

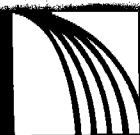
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# Groundwater Quality and Handpump Corrosion in West Africa

by Otto Langenegge

Water and Sanitation Report

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UNDP-World Bank  
Water and Sanitation  
Program

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# Groundwater Quality and Handpump Corrosion in Africa

Otto Langenegger



UNDP-World Bank Water and Sanitation Program

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# Preface

This report presents the experience from the World Bank-executed UNDP-INT/81/026 Handpumps Project, which analyzed groundwater quality and handpump corrosion in the West African subregion. First of all this report provides an overview of groundwater quality and its physico-chemical composition within the subregion comprising the following countries: Burkina Faso, Côte d'Ivoire, Ghana, Mali, and Niger. This information can be of interest to those sectors using or depending on groundwater, such as urban and rural water supply, agriculture, industry, and so forth. Additionally, this report covers subjects particularly related to the rural water supply subsector, such as the relationships between groundwater quality and user acceptance, groundwater pollution in the rural environment, variations of the physico-chemical composition of groundwater due to natural and anthropogenic effects, as well as some indications of groundwater quality as related to bacteriology.

Based on field experience and research work carried out during the Handpumps Project, this report primarily illustrates the problems associated with handpump corrosion: the effects of corrosion on handpump performance and mechanical reliability, on water quality, and on user acceptance. A number of corrosion indexes and corrosion tests have been applied in the fieldwork and tested for their usefulness in predicting handpump corrosion. The results of these tests are shown here along with a simple corrosion index based on pH, which has been recommended for use with galvanized rising mains and pump rods for handpumps.

The first part of the report is intended to serve as a source of reference on general aspects of water quality for project planners, water engineers, and technicians as well as for generalists, including community development specialists in the field of water supply and other technically oriented people dealing with groundwater resources.

The second part of the report, which deals mainly with handpump corrosion, addresses primarily decisionmakers, project planners, project engineers, and technicians involved in handpump-based community water supply schemes.

The main text has been condensed so that relevant details, especially on corrosion investigations and research, appear in the appendixes. This structure makes it easy to use the book as a reference because each chapter, subchapter, or appendix covers a specific subject.

Chapter 1 contains basic, background information on the Handpumps Project and on the development of the groundwater quality testing and corrosion research program.

Chapter 2 contains the results of groundwater quality testing, gives an overview of the project subregion, and compares the results from the different field trials. Whenever applicable, references are made to the WHO guideline values for qualifying the parameters under consideration and their possible effects on health, water treatment, technical aspects, and user reactions. In making the switch from traditionally used surface water to

groundwater, a handpump-based community water supply project encounters many factors that will affect user reaction and ultimate acceptance or rejection of the new water points. Appendixes 3-8 contain examples of these factors, such as variations in groundwater quality due to seasonal, technical, and anthropogenic factors; the relationships between aquifer rock types and groundwater chemical composition; and groundwater pollution.

Chapter 3 gives a brief introduction to corrosion chemistry, the different forms of corrosion, and some standard methods of predicting and measuring corrosion. Chapter 4 deals with field observations of corrosion, particularly the behavior of galvanized iron exposed to aggressive groundwater and the effect of corrosion on handpump performance and water quality.

Chapter 5 describes the field and laboratory research on handpump corrosion that was undertaken within the framework of the Handpumps Project. It covers subjects such as the aquifer-well-pump system, corrosion rates, corrosion products, and scale development as well as the effect of microbiological activity on corrosion.

The results of the application of several corrosion indexes and of a few corrosion tests are presented in Chapter 6. Chapter 7 contains the main conclusions from the groundwater quality investigations and from the research into handpump corrosion as well as some recommendations.

# Executive Summary

The physico-chemical composition of groundwater plays an important role in the study of groundwater quality, not only because of its impact on health, but also because of its effect on user acceptance, its effect on technical aspects of water use (e.g., corrosion), and its effect on industrial and agricultural applications.

This report provides a general overview of groundwater quality, particularly its physico-chemical composition, and the effect of groundwater quality on user acceptance and handpump corrosion. The data were obtained mainly from the West African field trials of the World Bank-executed UNDP-INT/81/026 Handpumps Project (Arlosoroff et al. 1987), which was carried out in Burkina Faso, Côte d'Ivoire, Ghana, Mali, and Niger.

Based on the water quality parameters used in the investigations for this report and on the WHO guideline values (WHO 1984), it can be stated that, apart from the pH, only a small percentage of the groundwater under natural conditions does not comply with the guideline values recommended by WHO. Approximately 50% of the water samples considered in this report had a pH below the WHO guideline range of 6.5-8.5.

In general, groundwater in the subregion has low concentrations of dissolved minerals, which is typical of water from basement formations. Groundwater hardness ranges from soft to moderately hard (up to 150 mg/l  $\text{CaCO}_3$ ). Soft water usually indicates aggressive water. Free carbon dioxide ( $\text{CO}_2$ ) is a component that commonly occurs in little-mineralized, aggressive water.  $\text{CO}_2$  concentration in the savanna region is about 70 mg/l (high), in the forest region 120 mg/l (very high). These levels clearly indicate the problem with aggressive groundwater and corrosion in the subregion. The large difference between the  $\text{CO}_2$  concentrations in the north (savanna) and the south (forest) may be due to microbiological processes associated with the decomposition of organic matter.

Within the Handpumps Project in the West African subregion, the most interesting and important conclusion of the water quality investigations was that handpump corrosion is the main cause of the iron problem in the subregion; the iron concentrations in groundwater under natural conditions are usually less than 1 mg/l.

The conclusions drawn with regard to bacteriological aspects were that: (1) the highest quality water is provided by drilled wells equipped with handpumps, although they, too, are vulnerable to bacteriological pollution; and (2) an acceptable standard of water quality can be provided by improved and protected open wells.

Hazardous constituents are relatively rare in the West African subregion. Only two significant cases are known to the author. In one, high levels of arsenic in groundwater (0.2-1.6 mg/l) caused skin problems to water users in an area in Burkina Faso. The WHO guideline value for arsenic is 0.05 mg/l (WHO 1984). The high concentration of arsenic, which was limited to a small area, apparently resulted from a natural occurrence of arsenic in the rock formations (Jong and Kikietta 1980).



The second case of a hazardous constituent in the groundwater, high fluoride concentrations (up to 2.8 mg/l), occurred in certain areas in the Côte d'Ivoire. While a fluoride content of approximately 1 mg/l reduces dental caries, higher concentrations cause dental and skeletal fluorosis. The WHO guideline value for fluoride is 1.5 mg/l. Although the reported concentrations in the Côte d'Ivoire may present a health hazard as to fluorosis, no cases of fluorosis have been reported (Babut 1984).

There might be other areas in the subregion where the chemical composition of unpolluted groundwater under natural conditions does not meet the WHO guideline values, but water authorities of the countries in the subregion have not revealed any other instances.

Groundwater pollution from human activities, measured by the nitrate ( $\text{NO}_3^-$ ) concentration, is generally negligible in the rural environment—that is, in small settlements. On the average, about 15% of 749 water samples exceeded the WHO guideline value of 45 mg/l for nitrate. There are, however, significant variations between different areas. For example, in one part of the Niger field trial 40% of the tested wells showed nitrate concentrations greater than 45 mg/l.

In densely populated settlements, such as large villages and towns, groundwater pollution by domestic waste and excrement reaches levels that might pose potential health hazards. Nitrate levels as high as 500 mg/l were measured in some cases. High degrees of pollution are usually indicated not only by nitrate but also by other classic pollution indicators such as ammonium, chloride, and sulfate, as well as by bacteriological parameters.

The bacteriological quality of the groundwater was based on analysis of coliform organisms. The results presented in this report suggest that about 70% of the wells equipped with handpumps in the subregion provide "good" to "acceptable" quality water and about 30% provide "poor" quality water.

A number of wells throughout the subregion have been abandoned by the users because of highly mineralized water, which they consider "salty." Such situations, generally a result of local geological factors such as pockets of inhomogeneous soil and specific rock compositions, can occur anywhere, but are generally negligible. In the 3000 Well Drilling Programme in Southern and Central Ghana, the percentage of boreholes not completed because of inadequate water quality was less than 2%. The majority of those uncompleted wells were located near the coast and had high chloride concentrations, probably due to salt water intrusion from the sea (GWSC-IDC n.d., ca. 1986).

Therefore, although groundwater in the West African subregion is rarely found objectionable on the basis of its natural chemical composition, the salinity of the groundwater should be tested as early as possible in the project, and certainly before a well is completed and equipped with a handpump. This test can be performed easily with an electrical conductivity meter, and can save funds and avoid misunderstandings and disappointments for both recipients and donors. For example, in Niger, it was realized only after completion of a well that the water from the large-diameter dug well would never be accepted by the people. The water had an electrical conductivity of 2850  $\mu\text{S}/\text{cm}$  and the

villagers were used to drinking surface water from the nearby River Niger, which had a conductivity of only about 100  $\mu\text{S}/\text{cm}$ .

The investigations and research performed within the Handpumps Project have also yielded a good understanding of the effect of corrosion on handpump performance and water quality, including the behavior of galvanized materials, corrosion rates of pump rods and rising mains, differences between internal and external corrosion of rising mains, and correlations between corrosion rates and certain parameters of water quality as well as the first results of the application of corrosion indexes, and some observations of the impact of microbiological processes on corrosion. Furthermore, the water quality testing within the West African field trials, as well as in other parts of the subregion, indicates that about 70% of the area in the Handpumps Project has corrosive groundwater. As a consequence, corrosion of handpumps is a problem. Thousands of handpumps are equipped with galvanized rising main and pump rod assemblies, which, as a general rule, are not resistant to corrosion under the prevailing groundwater conditions in the West Africa Region.

The effect of corrosion on handpumps is two-fold. First, it affects the mechanical performance, leading to broken pump rods and damaged pipes. Although these mechanical failures usually originate from a combination of causes (e.g., rubbing of rods on rising mains, fatigue of material, poor handling of the equipment, etc.), a high percentage of handpump failures are attributable to corrosion. In one particular project in western Africa, it was found that up to two-thirds of the handpump defects (rod breakage) were directly related to corrosion.

Second, corrosion by-products significantly affect water quality and, thus, affect user acceptance of water pumped with non-corrosion-resistant handpumps. The high iron concentration that results from corrosion makes water especially unacceptable to pump users because of its unpleasant taste, turbidity, and side effects such as discoloring food and staining laundry.

Cost effectiveness can also be significantly affected by handpump corrosion. Not only will recurrent costs increase due to the necessity of more frequent repairs, but the water points (boreholes) may also be unused or infrequently used due to water quality problems. Field experience indicates that handpumps drawing water with a total iron concentration greater than 5 mg/l are generally little used. Within the field trials of the West Africa Region it has been found that, in certain areas and at certain times, 60% of the monitored wells exceeded even 10 mg/l total iron.

Corrosion is a complex problem. It has been investigated for decades and is still incompletely understood. Corrosion affects both handpumps and distribution networks of water utilities. There are three factors that have a major impact on corrosion: water quality, the material the equipment is made of, and operating conditions.

Taking these factors into consideration, it is easy to understand that there is a principal difference between water supplies carried in the pipes of large distribution networks and water supplies from handpump-based point sources. Water supplied through distribution networks is usually treated between the source and the distribution network, but water treatment of point-source supplies for handpump-equipped boreholes is not feasible.

The key to solving the handpump corrosion problem is the material used for the pump equipment. Much effort has already gone into the application of corrosion-resistant materials for rising mains and pump rods. Research and development work has focused on stainless steel and plastic materials, and although remarkable progress has been made, certain problems remain.

Field observations have shown that generally, where groundwater is moderately to highly aggressive ( $\text{pH} < 6.5$ ), galvanization of mild steel rising mains and pump rods does not protect them from corrosion.

Generally, measured corrosion rates (expressed as diameter reduction) of rising mains and pump rods range from 0.0 to 0.5 mm/year. Galvanic, or bimetallic, corrosion, however, caused diameter reductions of up to 4 mm/year in pump rods.

There is a remarkable difference between internal and external corrosion of galvanized steel pipes. The internal surfaces of pipes are generally less corroded than the external surfaces. This may indicate that corrosion-resistant (e.g., stainless steel) rising mains should be used for the piping that is immersed in water, and galvanized rising mains for the piping that is, externally, not in contact with the water in the well. This hybrid version is recommended as a short- and medium-term solution, especially for deep (greater than 30 m) installations.

## **1. Background**

The World Bank-executed UNDP-INT/81/026 Handpumps Project was started in 1981 and terminated at the end of 1986. It was one of several UNDP projects in the water and sanitation sector within the International Drinking Water Supply and Sanitation Decade (1981-1990). The main objectives of the Handpumps Project were (1) to test handpumps in the laboratory, (2) to test handpumps in the field, and (3) to promote the technological development of handpumps.

The Handpumps Project was executed in five regions—East Africa, West Africa, Latin America, East Asia, and South Asia—and comprised seventeen countries. About 2000 handpumps of approximately 70 different makes were part of the field and laboratory testing program. In the West African subregion, the Handpumps Project consisted of six field trials in five countries: Burkina Faso, Côte d'Ivoire, Ghana, Mali, and Niger. Some 800 handpumps of ten different types were fully or partially integrated into the field trials.

Results of the Handpumps Project have been published in a series of reports. The most recent, "Community Water Supply: The Handpump Option" (S. Arlosoroff et al. 1987), includes a summary of the findings and recommendations of the Handpumps Project and a handpump selection guide.

In East African and Asian test areas of the Handpumps Project, in addition to testing handpumps in the field, emphasis was placed on the technological development of handpumps. These concerns were integrated into the field trials in West Africa, along with the issues of groundwater quality, handpump corrosion, user acceptance, and handpump use. It was clear in the early stages of the field trials in West Africa (1983) that handpump corrosion was a problem that was not limited to a particular project or to isolated cases, but that it existed throughout the subregion.

Handpump corrosion caused increased breakdown rates and had an adverse impact on water quality. The impact on water quality was caused mainly by high iron concentrations, which resulted in negative user reactions and disuse of water points. In the Handpumps Project, therefore, user reaction to water quality was considered from two aspects: from the users' reaction to the side effects caused by handpump corrosion and their reaction to the natural salinity of the groundwater, which by itself may influence user acceptance of new water points when the change from surface water to groundwater results in a significant change in taste.

Handpump use directly concerns planners of community water supply projects and, therefore, it is essential to determine the relationship between handpump use, handpump corrosion, and water quality. Pump use was measured with water meters in the West African subregion; about 200 of the approximately 800 handpumps tested were equipped with water meters.

Routine testing of groundwater quality was performed in the field by the monitoring teams of the Handpumps Project. The following parameters were measured: groundwater temperature, pH, electrical conductivity, turbidity, total iron, nitrate, and dissolved oxygen. The monitoring teams used thermometers, pH meters, electrical conductivity meters, oxygen test kits, spectrophotometers, and reagents to perform the tests. The additional water analyses, in the field and in the laboratory, were performed almost entirely by the author.

## **2. Groundwater Quality in Western Africa**

### **2.1 Introduction**

This report is based primarily on field data collected in the five countries in the West African subregion that participated in the Handpumps Project. The surface area of the subregion (3.34 million square kilometers) represents 11.1% of the land area of Africa, the population (51.2 million in 1988-89) represents 8.4% of the total population of the African continent. Population and area statistics and a map of the Handpumps Project area are presented in Appendix 1.

The West African subregion is characterized by a rather monotonous topography with flat to undulating plains, plateaus, and a few hilly, mountainous areas. The average altitude of the subregion is 200-500 m; the highest peak, which is located in the Aïr Massif in northern Niger, is about 2000 m.

There are remarkable differences in climate within the subregion, particularly with regard to rainfall and temperature, both in terms of annual means and seasonal variations. In the south, along the coast, the climate is heavily influenced by the Atlantic Ocean, where the mean annual rainfall is around 2000 mm and mean air temperature around 26°C. Toward the Sahara Desert, annual rainfall is less than 200 mm. The yearly amount of rainfall and the precipitation pattern make the southern part of the subregion very different from the northern part. The farther north, and thus the farther from the moderating influence of the Atlantic Ocean, the shorter and more irregular are the rainy seasons and the greater the daily and seasonal variations in air temperature. For example, in Abidjan, Côte d'Ivoire, on the Atlantic coast, the mean annual air temperature is 26.3°C with a mean monthly maximum of 30.6°C in April and a mean monthly minimum of 22.4°C in September (ASECNA 1979). The equivalent data for Niamey, Niger, much farther inland (about 800 km from the coast), are 29.1°C, 40.9°C in April, and 15.9°C in January, respectively (Direction de la Meteorologie Nationale 1988).

Vegetation in the subregion can be roughly divided into three main zones: the forest belt in the south, which lies approximately between 4 degrees and 7 degrees north latitude and averages annual rainfall of 1400 to 2300 mm; the savanna, which lies approximately between 7 degrees and 13 degrees north latitude and averages about 700 to 1400 mm annual rainfall; and the Sahel steppe zone, which lies at between 13 and 16 degrees north latitude, between the savanna and the desert, and averages annual rainfall of approximately 200 to 700 mm.

The general geology of the subregion is shown in the geologic map in Appendix 2. The dominant rock types (igneous, metamorphic, and sedimentary) found in the subregion are listed in Table 2.1, and each category is further broken down into acidic, intermediate, and basic rock types based on the acidic/basic rock classification system, which is dependent on the silica content of the rock (see Appendix 2). The distribution of acidic, intermediate, and basic aquifer rocks in each country of the subregion is presented in Table 2.2. About 75% of the aquifer rocks in the subregion (south of 18° north latitude)

are acidic or intermediate (see third column in Table 2.2), and groundwater originating from such aquifers is generally aggressive, that is, has a pH < 7. This strong relationship between aquifer rock type and pH of the groundwater enables us to estimate and map the probable acidity of groundwater with geologic maps. For more information on the relationship of aquifer rock type to pH of the groundwater see Appendix 5. Some basic data on groundwater levels and yields of drilled wells are presented in Appendix 3.

**Table 2.1**  
**Dominant Rock Types in the Subregion**

Rock Group	Acidic	Intermediate	Basic
<u>Igneous</u>	Granite Granodiorite Migmatite Rhyolite	Diorite Syenite Andesite Monzonite Epidiorite Trachyte	Basalt Dolerite Gabbro
<u>Metamorphic</u>		Gneiss Quartzite Phyllite Schist Metavolcanic	
<u>Sedimentary</u>	Sand Sandstone Arkose Greywacke Clay	Mudstone Shale	Limestone Dolomite

**Table 2.2**  
**Distribution of Aquifer Rock Types (Acidic, Intermediate, and Basic) in the Subregion**

Country	Acidic Rocks (%)	Intermediate Rocks (%)	Acidic + Intermediate Rocks (%)	Basic Rocks (%)
Burkina Faso	72.8	10.5	83.3	16.7
Côte d'Ivoire	63.2	35.8	99.0	1.0
Ghana	21.7	63.0	84.7	15.3
Mali	31.6	46.5	78.1	21.9
Niger	26.3	35.2	61.5	38.5
Total Subregion	38.5	38.8	77.3	22.7

## 2.2 Data Sources

The results presented in this report were derived from water analyses performed within the Handpumps Project, but other valuable information was also derived from other projects, particularly the 3000 Well Drilling Programme in Southern and Central Ghana and the Helvetas Project in Southern Mali. The primary data sources include:

- (i) Data collected by the monitoring teams in the field trials of the Handpumps Project, primarily measurements of temperature, pH, total iron, nitrate, and dissolved oxygen.
- (ii) Data collected by the author, which comprises data from the field trial areas and other parts of the subregion. All the water analyses related to the investigations of corrosion (laboratory tests and the Divo field trial in the Côte d'Ivoire) were performed by the author. The data set includes, in addition to those parameters already mentioned in (i), measurements of zinc, manganese, saturation index, ammonium, nitrite, chloride, hardness, alkalinity, calcium, magnesium, sulfate, sulfide, potassium, sodium, silica, carbon dioxide, fluoride, and bacteriological analyses (total coli).
- (iii) Data originating from external sources, that is, from the 3000 Well Drilling Programme in Southern and Central Ghana and the Helvetas Project in Southern Mali. Also, a local laboratory, ONAREM, was commissioned to analyze water samples from the Niger field trial.

The majority of the water quality data used and presented in this report originates from single analyses. An important aspect of water quality testing, however, is to measure the variation with time of the parameters that are used to determine water quality; for example, from one season to another. Generally, groundwater from deeper zones (weathered and fractured parts of basement formations) is little affected by seasonal changes (see Appendix 7).

## 2.3 Physical Parameters

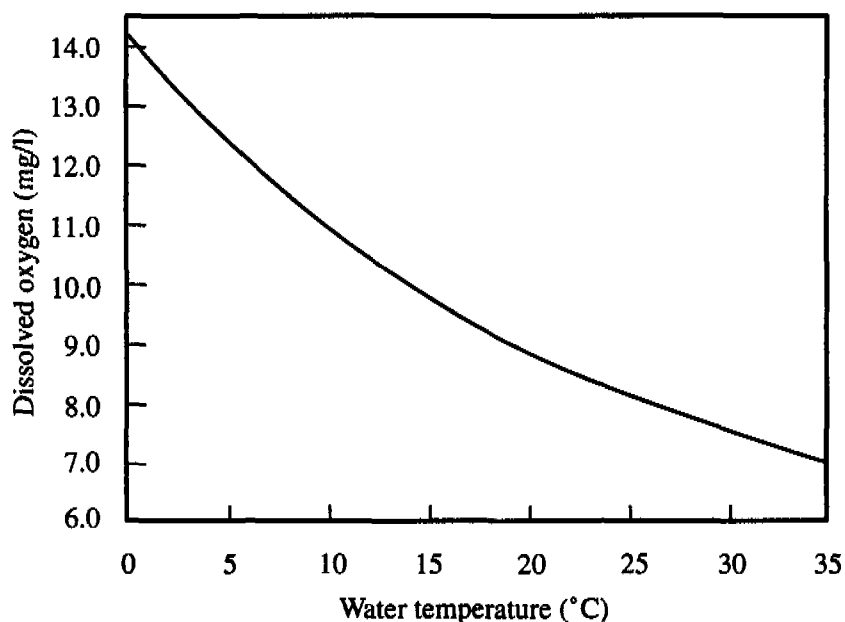
### 2.3.1 Groundwater Temperature

Temperature has a remarkable influence on certain physical characteristics of water as well as on chemical and bacteriological processes. For example, the viscosity of water decreases from 1.306 centipoise at 10°C to 0.798 centipoise at 30°C, and the solubility of carbon dioxide in water at normal atmospheric pressure decreases from 0.70 mg/l at 10°C to 0.38 mg/l at 30°C. The amount of dissolved oxygen in water, which is important in water chemistry and microbiology, also decreases with increase in temperature (Fig. 2.1).

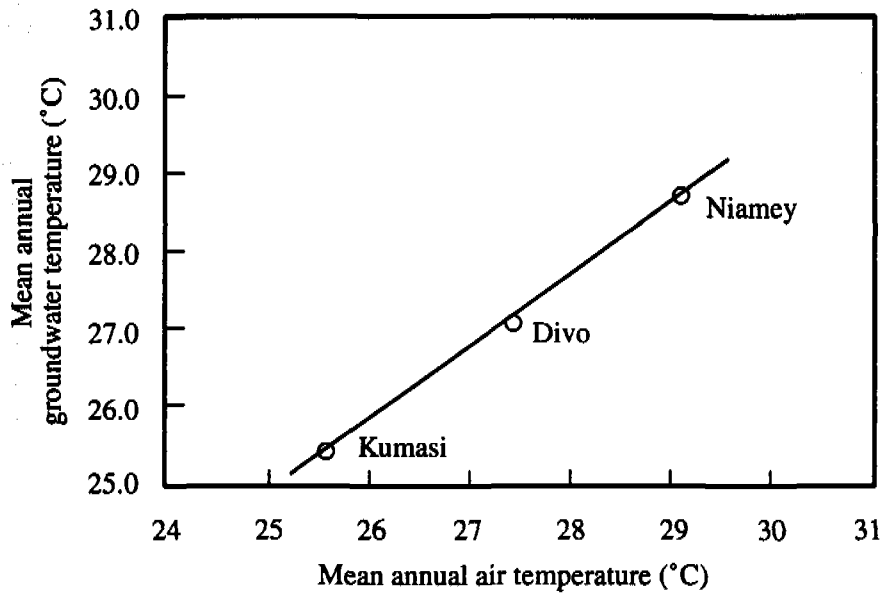


The mean annual groundwater temperature in the West African subregion ranges from 25°C to 30°C, which corresponds well with the mean annual air temperature (Fig. 2.2). Seasonal variations in groundwater temperature are small, with mean values of 0.5°C to 1.5°C. The groundwater temperatures in the different field trials are shown in Figure 2.3.

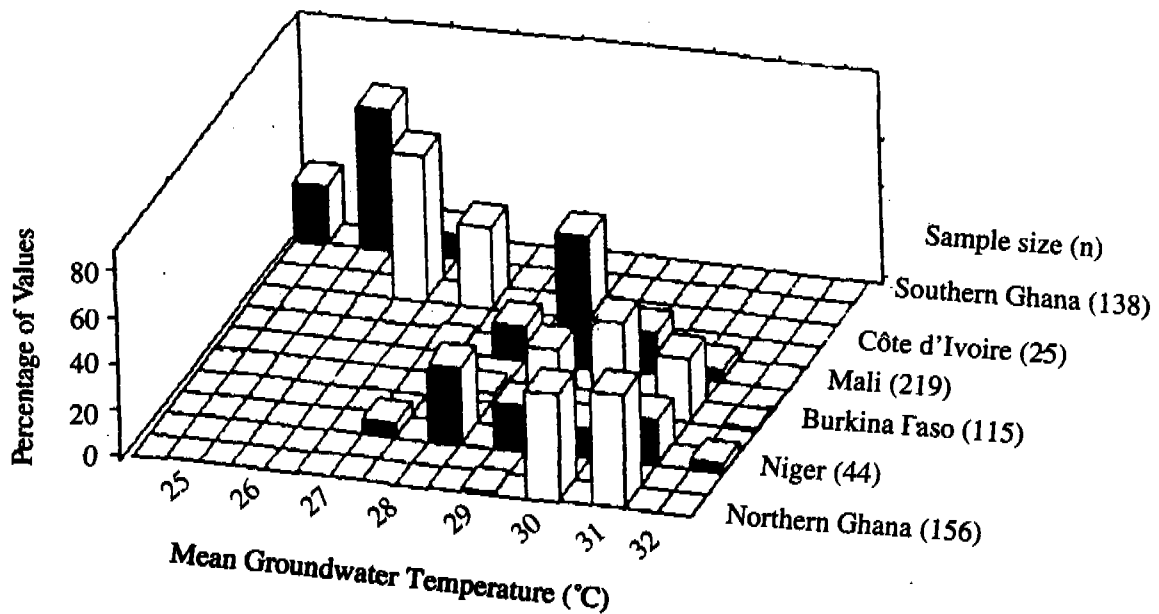
The results of laboratory tests provide evidence that high groundwater temperatures ( $\approx 30^\circ\text{C}$ ), such as those that prevail under tropical conditions in West Africa, have a significant influence on the microbiological processes that affect handpump corrosion (see Section 5.5). (The term "high groundwater temperature" refers to temperatures that are "high" with respect to those found in temperate climates, where groundwater temperatures are 8–12°C, or about 20°C lower than in the tropics.) Groundwater temperature also affects the physico-chemical characteristics of water, and these, too, must be considered when groundwater samples from different climatic zones are being compared. Further details about groundwater temperature characteristics in the subregion appear in Appendix 4.



**Figure 2.1 Solubility of oxygen ( $\text{O}_2$ ) in water versus water temperature at normal atmospheric pressure and at water vapor saturation**



**Figure 2.2 Mean annual groundwater temperature versus mean annual air temperature in the subregion**



**Figure 2.3 Groundwater temperature in the subregion**

### 2.3.2 pH

The pH is the ratio between hydrogen ( $H^+$ ) and hydroxide ( $OH^-$ ) ions in a solution and is defined as the negative logarithm of the activity of the hydrogen ion ( $aH^+$ ). Since the hydrogen activity in water (diluted solution) is about equal to the hydrogen concentration ( $cH^+$ ), the pH can be defined as:

$$\left| \text{pH} = - \log_{10} [cH^+] \right|$$

A  $\text{pH} = 7$  means that equal quantities of  $H^+$  and  $OH^-$  ions are in solution (the solution is at equilibrium; or the solution is neutral). A  $\text{pH} < 7$  means that there are more  $H^+$  than  $OH^-$  ions in solution, and the solution is acidic. A  $\text{pH} > 7$  means that there are excess  $OH^-$  ions, and the solution is basic or alkaline.

The pH is an important parameter in water chemistry because the effectiveness of most water treatment processes depends on the pH; and it is also important in hydrobiology and aquaculture.

The recommended drinking water value for pH is 6.5–8.5 (WHO 1984). This recommendation is not directly related to health hazards, but rather to minimizing technical problems in water distribution systems (corrosion, incrustation) or to avoiding inefficient chlorine disinfection. Therefore the WHO guidelines for drinking water also state that the acceptable pH range may be broader where no distribution systems are used.

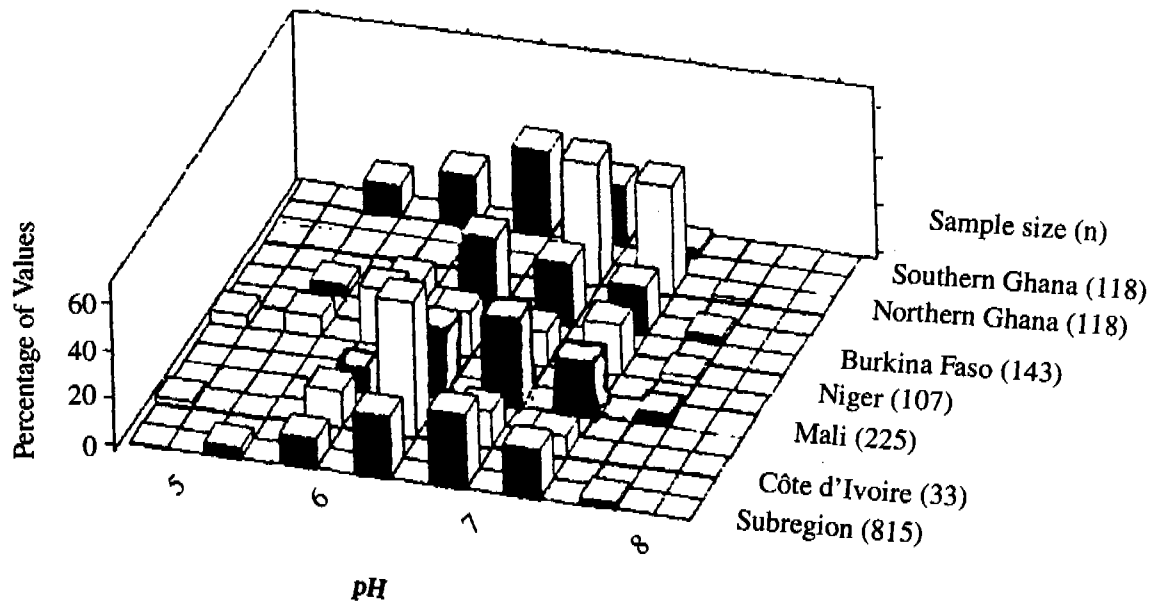
The pH of groundwater measured within the Handpumps Project in the West African subregion ranges from about 4.0 to 8.5, and in general, pH shows very little seasonal fluctuation. The pH, however, is influenced by corrosion. The pH of groundwater from a well equipped with a noncorrosion-resistant handpump can decrease (i.e., become more acidic) by as much as half a pH unit after replacement with a corrosion-resistant pump (see Section 4.4.5). Remarkable differences in pH, as well as in other parameters, have been observed in groundwater from wells that tap different aquifers; for example, shallow groundwater from the overburden versus water from a deeper bedrock aquifer. A well that draws water from two different aquifers is described in Appendix 7.

The pH is a useful indicator of corrosion (see Chapter 6) and can be measured relatively easily in the field. Groundwater with a  $\text{pH} < 7$  is widespread in the West African subregion, primarily due to the geological situation (Table 2.1). The pH of groundwater samples in the subregion is presented in Figure 2.4.

The relationship between rock type and pH, as well as an estimate of the percentage of the subregion's area that has aggressive groundwater ( $\text{pH} < 7$ ), is presented in Appendix 5.

### 2.3.3 Electrical Conductivity

Electrical conductivity (EC) is a measure of the ability of water to conduct an electrical current, and thus is an indication of the total amount of dissolved ions in water (expressed in microSiemens per centimeter at 25°C ( $\mu\text{S}/\text{cm}$  or  $\mu\text{mhos}/\text{cm}$ ).<sup>1</sup> The EC is very useful for determining water quality and is easily measured in situ with a portable conductivity meter.



**Figure 2.4 pH of groundwater in the subregion**

As EC is an indicator of the ions dissolved in water, which are about proportional to the amount of dissolved matter, the EC can also be used to estimate the total filterable residue or total dissolved solids (TDS). The TDS is obtained by multiplying the EC by an empirical factor, which ranges from 0.55 to 0.9 and depends upon the soluble components and the temperature. For drinking water, a mean value of 0.7 is suggested. The unit of TDS is milligrams total filterable residue per liter (mg/l) dried at 180°C. The EC increases with temperature at a rate of about 1.9% per degree centigrade.

The EC is not a good indicator of water quality with regard to health hazards. It is, however, an indicator of salinity, which is an important factor in taste, and taste is an important factor in user acceptance of water points. In the forest areas of the subregion,

<sup>1</sup>A list of units and conversion factors is presented in Appendix 15.

where surface water, which generally has a low TDS (and thus a low EC), is widely distributed and available more or less year round, people consider water with an EC of 300 to 500  $\mu\text{S}/\text{cm}$  "salty." In the Sahelian areas, where people are used to drinking groundwater, the threshold of "salinity" is around 1000  $\mu\text{S}/\text{cm}$ . WHO does not directly consider the EC in guidelines for drinking water quality (WHO 1984), but it does give recommendations for TDS because of taste considerations. Groundwater with TDS < 600 mg/l (EC of about 850  $\mu\text{S}/\text{cm}$ ), is considered "good," while groundwater with TDS > 1200 mg/l (EC of about 1700  $\mu\text{S}/\text{cm}$ ) becomes progressively less palatable. The WHO guideline value for TDS in drinking water is 1000 mg/l (EC of about 1400  $\mu\text{S}/\text{cm}$ ), which is close to the acceptance threshold for inhabitants of the Sahel areas of the West African subregion, but is far above the acceptance threshold for inhabitants of the forest zones.

The EC of rain water, surface water, and groundwater in the West African subregion is presented in Table 2.3. Groundwater usually shows little seasonal variation in EC.

**Table 2.3**  
**Electrical Conductivity of Rainwater, Surface Water, and Groundwater in the West African Subregion**

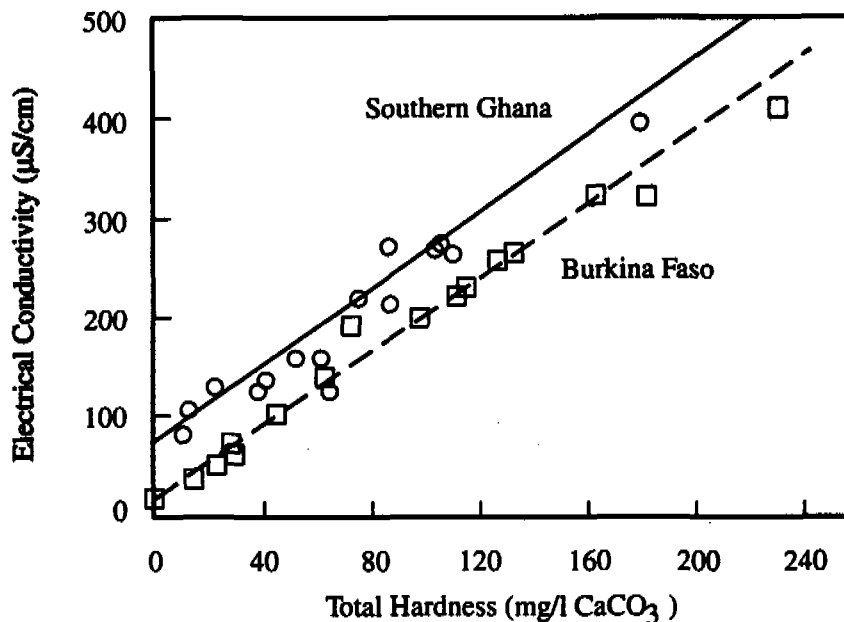
Type of water	Conductivity ( $\mu\text{S}/\text{cm}$ ) at 25°C
Rain	4 - 100
River	30 - 150
Ground	30 - 3000
Atlantic Ocean	45,000 - 55,000

The major constituents contributing to the EC are the hardness components calcium ( $\text{Ca}^{2+}$ ) and magnesium ( $\text{Mg}^{2+}$ ), but nitrate, chloride, and sulfate may also make significant contributions to the EC. The relationship between EC and total hardness (TH) of groundwater from two different areas of the subregion is shown in Figure 2.5.

The electrical conductivity data indicate that, in general, the groundwater in the subregion is of "good" quality with regard to salinity (Fig. 2.6). EC values greater than 1400  $\mu\text{S}/\text{cm}$ , which corresponds to the WHO recommended TDS guideline value of 1000 mg/l, are negligible.

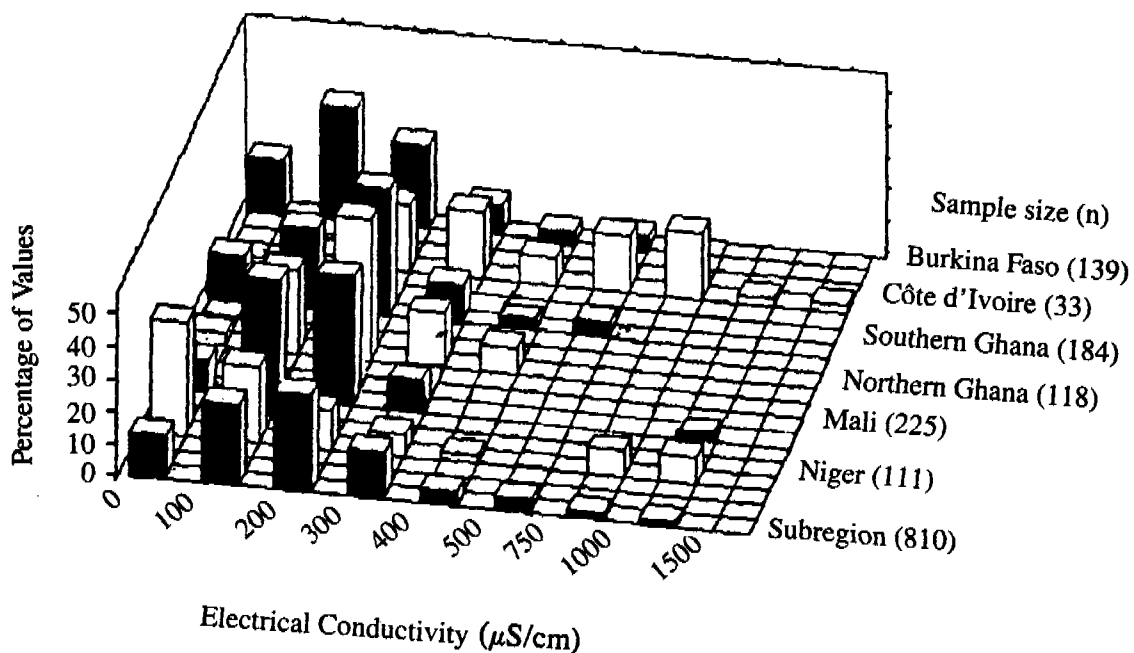
Pollution-derived constituents such as nitrate ( $\text{NO}_3^-$ ) and chloride ( $\text{Cl}^-$ ) can cause large differences in EC over relatively short distances. For example, in a village in southern Ghana (located in an area underlain by gneiss), the EC of groundwater from five dug wells that all tap the same aquifer varies from 140  $\mu\text{S}/\text{cm}$  to 760  $\mu\text{S}/\text{cm}$  over a distance of only 200 m. This situation, not unusual for village environments in the

subregion, indicates that the EC is influenced by external sources of pollution that are not related to the lithology of the aquifer. The breakdown of the EC into components provides evidence in support of this view (Table 2.4). The EC of groundwater from five drilled wells in the same village showed a similar pattern, and they had an average EC of 405  $\mu\text{S}/\text{cm}$ , the same as that from the five dug wells, indicating that both the dug and drilled wells tap the same aquifer.



