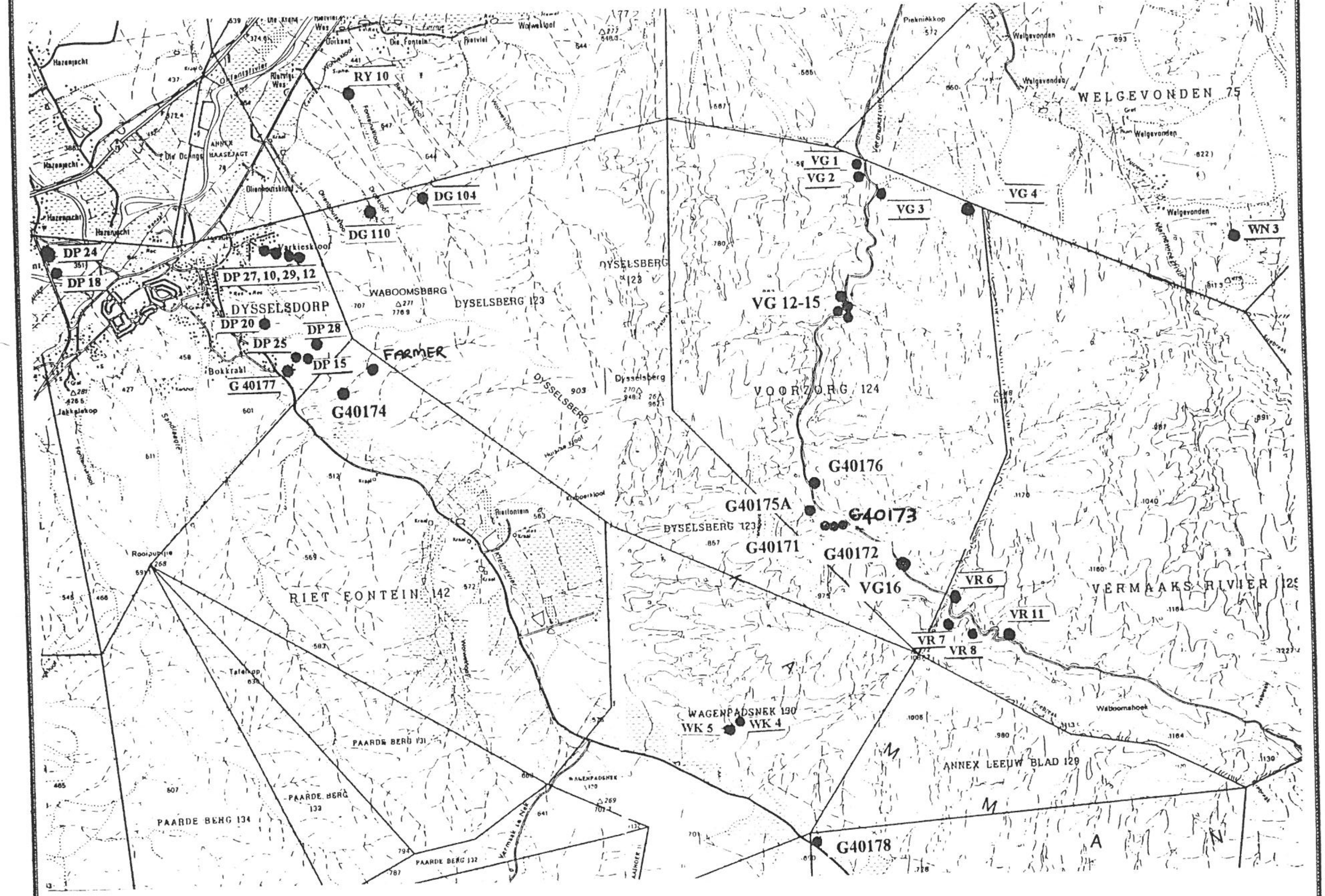
dd	Aggressivity	Population (log. cfu/ml)
1	Very High	4.1+1.6
2	Very High	3.6+1.4
3	High	3.4+1.4
4	High	3.2+1.2
5	Moderate	2.6+1.2
6	Moderate	2.2+1.4
>9	Background	1.2+1.2





SCALE 1: 50 000

POSITION OF BOREHOLES - WESTERN WELLFIELD



SCALE 1:70 000

POSITION OF BOREHOLES - EASTERN WELLFIELDS