**Figure 2.5** Electrical conductivity versus total hardness<sup>2</sup> of groundwater in the subregion

<sup>2</sup> "Hardness" (HD) in American usage.



**Figure 2.6 Electrical conductivity of groundwater in the subregion**

When groundwater can be obtained from dug wells, EC measurements can be used to select sites for drilled wells, locating them where the EC is lowest, since people usually prefer water with low salinity (i.e., low EC). Field experience regarding user acceptance of water points related to the EC is presented in Appendix 6.

**Table 2.4**

**Breakdown of the EC into Components: Total hardness (TH), Nitrate (NO<sub>3</sub><sup>-</sup>), Chloride (Cl<sup>-</sup>), and Other Compounds (from five dug wells that all tap the same aquifer)**

Well	Measured EC	Components of the measured EC			
		TH	NO <sub>3</sub> <sup>-</sup>	Cl <sup>-</sup>	Other
A	185	59	—	50	76
B	140	24	39	39	38
C	540	95	55	202	188
D	400	68	78	151	103
E	760	104	104	338	214

#### 2.3.4 Turbidity

Turbidity is caused by suspended materials such as mineral particles (silt, clay, corrosion products, etc.), soluble organic compounds, microorganisms (plankton, etc.), and other microscopic organisms and particles. Turbidity is thus a measure of water clarity and an indicator of its optical properties.

There are different methods for measuring turbidity, but the most frequently used is probably the nephelometric method. It involves the use of a turbidimeter and provides data in nephelometric turbidity units (NTU). Turbidity, like pH and EC, is quite easily measured in the field.

Turbidity does not have a direct effect on health, but high turbidity reduces the effectiveness of disinfection procedures because microorganisms can be protected from disinfection by suspended material. In addition, turbid water is less acceptable to consumers from an aesthetic viewpoint. The threshold at which turbidity can be detected by the naked eye is, according to WHO, above 5 NTU. The guideline value recommended by WHO is 5 NTU, but preferably less than 1 NTU when the water is to be disinfected. Typical turbidity measurements for water from different sources in the subregion are presented in Table 2.5.

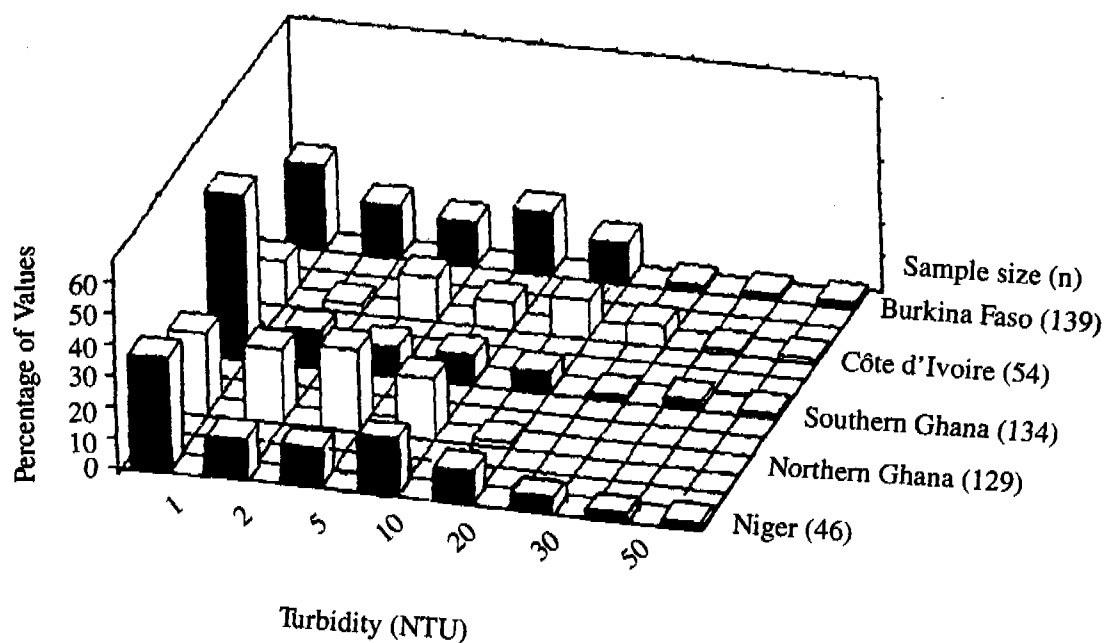
Most of the groundwater in the subregion usually has turbidity levels below 1 NTU (Fig. 2.7), but groundwater pumped from handpump-equipped wells can have higher turbidity and, thus, lower water quality, than the original groundwater because of the presence of suspended corrosion products, mud entering wells because of defective aprons or improperly installed pumps (poorly sealed base plates, etc.), and poorly designed pumps. For example, one poorly designed pump provided no communication between the atmosphere and the air in the well. During pump operation, the drawdown of the water level in the well caused low pressure in the well, which resulted in air and dirt being sucked into the well between the apron and base plate of the pump.

Typical ranges of turbidity of water from different sources is presented in Table 2.5, and the turbidity of water from handpump-equipped wells in the subregion is presented in Figure 2.7. The difference in turbidity of groundwater from handpump-equipped wells during the dry and the rainy season is shown in Figure 2.8, and the turbidity of groundwater from different types of water points is shown in Figure 2.9. Further details on turbidity are presented in Appendix 8.

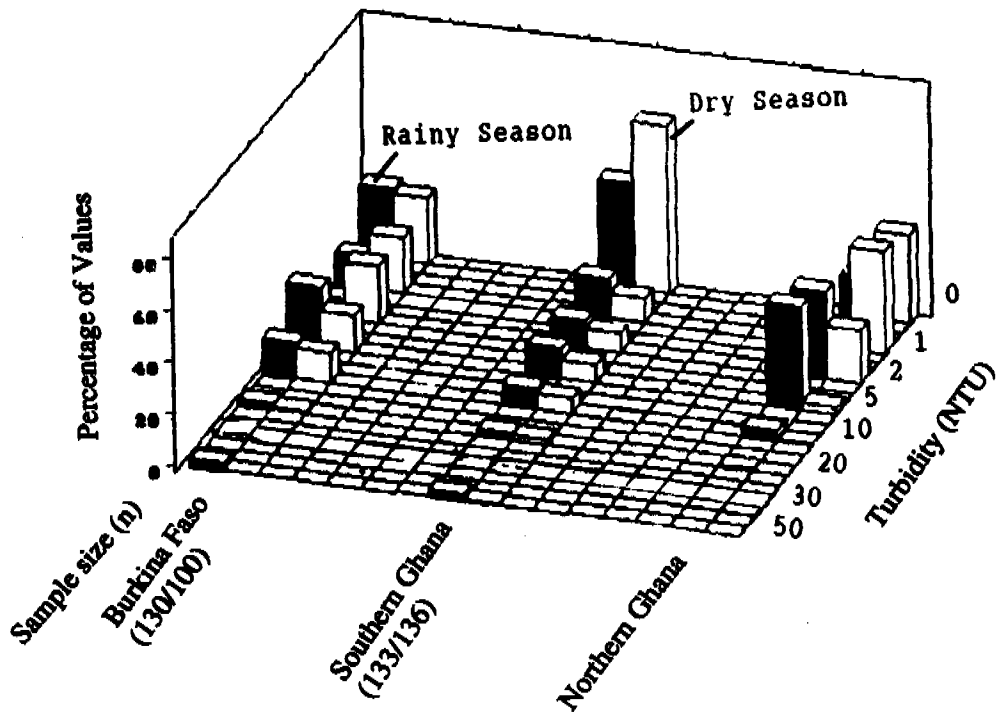


**Table 2.5**  
**Range of Turbidity (NTU) for Water of Different Origins in the Subregion**

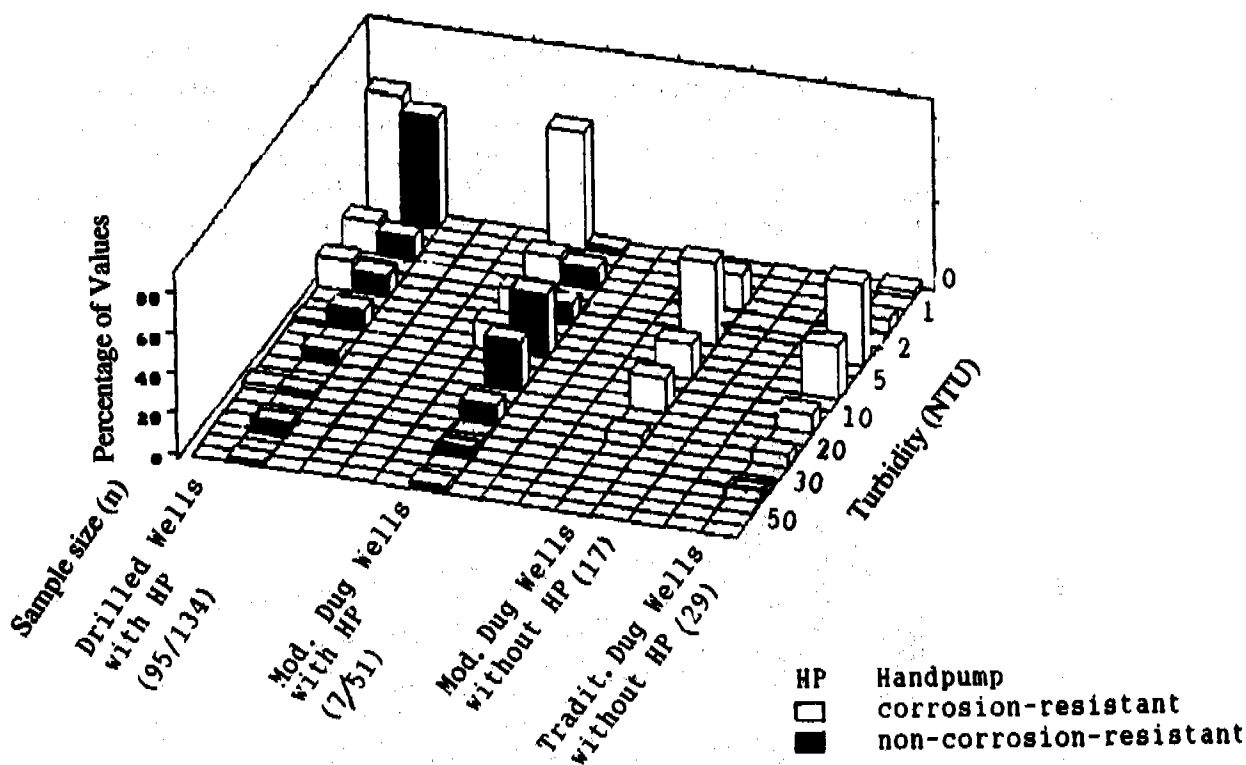
Source of water	Turbidity range (NTU)
Rain water	0.5 – 20
River water (muddy)	30 – 100
Groundwater from:	
■ Dug wells	2 – 10
■ Drilled wells with handpumps	0.2 – 1
■ Drilled wells with handpumps (affected by corrosion)	1 – 100
■ Drilled wells with handpumps (inadequate installation/design)	1 – 10



**Figure 2.7** Turbidity of groundwater from handpump-equipped wells in the subregion



**Figure 2.8** Turbidity of groundwater from handpump-equipped wells during dry and rainy seasons



**Figure 2.9 Turbidity of groundwater from different types of water points**

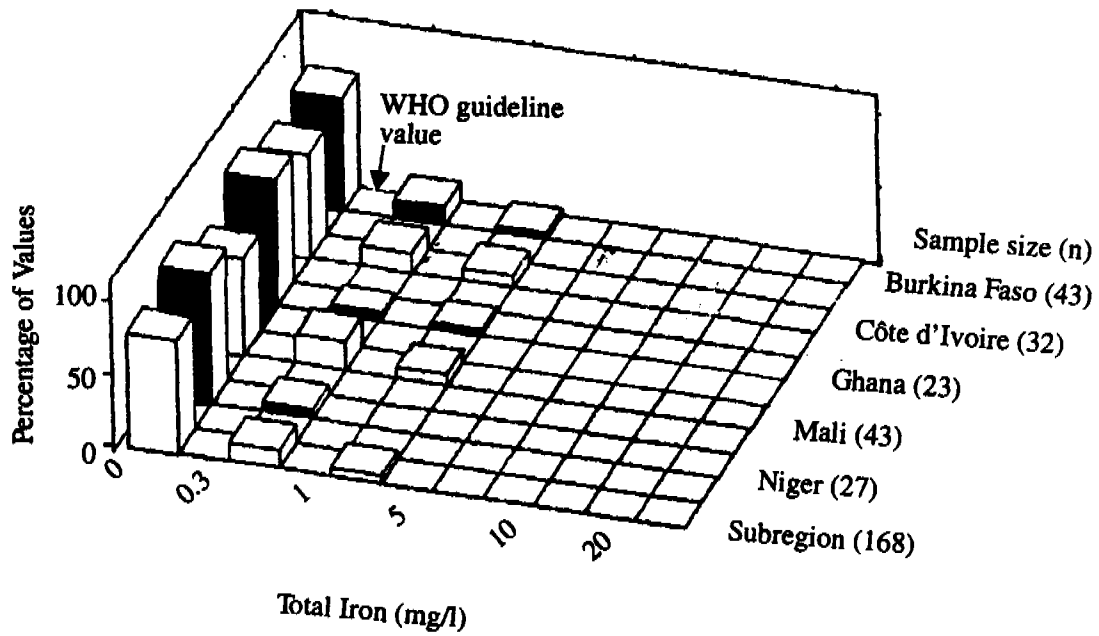
## 2.4 Chemical Parameters

### 2.4.1 Iron, Manganese

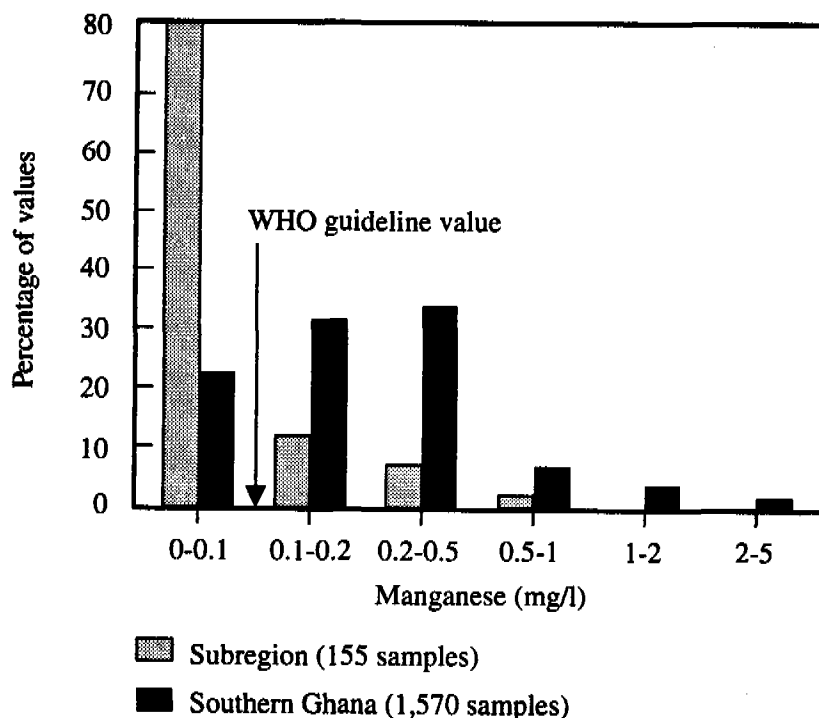
Iron (Fe) generally occurs in very low concentrations in aquifers in the West African subregion. Total iron (ferrous plus ferric) concentration in groundwater under natural conditions is usually less than 1 mg/l; manganese concentration is generally less than 0.3 mg/l. A high iron concentration is quite common, however, in pumped groundwater in the subregion because of handpump corrosion (see Section 4.4.3).

Guideline values for iron and manganese are 0.3 and 0.1 mg/l, respectively (WHO 1984), but these values are based on aesthetic and organoleptic considerations, not on health considerations. The large majority of consumer complaints about water quality all over the world are related to taste and/or odor problems and to aesthetic problems caused by turbid or discolored water and deposits (Mallevalle and Suffet 1987). This applies to rural areas in developing countries as well as to urban areas. Human beings are very sensitive to the taste, odor, and aesthetic parameters of water quality, and handpump corrosion has a very negative effect on these aspects (see Section 4.4).

Tests for iron in water must be performed immediately after sampling, that is, right on the spot, or the sample must be acidified for testing later. If this procedure is not followed, the results will be unreliable because of the rapid change from ferrous to ferric iron and further to other non-dissoluble iron compounds. Although personnel involved in water quality testing should be aware of this, often too little attention is paid to it in practice. Results of iron and manganese measurements in the subregion are presented in Figures 2.10 and 2.11.



**Figure 2.10** Total iron concentration in groundwater from wells equipped with corrosion-resistant handpumps

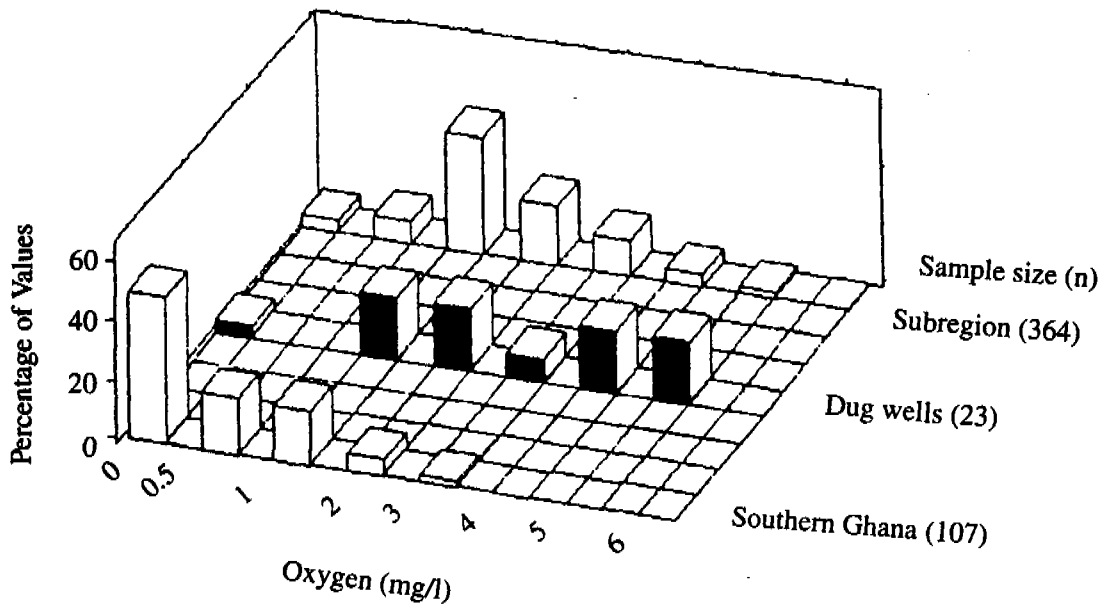


**Figure 2.11 Manganese concentration in groundwater from handpump-equipped wells in the subregion and in the 3000 Well Drilling Programme in Southern and Central Ghana**

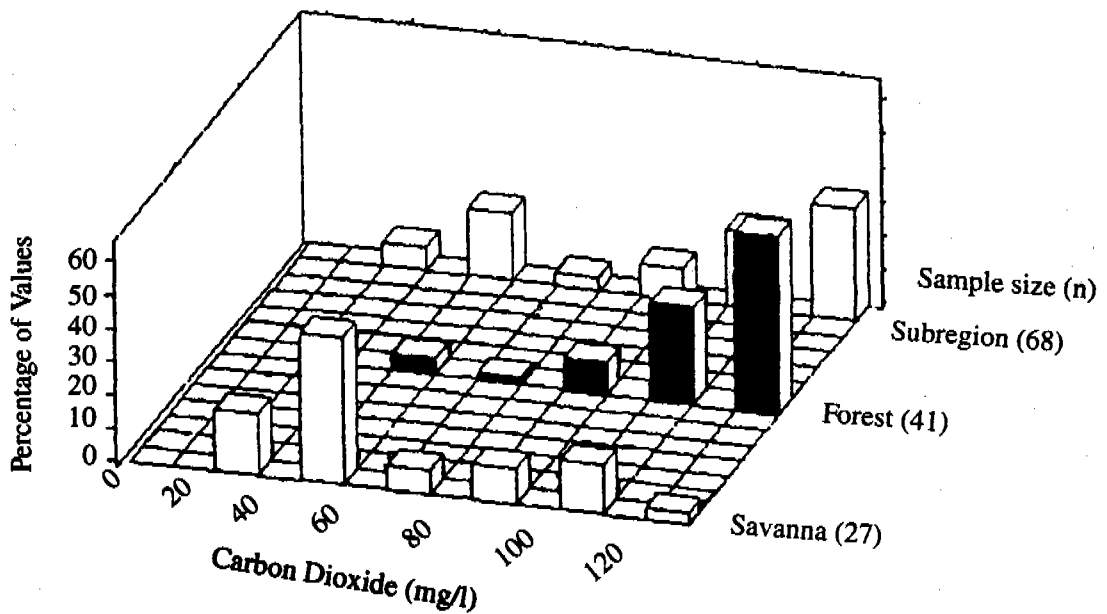
#### 2.4.2 Oxygen, Carbon Dioxide

Dissolved oxygen ( $O_2$ ) is an important factor in the chemistry and microbiology of water. The concentration of dissolved oxygen in groundwater from handpump-equipped wells in the subregion is usually between 0.7 and 4.5 mg/l in oxidizing environments (Fig. 2.12). Although oxidizing environments predominate in wells in the subregion, wells equipped with handpumps that are infrequently used or are affected by corrosion commonly have reducing environments, which are indicated by high levels of ammonium ( $NH_4^+$ ). The dissolved oxygen is also highly dependent on the temperature of the groundwater (see Fig. 2.1).

Groundwater in the savanna (north) has an average carbon dioxide ( $CO_2$ ) concentration of 70 mg/l, significantly lower than the 120 mg/l  $CO_2$  concentration in groundwater in the forest (south) (Fig. 2.13). This difference is a result of the very dissimilar environmental conditions, mainly climate and vegetation, in the two zones. There is a much larger biomass in the forest zone, and decomposition of this organic material results in the formation of  $CO_2$  (via microbiological processes) in the topsoil. This  $CO_2$ -enriched air in the interstices of the microbiologically active vadose zone is picked up by the rainwater as it percolates downward through the zone on its way to the aquifer. It has been suggested that the  $CO_2$  in the vadose zone is the major source of  $CO_2$  in the groundwater.



**Figure 2.12 Dissolved oxygen in groundwater from handpump-equipped wells in the subregion**



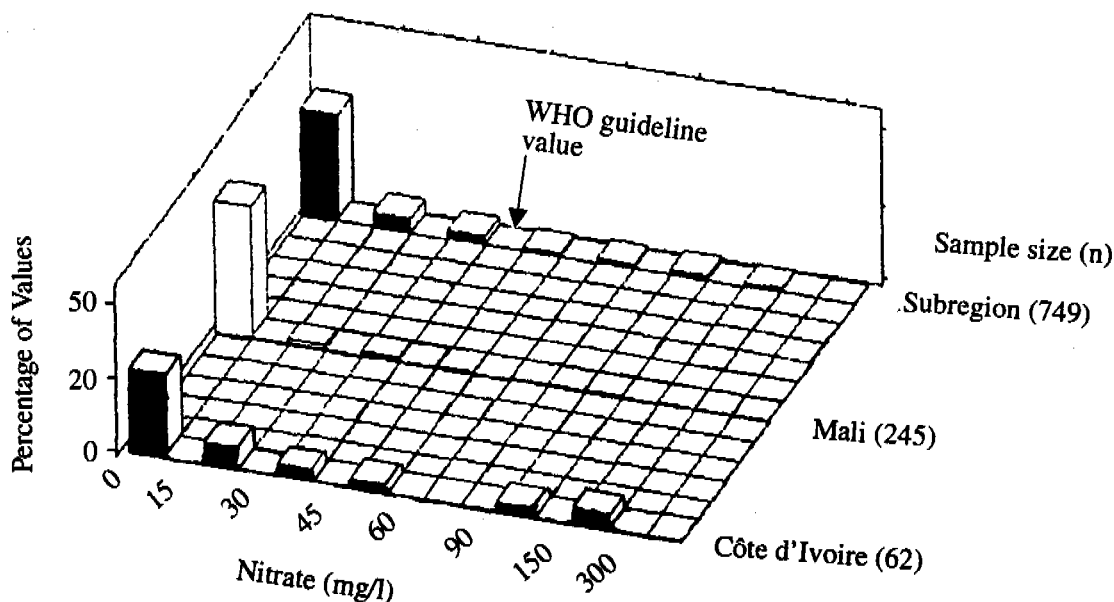
**Figure 2.13 Dissolved carbon dioxide in groundwater from handpump-equipped wells in different areas of the subregion**

### 2.4.3 Ammonium, Nitrite, Nitrate

Ammonium ( $\text{NH}_4^+$ ), nitrite ( $\text{NO}_2^-$ ), and nitrate ( $\text{NO}_3^-$ ) are classic indicators of organic pollution, but in a well equipped with a noncorrosion-resistant handpump, they may not be valid indicators of organic pollution. Nitrate is valid as a pollution indicator only under oxidizing conditions, because when there is little or no oxygen available, the nitrate is decomposed through denitrification.

Ammonium and nitrite concentrations in groundwater in the subregion are generally less than 0.1 mg/l and 0.01 mg/l, respectively. Excessively high concentrations can occur, however, in groundwater pumped from wells equipped with corrosion-affected handpumps. In reducing environments ammonium is predominant, and it reaches concentrations of 1 mg/l; under oxidizing conditions, nitrite is predominant and can reach concentrations as high as 0.5 mg/l. Thus, in a well with a corrosion-affected handpump, the presence of ammonium and nitrite is an indication of the microbiological processes of iron bacteria in connection with corrosion (see Sections 2.5 and 4.4.4), not an indication of organic pollution.

There are no WHO guideline values for ammonium and nitrite, but a WHO guideline value for nitrate was established because excessive levels of nitrate can cause methemoglobinemia in bottle-fed infants (blue babies) and because certain forms of cancer may result from very high nitrate concentrations (WHO 1984). The guideline value for nitrate is 10 mg/l nitrogen (N), which corresponds to 45 mg/l nitrate ( $\text{NO}_3^-$ ). About 15% of the tested wells in the subregion have nitrate levels higher than the 45 mg/l WHO guideline value (Fig. 2.14). The maximum nitrate concentration measured in the Handpumps Project in the West African subregion was 500 mg/l.



**Figure 2.14 Nitrate ( $\text{NO}_3^-$ ) in groundwater from handpump-equipped wells in the subregion**

Average nitrate concentration in groundwater in the subregion varies a great deal. In the Helvetas Project in Southern Mali, less than 5% of the 245 tested wells exceeded the WHO guideline value; in the field trial of the Handpumps Project in the Côte d'Ivoire, 25% of the monitored wells exceeded the guideline value; and in one area of the Niger field trial, 40% of the monitored wells exceeded the guideline value. For further details on nitrate in groundwater and an example of groundwater pollution in rural areas, see Appendix 8.

#### 2.4.4 Other Chemical Constituents

Additional components that have been included in the water quality investigations within the Handpumps Project in the West African subregion are total hardness, calcium, magnesium, alkalinity, potassium, sodium, sulfate, chloride, fluoride, and silica.

##### Total Hardness, Calcium, Magnesium

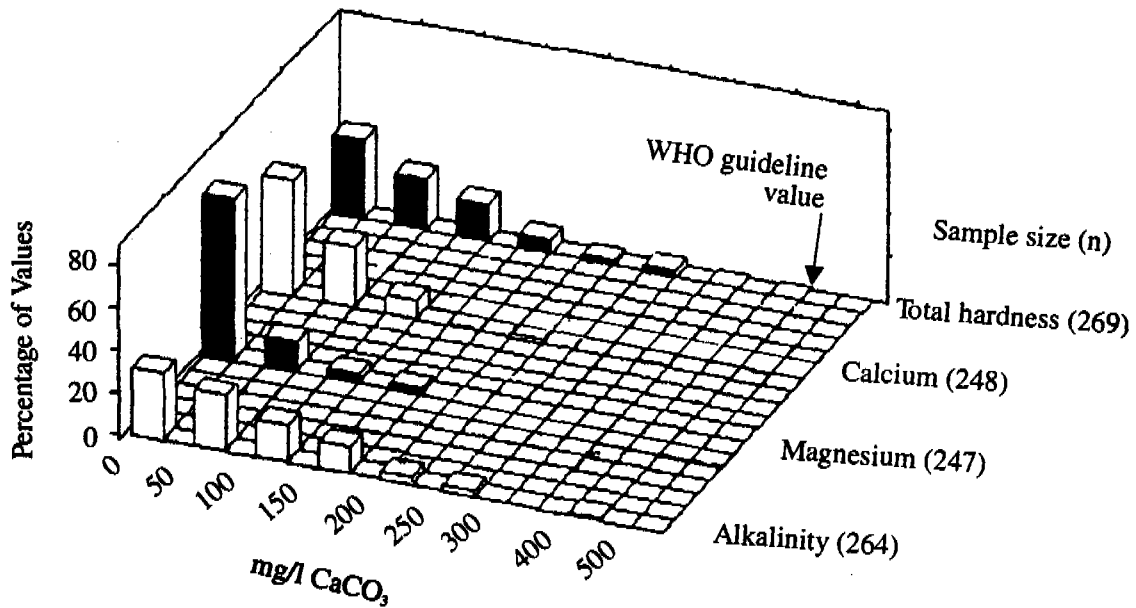
Total hardness (TH) is defined as the concentration of calcium and magnesium, and is expressed in mg CaCO<sub>3</sub> per liter. The WHO guideline value for total hardness is 500 mg/l (CaCO<sub>3</sub>). This is not based on health considerations, but on "taste and household-use considerations" (WHO 1984). No guideline values have been suggested by WHO for the individual components, calcium and magnesium.

In the Handpumps Project area in the West African subregion, the distribution of total hardness, based on the classification system in Table 2.6, is: soft and moderately hard (81.8%), hard (14.5%), and very hard (3.7%). Total hardness, calcium, magnesium, and alkalinity of groundwater from handpump-equipped wells in the subregion are shown in Figure 2.15. The cumulative frequency for values of total hardness of groundwater in the Handpumps Project, the 3000 Well Drilling Programme, and the Helvetas Project is shown in Figure 2.16 (for example, 70% of the samples showed a TH of 100 or less; about 85% of the samples in the 3000 Well Drilling Programme in Southern and Central Ghana [indicated by the square symbol] showed a TH less than 150).

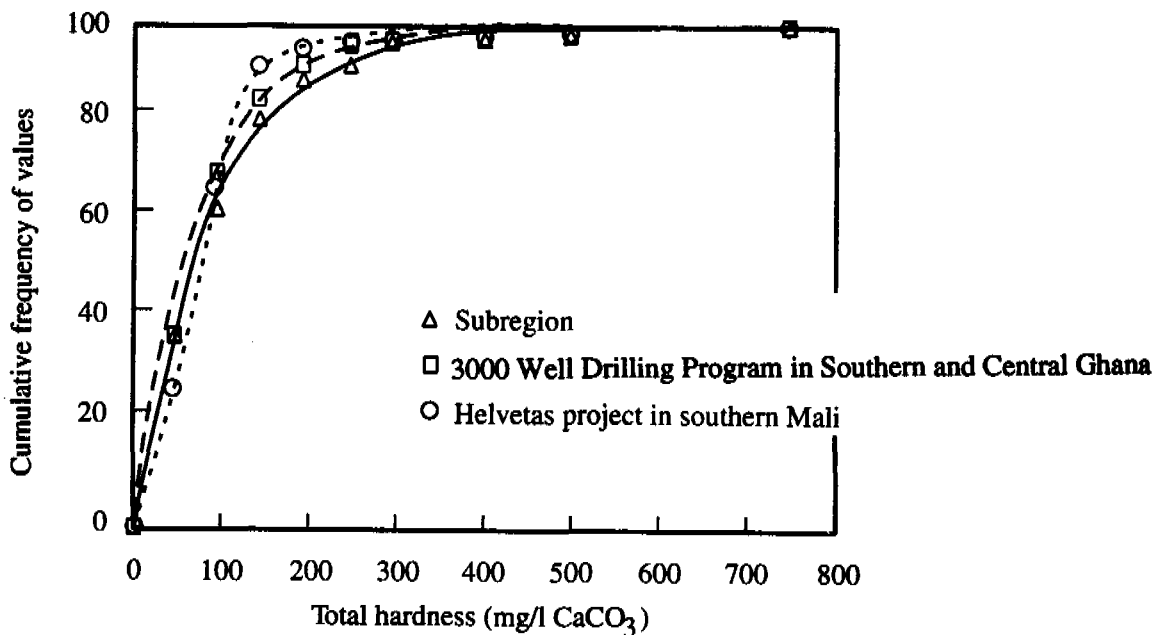
**Table 2.6**  
**Hardness Classification of Water (Sawyer and McCarty 1967)**

Hardness (mg/l CaCO <sub>3</sub> )	Water classification
0 - 75	soft
75 - 150	moderately hard
150 - 300	hard
> 300	very hard





**Figure 2.15 Total hardness, calcium, magnesium, and alkalinity of groundwater from handpump-equipped wells in the subregion**



**Figure 2.16 Cumulative frequency for total hardness of groundwater from handpump-equipped wells in the Handpumps Project, the 3000 Well Drilling Programme, and the Helvetas Project**

## Alkalinity

The alkalinity of water is defined as its capacity to neutralize acids. The main ions that contribute to the alkalinity of natural waters are hydroxide ( $\text{OH}^-$ ; hydroxide alkalinity), carbonate ( $\text{CO}_3^{2-}$ ; carbonate alkalinity), and bicarbonate ( $\text{HCO}_3^-$ ; bicarbonate alkalinity). For this report only bicarbonate alkalinity was measured, and therefore, the alkalinity corresponds to the so-called carbonate-hardness, which is equivalent to the sum of carbonate and bicarbonate alkalinity. The alkalinity, or carbonate-hardness, is usually higher than the total hardness. (The small difference can be seen in Fig. 2.16.)

## Sodium. Sulfate. Chloride. Fluoride

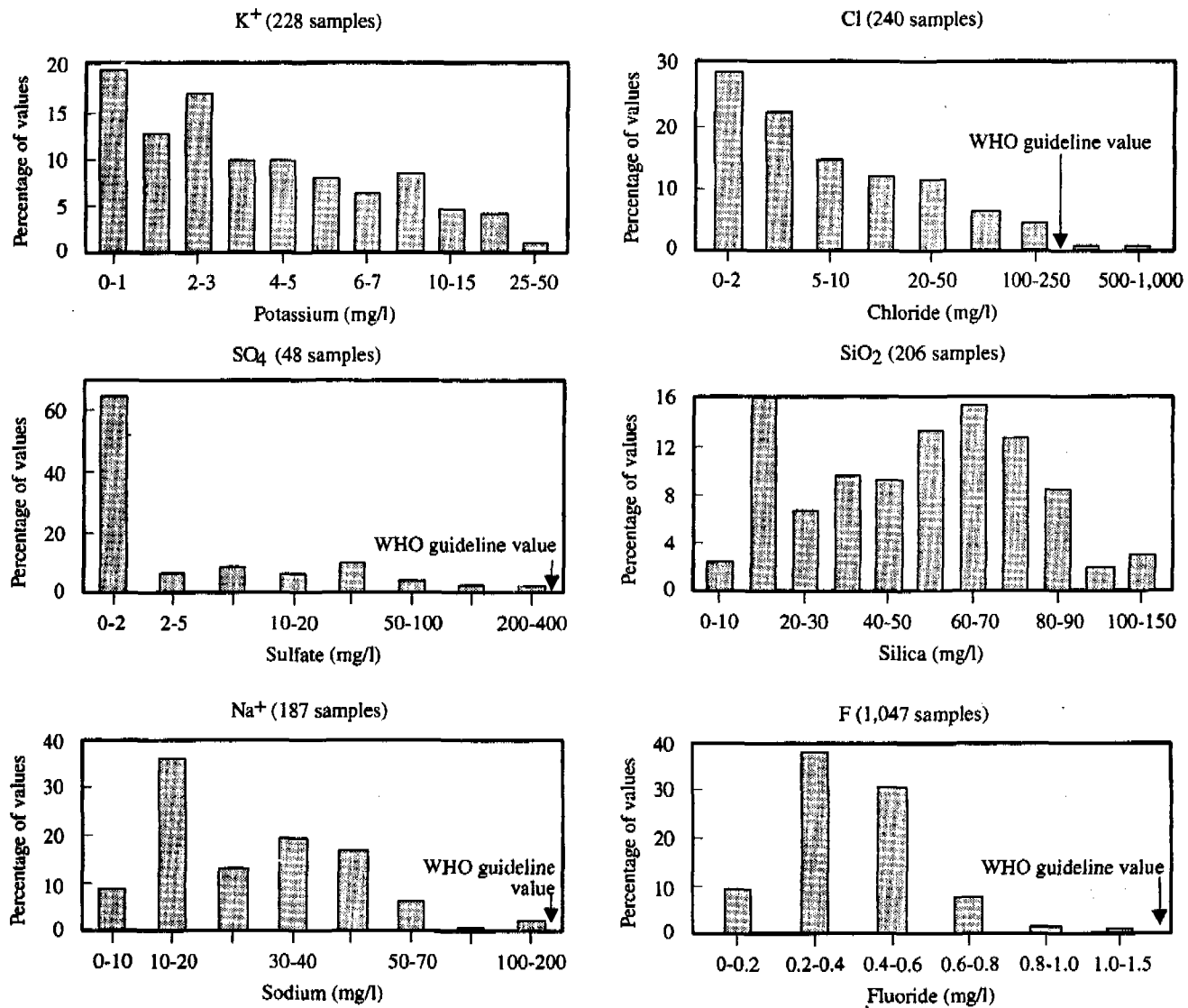
The WHO guideline values for sodium, sulfate, and chloride are based on taste considerations, while the value for fluoride is based on health hazards such as mottling of teeth at fluoride levels above 1.5 mg/l, and skeletal fluorosis at levels above 3 mg/l (WHO 1984).

Constituent	Guideline value
Sodium	200 mg/l
Sulfate	400 mg/l
Chloride	250 mg/l
Fluoride	1.5 mg/l

In the subregion, the WHO guideline values were exceeded only by chloride, and that was only in one of 240 samples (Fig. 2.17). Chloride, sulfate, and potassium can also be useful pollution indicators (see Appendix 8).

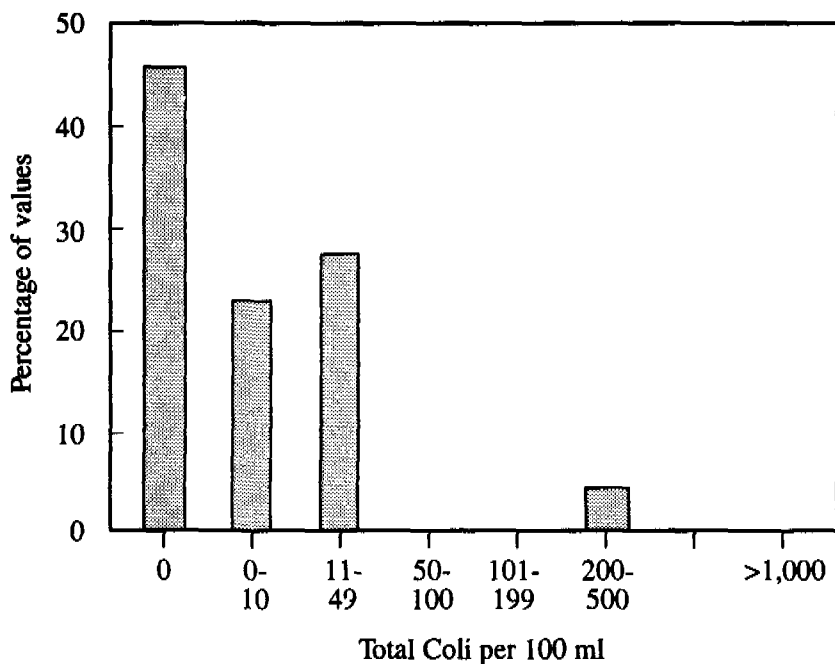
## 2.5 Bacteriology

The bacteriological tests carried out within the Handpumps Project in West Africa were limited to total coliform tests using the Millipore membrane filtration (MF) method. These results cannot be directly compared with the WHO guideline values because the WHO recommendation is based on the number of fecal coliforms as well as on the total coliform count. In addition to the guideline values for unpiped water supplies (0 fecal coliforms per 100 ml and 10 coliform organisms per 100 ml), WHO recommends that coliform organisms should not occur repeatedly. Although the data used in this report were obtained from single samples taken at random, they are nevertheless useful indicators of the bacteriological water quality of handpump-equipped boreholes.



**Figure 2.17 Potassium, sulfate, sodium, chloride, and silica in groundwater from handpump-equipped wells in the subregion, and fluoride concentration from wells in the 3000 Well Drilling Programme in Southern and Central Ghana**

(64 samples)



**Figure 2.18 Total coli counts in the Handpumps Project areas**

Samples from about 50% of the wells tested were positive for total coliform bacteria (i.e., one or more coliform organisms per 100 ml); about 30% contained more than 10 coliform organisms per 100 ml, which exceeds the WHO guideline value for unpiped water supplies. The frequency of values for total coliform counts is shown in Figure 2.18.

The data obtained for this report, although it was not based on the same classification system as WHO (i.e., it does not include specific information on the presence of *fecal* coliforms), still provide a general idea of the bacteriological water quality from different types of wells used in the subregion. The highly variable total coliform counts from area to area within the subregion can be attributed to factors such as well location, well environment, well construction, well condition, type and condition of handpumps, and hydrogeological conditions.

Conclusions regarding bacteriological water quality are: (1) drilled wells equipped with handpumps offer the highest degree of good water quality, but they, too, are vulnerable to bacteriological pollution; (2) water from improved and protected open wells can reach an acceptable standard of bacteriological water quality; and (3) the bacteriological quality of water during the dry season is usually better than during the rainy season.

Important findings from the two large-scale investigations of bacteriological groundwater quality, in the Côte d'Ivoire (Table 2.7) and in Burkina Faso (Table 2.8), are

the quantitative indications of the degree of groundwater pollution that occurs between the water source (well with handpump) and the consumer (house) (Table 2.9).

**Table 2.7**  
**Fecal Coliform Analyses of Water Samples from Handpump-Equipped Wells in the Côte d'Ivoire (Babut 1984)**

Water quality (number of fecal coliforms/100 ml)	Number of water samples (wells)	Percentage (%)
Potable (0)	491	27
Doubtful (0-5)	72	9
Pollution (>5)	293	34
Total	856	100

**Table 2.8**  
**Fecal Coliform Analyses of Water from Different Types of Water Points in Burkina Faso (De Lorenzi and Volta 1987)**

Type of water point	Number of water samples	Number of polluted water points (percent of total) <sup>b</sup>	Mean pollution (fecal coliforms per 100 ml)
Drilled wells with handpumps	688	53 (7.7%)	4.2 ± 0.27
Concrete-lined large- diameter dug wells (modern water points) <sup>a</sup>	250	34 (13.5%)	9.2 ± 1.24
Traditional dug wells without lining	44	29 (66%)	300

<sup>a</sup> Includes some covered wells with handpumps

<sup>b</sup> A water point is considered polluted if one or more fecal coliforms are detected

**Table 2.9**  
**Water Pollution That Occurs Between Unpolluted Water Point (Well with Handpump)**  
**and Consumer (De Lorenzi and Volta 1987)**

Stage	Pollution rate (%)	Pollution rate (fecal coliforms/100 ml)
Well with handpump	0	0
Transport	37.9	96.3
Storage	62	206.9
Consumption	100	348.7

The data in Table 2.9 indicate that water from an unpolluted water point (well with handpump) can become so polluted from inappropriate transport and storage methods that by the time it reaches the consumer there is no difference between it and water from traditional wells. Thus, the provision of water points that provide good quality water will not have the expected benefits to the health of the users if basic principles of hygiene are not observed. Therefore, water supply and sanitation projects must include hygiene education to achieve the objectives of water and sanitation projects.



### **3. Basics of Corrosion**

#### **3.1 Introduction**

Corrosion is the attack of the surface of materials by chemical processes. In this report the main focus is on the undesired corrosion of ferrous materials such as mild steel and galvanized iron, although corrosion also affects concrete, glass, plastic, and other materials.

Corrosion of ferrous materials has been a problem for centuries. It is estimated that in the United States the total annual cost of corrosion in 1975 alone was on the order of US\$70 billion (AWWA 1987), and that corrosion-caused losses to water distribution systems in 1978 amounted to US\$380 million (Prevost 1987).

Most metals occur in nature in the form of oxides (e.g., iron ore), which must be reduced to obtain the usable metals. Corrosion is simply the oxidation of metals, the process by which they return to their natural state, which from the energy viewpoint is the most stable configuration.

There are three types of corrosion (in this report primary emphasis will be placed on electrochemical corrosion): chemical, electrochemical, and physico-chemical. All three are oxidation-reduction (redox) processes.

- (i) Chemical corrosion occurs where any material (e.g., a metal) is in contact with oxidizing constituents (e.g., oxygen, hydrogen, carbon dioxide).
- (ii) Electrochemical corrosion, which is the most common, is based on electrochemical processes that occur in galvanic elements consisting of an anode (metal A), a cathode (metal B), and an electrolyte (conductive fluid). The classic example of electrochemical corrosion is bimetallic or galvanic corrosion, where two different metals (A,B) are electrically connected and in contact with an electrolyte.

Microgalvanic elements are always present on metal surfaces because the structure of metal surfaces is never entirely uniform (due to imperfections, impurities, and heterogeneous crystal structures). These microgalvanic elements are evenly distributed over the surface area and result in corrosion that is uniform across the metal surface.

- (iii) Physico-chemical corrosion is caused by a combination of physical and chemical effects (e.g., absorption of hydrogen by or diffusion of organic solvents through the surface of the attacked material).

The driving force for all corrosion processes is the tendency to approach the most stable energy state. When a metal electrode is in contact with an electrolyte, a half-potential develops at the interface between the metal and the electrolyte because the positive



metal ions dissolve and leave electrons behind on the metal surface. The strength of the potential developed depends on the properties of both the metal and the electrolyte. The galvanic series of metals are classified according to this potential, with the hydrogen electrode as the standard reference.

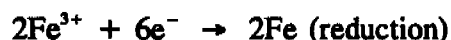
Corrosion can also be greatly influenced by biological processes, especially the microbiological activity of iron bacteria. These processes are particularly important in tropical areas where the groundwater temperature (around 30°C) favors microbiological activity and chemical reactions.

Corrosion is a complex phenomenon that has been studied for decades. The following statement indicates the state of the research today: ". . . it is evident that the complex phenomenon of corrosion is governed by such a variety of chemical, physical, biological, and metallurgical factors that a universal approach and solution is not possible. Equally evident is the well-recognized fact that no universal index exists for predicting corrosion in all types of water systems and for all water quality conditions" (AWWA-DVGW 1985).

### 3.2 Chemistry of Corrosion

As stated above, corrosion is a redox process in which one part is oxidized (electron donor) and the other part is reduced (electron acceptor). Some examples of such processes are given below.

#### Example 1: Redox process



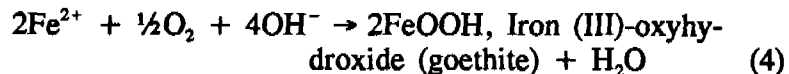
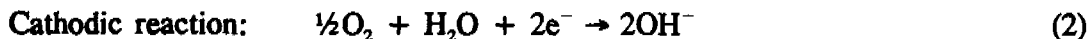
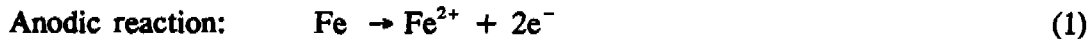
The iron oxide ( $\text{Fe}_2\text{O}_3$ ) is reduced to iron (Fe); aluminum (Al) is oxidized to aluminum oxide ( $\text{Al}_2\text{O}_3$ ). Thus, Al acts as the reductant and  $\text{Fe}_2\text{O}_3$  as the oxidant.

#### Example 2: Chemical corrosion



The above equation represents what occurs naturally on steel exposed to water vapor in the atmosphere. In this case, the corrosion process forms a protective layer of magnetite ( $\text{Fe}_3\text{O}_4$ ) on the surface. The formation of protective oxide layers at room temperature on the surfaces of aluminum, chromium, copper, and other metals is also a form of chemical corrosion.

**Example 3: Electrochemical corrosion (galvanic element)**

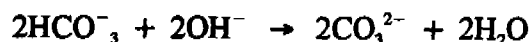


Only the very basic chemical equations of the corrosion process are shown in Example 3. These equations represent (1) the anodic reaction (dissolution of the metal ions), (2) the most important cathodic reaction (reduction of oxygen), and (3,4) two secondary reactions (formation of metal hydroxides or, in the case of iron, rust). Many other reactions are possible in connection with corrosion; their occurrence depends upon the type of metal, water quality, temperature, and other conditions.

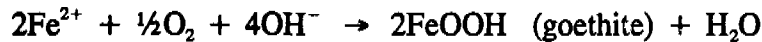
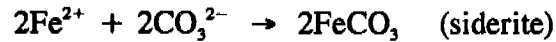
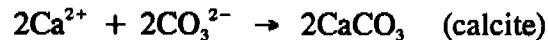
Another important cathodic reaction is the reduction of the hydrogen ion ( $\text{H}^+$ ) to hydrogen ( $\text{H}_2$ ). Where this reaction is dominant the term "hydrogen corrosion" is used; reduction of oxygen is called "oxygen corrosion."

The reactions of the so-called Siderite Model are presented below. This model is based on the assumption that the iron carbonate, siderite ( $\text{FeCO}_3$ ), plays an important role in the formation of protective scales on iron pipes. The suggested reactions are (AWWA-DVGW 1985):

**Primary reactions:**



### Secondary reactions:



### Tertiary reactions:



## 3.3 Forms of Corrosion

There are many different forms of corrosion. In the following, the most common forms of electrochemical corrosion are briefly described (Fig. 3.1). It should be emphasized again that all the forms of corrosion discussed in detail in this report are based on the corrosion cell, which corresponds to a galvanic element comprising an anode, a cathode, an electrical connection between the anode and the cathode, and an electrolyte.

### 3.3.1 Uniform Corrosion

Uniform corrosion is also called general, surface, or overall corrosion. It is characterized by a relatively even attack on the metal surface. This uniform corrosion of a single metal surface may be caused by the continuous shifting of microgalvanic cells over the metal surface.

Examples of uniform corrosion are the attack on metals by gases and vapors at high temperatures, and by acids and bases. Uniform corrosion commonly occurs on rising mains of handpumps, often combined with pitting (see Section 3.3.2).

### 3.3.2 Pitting or Local Attack

Pitting is the local concentration of corrosion, either in very little spots or over relatively large areas. It occurs in water distribution systems where anodic areas are stationary, and it can be caused by imperfections of materials, high oxygen or chloride concentrations, stray currents, damaged protective surface layers, and so on.

Pitting can develop rapidly, particularly where the anodes are small and, in the case of pipes, can result in perforation. Therefore, the rate of pitting and, thus, its depth of penetration, is more important than the size and number of local pits.

### 3.3.3 Galvanic or Bimetallic Corrosion

Galvanic corrosion occurs where two dissimilar metals are electrically connected and in contact with an electrolyte; for example, a galvanized iron pump rod with a brass pump cylinder. This combination corresponds to the classic galvanic element.

Galvanic corrosion can be uniform or local depending upon the structure of the metals, their geometry, and the electrolyte. The corrosion rate of galvanic corrosion is usually much higher than that of normal electrochemical corrosion. The rate depends upon the electrical conductivity of the electrolyte and the electrical potential between the two metals.

### 3.3.4 Crevice and Concentration Cell Corrosion

Crevice corrosion occurs in small spaces. An important phenomenon in connection with crevice corrosion is the so-called "concentration cell corrosion," which occurs when different concentrations of dissolved oxygen or hydrogen exist on the metal surface. The site with the higher concentration of oxygen or hydrogen becomes cathodic, the site with the lower concentration becomes anodic. Low oxygen or hydrogen concentration cells (anodes) develop easily in crevices and under rivets and bolts, for example, resulting in corrosion.

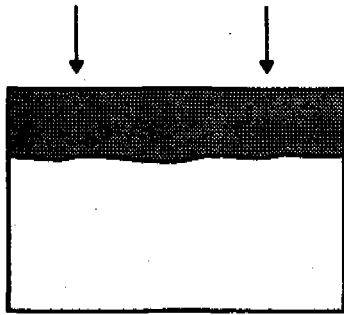
### 3.3.5 Intergranular or Intercrystalline Corrosion

Intercrystalline corrosion occurs only at the interfaces of crystals, and is observed in stainless steel.

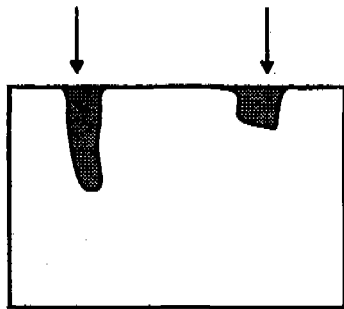
### 3.3.6 Stress-Corrosion Cracking

Stress-corrosion cracking can develop in any metal under tensile stress (static or dynamic) in a corrosive environment. The interactions of tensile stress, metallurgical characteristics, and a corrosive environment can lead to two types of cracking: intercrystalline (along the interfaces of the crystals) and transcrystalline (through the crystals).

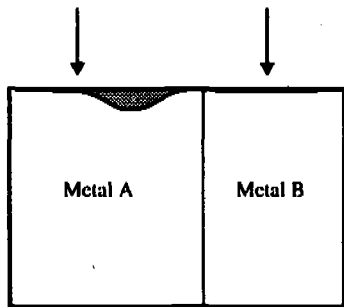
Stress-corrosion cracking may affect pump rods, particularly those under high tensile stress in deep pump installations. Stress-corrosion cracking characteristically results in shapeless cracking, which is typical of rod breakages.



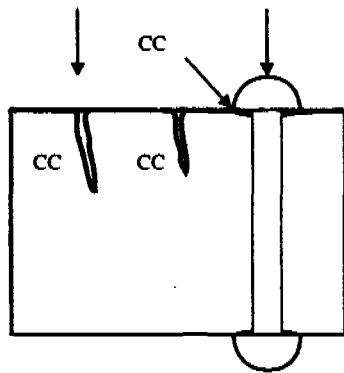
Uniform corrosion



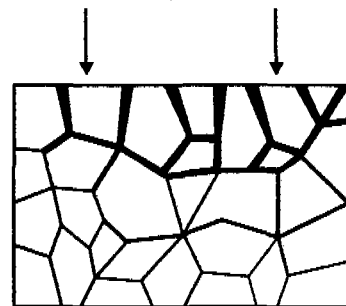
Pitting



Galvanic corrosion



Crevice (C) and concentration cell corrosion (CC)



Intergranular (crystalline) corrosion

**Figure 3.1 Different forms of corrosion**

### 3.4 Methods of Predicting and Measuring Corrosion

The corrosiveness of water can be predicted with corrosion indexes, which are based on chemical parameters of water quality. Although a variety of useful corrosion indexes have been developed during the past 100 years, there is no single corrosion index that can be applied for all water conditions. Results obtained using some of the most common corrosion indexes on groundwater from West Africa are presented in Chapter 6.

While predicting corrosion with corrosion indexes is useful, the complexity of the corrosion processes makes it imperative that corrosion be tested and monitored in-situ with corrosion test samples (e.g., coupons and pipe inserts) exposed to field conditions (e.g., in water distribution systems or in aquifer-well-handpump systems). Standard test methods have been developed (e.g., by ASTM, DIN, etc.) for testing and monitoring corrosion with test samples, but these methods often require relatively long periods of time (weeks or even months); while measurements of iron uptake and estimates of corrosion rate can be obtained much more quickly with electronic equipment (electrical resistance measurement, linear polarization method, galvanic current method, etc.).



## **4. Field Observations of Corrosion**

### **4.1 General Observations**

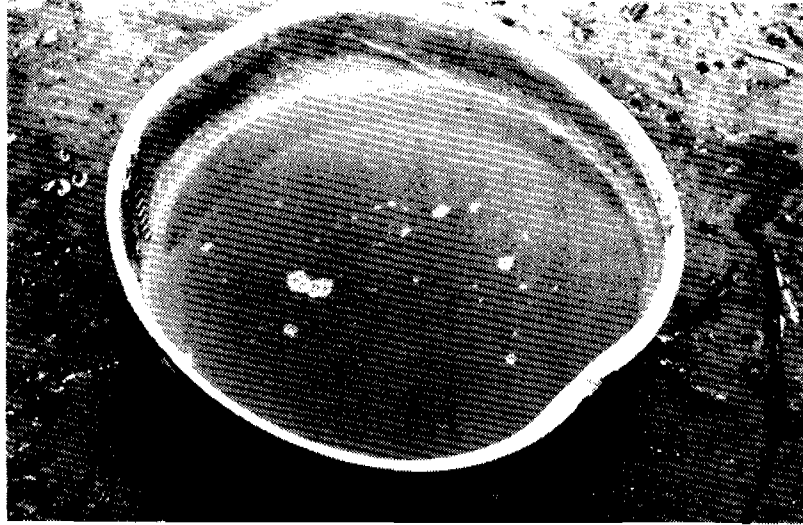
Pipes in water distribution systems and pipes in handpumps are subjected to quite different conditions, not only with respect to operation and water quality, but also with respect to the surfaces exposed to corrosion. In the water industry, the main concern regarding small-diameter galvanized pipes is internal corrosion; in handpumps, it is not only internal corrosion that is of concern, but also, for those parts of the rising mains that are immersed in water, external corrosion.

The following figures include some typical examples of corrosion and its effects on water quality in connection with handpumps.



**Figure 4.1 Well pad and pump stand of an India Mark II pump colored red-brown by corrosion products (southern Ghana)**

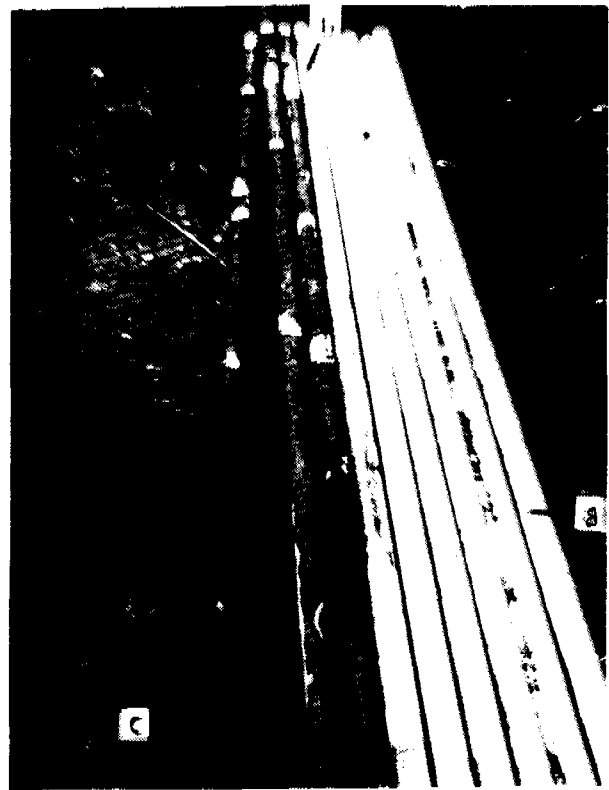




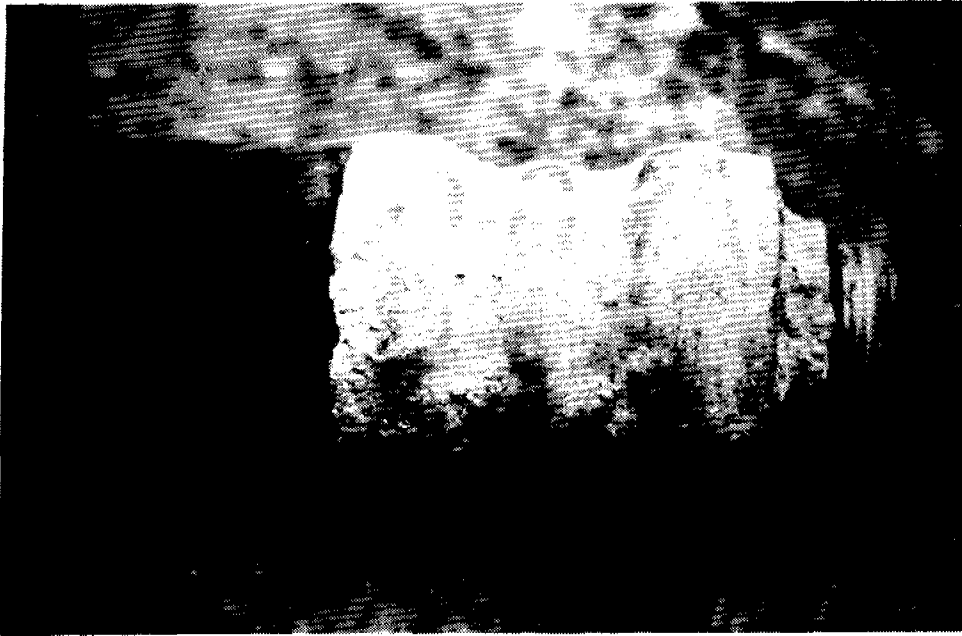
**Figure 4.2** Discolored (red) water from a handpump affected by corrosion

Three different zones can be distinguished:

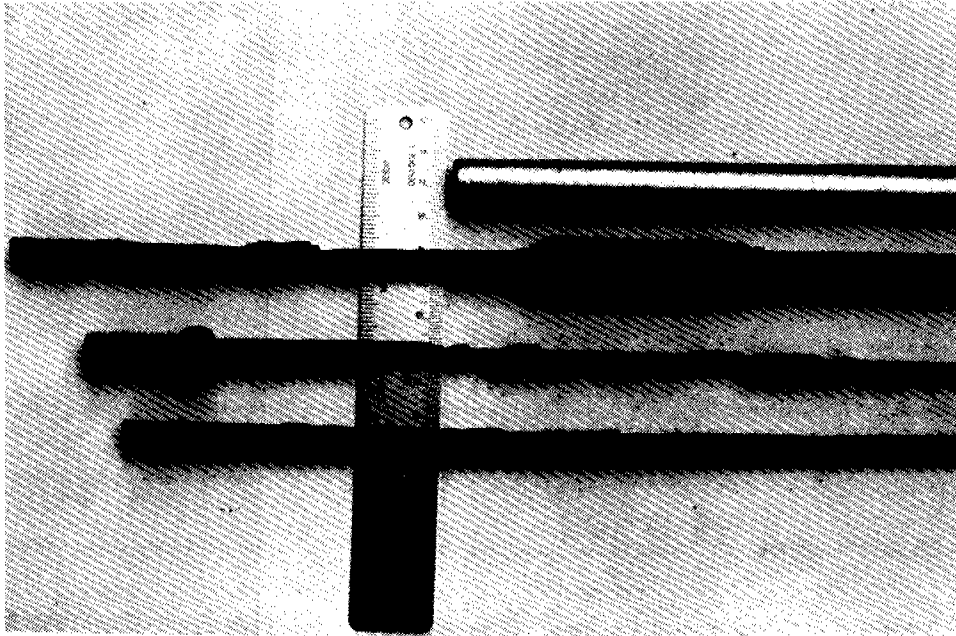
- (a) *No corrosion*: part of pipe above water level,
- (b) *Slight corrosion*: part occasionally immersed in water,
- (c) *Heavy corrosion*: part always immersed in water (covered by red-brown biofilm).



**Figure 4.3** Typical corrosion pattern of the external surface of galvanized rising mains in handpumps exposed to corrosive groundwater



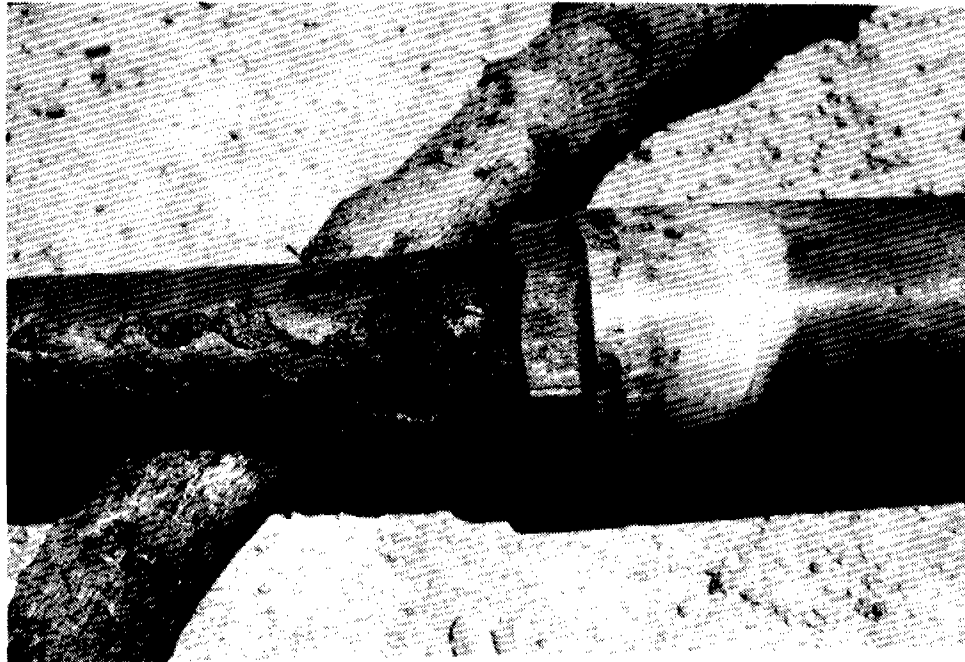
**Figure 4.4 Corroded metal cap of aluminum-alloy pumping element (diaphragm)**



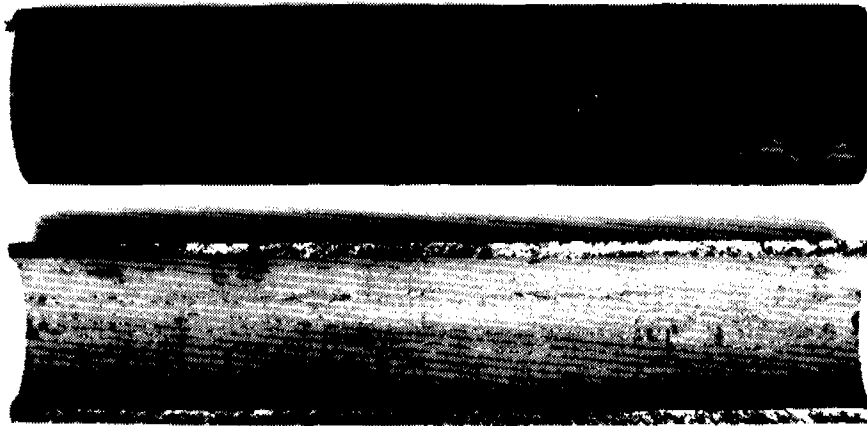
**Figure 4.5 Heavily corroded pump rods**



**Figure 4.6 Perforated rising main**



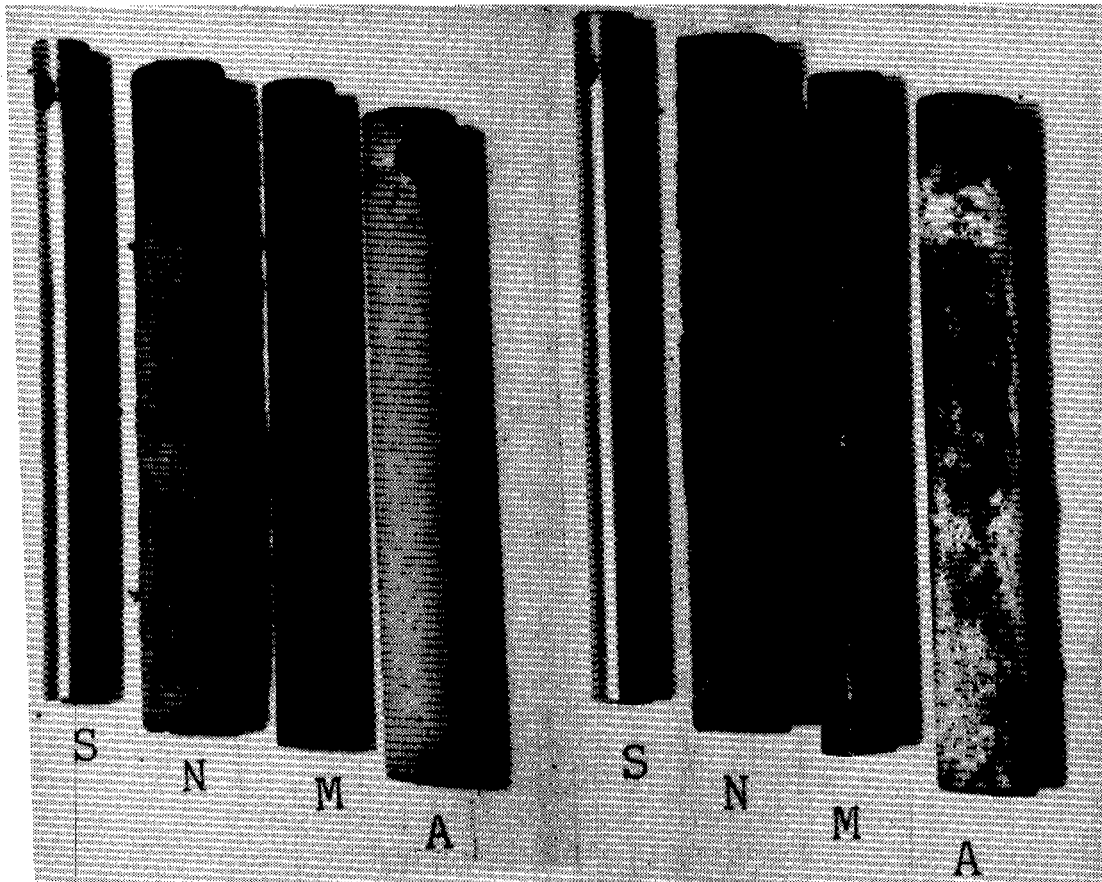
**Figure 4.7 Zinc removed from brass due to bimetallic corrosion between the galvanized pipe and the brass cylinder**



**Figure 4.8** Internal and external surfaces of galvanized pipe that were exposed to aggressive water. The external surface is more heavily corroded than the internal one.



**Figure 4.9** Fungus on the galvanized pipe of a handpump



S = stainless steel  
N = iron

M = electroplated iron  
A = galvanized iron

**Figure 4.10 Different types of surface layers (biofilms) on corroded mild steel test samples (Divo field trial, Côte d'Ivoire)**

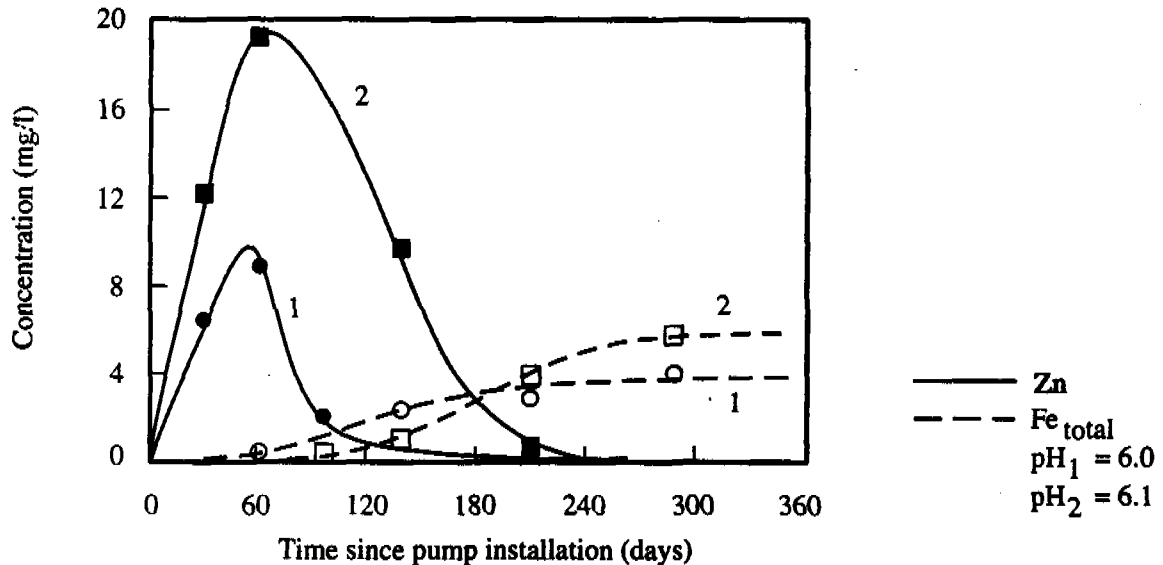
#### 4.2 Behavior of Galvanized Iron Exposed to Aggressive Groundwater

The purpose of galvanization of iron is to protect it from corrosion. Experience from the water industry indicates that the *quality* of the galvanization is very important with regard to corrosion resistance. This has led to the development of specifications for the galvanization of pipes. The standard for galvanized coating on rising mains and pump rods is a layer of zinc 60-70  $\mu\text{m}$  thick (DIN; ASTM).

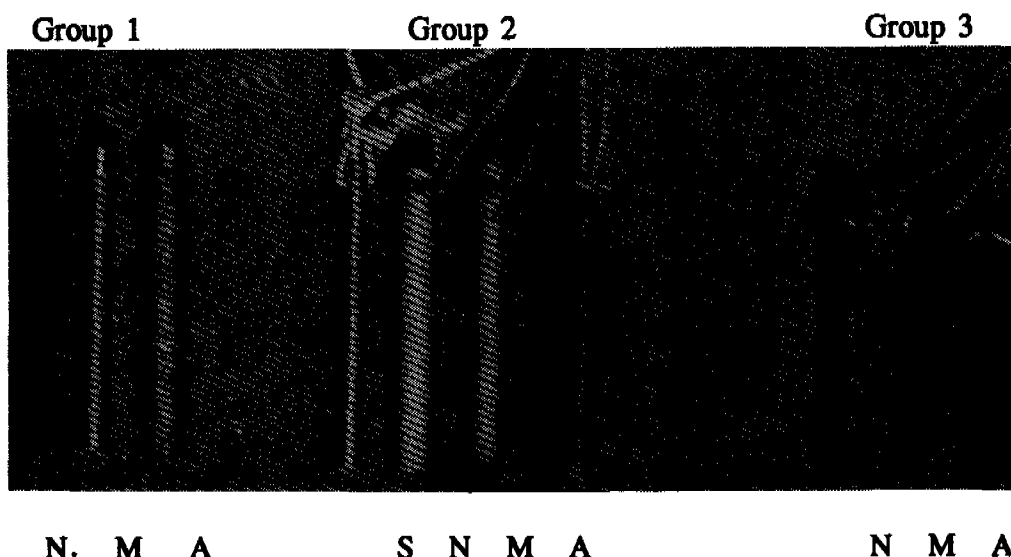
Field observations indicate, however, that under moderately to highly corrosive groundwater conditions ( $\text{pH} < 6.5$ ), the quality of galvanization does not have a significant impact on the resistance of handpumps and rising mains to corrosion. As shown in Figure 4.11, the galvanization of rising mains exposed to groundwater with a  $\text{pH} \approx 6$  was eaten away within approximately three to six months. In this example from the Côte d'Ivoire, however, the galvanized pipes met the ASTM specifications.

In Figure 4.11, it is also evident that iron begins to appear in the pumped water when the zinc concentration decreases, that is, the iron appears in the water as soon as the iron surfaces of the rising mains are exposed to the aggressive groundwater because the protective galvanization has been removed.

Figure 4.12 is a photograph of pump rod samples with different surface treatments, for example, no coating (mild steel), galvanized, and electroplated surfaces, that have been exposed to different corrosive conditions. The various colors of the surface, ranging from gray (galvanization) to bronze (zinc-iron interface) to silvery (iron), indicate the varying extent of corrosion.



**Figure 4.11** Zinc (Zn) and total iron ( $\text{Fe}_{\text{total}}$ ) concentrations in groundwater versus time since installation of two non-corrosion-resistant handpumps (Moyno with galvanized rising mains and pump rods; Cote d'Ivoire). The iron concentration increases after the zinc peaks; that is, as soon as the protective coating (galvanization) is no longer intact.



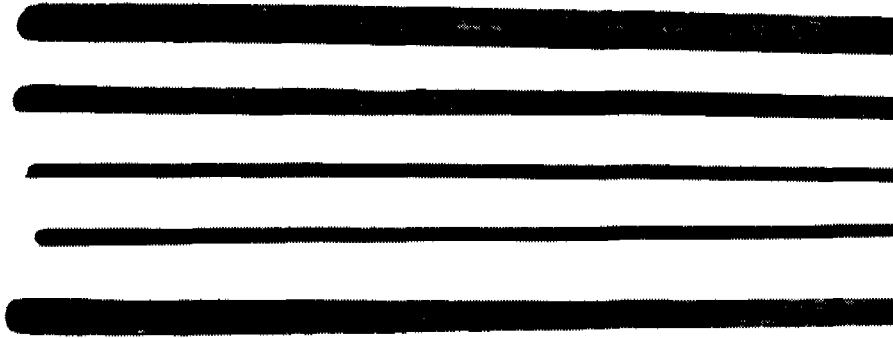
**Figure 4.12 Corrosion of pump rod samples with different surface treatments (biofilms have been cleaned from surface). Group 1: Nonexposed samples. Group 2: Samples exposed to corrosion (S = no attack visible; M, N = mill scale and electroplated layer completely removed; A = galvanization [interface zinc-iron] still intact). Group 3: Samples exposed to light corrosion (N = mill scale partially removed; A, M = protecting layers still intact). Legend: A = galvanized iron; M = electroplated iron; N = iron with mill scale (rust); S = stainless steel.**

#### 4.3 Effect of Corrosion on Handpump Performance

In the following, handpump performance is evaluated on the basis of: (1) breakdowns, where no water can be pumped, and (2) poor performance, where the discharge rate is reduced due to corrosion.

The parts of handpumps most vulnerable to corrosion-caused breakdowns are the pump rods. In the field trial in the 3000 Well Drilling Programme in Southern and Central Ghana, up to two-thirds of the handpump breakdowns were due to rod failures directly or indirectly attributable to corrosion. Typically, this type of failure is caused by galvanic corrosion, which occurs if the pump rods are made of galvanized iron and the pistons are made of brass.

The impact of corrosion on handpump performance through mechanical failures is in many cases the result of a combination of factors. One especially important factor in mechanical failures of handpumps in the field is the rubbing of pump rods on rising mains (Figs. 4.13 and 4.14). In this report, however, whenever reference is made to corrosion-linked problems, corrosion is thought to be the primary cause of the failure.



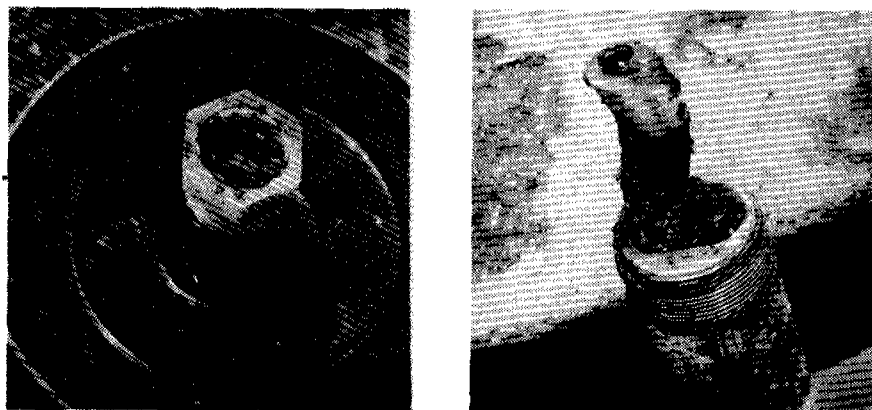
**Figure 4.13 Pump rods heavily affected by rubbing and corrosion**



**Figure 4.14 Rising mains heavily affected by rubbing and corrosion**



Reduced discharge rates (poor performance) can result from leaks in the rising mains caused by corrosion (e.g., pipe perforation and damage to threads) (see Fig. 4.6). The threads of both pump rods and rising mains are weak points that are particularly vulnerable to corrosion for two reasons: (1) because any protective coating applied to rods and pipes is removed when the threads are cut or is easily damaged during pump installation and maintenance; and (2) thread cutting removes material, thus reducing the wall thickness of pipes and the diameter of rods. Figure 4.15 illustrates a corrosion-caused problem in a handpump with helical rotor pumping elements.



**Figure 4.15** Corrosion products from the internal surface of rising mains can increase wear on the pumping element (left), block the foot valve (right), and make pumping hard, especially with a helical rotor pump

Some cases of disconnected rising mains due to corrosion-damaged threads were reported in the Handpumps Project. Such failures of rising mains not only make handpumps inoperational, but also present the risk that the cylinder assembly will fall into the well if the rods, which may also be weakened by corrosion, cannot support the additional load caused by the pipe failures.

Table 4.1 contains statistics of handpump breakdowns from the field trial in the 3000 Well Drilling Programme in Southern and Central Ghana. The two categories of defects, broken rods and worn pumping elements (second and third columns in Table 4.1), were directly or indirectly caused by corrosion. Galvanic corrosion was responsible for one-third of the broken pump rods.

**Table 4.1**  
**Defects That Caused Handpumps to Be Out of Service in the Field Trial in Southern and Central Ghana (June 1982–June 1984)**

Type of Pump (number)	Total defects	Number of Defects (%)					Various above-ground defects
		Rod broken	Pumping element worn	Rod disconnected	Pipe disconnected	Pumping element disconnected	
India Mark II (223)	122 (100%)	78 (63.9%)	10 (4.5%)	10 (8.2%)	20 (16.4%)	4 (3.3%)	10 (8.2%)
Moyno (54)	37 (100%)	20 (54.2%)	10 (27%)	5 (13.5%)			2 (5.4%)
<b>Total (277)</b>	<b>159 (100%)</b>	<b>98 (61.6%)</b>	<b>10 (6.3%)</b>	<b>15 (9.4%)</b>	<b>20 (12.4%)</b>	<b>4 (2.5%)</b>	<b>12 (7.6%)</b>

#### 4.4 Effect of Corrosion on Water Quality

Corrosion products can have a major impact on water quality through bad taste, high concentrations of iron, and red water, and thus can affect pump use and user acceptance, leading even to abandonment of handpump-equipped water points. This can be particularly important in areas where traditional water points (rivers, ponds, etc.) offer easily accessible water all or almost all year round, as is quite common in the forest zone of the subregion. The main effects of corrosion on water quality observed in the field are presented in the following sections.

##### 4.4.1 Taste

Metal ions, mainly iron, but also zinc, are the main corrosion products that influence the taste of water. These components give the water a bitter taste. The threshold concentration of iron detectable by people is approximately 3 mg/l, that of zinc approximately 5 mg/l (Mallevalle and Suffet 1987).

Other compounds such as ammonium and hydrogen sulfide, which occur under reducing conditions and are due to microbiological activities (iron bacteria, sulfate-reducing bacteria), can also affect the taste of water.

Taste is a subjective parameter and, thus, is not easy to quantify. Results from the Niger field trial do show, however, that people are sensitive to the taste of water, and that handpump corrosion can adversely affect the taste of the water. In this field trial, over

50% of the users experienced a deterioration in taste after the handpumps were installed. Salinity, another factor that affects taste, is discussed in Section 2.3.3.

#### 4.4.2 Turbidity

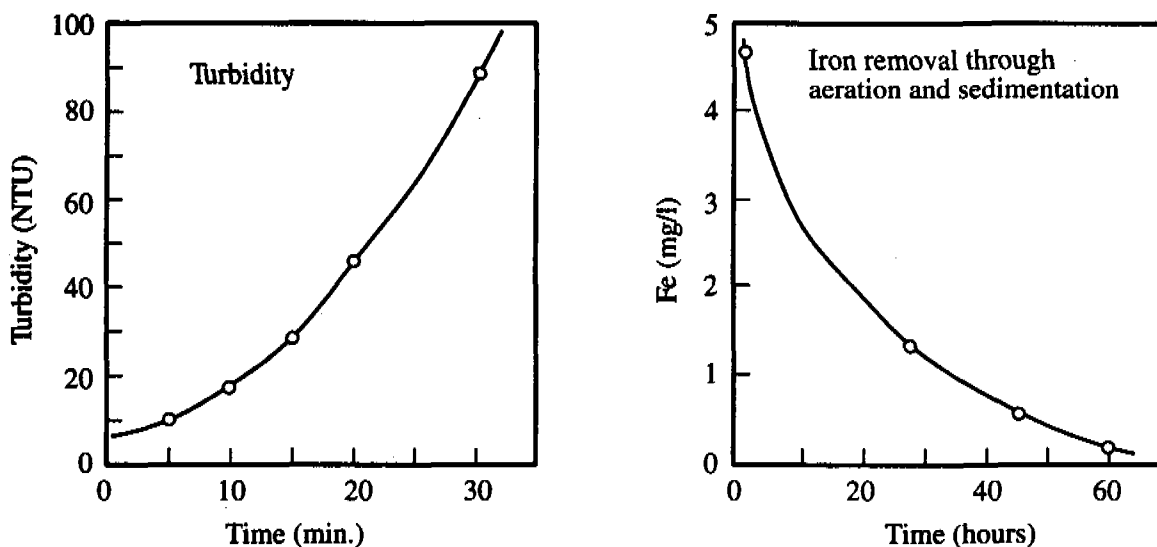
Turbidity (discoloration of water), another parameter affecting consumer acceptance of water points, can also be affected by handpump corrosion (Fig. 4.16). Turbidity (red water) in connection with handpump corrosion, is the result of the presence of corrosion products such as particles of iron hydroxide, iron carbonate, iron oxide, and the microbiological products of iron bacteria. Some data on the chemical composition of dried corrosion products are presented in Appendix 11.

As to turbidity and handpump corrosion, two different effects can be distinguished. First, the handpump produces red water early in the morning after it has not been used for several hours at night. This effect, which usually disappears after a few minutes of continuous pumping, is caused by the accumulation of corrosion products (flakes, scales, biofilm debris, suspended iron compounds) in the rising main assembly and in the well during the night.

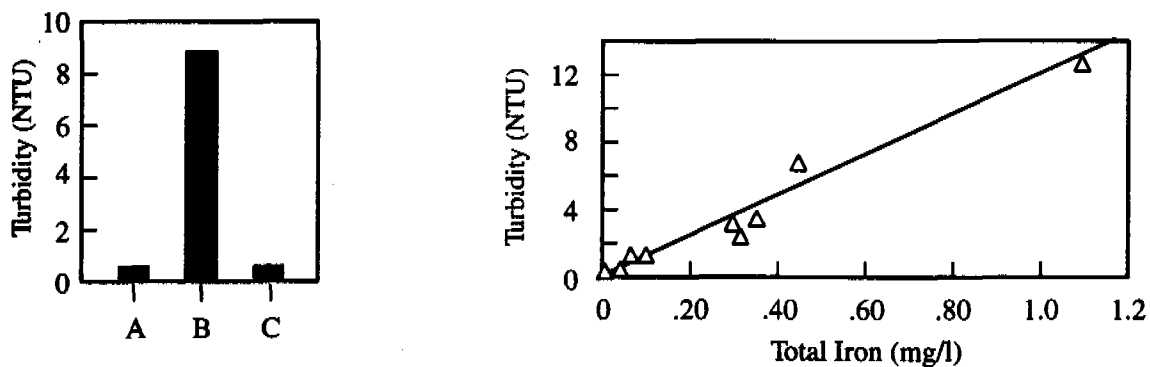
The second effect is the discoloration of the water, which is free of turbidity when pumped, but develops a red-brown color after a few minutes to a few hours. This phenomenon is mainly caused by the transformation of dissoluble ferrous iron ( $\text{Fe}^{2+}$ ) to iron hydroxides and iron oxides when exposed to oxygen in the air. This can also occur in connection with the red water early in the morning.

Turbidity usually disappears after a few hours because the particles settle out, which represents the removal of iron from the water. The development of turbidity and the effect of iron removal on groundwater from corrosion-affected handpumps by simple aeration and sedimentation are shown in Figure 4.16.

In the Divo field trial in the Côte d'Ivoire, the turbidity of groundwater from wells about one month after pump installation ranged from 0.3 to 0.9 NTU (average 0.5 NTU) for eleven Moyno pumps with non-corrosion-resistant downhole components of galvanized rising mains and pump rods. About one year later, the turbidity was between 1 and 60 NTU (average 11 NTU). The more than twenty-fold increase in turbidity was due to corrosion. The relationship between total iron concentration and turbidity in these wells is depicted in Figure 4.17.



**Figure 4.16** Development of turbidity in groundwater from a well with a corroded handpump (left), and iron removal by aeration and sedimentation in a sample bottle (right)



**Diagram a.** Mean turbidity of water from:

A: non-corrosion-resistant handpumps at the time of installation

B: about one year later

C: corrosion-resistant handpumps about one year after installation

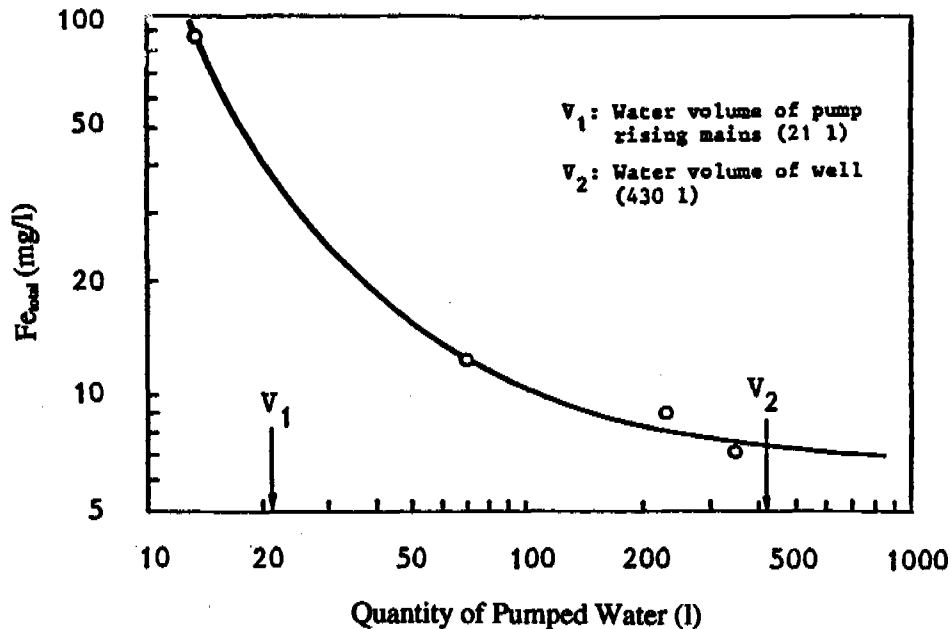
**Diagram b.** Turbidity versus total iron (caused by corrosion)

**Figure 4.17** Effect of handpump corrosion on turbidity (Côte d'Ivoire)

#### 4.4.3 Iron, Zinc

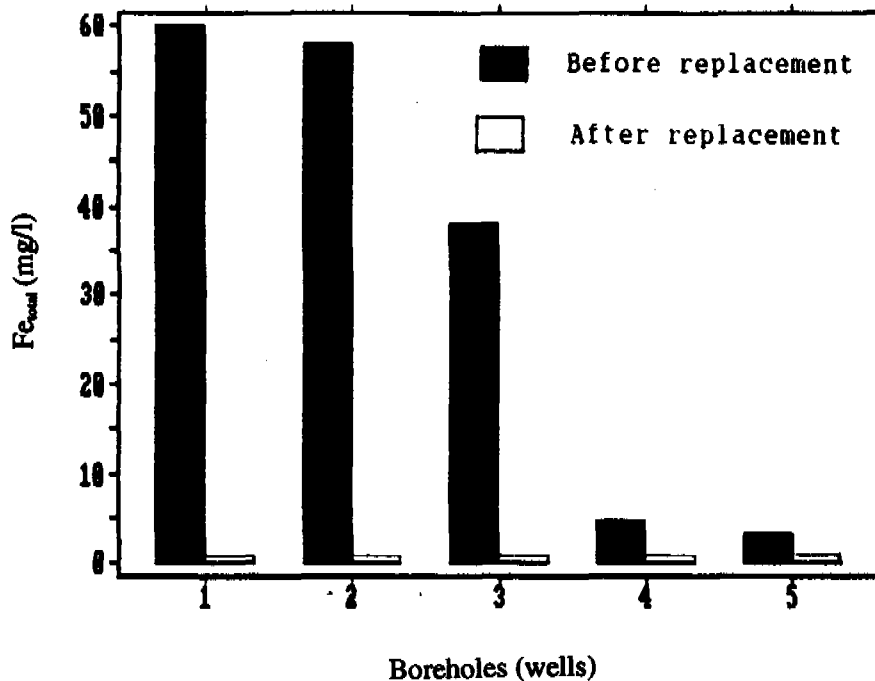
One of the most important findings of the water quality investigations conducted within the Handpumps Project in the West African subregion is that handpump corrosion is the primary cause of the iron problem in the subregion.

There are two effective methods to determine if handpump corrosion is the cause of the iron problem in a well. The first method is to perform a pumping test and to measure the iron content over time. If corrosion is the major source of iron, then the iron concentration will decrease rapidly after a few minutes of continuous pumping (Fig. 4.18). Field experience indicates that if handpumps are used more or less continuously (i.e., without interruptions of more than one or two hours during the day), then the iron content derived from corrosion will not exceed one or two mg/l for groundwater with a pH = 6-6.5.



**Figure 4.18** Total iron content of groundwater from a drilled well equipped with a non-corrosion-resistant handpump (Moyno with galvanized rising mains and pump rods) versus quantity of pumped water. This test was started after the pump had been locked for 13.5 hours overnight. Before it was locked in the evening, the iron content was 1.9 mg/l. The average quantity of water pumped daily is 3.5 cubic meters.

The second method for verifying the source of the iron problem in handpump-equipped wells is to replace non-corrosion-resistant handpumps with corrosion-resistant ones (Fig. 4.19).



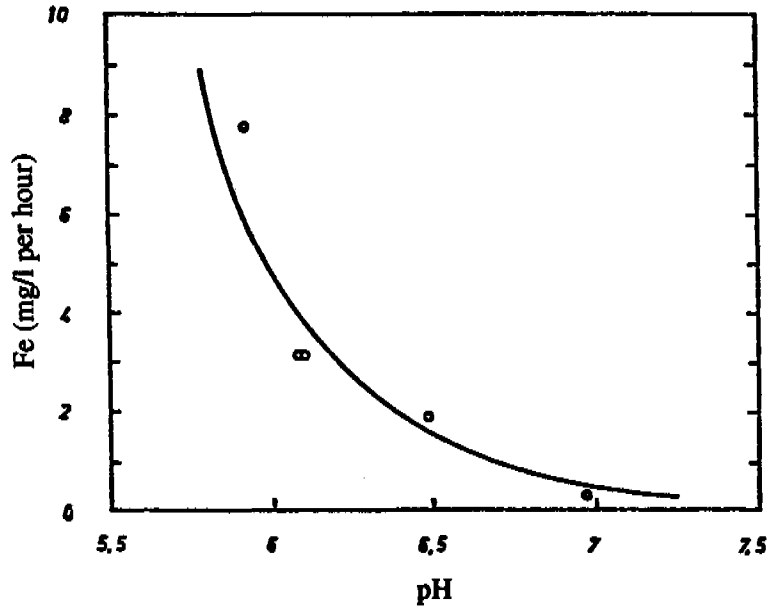
**Figure 4.19** Total iron concentration ( $Fe_{total}$ ) in five boreholes after the replacement of non-corrosion-resistant handpumps (India Mark II and Moyno) with corrosion-resistant handpumps (Vergnet). Wells no. 1, 2, and 3 had been used infrequently, if at all, prior to replacement of the pumps.

Although steel casing is rarely installed in boreholes in handpump-equipped water points in West Africa, a few steel-cased wells still exist. In such cases, corrosion of the well casing also contributes to the iron problem (Chilton and Lewis 1989).

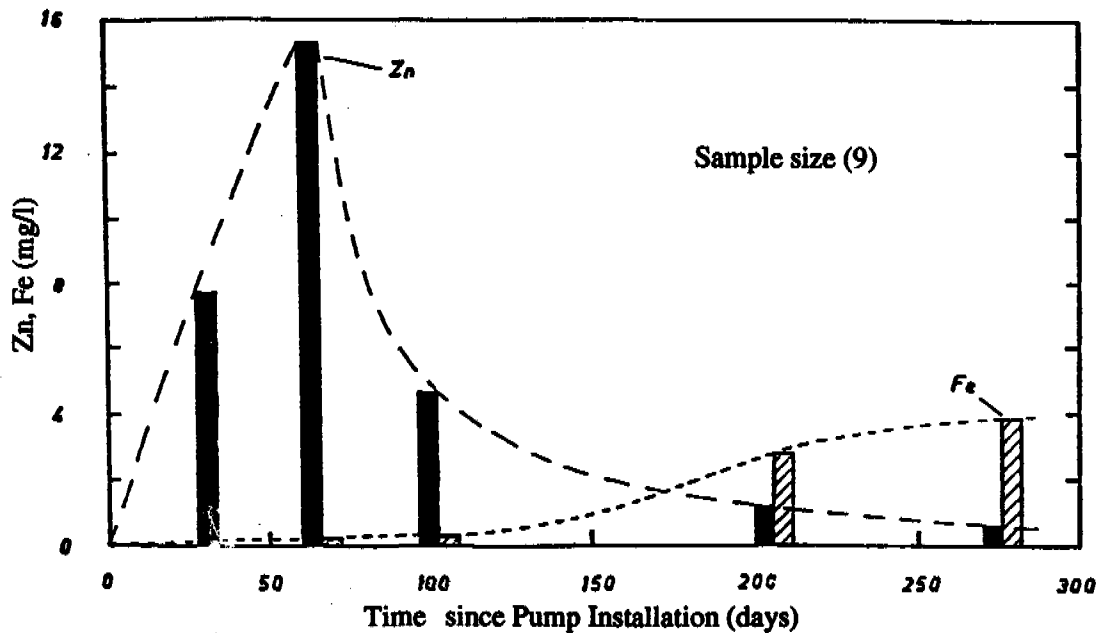
Corrosion processes can proceed rapidly, as shown in Figure 4.20, where the iron increase rate due to internal corrosion of the rising main assembly is plotted versus the pH. The approximate production rate of corrosion material (measured as total iron in the water) is 2 and 4 mg/l at a pH of 6.5 and 6, respectively. In this case, field and laboratory results correspond. The dissolution of iron by corrosion is supported by the similarity of Figure A.14.3 (corrosion rate versus pH, see Appendix 14) and Figure 4.20. The iron increase, however, does not necessarily equal the total amount of iron dissolved by corrosion because some of the iron is integrated into the biofilm and other mineral compounds that form scale on the metal surfaces.

The mean zinc (Zn) and total iron ( $Fe_{total}$ ) concentrations in groundwater from nine wells with galvanized rising mains and pump rods are plotted versus time since

installation in Figure 4.21. The pH of the groundwater from these wells was between 5.9 and 6.9, the electrical conductivity between 250 and 850  $\mu\text{S}/\text{cm}$  (field trial Divo, Côte d'Ivoire). The galvanization of the rising mains and pump rods was eaten away within only a few months, resulting in exposure of the unprotected iron surfaces to the corrosive environment (also see Fig. 4.11).

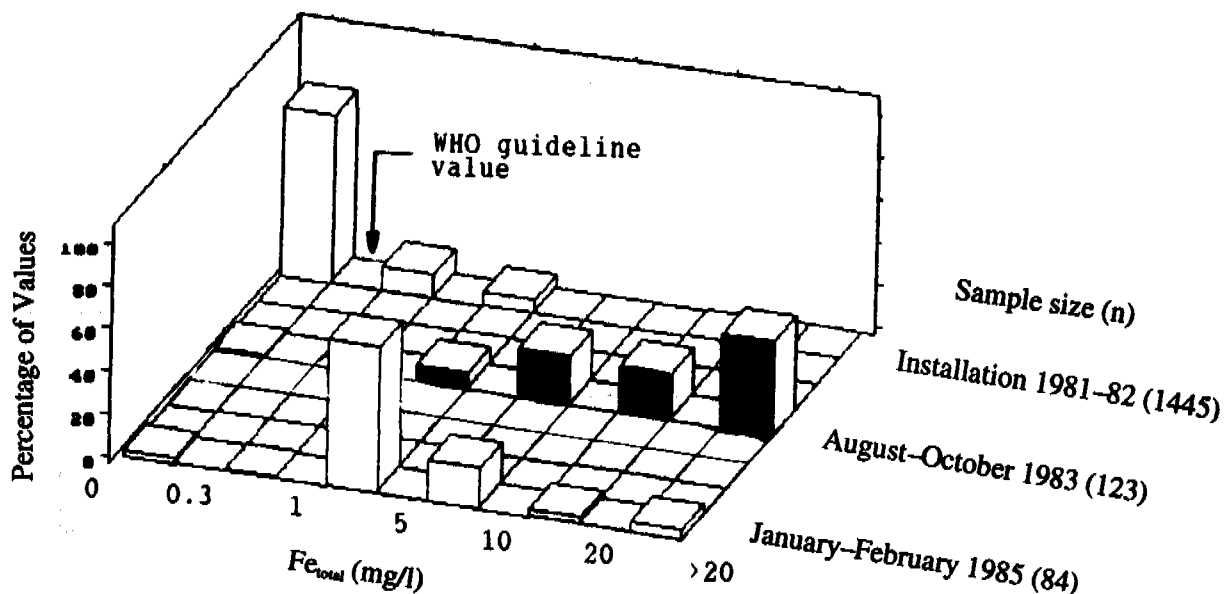


**Figure 4.20** Iron increase rates versus pH in rising mains of non-corrosion-resistant handpumps



**Figure 4.21** Zinc (Zn) and total iron ( $\text{Fe}_{\text{total}}$ ) concentration in groundwater versus time since installation of handpumps with galvanized downhole components (nine wells)

When non-corrosion-resistant handpumps are used in areas with aggressive (corrosive) groundwater, poor quality water (high iron concentrations due to handpump corrosion) can lead to disuse of the pump. Because of the high iron concentration in the area of the 3000 Well Drilling Programme in Southern and Central Ghana (Fig. 4.22), a high percentage of these wells were infrequently used only one or two years after pump installation, mainly because of the iron problem. More than 40% of the groundwater samples from 120 wells had total iron concentrations exceeding 20 mg/l. The dramatic decrease in the iron concentration in the well water about one and one-half years later was attributed to: (1) more intensive use of the pumps because of an extremely dry season that left many traditional water sources dry, and (2) the encouragement of the villagers by the Handpumps Project Monitoring Team to use the handpumps. Although more intensive and regular use of the handpumps does not stop corrosion, it significantly reduces its effects on water quality because the corrosion products are flushed out more or less continuously.

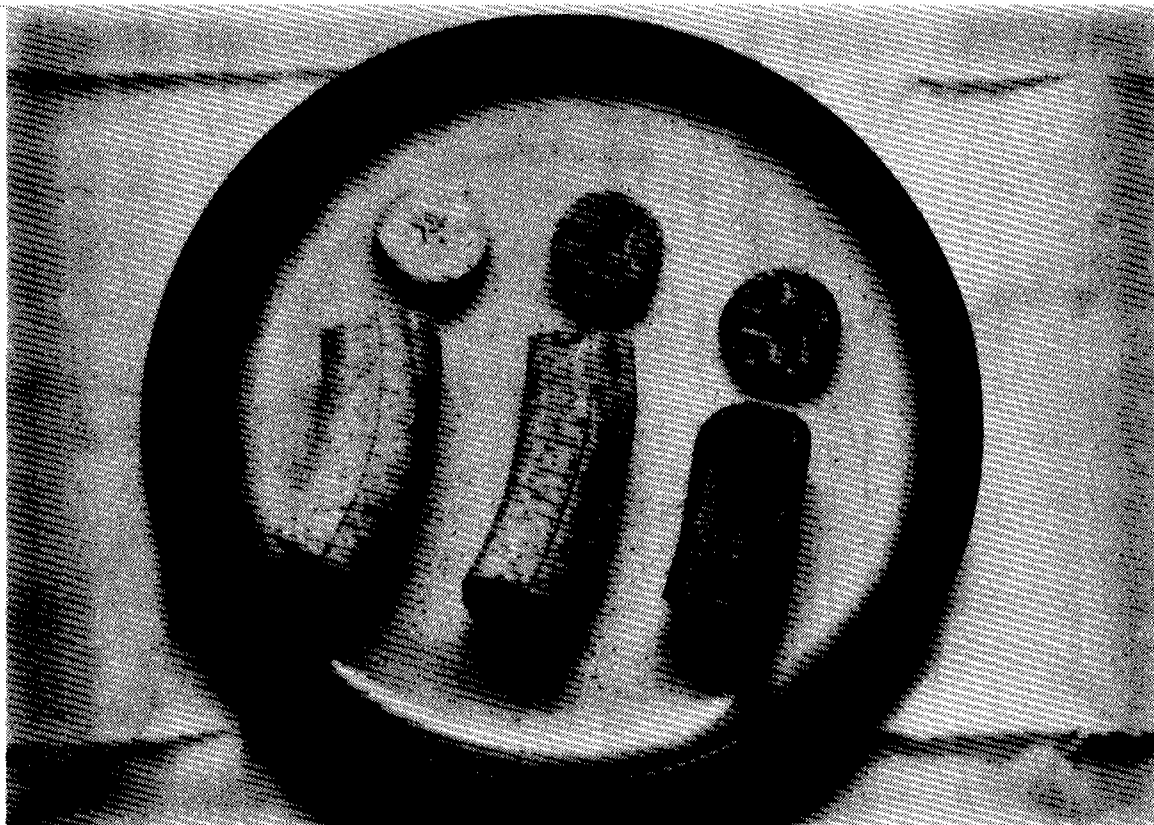


**Figure 4.22** Total iron concentration in groundwater from wells with corroded handpumps with galvanized downhole components at the time of: pump installation, about 1-2 years later, and 2-4 years later (data from field trial in southern Ghana within the 3000 Well Drilling Programme in Southern and Central Ghana)

Discolored food (Fig. 4.23) and stained laundry from high iron concentrations in water are rather common complaints from pump users in certain areas. It is not easy to determine thresholds of iron concentration and other parameters that affect these



problems because there are several factors that must be considered (water quality, transformation of iron into different compounds, water storage, cooking, and ingredients).



**Figure 4.23 Discoloration of plantains cooked in water with different levels of iron concentration**

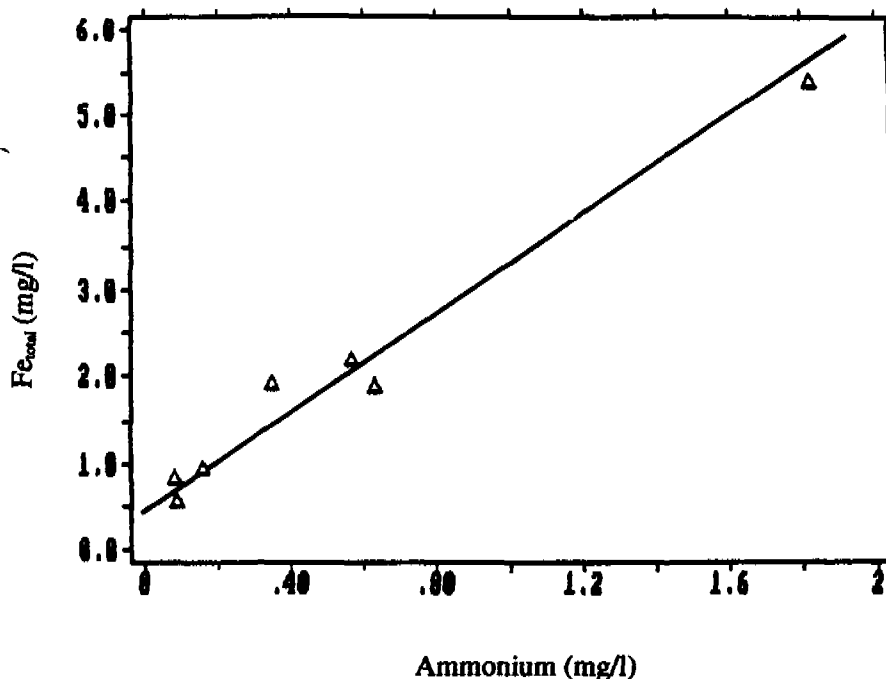
From what has been presented so far in Section 4.4, it is evident that there are two important aspects to consider when determining the iron and zinc content of groundwater from corrosion-affected handpumps:

- (1) The iron and zinc concentrations can vary significantly depending upon when the samples are taken; that is, early in the morning after a pump has not been used for a few hours, during heavy use, or in relation to how much a handpump is used per unit volume over time.
- (2) Iron tests must be performed immediately after sampling at the well site; otherwise the samples must be preserved by acidification in order to obtain reliable results.

The importance of these two points is illustrated in Figure 4.16 and Figure 4.18.

#### 4.4.4 Ammonium, Nitrite

Ammonium ( $\text{NH}_4^+$ ) and nitrite ( $\text{NO}_2^-$ ) are produced by microbiological activity involved in the decomposition of organic matter (nitrification and denitrification processes). The relationship between ammonium and total iron in groundwater from wells equipped with non-corrosion-resistant handpumps suggests that iron bacteria (biofilm) are the primary source of ammonium (Fig. 4.24). Supporting evidence for this suggestion is provided by the decrease in  $\text{NH}_4^+$  and  $\text{NO}_2^-$  concentration in two wells after the replacement of non-corrosion-resistant pumps with corrosion-resistant ones (Fig. 4.25). Ammonium is predominant under reducing conditions and nitrite under oxidizing conditions (see Appendix 8). The consequence of these findings is that, under corrosive conditions, ammonium and nitrite cannot be considered classic pollution indicators, as they are under oxidizing conditions (see section 2.4.3).

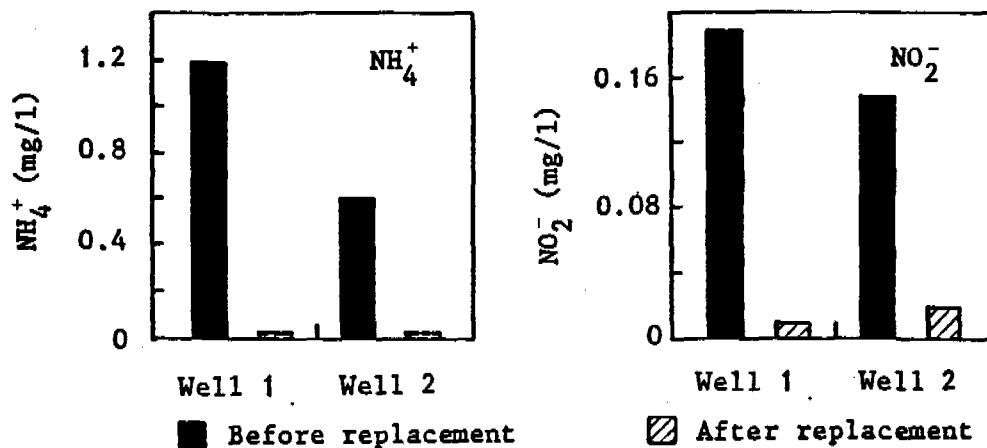


**Figure 4.24 Ammonium ( $\text{NH}_4^+$ ) concentration versus total iron ( $\text{Fe}_{\text{total}}$ ) concentration in groundwater from wells with non-corrosion-resistant handpumps (southern Ghana)**

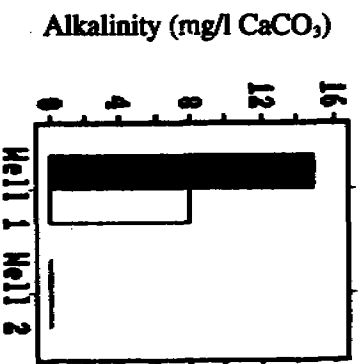
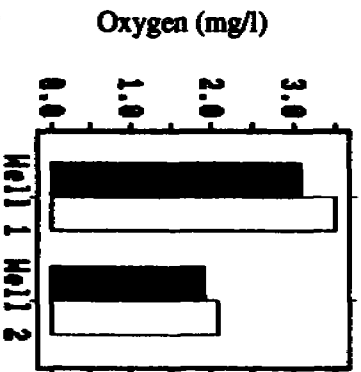
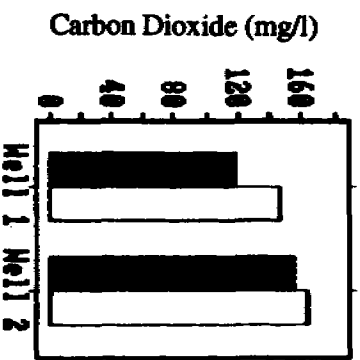
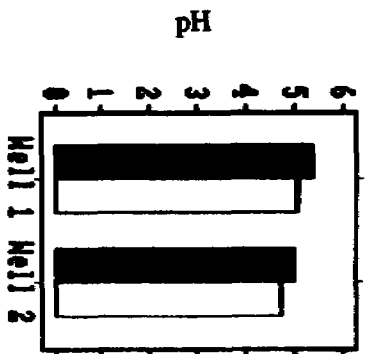
#### 4.4.5 Other Parameters

Handpump corrosion affects not only iron, manganese, zinc, ammonium, and nitrite but also pH, free carbon dioxide, dissolved oxygen, alkalinity, and possibly other parameters that affect water quality (Fig. 4.26 and Appendix 9).

To summarize, handpump corrosion can affect a variety of the parameters used to indicate water quality. The extent of this effect depends upon the corrosiveness and the natural composition of the groundwater, the material being attacked, and the operating conditions of the handpumps.



**Figure 4.25** Change in concentration of ammonium ( $\text{NH}_4^+$ ) and nitrite ( $\text{NO}_2^-$ ) in groundwater from two wells in southern Ghana before and two days after replacement of non-corrosion-resistant handpumps (Moyno and India Mark II) with corrosion-resistant handpumps (Grundfos)



■ Before replacement

□ After replacement

**Figure 4.26 Change in pH, free carbon dioxide (CO<sub>2</sub>), dissolved oxygen (O<sub>2</sub>), and alkalinity of groundwater from two wells in southern Ghana before and two days after the replacement of non-corrosion-resistant handpumps (Moyno and India Mark II) with corrosion-resistant handpumps (Grundfos)**



## **5. Field and Laboratory Research on Handpump Corrosion**

### **5.1 Introduction**

A variety of tests and investigations on handpump corrosion were carried out, both in the field and in the laboratory, to gain a better understanding of the effect of corrosion on handpump performance and water quality, to demonstrate and quantify these effects, and to propose and test measures to counter these effects.

There are four subjects to consider: (1) the aquifer-well-pump system, describing the effect of handpump corrosion on water quality; (2) corrosion rates of rising mains and pump rods; (3) corrosion products and development of scales; and (4) the effect of microbiological processes on corrosion. Details on these investigations are presented in Appendixes 9-14.

### **5.2 The Aquifer-Well-Pump System**

The effect of handpump corrosion on water quality is best described and understood by analyzing separately the different parts of the handpump-equipped well: (1) the aquifer, (2) the well, and (3) the handpump. These three parts have significantly different characteristics with regard to handpump corrosion and water quality (see Appendix 9).

Field observations indicate that handpump corrosion can cause significant changes in water quality if the handpump is not used for several hours. Parameters such as iron concentration, turbidity, dissolved oxygen, alkalinity, nitrate, sulfate, and silica are particularly affected by corrosion, and these effects are especially severe inside the pump. This results in the early morning red water problem after a corrosion-affected handpump has not been used for several hours (i.e., during the night). The A-W-P system also makes it easier to understand the differences observed between internal and external corrosion of rising mains and the relationship between operating conditions of handpumps and the effect of handpump corrosion on water quality.

The main findings of these investigations are: (1) the less a handpump is used, the more corrosion affects the water quality, and (2) the internal surfaces of non-corrosion-resistant rising mains have a greater tendency to develop protective coatings against corrosion than the external surfaces do.

### **5.3 Corrosion Rates of Pump Parts**

Corrosion rates are defined in two ways: as penetration rate, in millimeters per year (mm/y); or as mass loss per unit area, in milligrams per square centimeter per day ( $\text{mg}/\text{cm}^2/\text{d}$ ).

Field measurements on the corrosion rate of rising mains and pump rods can be summarized as follows:

1. The corrosion rates (penetration) measured in the field over a period of fifteen months since pump installation were in the following ranges:

Galvanized rising mains (external)	0 - 0.25 mm/y
Galvanized rising mains (internal)	0 - 0.15
Galvanized (electroplated) pump rods	0 - 0.16
Stainless steel pump rods	0 - 0.025

There is a notable difference in corrosion rate between the external surface and the internal surface of rising mains (see Section 5.2).

According to the adjective rating of corrosion damage developed by Clarke in 1980 (see Appendix 10), the measured corrosion rates are "mild" (<0.05 mm/y) and "moderate" (0.05–0.5 mm/y), respectively.

2. Under conditions of galvanic corrosion, penetration rates of up to 2 mm/y were observed on piston rods adjacent to the contact between the brass piston and the galvanized-iron pump rod. According to the adjective rating mentioned above, galvanic corrosion rates are "extreme."
3. The corrosion rates decreased over time due to the protective effect of biofilms, scales, and corrosion products that were deposited on the corroded surfaces.
4. The corrosion rates showed a strong dependency on pH; that is, the lower the pH, the higher the corrosion rates.

Details on the field measurements of corrosion rates are presented in Appendix 10.

#### 5.4 Corrosion Products and Development of Scales

Rising mains and pump rods that are in contact with water are generally covered with red-brown mud (biofilms). Such corrosion products are composed of iron (40–60%), zinc, calcium, magnesium, potassium, sodium, and aluminum (0.1–4%), and the remainder may be silica and organic matter from iron bacteria.

The composition of the corrosion products from the internal surfaces of rising mains are significantly different from those of the external surfaces. The corrosion products on the internal surfaces generally have higher concentrations of calcium, magnesium, sodium, and aluminum. This is caused by variations in the water quality due to intermittent use of the handpumps (see Section 5.2 and Appendix 11).

Depending upon the water quality the corrosion products range from very soft crusts (sometimes with a powdery texture) to hard crusts, with a wide range of mixtures between these two extremes. A very soft crust can be considered a typical biofilm, the hard crust is a protective coating (hard scale).

Field observations on the development of protective scales and biofilms, respectively, indicate that:

- (1) The external surfaces of galvanized rising mains are usually covered with reddish mud (biofilm). When dried, the reddish mud has a powdery structure, and falls off easily.
- (2) On the internal surfaces of rising mains the development of protective coatings (scales) was observed when pH levels were greater than 6.5 and when the conductivity was greater than 300  $\mu\text{S}/\text{cm}$ .

More information on corrosion products and scale development is presented in Appendix 11.

### 5.5 Effect of Microbiological Activity on Corrosion

Field observations and laboratory tests indicate that microbiological activity plays an important role in handpump corrosion under tropical conditions. Biofilms, which are mainly the direct result of the activity of iron bacteria, develop on mild steel surfaces within 30 to 40 hours when they are exposed to groundwater with a temperature of 25–30°C. No biofilms or only traces of biofilms were observed when groundwater temperatures were 8–10°C (refrigerated samples).

On the positive side, biofilms have a protective effect with regard to corrosion. On the negative side, and especially with regard to handpumps, the debris originating from biofilms in the pumped water is a nuisance from the organoleptic and aesthetic viewpoint.

The results of laboratory tests related to microbiology and corrosion are presented in Appendix 12.





## 6. Corrosion Indexes and Corrosion Tests

### 6.1 Introduction

In the water industry, methods to predict whether corrosion will occur (and if so how severe it will be) have been sought since noncorrosion-resistant materials were used in distribution systems. Progress in both water chemistry and measuring techniques has resulted in the creation of corrosion indexes to help predict corrosion.

No single corrosion index, however, is useful over the entire range of different water qualities; each is limited in its application and each has shortcomings (see Section 3.1). Nevertheless, in the water industry, corrosion indexes are widely used to assess raw water quality with regard to corrosiveness, and corrosion tests are used to control the corrosiveness of the water in distribution systems. To compensate for the limited validity of each corrosion index, it is essential that several techniques be used when testing water quality with regard to corrosion in distribution systems.

The purpose of this chapter is to present some of the most common and widely used corrosion indexes, to apply them to the situations considered in this study, and to correlate the results with the corrosion rates observed in the field. The same shall be done with parameters and tests that have potential for use as corrosion indexes (e.g., pH, marble test, and iron uptake test).

It is important to keep in mind that: (1) the range of water quality covered in this study, although quite representative of West Africa, is limited; and (2) that the corrosion indexes referred to have been developed primarily with regard to internal corrosion in distribution networks and for controlling the efficiency and quality of water treatment, not for waterpoints with handpumps.

### 6.2 Water Quality-Based Corrosion Indexes

The following corrosion indexes, which are based on water quality, were applied and tested in the field trial in the Côte d'Ivoire:

- Saturation Index (SI)
  - SI according to Langelier
  - SI according to Larson
  - Measured SI (marble test)
- Ryznar Stability Index (I)
- Driving Force Index (DFI)
- Riddick Index (RI)
- pH and Redox Potential (Eh)

Field measurements of corrosion rates (see Appendixes 10 and 14) were used to compare and evaluate the various corrosion indexes. All the corrosion indexes used provided comparable results, and the results also correlated with the measured corrosion rates. Details on the corrosion indexes appear in Appendix 13.

### **6.3 Corrosion Tests**

A variety of techniques are used in corrosion research and corrosion control, the main ones applied in the water industry are:

- (1) observation of test samples (pieces of pipes, coupons, inserts, nipples) exposed to field conditions (distribution networks) with regard to corrosion, scale formation, and so forth;
- (2) measurement of the metal uptake, for example, in test circuits (pipe loops) connected to distribution networks or with coupons in the laboratory (immersion tests); and
- (3) electrical instrumentation (electrical resistance measurement of metals exposed to corrosion, polarization measurements, and galvanic current measurements).

The advantage of methods (2) and (3) is that they require less time than method (1). In situ observations of corrosion rates, for example, usually require several weeks or even months, while metal uptake and electrical instrumentation methods can provide results in hours or days. Most of the tests are specified in standards (DIN, ASTM, etc.).

The same basic methods as described above were used to investigate handpump corrosion. The following field and laboratory tests were carried out:

- (a) field measurement of corrosion rates of pump rods and rising mains of handpumps;
- (b) field measurement of the diameter reduction (corrosion rate) of corrosion test samples (pump rod samples of different materials) after exposure to groundwater in wells;
- (c) laboratory measurement of corrosion rates of pump rod samples and coupons; and
- (d) laboratory measurement of the iron uptake in water samples to which coupons and pump rod samples were exposed (immersion tests).

The results of the corrosion rate measurements on handpumps are presented in Section 5.3. The results of the corrosion and iron uptake tests are presented in Appendix 14.



## 7. Conclusions and Recommendations

The quality of groundwater in the West African subregion comprising the five countries that participated in the World Bank-executed UNDP-INT/81/026 Handpumps Project (Burkina Faso, Côte d'Ivoire, Ghana, Mali, and Niger) is, based on the physico-chemical parameters presented in this report and on the WHO guideline values, in general "good" and, thus, suitable for drinking water. The values for one parameter, however, pH, are below the WHO guideline range (6.5–8.5) in 50% of the areas tested. That is, groundwater in the subregion is characterized by low pH and, therefore, is aggressive. It is estimated that about 75% of the groundwater in the subregion has a pH < 7.

The predominance of aggressive groundwater, especially with a pH < 6.5, causes corrosion problems. The corrosion of handpumps (rising mains and pump rods) is a serious problem in community water supply that affects handpump performance by increasing breakdown rates (mainly due to broken pump rods) and by reducing the performance of the pumps by leakage. Handpump corrosion also causes high iron concentrations in the groundwater, which results in a number of adverse side effects (taste, discoloring food, staining laundry, red water, etc.).

The most important conclusions about handpump corrosion from the investigation and research of the Handpumps Project are: (1) total iron concentration in natural groundwater is rarely greater than 1 mg/l, (2) corrosion is usually the cause of the well-known red water (iron) problem in handpump-equipped wells, (3) galvanization does not protect rising mains and pump rods from corrosion under the prevailing groundwater conditions in the subregion (pH < 6.5), and (4) the less a corrosion-affected handpump is used, the more serious the iron problem becomes.

pH and electrical conductivity are useful parameters for predicting handpump corrosion. Electrochemical corrosion of mild steel depends to a large degree on the pH and only moderately on the electrical conductivity. Galvanic, or bimetallic, corrosion on the other hand, depends largely on the electrical conductivity (in the range below 500  $\mu\text{S}/\text{cm}$ ) and very little on the pH. The corrosion rates due to galvanic corrosion are significantly higher than those due to other types of electrochemical corrosion.

The taste of water plays an important role in user acceptance. "Poor" taste is often the reason why new water points, such as handpump-equipped wells, are not accepted by the beneficiaries, and the "poor" taste is often caused by corrosion of the handpump. The conductivity, as a measure of total dissolved minerals, is an excellent taste indicator, and there are relatively well-defined thresholds where taste begins to play an important role in user acceptance of water points. In the forest areas, where surface water is traditionally the main water source, merely the change to groundwater, which usually has a higher degree of mineralization (salinity) than surface water, can cause user acceptance problems. The threshold range above which people usually start complaining about the taste (salinity, expressed as conductivity) is 300–500  $\mu\text{S}/\text{cm}$  in the forest zone and approximately 1000  $\mu\text{S}/\text{cm}$  in the savanna. As a consequence the taste of the water can have a remarkable effect on user acceptance and, thus, on the success or failure of a community

water supply project. In cases where the use of new water sources will provide water that differs notably in taste (salinity) from water from traditional sources, the beneficiaries of such projects should be prepared for the changes.

Seasonal variations in the physico-chemical composition of groundwater are generally small in water pumped from basement formations, except in situations where a well taps both shallow groundwater (e.g., from the overburden) and groundwater from the bedrock (weathered and fractured zones). Groundwater from the overburden usually shows a lesser degree of mineralization, a lower pH, and a lower electrical conductivity than water from the bedrock.

Shallow aquifers in the overburden are usually more susceptible to groundwater pollution than deep aquifers, and this is often indicated by higher nitrate concentrations in the shallower aquifers. The single most important cause of groundwater pollution in the rural environment is the random disposal of organic waste and excrement in and around settlements. There is a strong relationship between nitrate concentration in groundwater and the size (density) of the settlement. While the degree of physico-chemical groundwater pollution can generally be considered negligible in small- to medium-size villages (i.e., less than 1000 inhabitants) the contrary is true in large and densely populated villages and towns, where nitrate especially can reach levels far beyond the WHO guideline value. Improperly maintained wells are another frequent pollution factor.

In general, little is known about groundwater quality even in areas where data have been collected. There is a need to establish data bases and to make the information available in a usable form to decisionmakers, project planners, project engineers, and others.

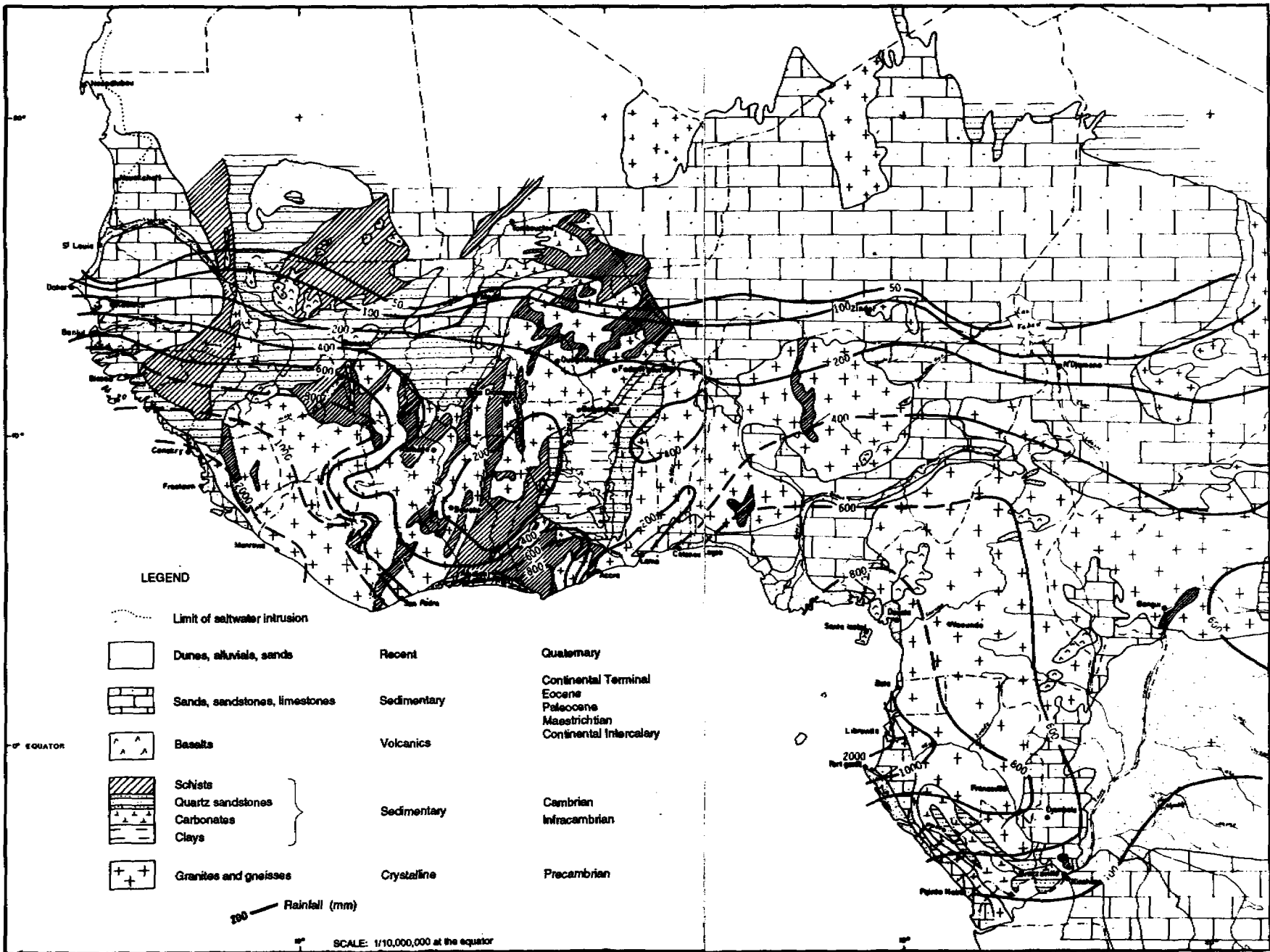
On the basis of the results and experience from the Handpumps Project in the *West African subregion with regard to groundwater quality and handpump corrosion*, it is highly recommended that the following points be taken into consideration, especially in connection with handpump-based community water supply schemes:

1. Since the physico-chemical composition of groundwater can significantly affect community water supply projects, especially with regard to user acceptance and handpump corrosion, it is necessary to assess the groundwater quality in the early stages of project preparation and, if necessary, to consider it accordingly (e.g., type of handpump selected, preparation of beneficiaries for changes in taste, etc.).
2. If the groundwater is aggressive, only corrosion-resistant handpumps should be used. The pH-based corrosion index (see Appendix 13, Section 5) should be used to determine the applicability of galvanized downhole components for handpumps. According to this index, galvanized material is not suitable for groundwater with pH < 6.5, and only in a limited way for groundwater with pH = 6.5–7. For existing water supply schemes that have corrosion-affected handpumps, it is

recommended that non-corrosion-resistant rising mains and pump rods be replaced with corrosion-resistant ones.

3. In situations where the water for a new water supply project has a significantly different taste from the water of traditional sources, the beneficiaries should be prepared for such a change in order to minimize user acceptance problems. This can be particularly important where people are used to drinking surface water and, because of a water supply project, must begin using groundwater, which is usually harder (more mineralized) than surface water.
4. To reduce pollution of groundwater and wells, more emphasis must be placed on appropriate disposal practices of solid and liquid wastes, proper drainage and cleanliness around drainage sites, and proper maintenance of handpumps and wells.
5. If handpumps are installed on large-diameter dug wells it is essential, in order to prevent pollution of the wells, that no splashed water be allowed to flow back into the wells. Well aprons should be designed so that splashed water drains easily away and does not enter the wells.
6. Whenever possible, animals should not be watered at the water points that are used as a source of drinking water for people.
7. More attention should be paid to proper well construction, especially with regard to sealing off and preventing the flow of the undesired shallow groundwater (from the overburden) into the well, using correctly sized gravel packs, and making sure that the boreholes are vertical.
8. Water testing must be performed according to the procedures indicated and recommended by the manufacturers of the equipment and reagents. Even the performance of water tests with simple test kits and electrical equipment (pH meter, conductivity meter, spectrophotometer) requires a basic understanding of chemistry and, thus, adequate training. Nonspecialists performing water tests should be supervised by qualified people. Another important factor in water testing, especially in the tropics, is careful control of the reagents (quality, shelf life, storage, supply) and calibration of the instruments. If such controls are not followed, the validity of water tests is questionable.
9. Groundwater quality data should be collected and entered into data bases and made available to those involved with water resources. Whenever possible, such data should be evaluated, processed, and presented (e.g., in the form of reports and maps) within the framework of projects.





**Table A.2.1**  
**Distribution of Igneous, Metamorphic, and Sedimentary Rocks in the Subregion (as Percentage of the Total Surface Area)\***

Country	Igneous Rocks (%)				Metamorphic Rocks (%)				Sedimentary Rocks (%)			
	Acidic	Inter- mediate	Basic	Total	Acidic	Inter- mediate	Basic	Total	Acidic	Inter- mediate	Basic	Total
Burkina Faso	59.8	0.1	0.1	60.0	0	10.0	11.9	21.9	13.0	0.4	4.7	18.1
Côte d'Ivoire	61.9	0	0.2	62.1	0	34.1	0.8	34.9	1.3	1.7	0	3.0
Ghana	21.7	0	0.3	22.0	0	36.5	0	36.5	0	26.5	15.0	41.5
Mali <sup>b</sup>	7.5	0	3.4	10.9	0	6.5	0	6.5	24.1	40.0	18.5	82.6
Niger <sup>b</sup>	4.1	0	0.3	4.4	0	0.9	0	0.9	22.2	34.3	38.2	94.7
Total Subregion	22.1	0.1	1.3	23.4	0	12.3	1.6	13.9	16.4	26.5	19.8	62.7

\*compiled from geologic maps

<sup>b</sup>only the area south of 18° north latitude has been considered

**Remarks** Although the acidic/basic system of igneous rock classification (which is based on SiO<sub>2</sub> content) is rarely used today in the field of geology, it was quite useful in this report because of the relationship between rock type and groundwater acidity. The classification (acidic, intermediate, basic) for metamorphic and sedimentary rocks is based on the pH of groundwater in the aquifers made up of these rocks (see Section 2.3.2 and Appendix 5).

### Appendix 3. Aquifer and Well Characteristics

The groundwater level of an aquifer and its seasonal variations are important factors for the exploitation of groundwater. Deep groundwater levels mean high drilling costs, large investments for pump equipment, and high operating costs. The use of handpumps, however, is limited by the amount of energy that a human being can make available for lifting water. Dynamic water levels (pumping lifts) deeper than 45 m are considered very deep for handpumps. Within the Handpumps Project handpumps were classified according to pumping lift (Arlosoroff et al. 1987):

Suction pumps	0 - 7 m
Low lift pumps	0 - 12 m
Intermediate lift pumps	0 - 25 m
High lift pumps	0 - 45 m

Handpumps for pumping lift greater than 45 m are usually designed to be operated by two or more people.

In the Handpumps Project area, the mean static water level is about 15 m, with a range from 8 m in northern Ghana to about 40 m in Niger (Fig. A.3.1). Seasonal variations in groundwater level are small. Variations in groundwater levels between the rainy season and the dry season were less than 2.5 m for about 30% of the field trials in southern Ghana and for about 70% of the field trials in northern Ghana (Fig. A.3.2).

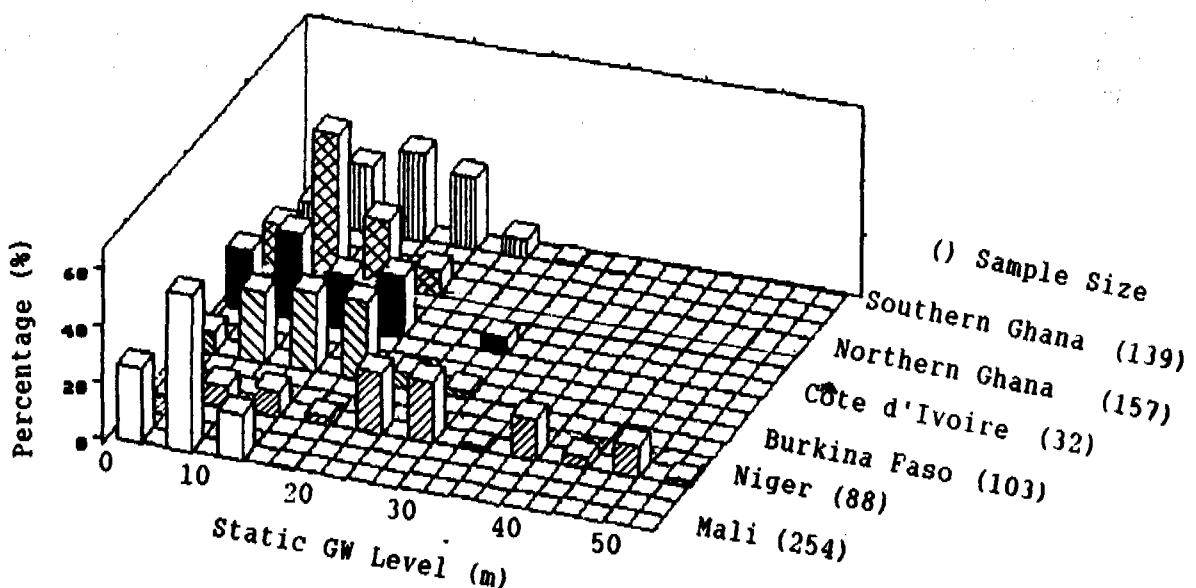
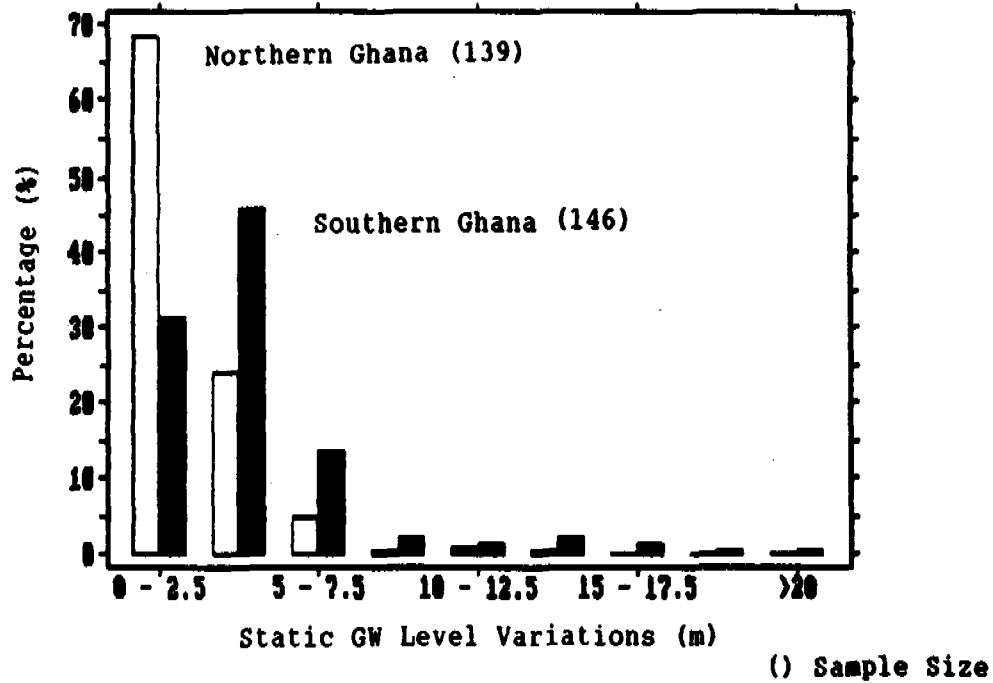
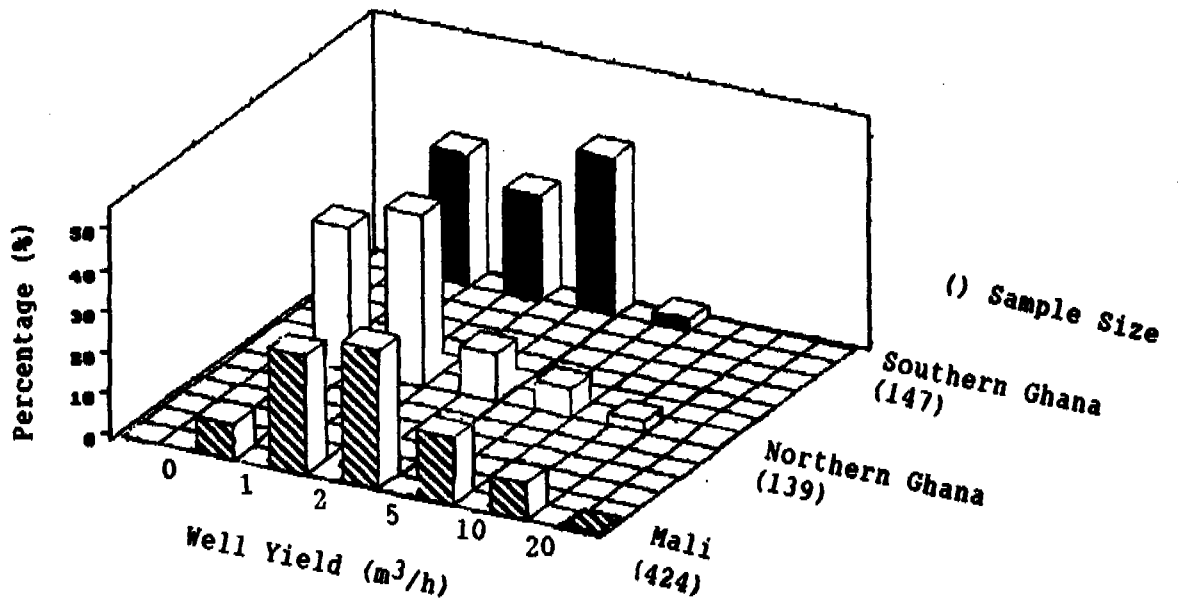


Figure A.3.1 Static groundwater levels in the subregion



**Figure A.3.2 Seasonal variation of static groundwater levels in northern and southern Ghana**

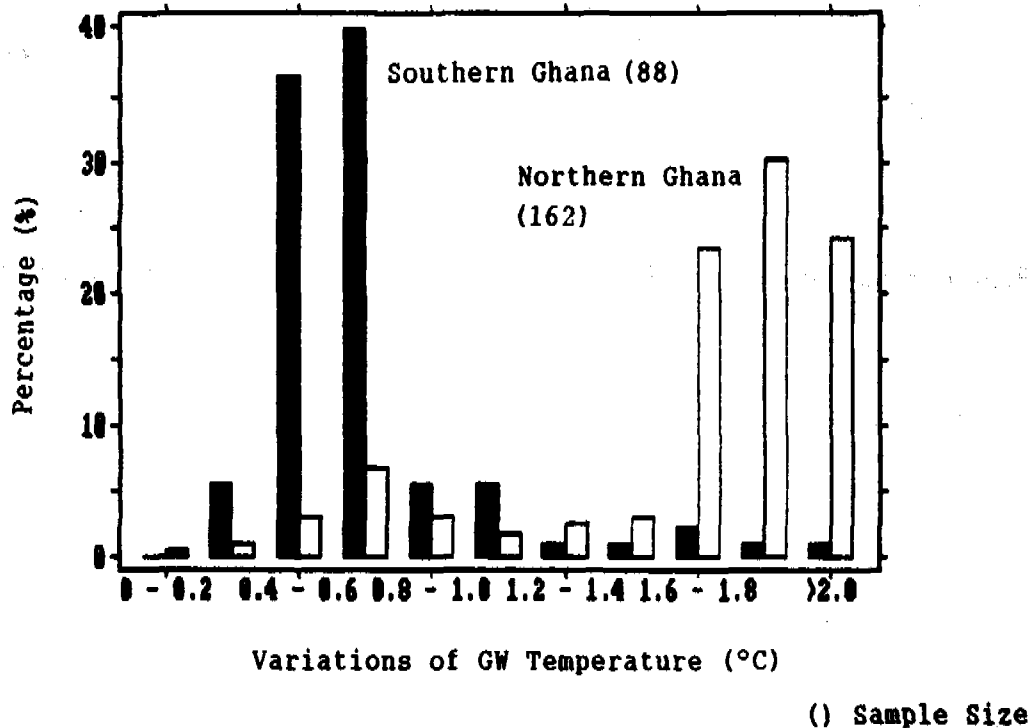
Well yields from four different projects in the subregion are depicted in Figure A.3.3. Of the drilled wells, about 20% had yields less than 1 m<sup>3</sup>/h, 60% between 1 and 5 m<sup>3</sup>/h, and 10% more than 5 m<sup>3</sup>/h. The main water-bearing strata in the hard rock formations are usually the weathered and fractured zones.



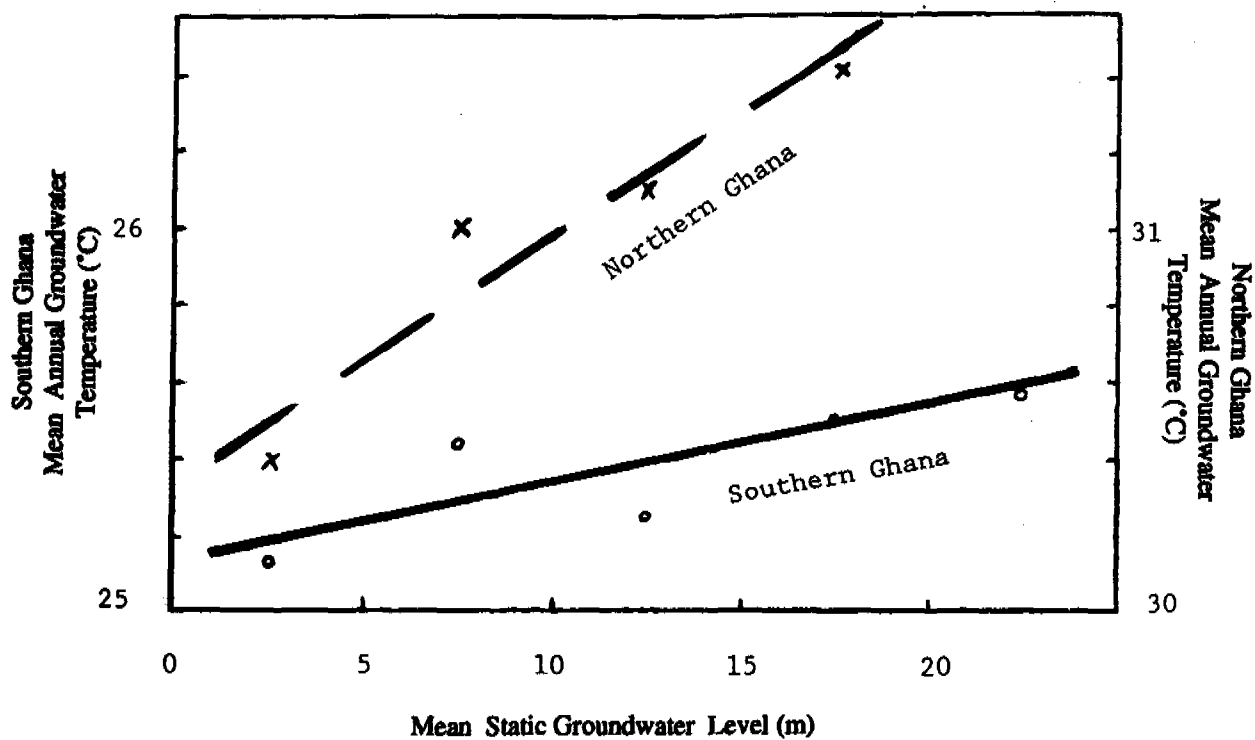
**Figure A.3.3 Yield from drilled wells in northern and southern Ghana, and Mali**

#### Appendix 4. Groundwater and Air Temperatures in the Subregion

In general, groundwater temperatures have a strong correlation with air temperatures. Even seasonal variations in air temperatures are reflected in groundwater temperatures (see Figs. 2.2 and 2.3). For example, air temperatures vary more in northern Ghana (savanna) than they do in southern Ghana (forest), and this is also true of seasonal groundwater temperatures; that is, variations are greater in northern Ghana than in southern Ghana (Fig. A.4.1). The mean seasonal groundwater temperature variation (difference between maximum and minimum temperature measured during the field trials) in northern Ghana was 1.7°C, in the south 0.7°C. There is also a strong relationship between groundwater level and groundwater temperature (Fig. A.4.2).



**Figure A.4.1 Seasonal groundwater temperature variation in drilled wells in northern and southern Ghana**

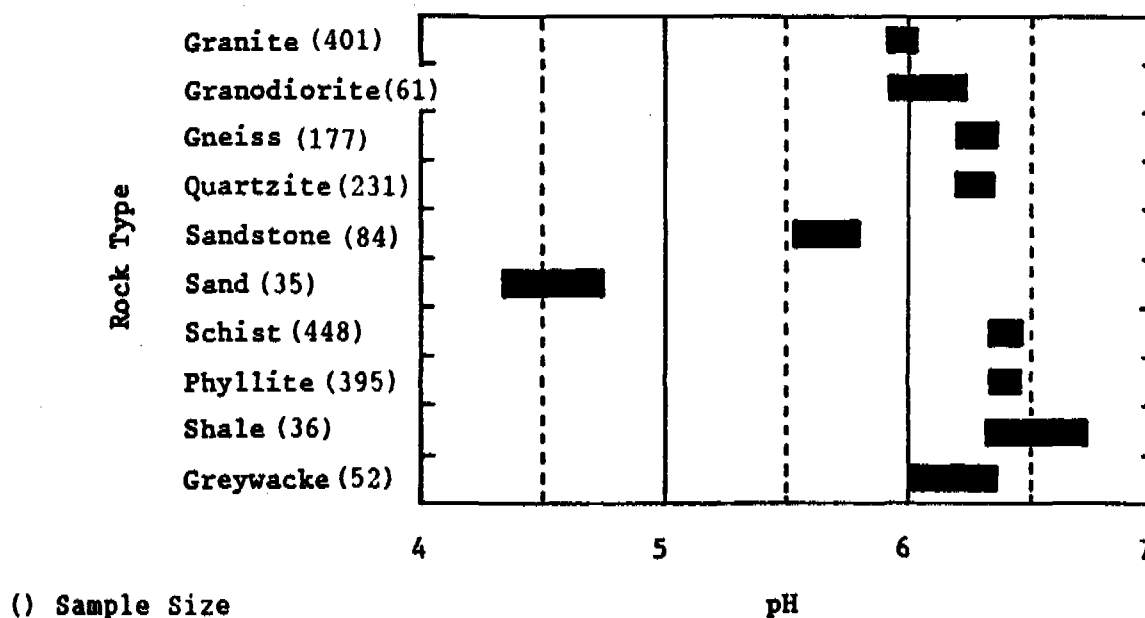


**Figure A.4.2 Mean groundwater temperature versus mean groundwater level in northern and southern Ghana**

**Appendix 5. Relationship between Rock Type and pH: Applications for Mapping Corrosiveness and Salinity of Groundwater**

The pH of groundwater depends on several factors, the most important of which is probably the lithology of the aquifer. Other factors include the characteristics of the subsurface (zone of aeration, vadose water zone) through which surface water must pass on its way to the aquifer, the climate, and the type and amount of vegetation.

The relationship between the pH of the groundwater and the lithology of the aquifer (Fig. A.5.1) allows maps of the areal distribution of groundwater corrosiveness (with pH and possibly other parameters as corrosion indexes) to be created with geological maps (Langenegger 1989).

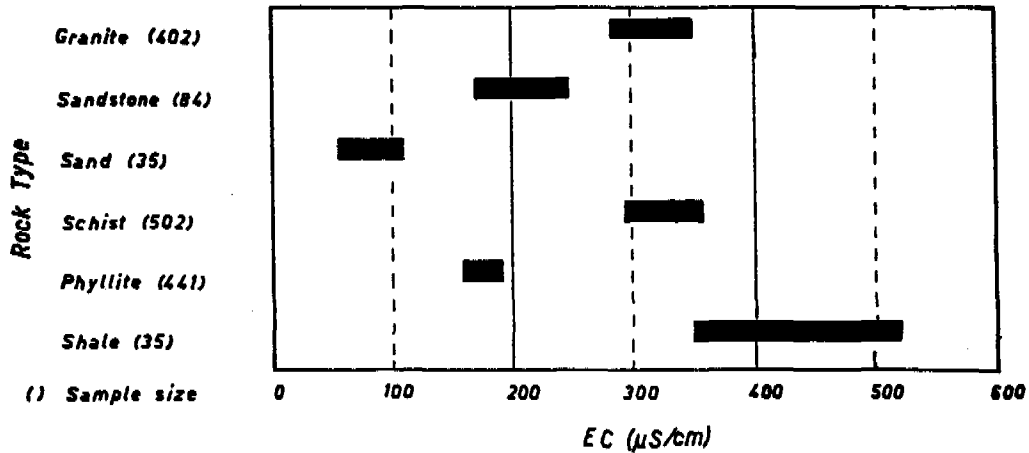


**Figure A.5.1 Relationship between rock type and pH (3000 Well Drilling Programme in Southern and Central Ghana). The ranges indicate the limits of the 95% confidence intervals for the mean pH values.**

The distribution of aquifer rock types (acidic, intermediate, and basic) based on the rock classification system noted in Section 2.1 and on the relationship between rock type and pH, indicates that about 75% of the subregion has groundwater with a pH < 7.



Field observations indicate that there is also a strong relationship between the lithology of the aquifer and the electrical conductivity (EC) of the water from the aquifer (Fig. A.5.2).



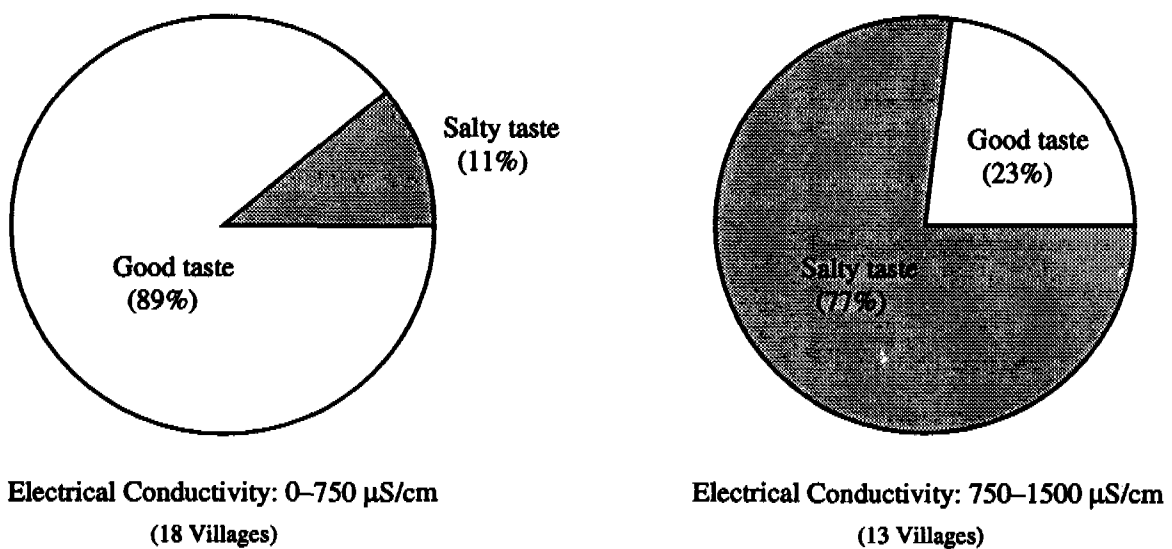
**Figure A.5.2 Relationship between rock type and EC (3000 Well Drilling Programme in Southern and Central Ghana). The ranges indicate the limits of the 95% confidence intervals for the mean EC values.**

As with the pH (Fig. A.5.1), there is some overlap of EC ranges among different rock types. This situation limits the reliability of a test for determining aquifer rock type (and vice versa) when only one parameter, such as EC or pH, is measured. In combination, however, EC and pH provide a very useful pair of easily measurable parameters for identifying the aquifer rock type.

## Appendix 6. The Impact of Groundwater Conductivity (salinity) on User Acceptance

Salinity has a major effect on taste and, thus, on user acceptance of water. In this report salinity is a measure of the concentration of dissolved minerals (salts) in water, not just the concentration of sodium chloride (NaCl).

There is no clearly defined threshold between non-salty and salty water, but the information presented in Figure A.6.1 supports the statements made in the text that in the savanna areas groundwater with an EC greater than 1000  $\mu\text{S}/\text{cm}$  is generally considered salty while in the forest areas the threshold is 300–500  $\mu\text{S}/\text{cm}$ .



**Figure A.6.1** User perception of taste based on its electrical conductivity (salinity) (Handpumps Project area in Niamey, Niger)

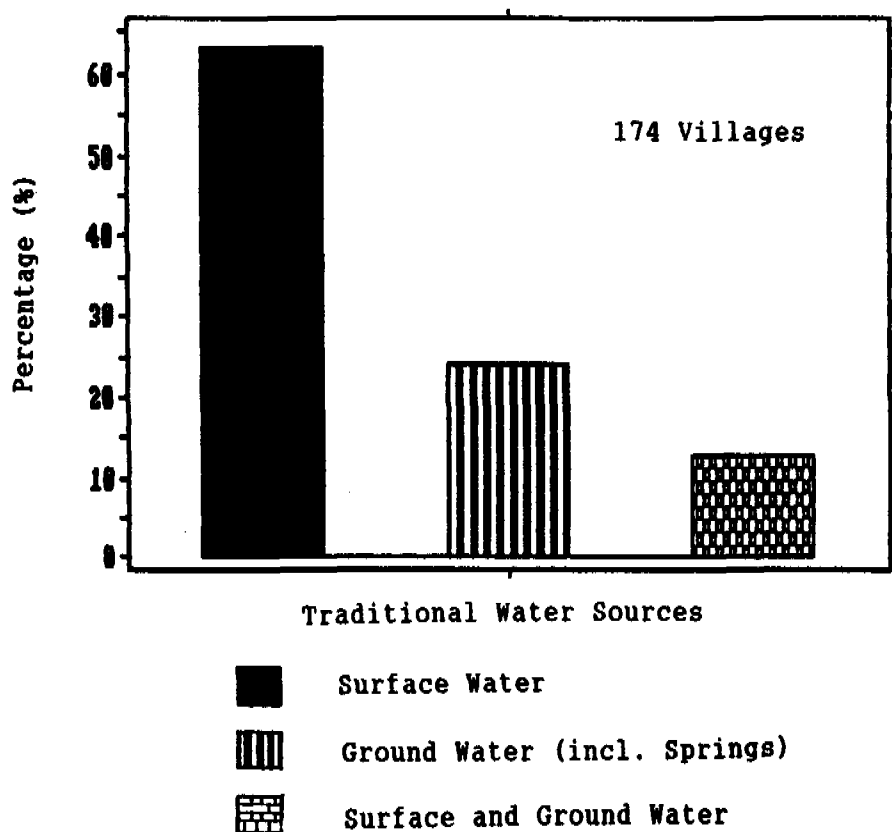
The EC can be used to estimate the change in taste (related to salinity) that will occur where water supply projects introduce new water sources. A survey within the 3000 Well Drilling Programme in Southern and Central Ghana revealed that over 60% of the rural population depended entirely on surface water (which generally has a low EC), about 13% used surface water and groundwater, and about 24% used mainly groundwater including springs (Figs. A.6.2 and A.6.3), a situation typical of the forest areas.

The EC of traditional water sources (surface water) and of groundwater from drilled wells in the 3000 Well Drilling Programme in Southern and Central Ghana is presented in Figure A.6.3. Of the 53 villages considered, the change from the traditional water source to the new water points (drilled wells with handpumps) resulted in an increase

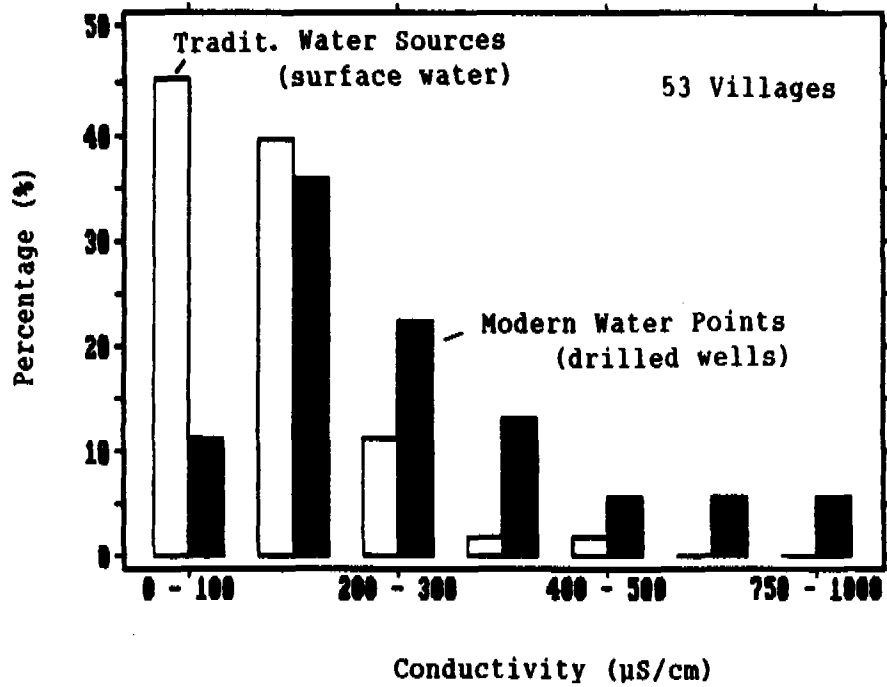
of the mean EC from 127  $\mu\text{S}/\text{cm}$  to 270  $\mu\text{S}/\text{cm}$ . Furthermore, 30% of the new water points had EC values higher than the aforementioned lower threshold limit of "salinity" (300  $\mu\text{S}/\text{cm}$ ), while only 4% of the traditional water points exceeded that threshold.

Such a change in water quality can by itself have a significant effect on user acceptance of new water points. In such situations, infrequent use of handpumps is not uncommon, and in cases where handpumps are affected by corrosion, infrequent use of the handpumps increases the water quality problem related to corrosion (high iron concentrations). This can easily result in the total abandonment of handpumps by the users (see Chapter 4).

Therefore, the possible user reaction to the change in the taste of water that accompanies a change in the source (e.g., from traditional water point of surface water to a new handpump-equipped well that taps groundwater) should be taken into account in the early preparation stages of a project and, if necessary, the beneficiaries of such projects should be prepared for the new situation by information campaigns.



**Figure A.6.2** Distribution of traditional water sources in villages within the 3000 Well Drilling Programme in Southern and Central Ghana



**Figure A.6.3** Electrical conductivity of water from traditional sources (surface water) and from modern drilled wells (data from 53 villages in the 3000 Well Drilling Programme in Southern and Central Ghana)

## Appendix 7. Seasonal Variations in Water Quality

Variations in certain parameters over time are an excellent indicator of groundwater quality (physico-chemical and bacteriological composition). Variations in groundwater quality are usually linked to the recharge of aquifers, which is connected with the rainy seasons in the subregion. Small seasonal variations of physico-chemical parameters indicate that the groundwater is influenced very little by external elements.

Deep groundwater from bedrock formations usually shows little seasonal variation, while shallow groundwater, for example, from the overburden, is generally more susceptible to such variations. In the Côte d'Ivoire field trial, seasonal variations of total hardness and electrical conductivity were within 10% of the mean values for 50% and 57% of the monitored wells, which tapped deep aquifers (Fig. A.7.1 and A.7.2). Field investigations indicate that wells that produce water with relatively high variations in physico-chemical composition are affected by shallow groundwater (Fig. A.7.3).

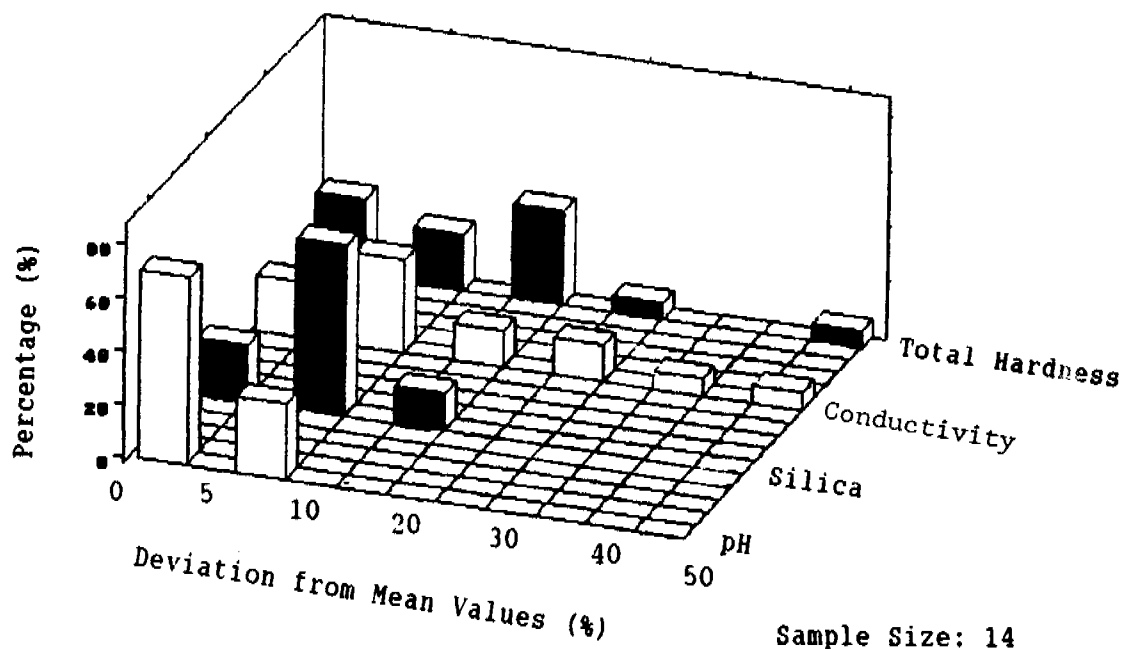
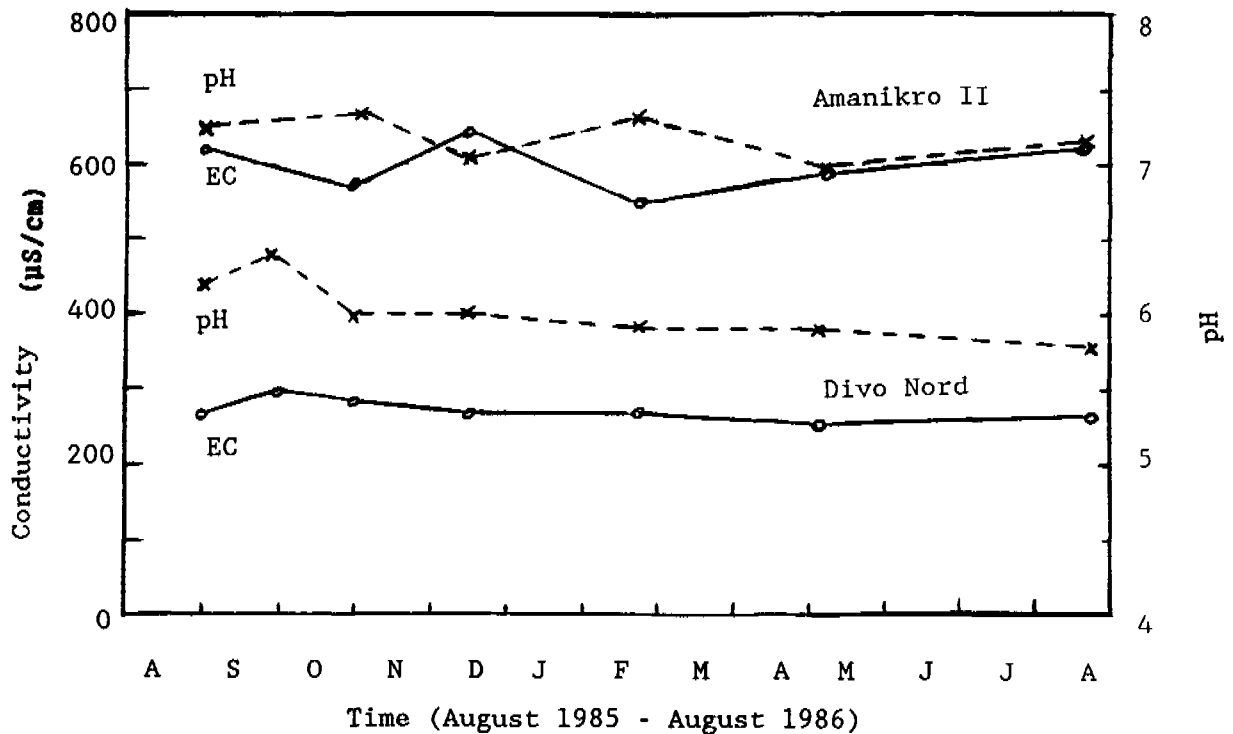
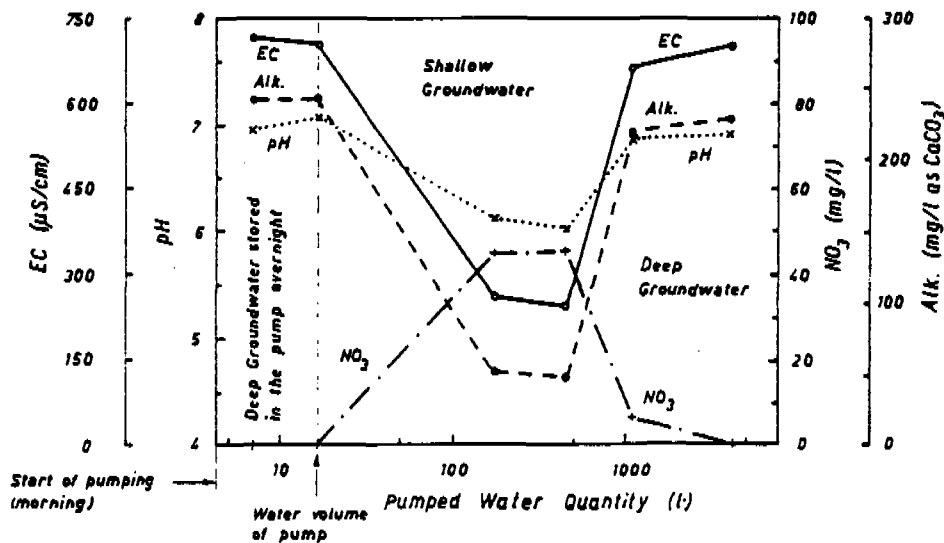


Figure A.7.1 Deviation of total hardness, electrical conductivity, silica, and pH from their mean values (August 1985–August 1986)



**Figure A.7.2** Electrical conductivity and pH of two wells versus time (August 1985–August 1986, Côte d'Ivoire)



**Figure A.7.3** Variation in physico-chemical composition of groundwater from a granitic aquifer (tapped at a depth of 40 m) due to mixing with shallow groundwater from the overburden during a pumping test (Côte d'Ivoire)

## Appendix 8. Groundwater Pollution

The purpose of this appendix is to briefly describe the main types of groundwater pollution that occur in the rural environment of the subregion, and, on the basis of a few examples, to illustrate the extent of groundwater pollution encountered during the investigations for this report.

It is convenient to distinguish between two types of pollution: pollution of aquifers (groundwater pollution) and pollution of water points (in this case handpump-equipped wells).

### Groundwater Pollution

The main sources of groundwater pollution of aquifers in the subregion are:

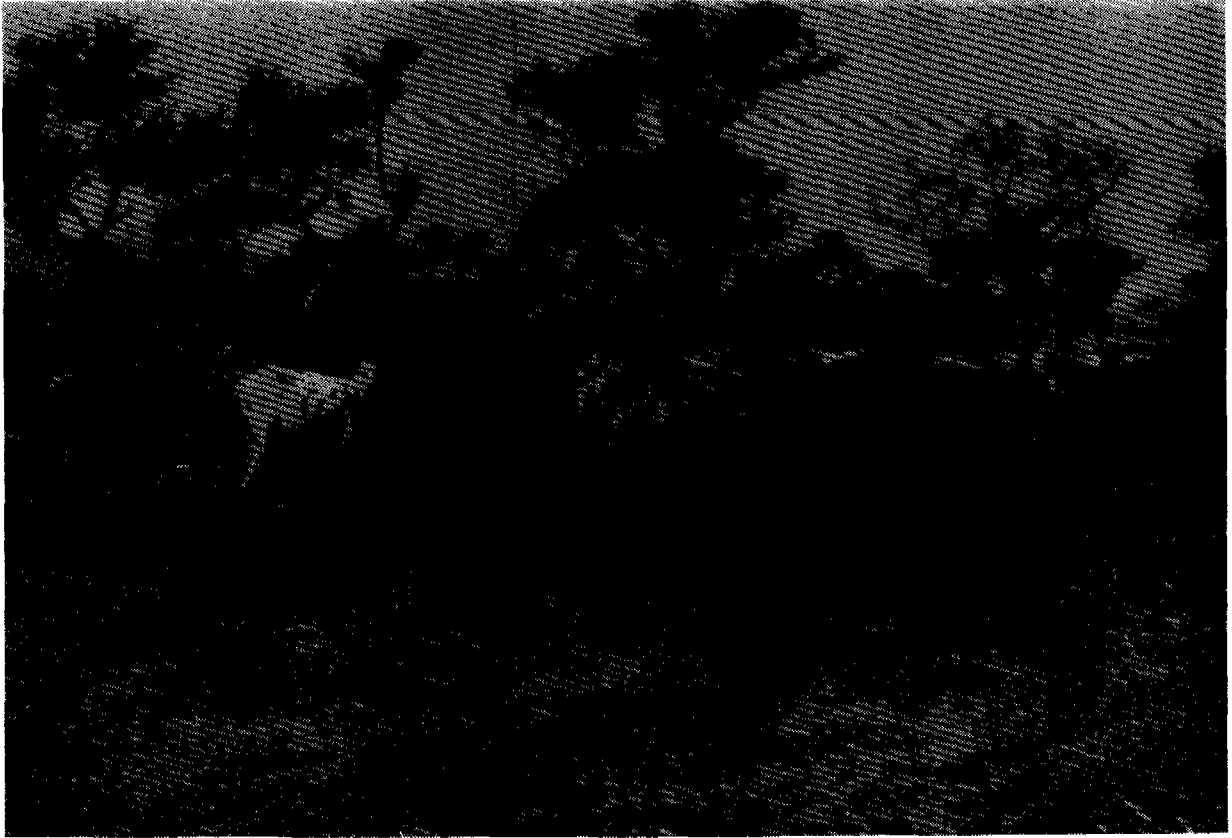
- Organic wastes (domestic refuse and excrement)
- Presence of livestock around water points
- Inadequate sanitary conditions and poor drainage around water points
- Agriculture (fertilizers, pesticides, etc.)

The single most frequent source of aquifer pollution in rural settlements of the subregion is domestic organic waste. Nitrate, which is an excellent indicator of this type of pollution, is especially high where wells are located in densely populated settlements, such as large villages and towns, which usually have poor waste disposal facilities. Under such conditions, nitrate levels of up to 500 mg/l have been recorded (Groen et al. 1988; Langenegger 1981).

Even wells located some distance from the nearest village can produce water with relatively high nitrate content if, for example, the well is used intensively for watering cattle; this creates conditions similar to those in a feedlot (Fig. A.8.1). Such concentrations of livestock around water points that are also a source of water for human use present pollution hazards. The degree of health hazard in such a case depends on the hydrogeological situation and on the sanitary conditions of the wells and their environment.

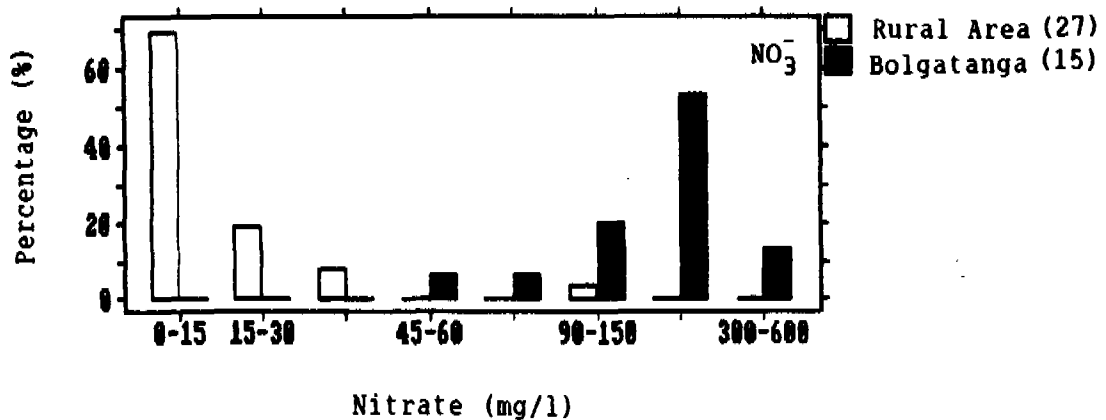
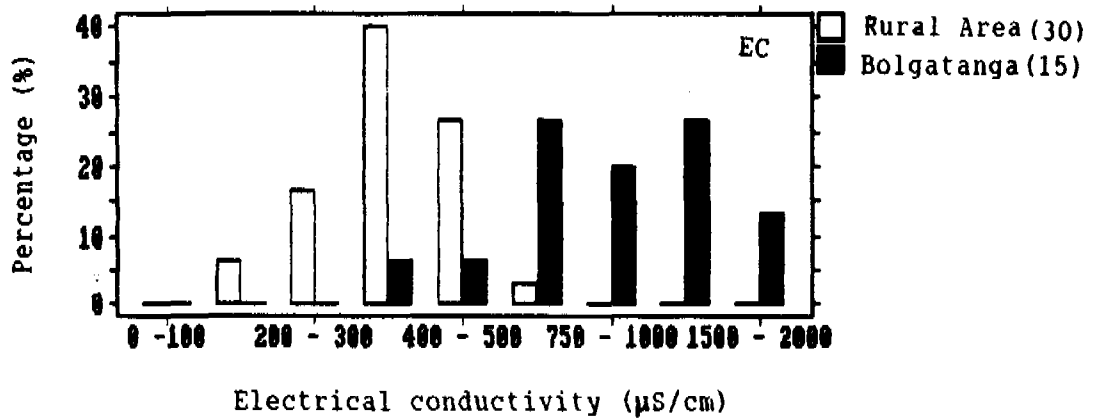
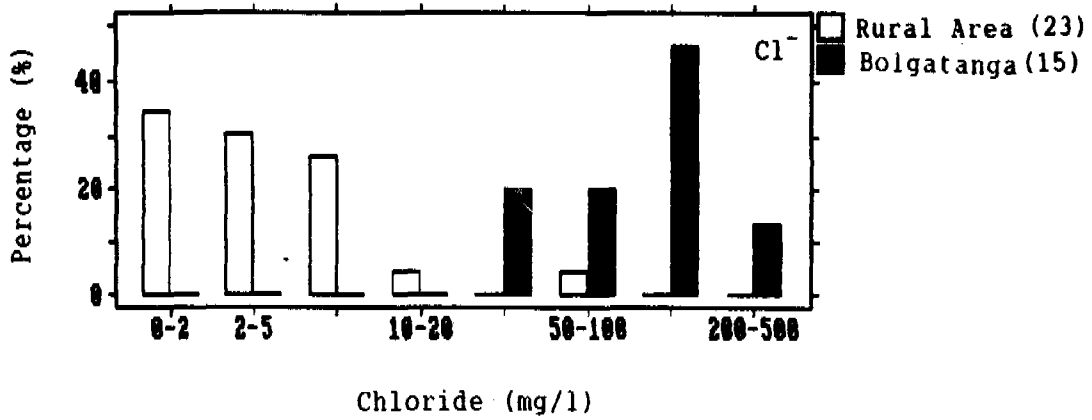
Although in some areas there are indications that groundwater pollution is caused by the application of fertilizers to crops, the water quality investigations performed within the Handpumps Project did not provide sufficient evidence to quantify this kind of pollution. Akiti (1982) has suggested that there is a connection between an increase in the use of fertilizers and an increase of nitrate in groundwater in northern Ghana. Certainly intensive or excessive use of fertilizers is a potential factor in groundwater pollution and, therefore, should be taken into account in development plans.

Bolgatanga, in northern Ghana, has a population of about 30,000. In addition to the town water supply there are many private and public dug wells; most are in good condition and some even have covers. Typical of such settlements in the subregion, however, the sanitary conditions of the town are rather poor, and have a significant impact



**Figure A.8.1 Livestock around a handpump-equipped drilled well in Burkina Faso are a potential source of groundwater pollution.**





**Figure A.8.2 Comparison of the quality of shallow groundwater from Bolgatanga with that from nearby rural areas**

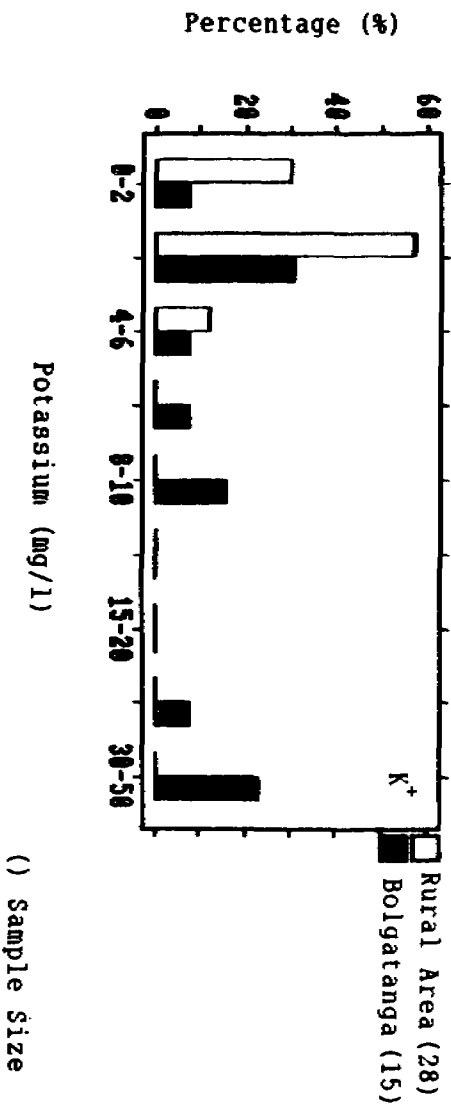
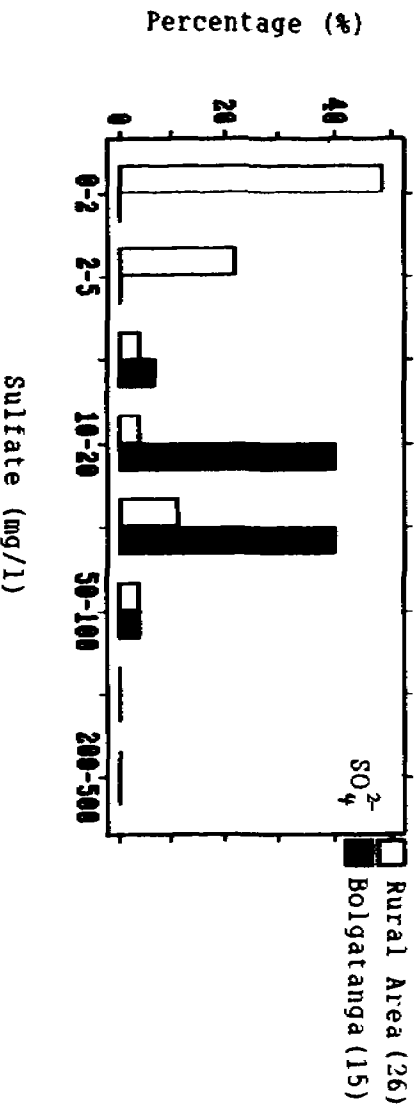
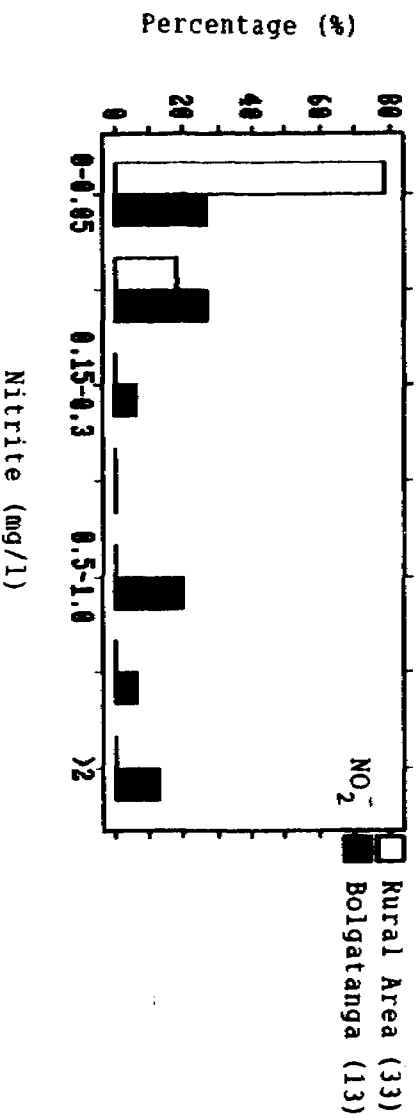


Figure A.8.2, continued.

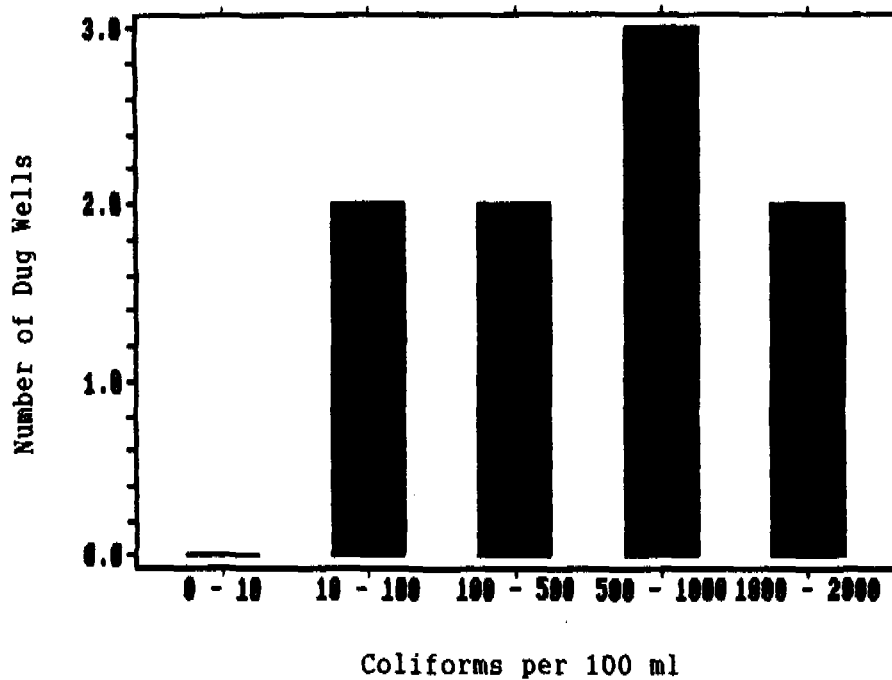
on groundwater quality. Comparison of the concentration of chemical constituents in groundwater obtained from dug wells in Bolgatanga and in groundwater obtained from drilled wells in nearby rural areas provides a good example of the severity of the pollution in large settlements in the subregion (Fig. A.8.2). Water level in the dug wells was 3–6 m, in the drilled wells 1–20 m. The study area is underlain by granitic rocks, and the investigations were carried out during the dry season in January 1988.

The results not only indicate the poor physico-chemical quality of the groundwater in rural towns and large villages in the subregion, but they also illustrate how the different "classic" pollution indicators complement each other. As a matter of fact, the water from a handpump-equipped drilled well in Bolgatanga showed a comparable degree of pollution to water from the dug wells (Table A.8.1).

**Table A.8.1**  
**Physico-Chemical Composition of Groundwater from a Handpump-Equipped Drilled Well in Bolgatanga**

Constituent	Value
Conductivity (EC)	1250 $\mu$ S/cm
Chloride	190 mg/l
Sulfate	3 mg/l
Potassium	6.5 mg/l
Nitrate	140 mg/l
Nitrite	0.26 mg/l

The concentration of coliform organisms in groundwater from the Bolgatanga dug wells was between 20 and 1250 per 100 ml, indicating a high degree of bacteriological contamination and a potential health hazard to the users (Fig. A.8.3).



Sample Size: 9

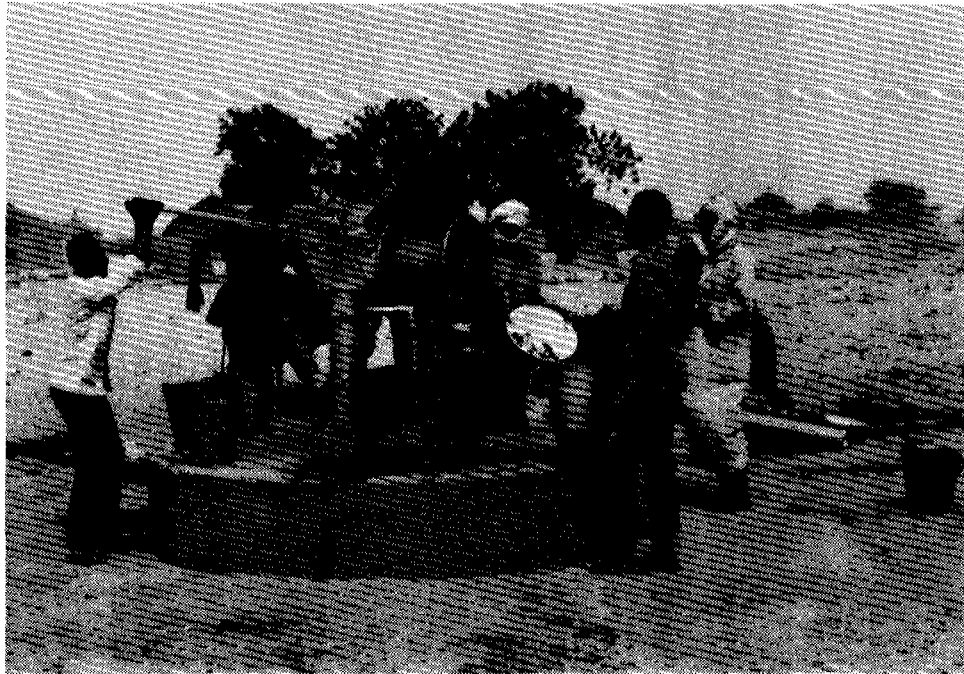
**Figure A.8.3 Coliforms per 100 ml in groundwater from dug wells in Bolgatanga**

### Well Pollution

The second type of pollution, well pollution, is caused by:

- Improper well construction or defective wells
- Improperly installed or defective handpumps
- Poor handpump design and handpump corrosion

The following example demonstrates well pollution due to improperly installed handpumps. In the Niger field trial of the Handpumps Project, handpumps were installed on large-diameter dug wells. The pumps, two on each well, were fixed on two metal beams, which were cemented into the protecting ring (uppermost part of the concrete-lined well casing) (Fig. A.8.4). The tops of the wells were covered with two semi-circular metal sheets screwed onto the metal beams. The joints of the two metal plates were not sealed, which resulted in a backflow of spilled water from the well cover into the well. Although the slots along the joints of the metal sheets and around the base plates of the handpumps were small (only a few millimeters), enough water and dirt flowed back through them to pollute the water in the well. Thus, instead of improving the water quality of the wells by installing handpumps as would be expected, the water quality decreased.



**Figure A.8.4 Handpumps installed on a dug well in Niger**

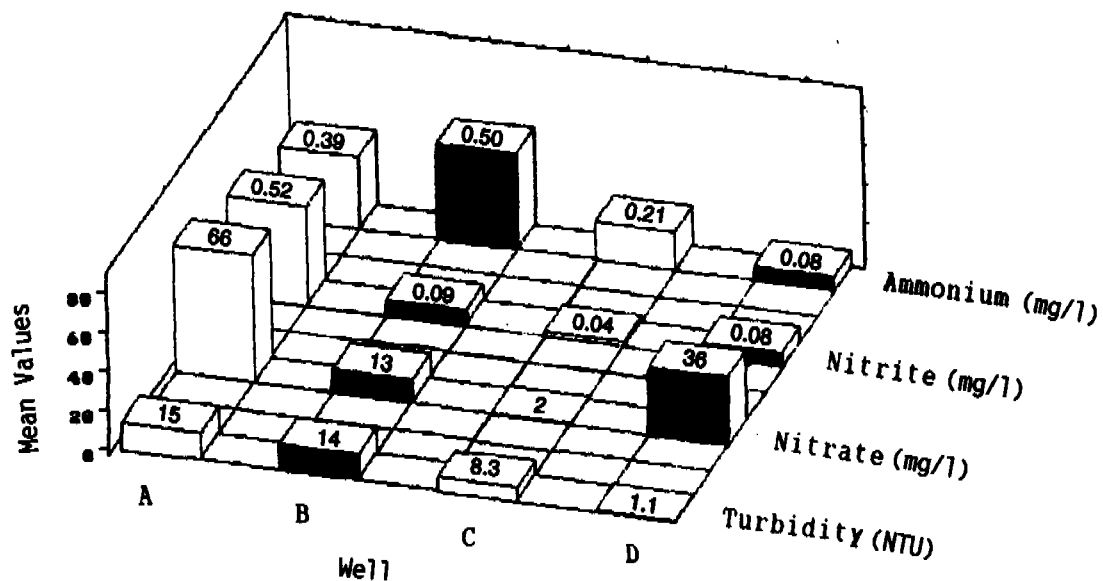
Analyses of water samples taken from: (1) handpump-equipped dug wells where the backflow of spilled water was a problem, (2) from dug wells with broken handpumps, whose metal covers were removed in order to get water with buckets, and (3) from dug wells without any handpumps are shown in Figure A.8.5. Although the sample size is small, the results are illustrative and indicate that water from the handpump-equipped wells, with pumps in normal operating condition, had the poorest quality of water. The problem was solved by using well covers made of concrete slabs, which protected the wells from the backflow of spilled water (Table A.8.2).

As illustrated in this appendix, there are several sources of groundwater and well pollution. The major problems in the rural environment are groundwater pollution by point sources (domestic waste and inadequate sanitary facilities and practices), improperly installed wells, and from the sanitary point of view, poorly maintained and poorly protected water points.

While groundwater and water point pollution in the rural environment (small and dispersed settlements) does not generally reach extreme levels, alarming levels are rather common in large villages and rural towns.

Groundwater pollution in rural areas of developing countries could be drastically reduced by applying basic principles of sanitation (especially waste and excrement disposal), proper well construction, and water point protection. But these factors alone are not enough to make a water project successful. The beneficiaries must understand the basics

of hygiene in order to convince them of the need to accept and follow new waste disposal and sanitation practices.



- Legend:**
- A Dug wells with operational handpumps (5 wells)
  - B Dug wells with broken handpumps (2 wells)
  - C Dug wells without handpumps (3 wells)
  - D Drilled wells with handpumps (3 wells)

**Range of Mean Values:**  
(vertical axis)

Ammonium	0-0.8 mg/l	Nitrite	0-0.8 mg/l
Turbidity	0-80 NTU	Nitrate	0-80 mg/l

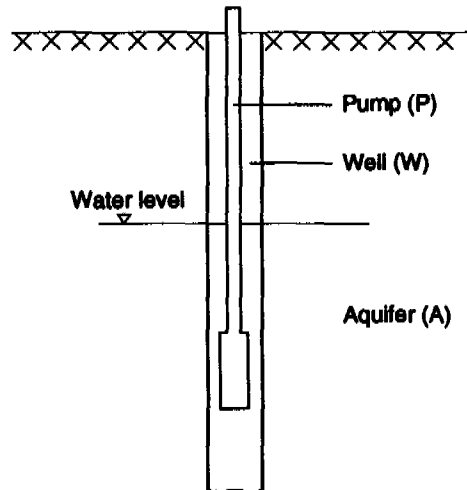
**Figure A.8.5** Mean concentration of ammonium, nitrite, nitrate, and turbidity indicating the effect of improperly installed handpumps on the water quality of dug wells

**Table A.8.2**  
**Mean Values of Turbidity, Ammonium, and Nitrite of Two Dug Wells Before and After Replacement of Metal Well Covers with Concrete Well Covers**

Component	Type of Well Cover	
	nonselaled (metal)	sealed (concrete)
Ammonium (mg/l NH <sub>4</sub> <sup>+</sup> )	0.45	0.18
Nitrite (mg/l NO <sub>2</sub> <sup>-</sup> )	0.04	0.01
Turbidity (NTU)	22	10

## Appendix 9. The Aquifer-Well-Pump System

In order to describe and understand the mechanism of handpump corrosion, it is useful to distinguish three different parts: (1) the aquifer, (2) the well, and (3) the pump (rising main-cylinder assembly) (Fig. A.9.1).



**Figure A.9.1** The aquifer-well-pump system

The water quality of these three elements can be characterized as follows:

**Aquifer (A):** The water quality is determined by the environment (hydrogeology, climate, anthropogenic factors) and is, apart from minimal seasonal variations, of a constant composition.

**Well (W):** A number of variables can have an effect on the water quality, for example corrosion of well screens, well casings, and pump parts, degassing through pressure release, aeration, pump operating conditions, and daily discharge rates. As for corrosion, the specific external surface area of rising mains per water volume in a drilled well in a typical handpump application ranges from 10 to 60 cm<sup>2</sup>/l.

**Pump (P):** The same variables apply to the pump as to the well, but the specific internal surface area of rising mains (including the surface area of the pump rods) per water volume is about 2000 cm<sup>2</sup>/l.

Field observations have indicated that there are differences in water quality in the different parts of the A-W-P system. Pumping tests performed on wells with non-



corrosion-resistant handpumps provided data on typical water quality variations in the A-W-P system of a corrosion-affected well during the course of a full 24-hour day. A hypothetical example is presented in Fig. A.9.2. The composition of the pumped water in the evening, after the handpump had been intensively used, is presented in the left margin of the shadowed areas of the diagrams in Figure A.9.2. At that time, the water was only very slightly or not at all affected by corrosion. The shadowed areas indicate the night, when the handpump was locked for 13.5 hours. During this pause, the water in the pump (P) and in the well (W) were heavily affected by corrosion, which is illustrated by the shadowed zones in Figure A.9.2. For example, the iron concentration in the pump increased from 1.9 to 105 mg/l, the conductivity from 260 to 360  $\mu\text{S}/\text{cm}$ , the turbidity from 5 to 180 NTU, and the total hardness decreased from 59 to 49 mg/l (as  $\text{CaCO}_3$ ). The changes in water quality are much higher in the pump (P) than in the well (W), mainly because the specific metal surface area per water volume is much higher in the pump than in the well.

The diagrams in Figure A.9.2 indicate that most of the constituents return to values close to those of the groundwater in the aquifer (A) after continuous pumping of about 100 liters. In other words, the difference in water quality between the three parts (aquifer, well, pump) is negligible if a handpump is used more or less continuously. Handpumps are usually operated intermittently, however, with interruptions of several hours, particularly at night. The results from the data in Figure A.9.2 have been confirmed by pump tests performed on other wells.

In addition to variations in water quality due to corrosion, the results presented in Figure A.9.2 also illustrate a remarkable difference between internal and external corrosion, especially with regard to total hardness, calcium, and silica. The iron concentration is dependent on the specific metal surface area per water volume. The decrease in concentration of calcium and magnesium is related to the changes in pH and free carbon dioxide, and indicates that calcium and magnesium are deposited as scale (protective coating) on the metal surfaces in the pump assembly. The difference between the degree of internal versus external corrosion is generally easy to note by (1) comparing the roughness of the internal and external surfaces of the rising mains, and (2) noting the differences in mineralogical composition of the internal and external corrosion products (biofilm, protective scale) (see Appendix 11).

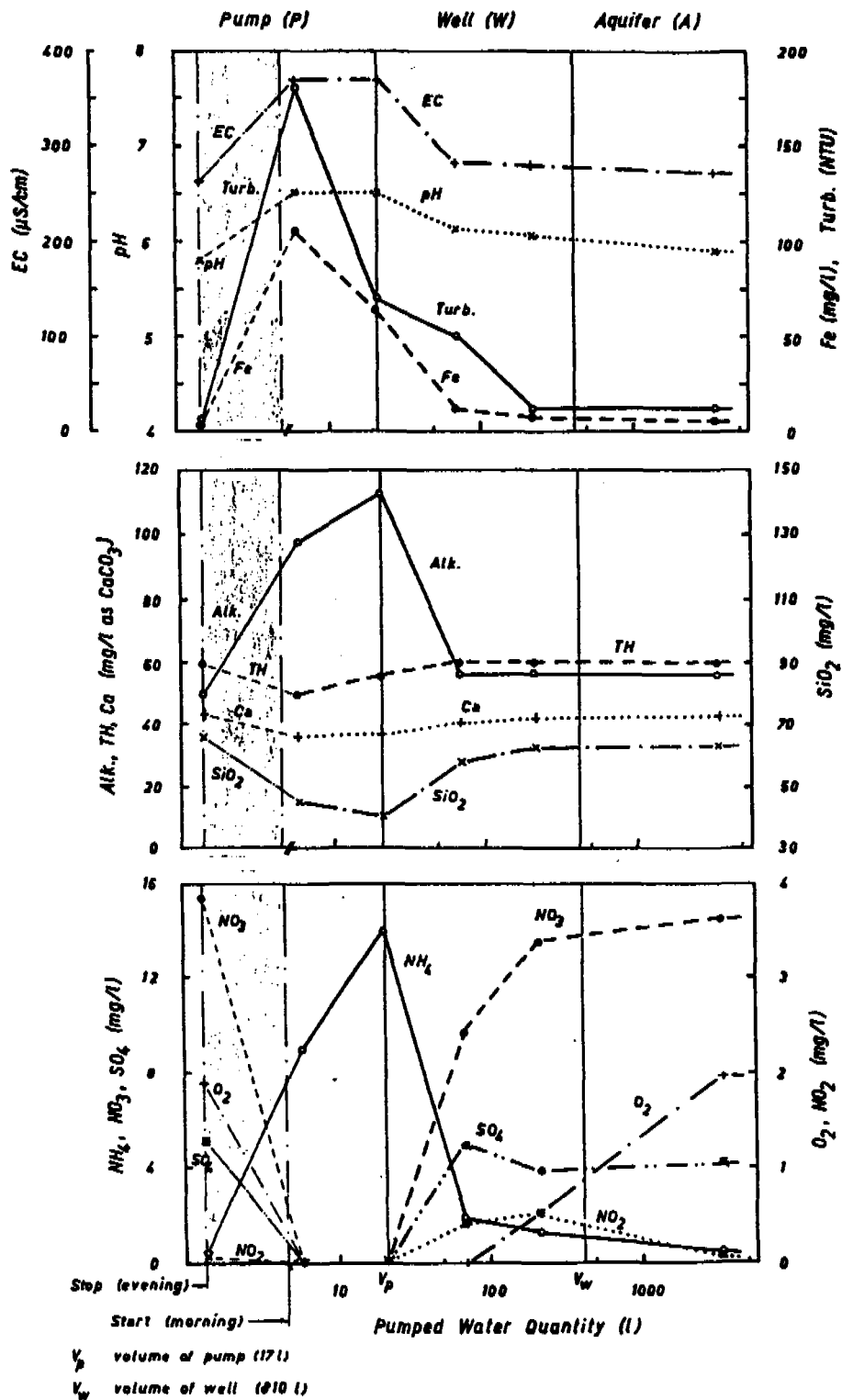


Figure A.9.2 Typical variations in water quality (from a well affected by handpump corrosion) as a function of operating conditions (Côte d'Ivoire)

## Appendix 10. Corrosion Rates

Corrosion rates can be measured in different ways. Two of these are:

- (1) Penetration rate:
  - milliinches (mils) per year (mpy)
  - millimeters per year (mm/y)
  - micrometers per year ( $\mu\text{m}/\text{y}$ )
  
- (2) Mass loss per unit area:
  - milligrams/cm<sup>2</sup> per day (mg/cm<sup>2</sup>/d)
  - grams/m<sup>2</sup> per day (g/m<sup>2</sup>/d)

Usually, penetration rate is used to measure corrosion damage (Table A.10.1), but sometimes it is useful to use diameter reduction (mm/y) as a measure of corrosion rate because most of the corrosion samples used for this report were coupons from pump rods. The diameter reduction is equal to twice the penetration rate:

$$\text{diameter reduction} = \text{penetration rate} \times 2$$

**Table A.10.1**  
**Adjective Rating of Corrosion Damages (Clarke 1980)**

Metal Penetration	Rating
< 0.05	mild
0.05 to 0.5	moderate
0.5 to 1.25	severe
> 1.25	extreme

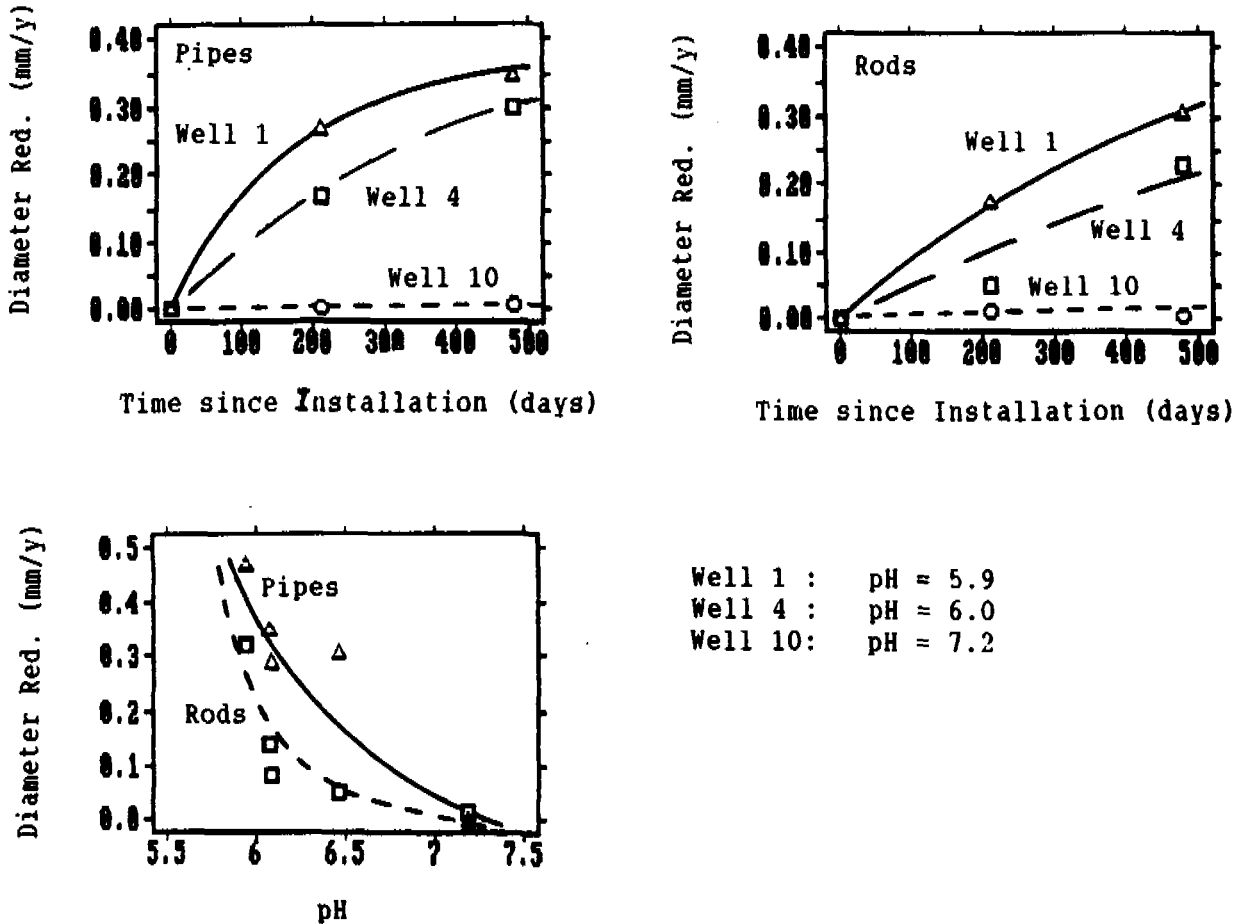
The rate of internal corrosion in rising mains was between 0 and 0.3 mm/y. In addition to corrosion, however, the rubbing between pump rods and rising mains can also reduce the diameter of the pump rod and the wall thickness of the rising main. This effect, which makes accurate corrosion rate measurements difficult, was not taken into account in the results presented in this report.

Galvanic corrosion can cause much higher corrosion rates than other forms of corrosion. In southern Ghana, for example, galvanic corrosion rates as high as 4 mm/y

diameter reduction were observed on galvanized pump rods adjacent to the point of contact with the pump cylinder, which was made of brass.

Flow velocity, although it can increase the corrosion rate of galvanized pipes significantly when the velocity is greater than 1 m/s (AWWA-DVGW 1985), was not considered in this report because the maximum flow velocity of water in the rising mains of handpumps was only about 0.3 m/s. There are, however, two elements related to flow velocity that aggravate the red water problem in the morning: (1) the change from the steady-state (no water flow overnight) to the non-steady-state (pump operation) condition resulting in loosening and flushing of corrosion particles and biofilm debris, which formed overnight, from pipe and pump rod surfaces, and (2) vibration of the downhole components of handpumps during pump operation, which also helps to loosen corrosion particles.

Corrosion rate measurements of rising mains (external diameter) and pump rods taken over a period of about sixteen months are presented in Figure A.10.1.



Note: For details on the characteristics of these wells, see Table A.13.1.

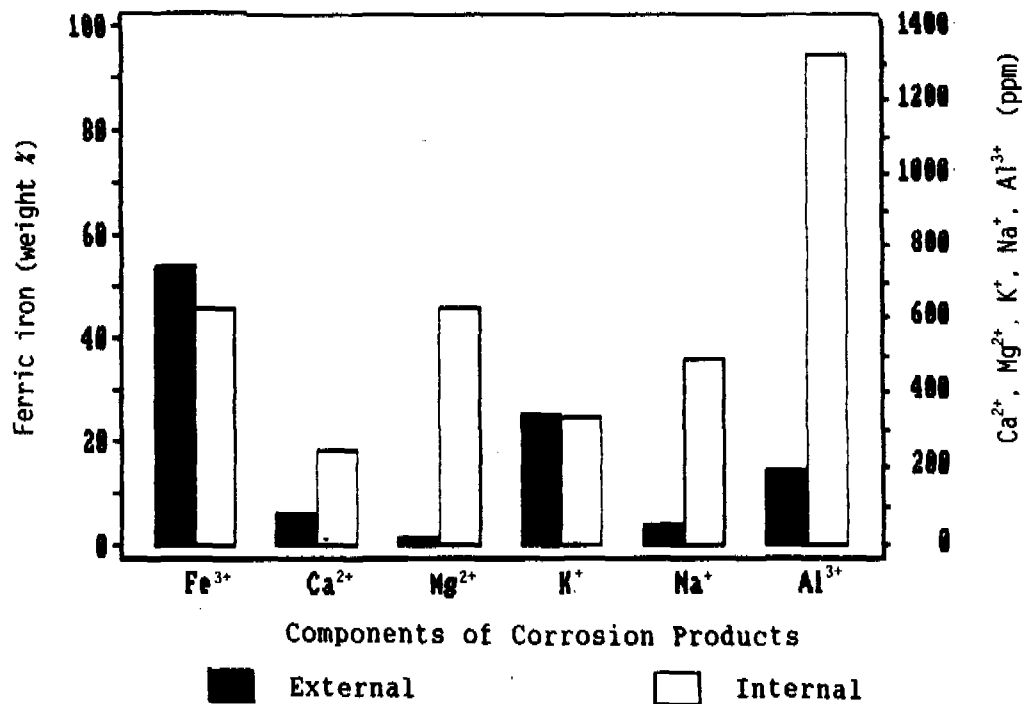
Figure A.10.1 Corrosion rates of galvanized rising mains and pump rods versus time and pH

## Appendix 11. Corrosion Products and Development of Scales

Dried corrosion products of red-brown mud (biofilm) from: (1) internal and external surfaces of pipes and rods, (2) corrosion test samples (pump rod samples), (3) the bottom of boreholes, and (4) sediments of corrosion tests carried out in the laboratory were analyzed for their chemical composition.

The main constituent of such corrosion products was (as weight percent) iron (40–60%). Zinc, calcium, magnesium, potassium, sodium, and aluminum made up 0.1–4%, and the remainder may be organic matter (which originated from the activities of iron bacteria) and silica.

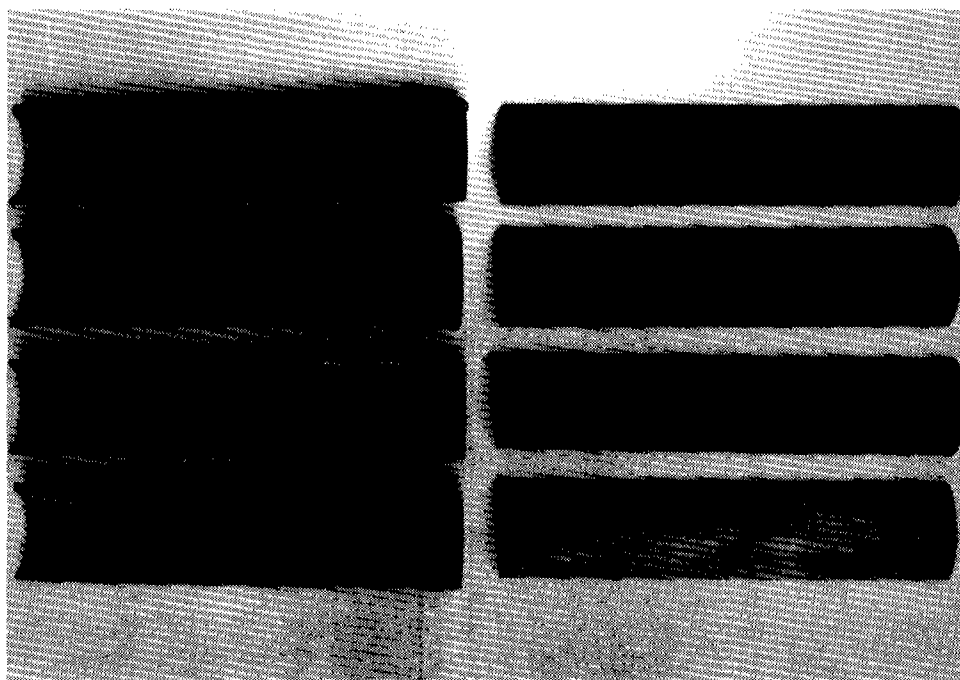
There is a striking difference between the chemical composition of dried corrosion products from internal and from external surfaces of rising mains (Fig. A.11.1), which reflects the difference in the quality of the water found in the handpump (rising main) versus that found in the well (see Section 5.2 and Appendix 9). It also provides evidence that, although biofilm forms on both internal and external surfaces, conditions for the formation of protective scale are more favorable on the internal than on the external surfaces of rising mains (see Fig. A.11.2).



**Figure A.11.1** Ferric iron (Fe<sup>3+</sup>), calcium (Ca<sup>2+</sup>), magnesium (Mg<sup>2+</sup>), potassium (K<sup>+</sup>), sodium (Na<sup>+</sup>), and aluminum (Al<sup>3+</sup>) in corrosion products (weight percent) from internal and external surfaces of rising mains (southern Ghana; average of two samples)

It is essential to distinguish between those corrosion products that are produced on metal surfaces immersed in water (thus influenced by the activity of iron bacteria), and those produced on metal surfaces exposed to water vapor (including rain) in the air (atmospheric corrosion). Atmospheric corrosion rates are significantly lower than those observed in water, and the primary corrosion product is rust (primarily iron (III)-oxyhydroxide such as  $\text{FeOOH}$ ).<sup>3</sup> Rust may also occur on rising mains of handpumps when corroded pipes, with their galvanized layer gone, are installed above the water level. The external pipe surfaces are then no longer immersed in water, which results in atmospheric corrosion. The same effect can be observed on rising mains (with their galvanized layer no longer intact) exposed to the atmosphere in dumps or stores.

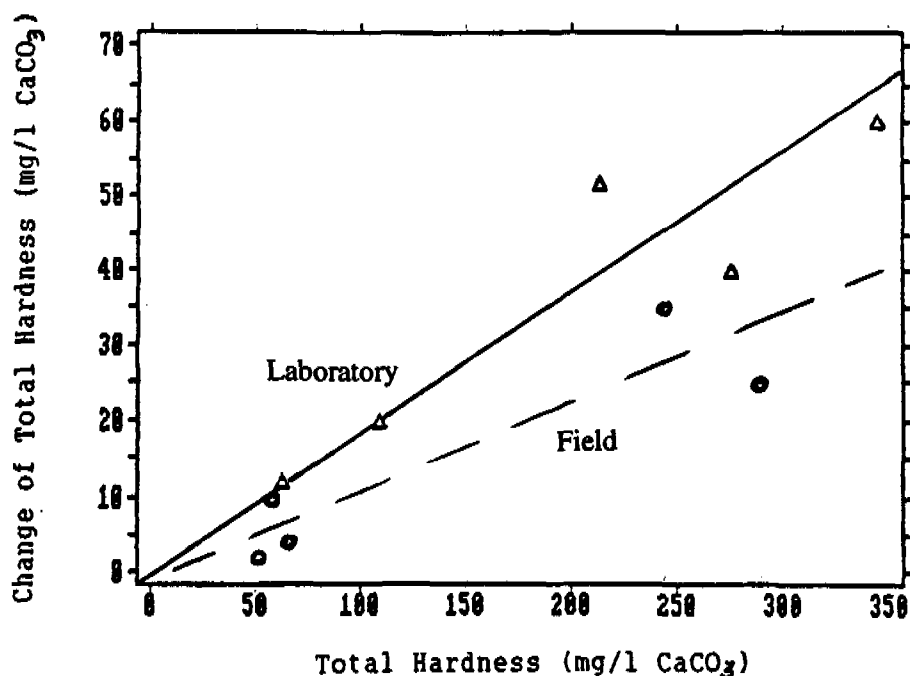
The chemical composition of the corrosion products suggests that the total hardness of the water is particularly important in scale formation, and that the amount of calcium and magnesium deposited in the biofilm (scale) also depends upon the hardness of the water. In other words, the harder the water, the more calcium and magnesium can be deposited, and the more favorable are the conditions for the development of a protective biofilm (scale). In investigations for this report, it was noted that the total hardness of groundwater decreased (under field and laboratory conditions) due to corrosion-induced changes in water quality (see Fig. A.11.3; Section 5.2; and Appendix 9).



**Figure A.11.2** Internal and external surfaces of galvanized rising mains

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<sup>3</sup> Two pumprod samples made of milled steel were exposed to the atmosphere in Abidjan, Côte d'Ivoire, for 11 months. The corrosion rate measured was  $< 0.02$  mm/y.



Note: The data used for Figure A.11.3 was obtained from pumping tests (Appendix 9) and immersion tests (Appendix 14). The change in total hardness is the difference in total hardness before and after the tests.

**Figure A.11.3. Change in total hardness of groundwater versus total hardness. Decrease in TH was due to corrosion-caused changes in water quality.**

Biofilm (not protective scale) from the external surfaces of rising mains eventually settles to the bottom of wells. The average iron concentration (weight percent) of four mud samples from the bottom of drilled wells equipped with non-corrosion-resistant handpumps was 33%, with a minimum value of 16.6% and a maximum value of 42.6%. These results correspond to those obtained from the mud analyses presented in Figure A.11.1.

Detailed investigations of the surfaces of rising mains and pump rods with respect to the formation of protective layers (scales, biofilms) or the extent of corrosion of the galvanized coating were not possible within the Handpumps Project. The following qualitative conclusions can be drawn, however, from the combination of (1) visual inspections of rising mains that were exposed to different types of groundwater for periods of 16 to 30 months, (2) parameters of water quality (Table A.11.1), and (3) results of pumping tests (Appendix 10).

- (1) The development of protective scale on the external surface of galvanized rising mains was observed only in one well (No. 10). The groundwater in this well had a pH = 7.2, EC = 600  $\mu$ S/cm, and total hardness = 215 mg/l (as

$\text{CaCO}_3$ ). The scale was gray-white in color. No clear indication of scale development was observed on external surfaces of rising mains at  $\text{pH} < 7$ .

- (2) The external surfaces of rising mains, except for the case mentioned under point (1), are usually covered with red mud (biofilm), which is powdery when dried and falls off easily (Fig. A.11.2). This biofilm can be as thick as 2 mm.
- (3) The development of a thin, protective scale of grayish appearance on the internal surface of rising mains was observed in groundwater with  $\text{pH} > 6.5$  and  $\text{EC} > 300 \mu\text{S}/\text{cm}$ . In all other cases, however, a red-brown crust (biofilm) was observed. Some of these crusts were, when dried, relatively hard and adherent to the surface. Others were very soft, with a powdery or crumbling consistency, similar to those generally observed on the external surfaces of pipes. The chemical composition of such "bio-scales" (a mixture of a scale composed of carbonates and various other mineral compounds, and a biofilm composed of various iron and organic compounds) depends on the water quality and the operating conditions of the pump. The one primary difference between the two coatings was that "real" scales were observed on the intact zinc layer, while "bio-scales" (crusts) were generally located directly on the iron surfaces.
- (4) Biofilms were also observed on materials other than iron, for example on stainless steel, aluminum, plastic, and galvanized and scale-protected surfaces of pipes (Fig. A.11.4).
- (5) While scales on both internal and external surfaces of rising mains and on pump rods seem to protect them from corrosion, "bio-scales" do not completely protect the surfaces from corrosion, although they do reduce corrosion.
- (6) Scales on the internal surfaces are often partially destroyed by the rubbing of the pump rods and rising mains. Damage caused by rubbing is usually local and is concentrated in areas near the rod connectors.



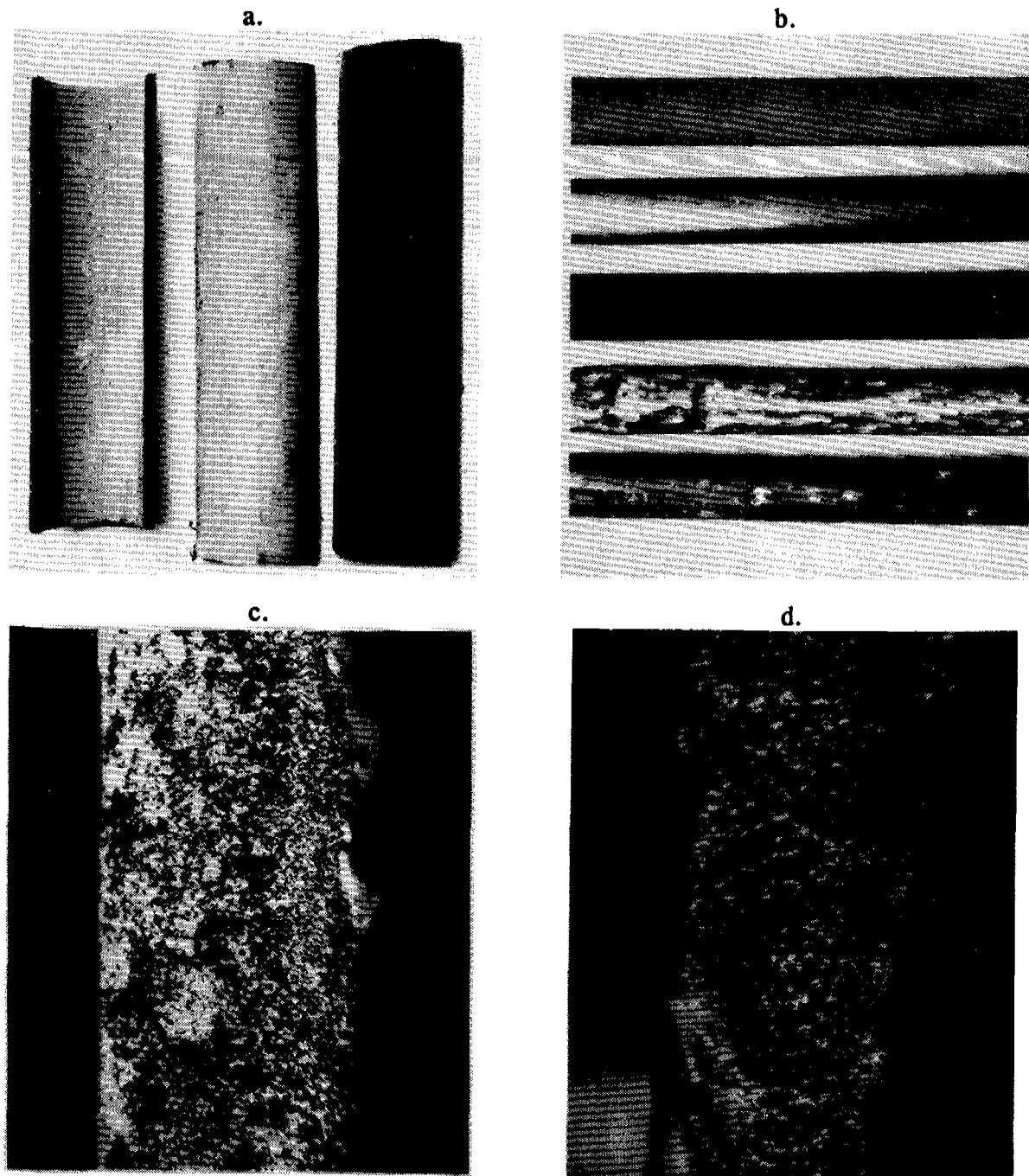
**Table A.11.1**  
**Field Observations of Scale and Biofilm Development on Galvanized Rising Mains**

External Surface								
Well No.	pH <sup>a</sup>	EC <sup>a</sup>	Biofilm	Bioscale (crust)	Scale	Consistency	Galvanization	Remarks
1	5.95	270	+	-	-	S	-	
3	6.10	260	+	-	-	S	-	
4	6.10	310	+	-	+/-	H	+/-	
8	6.50	755	+	-	-	S	-	
10	7.20	595	+	-	+	H	+	white biofilm

Internal Surface								
Well No.	pH <sup>a</sup>	EC <sup>a</sup>	Biofilm	Bioscale (crust)	Scale	Consistency	Galvanization	Remarks
1	5.95	270	+	+	-	S/M	-	some rubbing
3	6.10	260	+	+	-	M/H	+/-	rubbing
4	6.10	310	+	-	+	H	+	
8	6.50	755	+	+	-	M	+/-	
10	7.20	595	+	-	+	H	+	

<sup>a</sup>mean values

Legend:      +      existent                      S = soft  
                  -      nonexistent                    H = hard  
                  +/-      partially existent            M = medium



- a. Biofilms on plastic rising mains: left (internal), center (external), right (external without biofilm)
- b. Biofilms (top two) and black oxide (middle) on aluminum pump rods, and slightly corroded (bottom two) aluminum pump rods
- c. Biofilms on iron pump rod test sample
- d. Partially removed biofilm on an iron pump rod test sample with calcite crystals

**Figure A.11.4 Biofilms on different materials**

## Appendix 12. Effect of Microbiological Activity on Corrosion

Microbiological processes are involved in handpump corrosion (see Section 2.4.3). To determine what impact the microbiological processes of iron bacteria have on handpump corrosion, sterilized samples (pump rod samples made of mild steel) were exposed to groundwater from two different wells (Fig. A.12.1). One of the wells was equipped with a corrosion-resistant handpump, the other with a non-corrosion-resistant handpump. The tests were conducted with unfiltered water and with filtered water. One of the unfiltered samples taken from the well with the non-corrosion-resistant handpump was kept in the refrigerator at a temperature of about 10°C. The filtration of the water samples was carried out with Millipore equipment using filters with a pore size of 0.45 µm. The temperature of the water samples, except for the one kept in the refrigerator, was 26–27°C, which corresponds to the groundwater temperature. All of the samples were protected from light. The oxygen concentration in the water was 2–4 mg/l, similar to the oxidizing conditions that prevail in the field (well and aquifer).

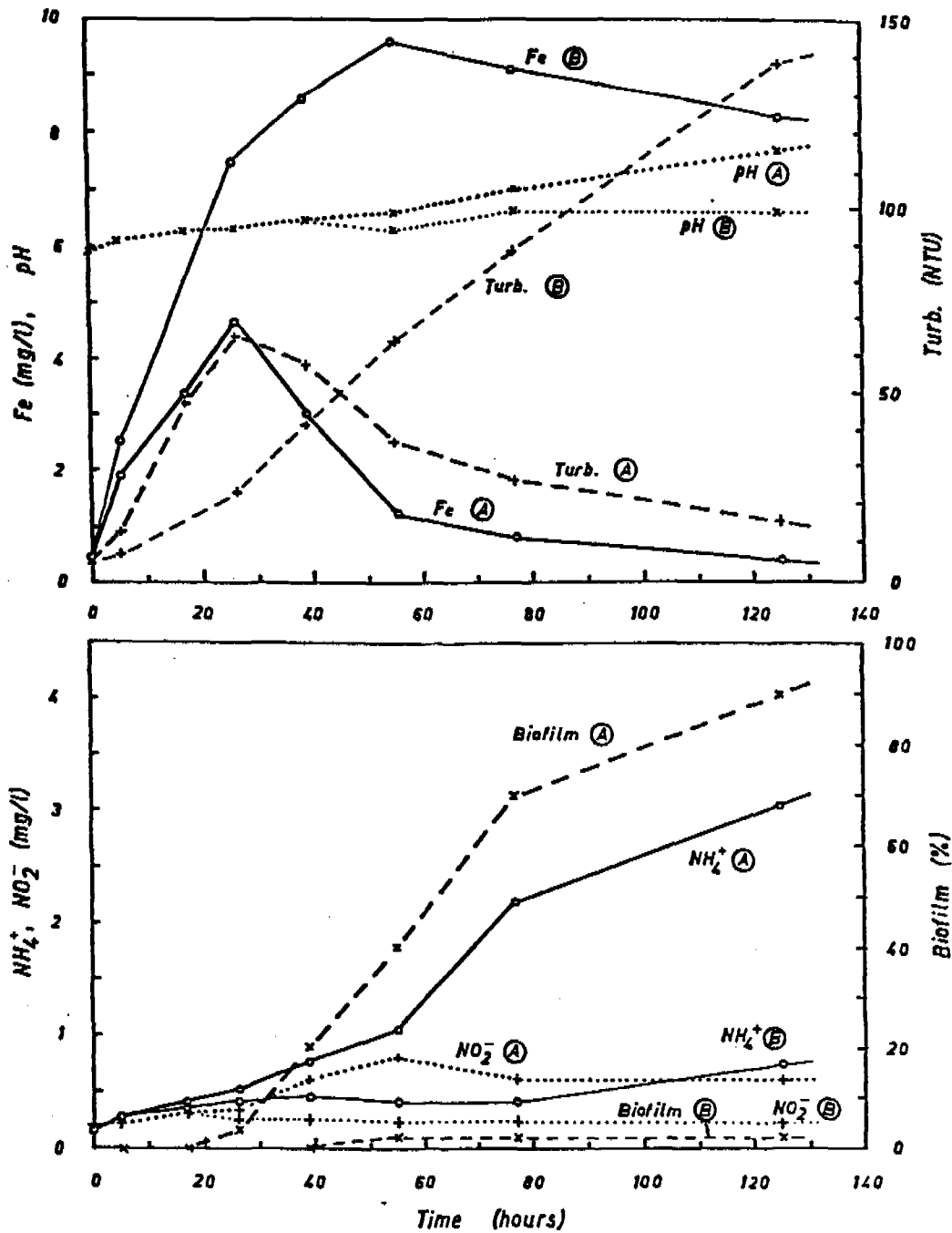
The results of these tests can be summarized as follows (Fig. A.12.1):

- (i) Biofilms (red mud) developed within 30–40 hours on the surfaces of all the samples kept at 26–27°C, which is suggested to be mainly the result of the activity of iron bacteria.
- (ii) The concentration of ammonium ( $\text{NH}_4^+$ ) increased with the development of the biofilms.
- (iii) The chemical composition of the dried biofilms was (average values of three samples as weight percent):

Total Iron ( $\text{Fe}_{\text{total}}$ )	61.4%
Zinc (Zn)	0.9%
Calcium (Ca)	0.8%
Magnesium (Mg)	0.7%
Potassium (K), sodium (Na)	0.2%
Others: Aluminum (Al), silica ( $\text{SiO}_2$ ), organic matter, etc.	36.0%
Total	100.0%

- (iv) The dissolution of iron by corrosion (measured as total iron concentration or iron uptake) decreased as the ammonium concentration increased and as biofilms developed.
- (v) The pattern of nitrite ( $\text{NO}_2^-$ ) production follows that of ammonium, with a short time lag.

- (vi) Nitrate ( $\text{NO}_3$ ) is suggested to have played an important role in the test. The nitrate level decreased over time and, after its depletion, the biofilms became inactive (color change from red to dark red-brown, decrease of ammonium and nitrite, increase of iron uptake).
- (vii) The development of biofilms was slower and the maximum iron uptake slightly less in water from the well with the corrosion-resistant handpump than in water from the well with the non-corrosion-resistant handpump, which may be a result of the difference in water quality of the samples. In the water from the well with the corrosion-resistant handpump (the first case), nitrate content was 3.5 mg/l and the pH was 6.2; in the second case, nitrate content was 17 mg/l and pH was 5.9. Another important factor might be that there is a significantly higher population of iron bacteria due to corrosion in the water sample from the well with the non-corrosion-resistant handpump than in the other sample.
- (viii) The tests performed with filtered water showed a significant delay in developing a biofilm and, as a consequence, a higher maximum iron uptake in comparison with unfiltered water. This effect is attributable to the reduction of the iron bacteria population through filtration.
- (ix) No biofilm, or only a very limited amount, was developed in the sample kept in the refrigerator. As a consequence, there was very little production of ammonium and nitrite, but a much higher and rather constant iron uptake, in comparison with the other samples.



Water temperature : A = 26 °C  
B = 10 °C

Note: The biofilm development (expressed in percent) is a qualitative measure based on visual estimates of thickness. The results shown come from tests performed with unfiltered water from a drilled well equipped with a non-corrosion-resistant handpump.

**Figure A.12.1 Biofilm development on mild steel pump rod samples under corrosive conditions, and its impact on water quality**

### **Appendix 13. Water Quality-Based Corrosion Indexes**

There are many parameters that have an effect on corrosion and, thus, are useful as corrosion indexes. The pH, conductivity, temperature, alkalinity, organic matter, suspended solids; the concentrations of calcium, magnesium, chloride, sulfate, silicate, phosphate, free carbon dioxide, dissolved oxygen; and biological factors are all partially considered in corrosion indexes.

The characteristics of the wells that were used for the corrosion research and the field data on water quality presented in this report were the basis for the application of corrosion indexes (Table A.13.1). The corrosion rate of mild steel pump rod samples in the field was used as a reference for comparing the results obtained by the different corrosion indexes (see Fig. A.14.3 in Appendix 14).

**Table A.13.1**  
**Mean Values of Parameters Used to Describe Water Quality and Characteristics of the Wells Used for the Corrosion Investigations**

Parameters of Water Quality													
Well No.	pH	EC ( $\mu\text{S/cm}$ )	$\text{NO}_3^-$ (mg/l)	TH <sup>a</sup> (mg/l)	$\text{Ca}^{2+}$ (mg/l)	Alk. <sup>a</sup> (mg/l)	$\text{Na}^+$ (mg/l)	$\text{K}^+$ (mg/l)	$\text{SO}_4^{2-}$ (mg/l)	$\text{SiO}_2$ (mg/l)	Cl <sup>-</sup> (mg/l)	$\text{CO}_2$ (mg/l)	$\text{O}_2$ (mg/l)
1	5.95	270	17	59	42	56	30	5.1	4.2	68	29	139	1.9
2	6.00	235	13	54	31	58	31	4.0	0.3	81	26	122	2.5
3	6.10	260	7	67	35	66	25	6.2	0	74	33	118	3.0
4	6.10	310	12	55	37	66	38	6.8	0	79	43	122	2.9
5	6.25	380	3.5	107	76	92	32.5	6.9	0.8	76	52	112	2.3
6	5.80	440	52	75	54	41.5	42	3.5	7.0	66	47.5	120	3.5
7	6.40	255	2.4	86	59	100	13	5.2	2.2	62	10	90	1.2
8	6.45	755	23	249	173	161	62	4.1	37.5	55	117	126	0.4
9	6.85	850	0	340	212	224	46.5	8.9	68	87	100	96	2.0
10	7.20	595	0	215	145	225	50	4.0	8.2	62	39	52	0.8

Well characteristics											
Well Type <sup>b</sup>	1	2	3	4	5	6	7	8	9	10	
Static WL (m)	15.7	7.8	16.8	1.7	5.4	9.6	19.5	19.6	5.3	4.0	
Well Depth (m)	49.5	45	54	45	45	85	67.6	45	45	76.5	
Well Yield (m <sup>3</sup> /h)	3.0	8.2	1.5	1.5	6.5	60	14.4	1.0	10.8	0.9	
Handpump <sup>c</sup>	CR	NCR	CR	CR	NCR	NCR	CR	CR	NCR	CR	
Water Intake (m) <sup>d</sup>	38	43	31	31	39	81	55	34	43	33	

<sup>a</sup>mg/l as CaCO<sub>3</sub>

<sup>b</sup>all wells located in granitic rock

<sup>c</sup>NCR = Moyno pumps with galvanized rising mains and pump rods (non-corrosion-resistant); CR = PEK pumps with plastic rising mains and aluminum pump rods (corrosion-resistant)

<sup>d</sup>Depth of main water-bearing strata

### 13.1 Saturation Index (SI)

#### SI according to Langelier

The Langelier Index (LI), or Saturation Index (SI), is probably the most commonly used corrosion index. It is based on the chemical equilibrium equation for calcium carbonate ( $\text{CaCO}_3$ ) and is an indicator of the tendency of water to deposit or dissolve  $\text{CaCO}_3$ , (AWWA-DVGW 1985; APHA-AWWA-WPCF 1980):

$$LI = \text{pH}_a - \text{pH}_s$$

Where:  $\text{pH}_a$  = actual (measured) pH  
 $\text{pH}_s$  = equilibrium pH at  $\text{CaCO}_3$  saturation

The meaning of the LI is (in the following only the abbreviation SI is used):

- SI > 0 : Tendency toward  $\text{CaCO}_3$  deposition (scale formation)
- SI = 0 : Saturation with  $\text{CaCO}_3$  (equilibrium)
- SI < 0 : Undersaturation with  $\text{CaCO}_3$  (dissolution of  $\text{CaCO}_3$ )

It is assumed that when the value of SI is negative (SI < 0), it indicates corrosiveness (AWWA-DVGW 1985).

#### SI according to Larson

Larson modified the determination of the pH of saturation ( $\text{pH}_s$ ) by considering the effects of temperature and ionic strength on equilibrium constants (APHA-AWWA-WPCF 1980).

$$SI = \text{pH}_a - \text{pH}_s$$

Where:  $\text{pH}_a$  = actual (measured) pH  
 $\text{pH}_s = A + B - \log [\text{Ca}^{2+}] - \log [\text{alkalinity}]$   
A, B = Constants as function of temperature and total filterable residue

#### Measured SI (marble test)

A simple method for measuring the pH of saturation ( $\text{pH}_s$ ) and, thus, the SI is to add marble powder or marble pellets to the water sample. If the water is undersaturated with  $\text{CaCO}_3$ , marble powder will be dissolved and cause a change in pH. The measured pH ( $\text{pH}_m$ ) after adding the marble powder is assumed to correspond with the  $\text{pH}_s$ .



$$SI = \Delta pH = pH_a - pH_m$$

Where:  $pH_a$  = actual pH (before adding marble powder)  
 $pH_m$  =  $pH_s$  = pH after adding marble powder (pH of saturation)

### Results of the SI tests

The results of the three different SI tests applied to the data in Table A.13.1 are presented in Table A.13.2 and Figure A.13.1. The calculated saturation indexes all indicate approximately the same range of corrosiveness, that is, from slightly corrosive ( $SI \approx -0.1$ ) to heavily corrosive ( $SI \approx -2.7$ ). There are systematic trade-offs, however, among the different SI methods. The measured SI (marble test), especially in the low range ( $SI < -0.5$ ), differs significantly from the computed SI (by up to 1.5 SI units).

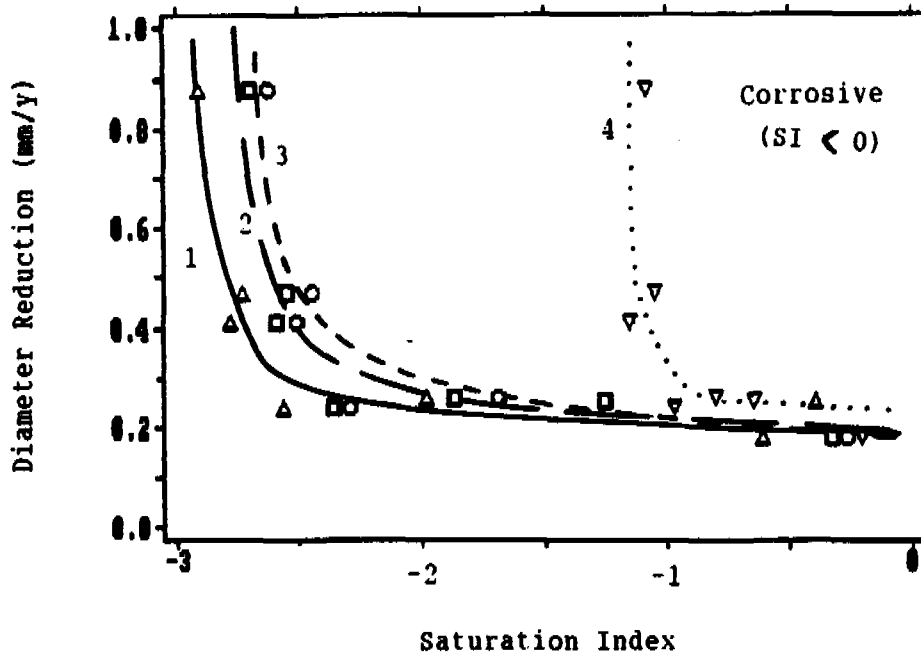
The curves in Figure A.13.1 indicate a relationship between the corrosion rate (diameter reduction) of mild steel and the saturation index (SI). The curves deviate relatively sharply at SI levels of about  $-2.5$  (for the computed SI) and about  $-1$  (for the measured SI). At these points, the corrosion rates increase rapidly with decreasing SI.

**Table A.13.2**  
**Comparison of Results of the Different Saturation Indexes (SI)**

Well No.	pH	EC ( $\mu S/cm$ )	Saturation Indexes			
			Langelier		Larson	Marble Test
			Computed <sup>a</sup>	Graphical <sup>b</sup>		
1	5.95	270	-2.73	-2.55	-2.45	-1.05
2	6.00	235	-2.78	-2.59	-2.51	-1.15
3	6.10	260	-2.61	-2.37	-2.33	-0.95
4	6.10	350	-2.56	-2.36	-2.29	-0.97
5	6.25	380	-1.98	-1.86	-1.69	-0.80
6	5.80	440	-2.91	-2.70	-2.62	-1.08
7	6.40	255	-1.89	-1.71	-1.61	-0.79
8	6.45	755	-1.19	-0.88	-0.86	-0.40
9	6.85	850	-0.61	-0.32	-0.26	-0.20
10	7.20	595	-0.39	-0.16	-0.07	-0.10

<sup>a</sup>Strohecker and Langelier (Höll 1971)

<sup>b</sup>Faust (1980)



Legend: 1 = SI Langelier (computed)      3 = SI Larson  
 2 = SI Langelier (graphical)      4 = SI Measured (marble test)

Figure A.13.1 Corrosion rate versus Saturation Indexes (SI)

### 13.2 Ryznar Stability Index (I)

The Ryznar Stability Index (I) is an empirical expression defined as (Driscoll 1986; Faust and Aly 1983):

$$I = 2pH_a - pH_s$$

$$I = S - C - pH_a$$

Where:  $pH_a$  = actual (measured) pH  
 $pH_s$  = equilibrium pH at  $CaCO_3$  saturation  
 S = Constant derived from the calcium concentration and alkalinity  
 C = Constant derived from the total dissolved solids

The interpretation of the Ryznar Stability Index with regard to corrosion is:

$I < 7$  : non-corrosive  
 $I > 7$  : corrosive

The results of the Ryznar Stability Index applied to the data in Table A.13.1 are presented in Figure A.13.2. The curve shows the same characteristics as the SI curves in Figure A.13.1.

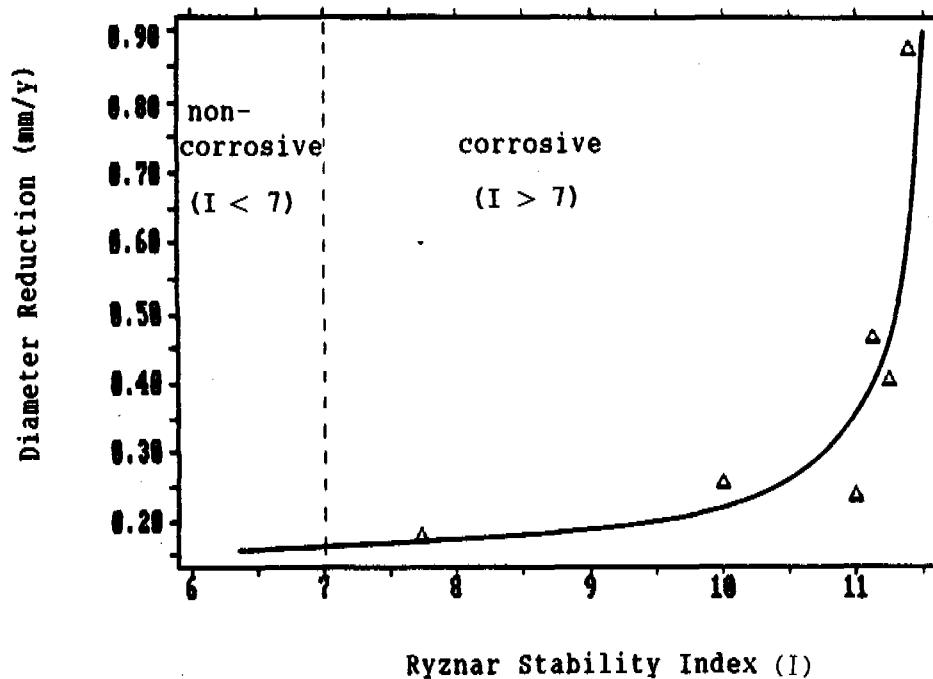


Figure A.13.2 Corrosion rate versus Ryznar Stability Index (I)

### 13.3 Driving Force Index (DFI)

The Driving Force Index (DFI), also an empirical measure for determining calcium carbonate concentration, has been defined by McCauley (APHA-AWWA-WPCF 1985):

$$DFI = \frac{[Ca^{2+}] [CO_3^{2-}]}{10^{10}K_s}$$

where:  $[Ca^{2+}]$  = Calcium concentration (mg/l  $CaCO_3$ )  
 $[CO_3^{2-}]$  = Carbonate concentration (mg/l  $CaCO_3$ )  
 $K_s$  = Solubility product constant for  $CaCO_3$

The DFI can be calculated from the SI according to the following relationship:

$$DFI = 10^{(SI-7)}$$

The interpretation of the DFI is as follows:

DFI > 1 : Tendency toward  $\text{CaCO}_3$  deposition (scale formation)

DFI = 1 : Saturation with  $\text{CaCO}_3$  (equilibrium)

DFI < 1 : Undersaturation with  $\text{CaCO}_3$  (dissolution of  $\text{CaCO}_3$ )

In view of corrosion, DFI < 1 is assumed to be corrosive.

The results of the application of the Driving Force Index to the data presented in Table A.13.1 are depicted in Figure A.13.3.

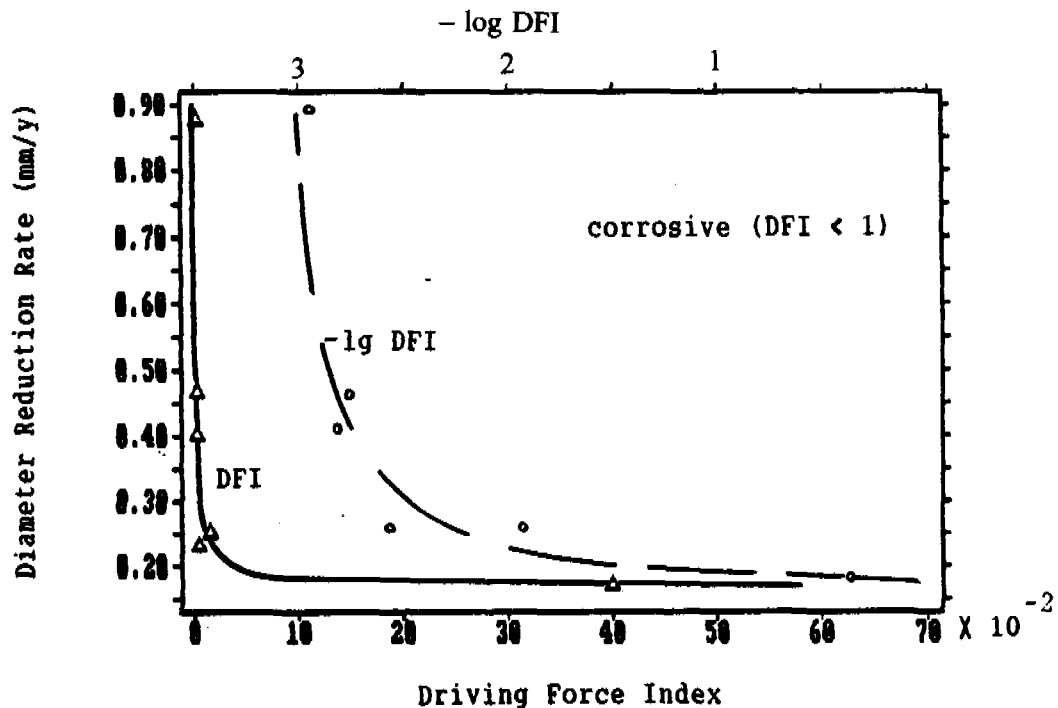


Figure A.13.3 Corrosion rate versus Driving Force Index

### 13.4 Riddick Index (RI)

In developing the Riddick Index (RI), Riddick (AWWA-DVGW 1985) considered a variety of parameters that might influence corrosion. The definition of this empirical index is:

$$RI = \frac{75}{Alk} [(CO_2) + \frac{1}{2}(HD - Alk) + Cl^- + 2NO_3^- \left( \frac{10}{(SiO_2)} \right) \left( \frac{DO + 2}{(DO_{sat})} \right)]$$

where:

Alk	=	Alkalinity (mg/l CaCO <sub>3</sub> )	Cl <sup>-</sup>	=	Chloride (mg/l)
HD	=	Hardness (mg/l CaCO <sub>3</sub> )	SiO <sub>2</sub>	=	Silica (mg/l)
NO <sub>3</sub> <sup>-</sup>	=	Nitrate (mg/l N)	DO	=	Dissolved oxygen (mg/l)
CO <sub>2</sub>	=	Free carbon dioxide (mg/l)	DO <sub>sat</sub>	=	DO at saturation (mg/l)

The relationship of the Riddick Index to corrosion is:

RI ≤ 25	non-corrosive
25 < RI ≤ 50	moderately corrosive
50 < RI ≤ 75	corrosive
RI > 75	very corrosive

The results obtained from applying the RI to the data in Table A.13.1 are presented in Figure A.13.4

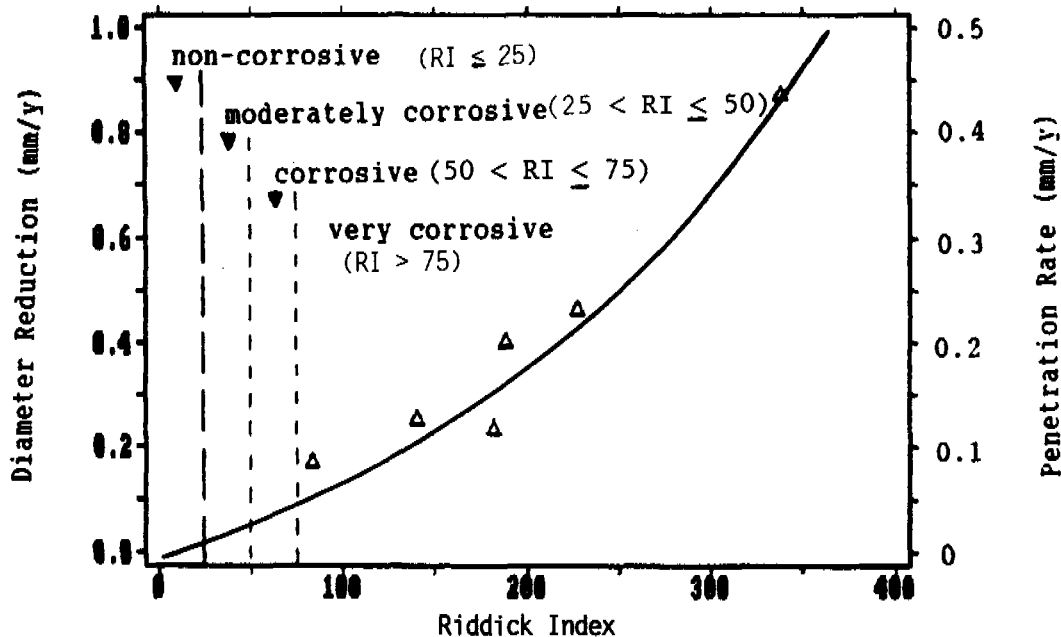


Figure A.13.4 Corrosion rate versus Riddick Index (RI)

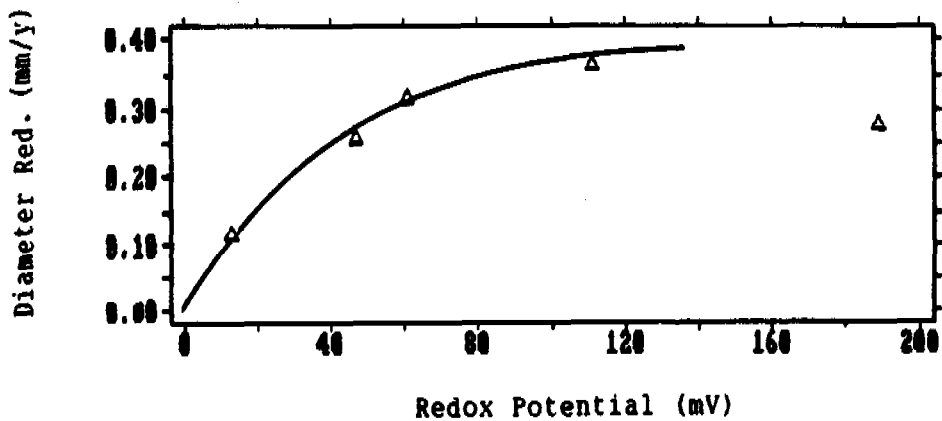
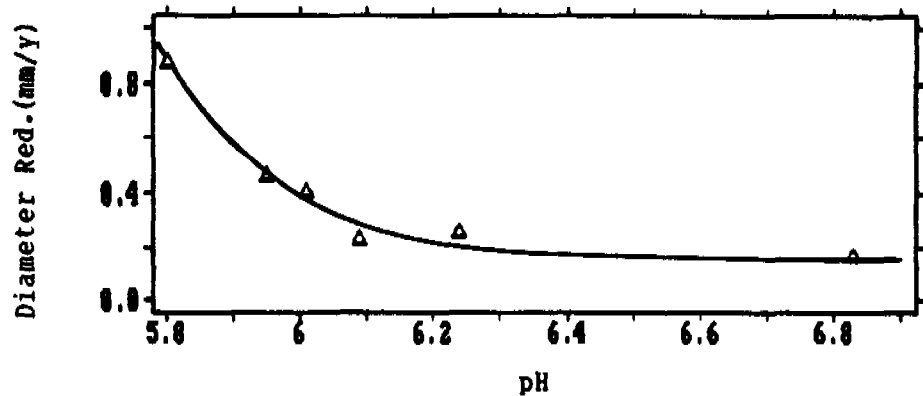
### 13.5 pH and Redox Potential (Eh)

On the basis of the field experience in the West African subregion, a pH-based corrosion index, with regard to the use of galvanized pump rods and rising mains, has been suggested by Langenegger (1989) (Table A.13.3).

The results obtained from applying the pH and the Redox Potential (Eh) as corrosion indexes to the data in Table A.13.1 are presented in Figure A.13.5. Three graphs that show the Saturation Indexes (SI) versus pH, the Redox Potential (Eh) versus pH, and the carbon dioxide (CO<sub>2</sub>) versus pH are presented in Figure A.13.6.

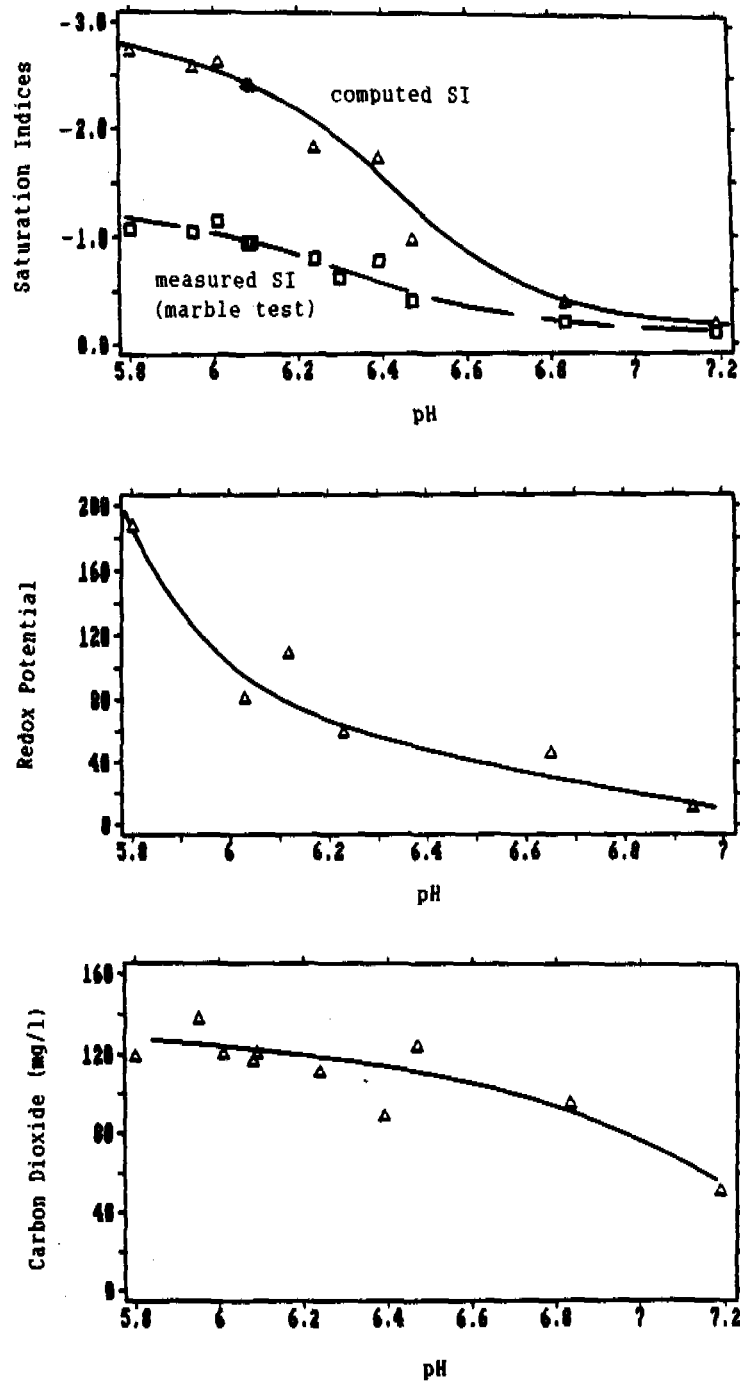
**Table A.13.3**  
**pH-based Index for Applicability of Galvanized Downhole Components**

pH	Application of galvanized material	Diameter reduction (mm/y)	Rating of corrosion damage
pH > 7	suitable	< 0.1	negligible
6.5 < pH ≤ 7	limited	0.1 - 0.2	mild
6 ≤ pH ≤ 6.5	not recommended	0.2 - 0.4	mild
pH < 6	not recommended	> 0.4	moderate to severe (to extreme)



Note: The measurements of the redox potential may be affected by a systematic error because there were no standards available.

Figure A.13.5 Corrosion rate versus pH and corrosion rate versus redox potential (Eh)



**Figure A.13.6 Saturation Indexes (SI) versus pH, Redox Potential (Eh) versus pH, and carbon dioxide (CO<sub>2</sub>) versus pH**



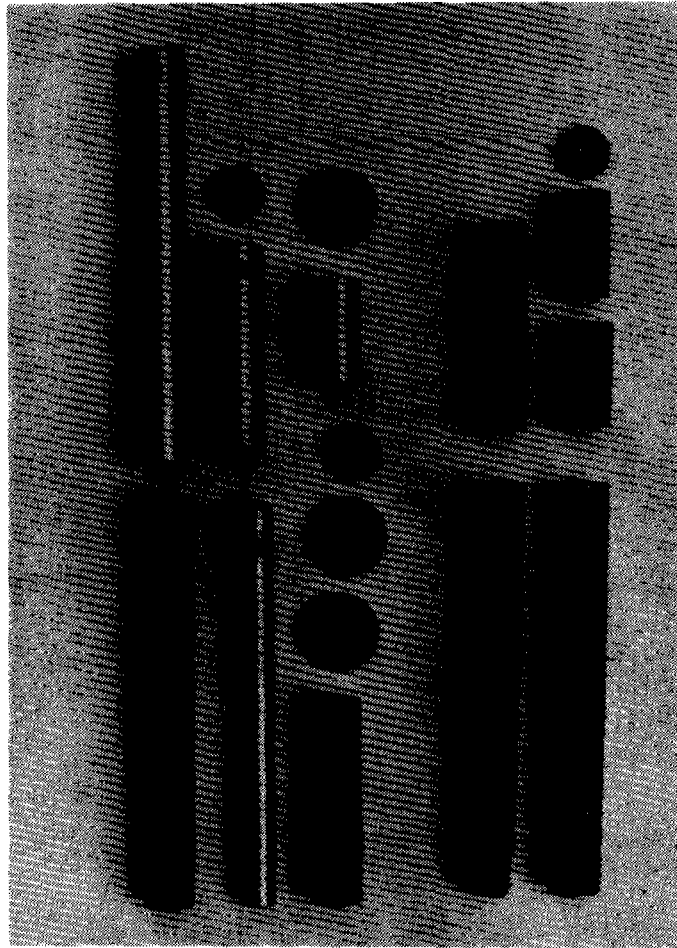
## Appendix 14. Corrosion Tests

Corrosion rate measurements on different types of pump rod samples and coupons were conducted in the field and in the laboratory over time periods ranging from a few days to fourteen months. Iron uptake (immersion) tests were also part of the corrosion tests performed in the laboratory. The specifications of the materials tested are given in Table A.14.1, and a photograph of the types of samples is shown in Figure A.14.1.

**Table A.14.1**  
**Specifications of Corrosion Test Samples (Coupons), Pump Rods, and Rising Mains**  
**Used for Corrosion Rate Measurements**

Type of sample	Material	Specifications	Dimensions L x D x T (mm)	Approximate weight (g)
<b><u>Pump parts:</u></b>				
Pipes	GI		3000 x 42.4 (1 ¼-in)	
Pump rods	EI		3000 x 11	
<b><u>Pump rod samples:</u></b>				
S	SS		100 x 9	48
N	MI		100 x 14 / 50 x 14	120/59
M	EI		100 x 11.1	73
A	GI		100 x 14	120
<b><u>Corrosion test samples:</u></b>				
SGS-1	MS	BS.970220 MO7 leaded	100 x 12.6	98
SGS-2	MS	BS.970220 MO7 leaded	50 x 12.6	49
SGS-3	MS	BS.970220 MO7 leaded	25 x 12.6	24
SGS-4	MS	BS.970220 MO7 leaded	12.6 x 2.5	5.3
SGS-5	MS	BS.970220 MO7 leaded	19.0 x 2.52	2.3

**Note:** GI: galvanized iron (mild steel)      MS: mild steel (without mill scale)  
 EI: electroplated iron (mild steel)      L: length  
 SS: stainless steel      D: diameter  
 MI: mild steel (with mill scale)      T: thickness



**Figure A.14.1 Pump rod samples and coupons used for corrosion tests**

#### 14.1 Field Measurement of Corrosion Rates

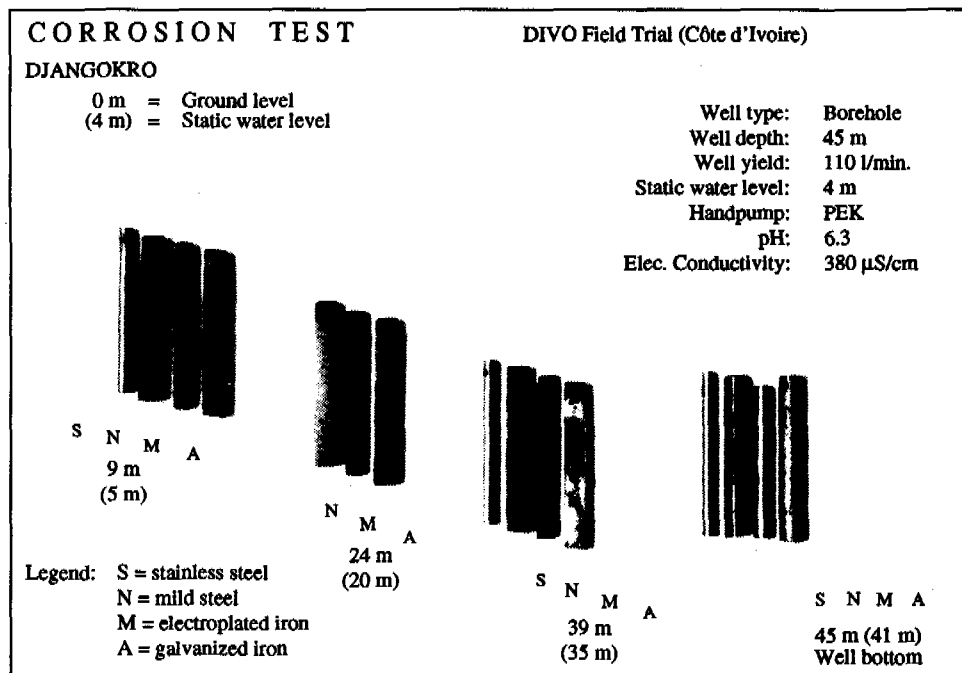
The corrosion tests in the field were conducted on pump rod samples made of mild steel (galvanized, electroplated, non-protected) and stainless steel over a period of fourteen months. The samples were immersed in groundwater in drilled wells with corrosion-resistant handpumps in the Divo field trial in the Côte d'Ivoire. The diameters of the samples were measured with a micrometer at intervals of one to three months (Fig. A.14.3).

A corrosion rate between about 0.1 and 1 mm/y was observed in the samples. There was an increase in corrosion rate with decreasing pH, a decrease in corrosion rate over time, and a decrease in corrosion rate with increasing immersion depth below the groundwater level (Fig. A.14.3).

Test samples with different surface treatments showed different rates of corrosion (Fig. 4.12), but there was insufficient data from the field observations to indicate the effectiveness of the different surfaces (galvanization, electroplating, mild steel) against corrosion. There were also inconsistencies noted in the observed corrosion rates:

- The observed corrosion rate of stainless steel ranged from 0.01 to 0.05 mm/y (diameter reduction).
- There was a slight tendency (although only in individual cases) for protective scales to form only on galvanized surfaces, perhaps indicating that galvanized (zinc) surface coatings tend to be more favorable for formation of protective scale than electroplated or mild steel surfaces.
- The corrosion rate of electroplated samples was usually slower than that of galvanized samples.
- In certain cases the mild steel samples showed the slowest corrosion rate.

There are many factors that might be responsible for these inconsistencies, among them the material, surface conditions, conditions in the well, and so on. Laboratory tests, however, indicate that the corrosion rates of galvanized and electroplated surfaces are about equal (see Section 14.2).



**Figure A.14.2** Test samples after fourteen months of exposure to groundwater in well no. 2 (see Table A.13.1)

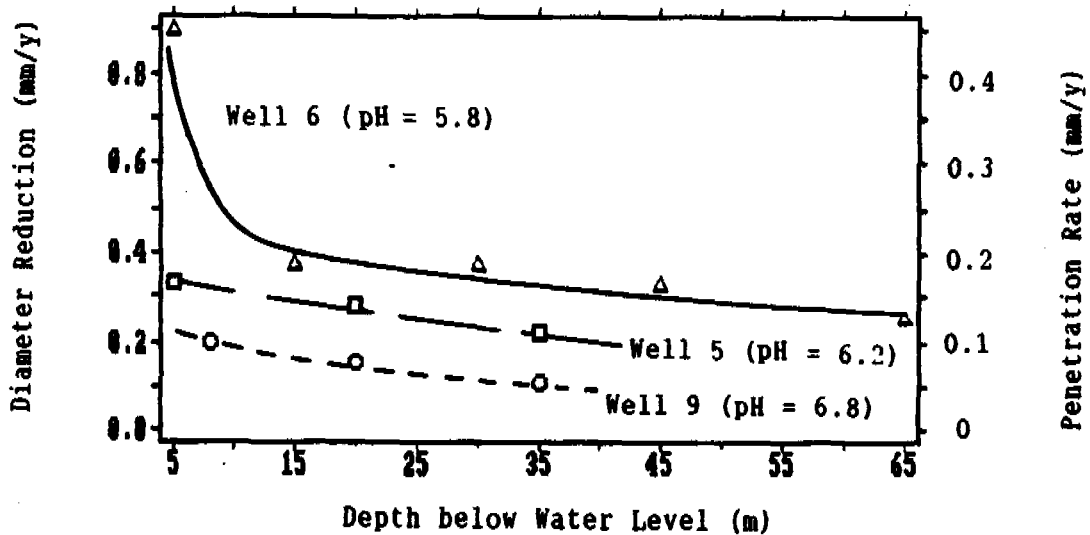
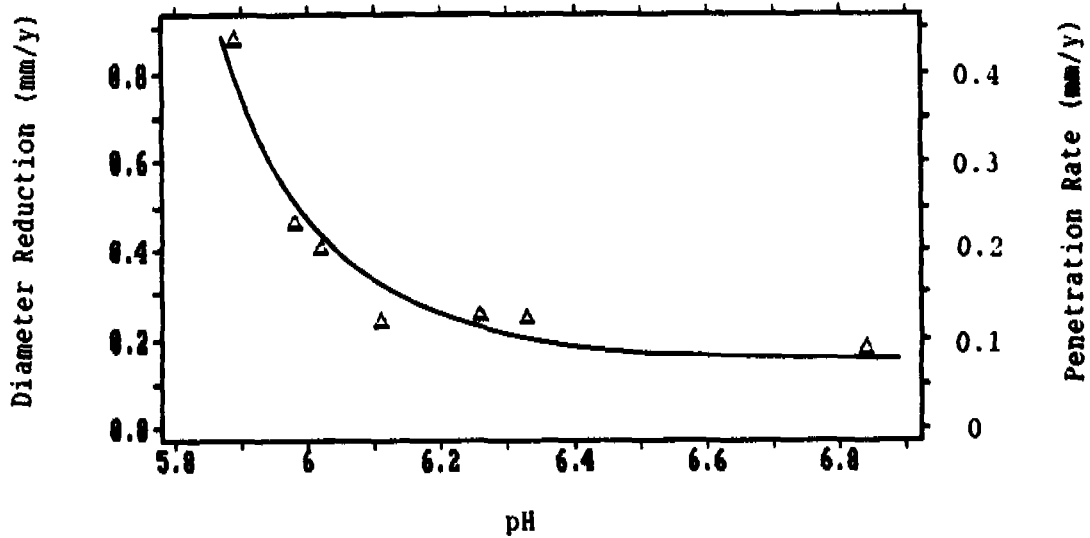
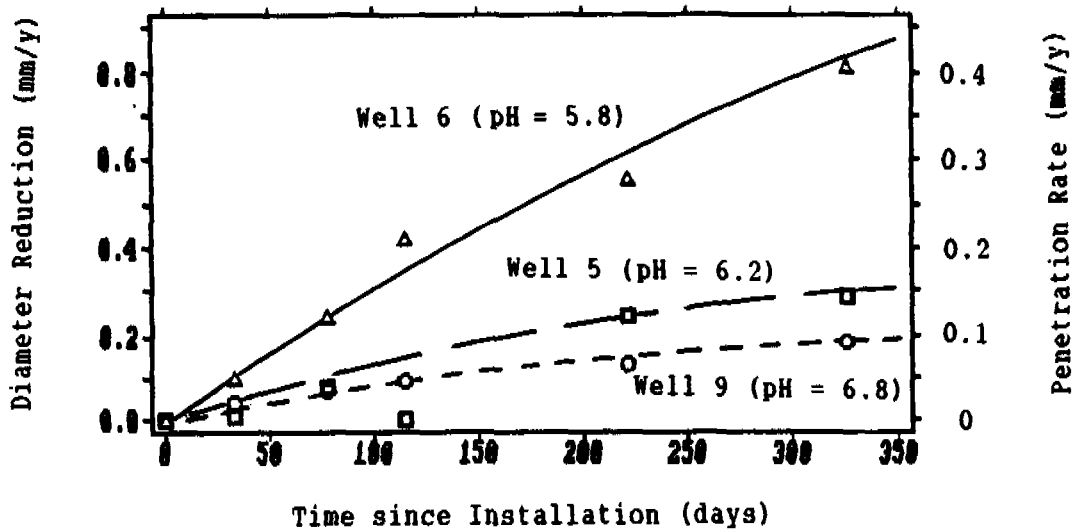


Figure A.14.3 Corrosion rate of pump rod samples immersed in groundwater in drilled wells versus time, pH, and depth below groundwater table

## 14.2 Laboratory Measurement of Corrosion Rates

A series of corrosion rate measurements under laboratory conditions (immersion tests) were carried out with SGS mild steel samples over periods of between five and twenty days. The samples were exposed to different types of groundwater, as well as to groundwater that was artificially adjusted (pH, conductivity). The corrosion rates were determined on the basis of weight loss. The purpose was to investigate the corrosion rates under controlled water quality conditions, to quantify galvanic (bimetallic) corrosion rates, to verify the impact of the pH and the conductivity on corrosion rates, and to correlate laboratory tests with field tests.

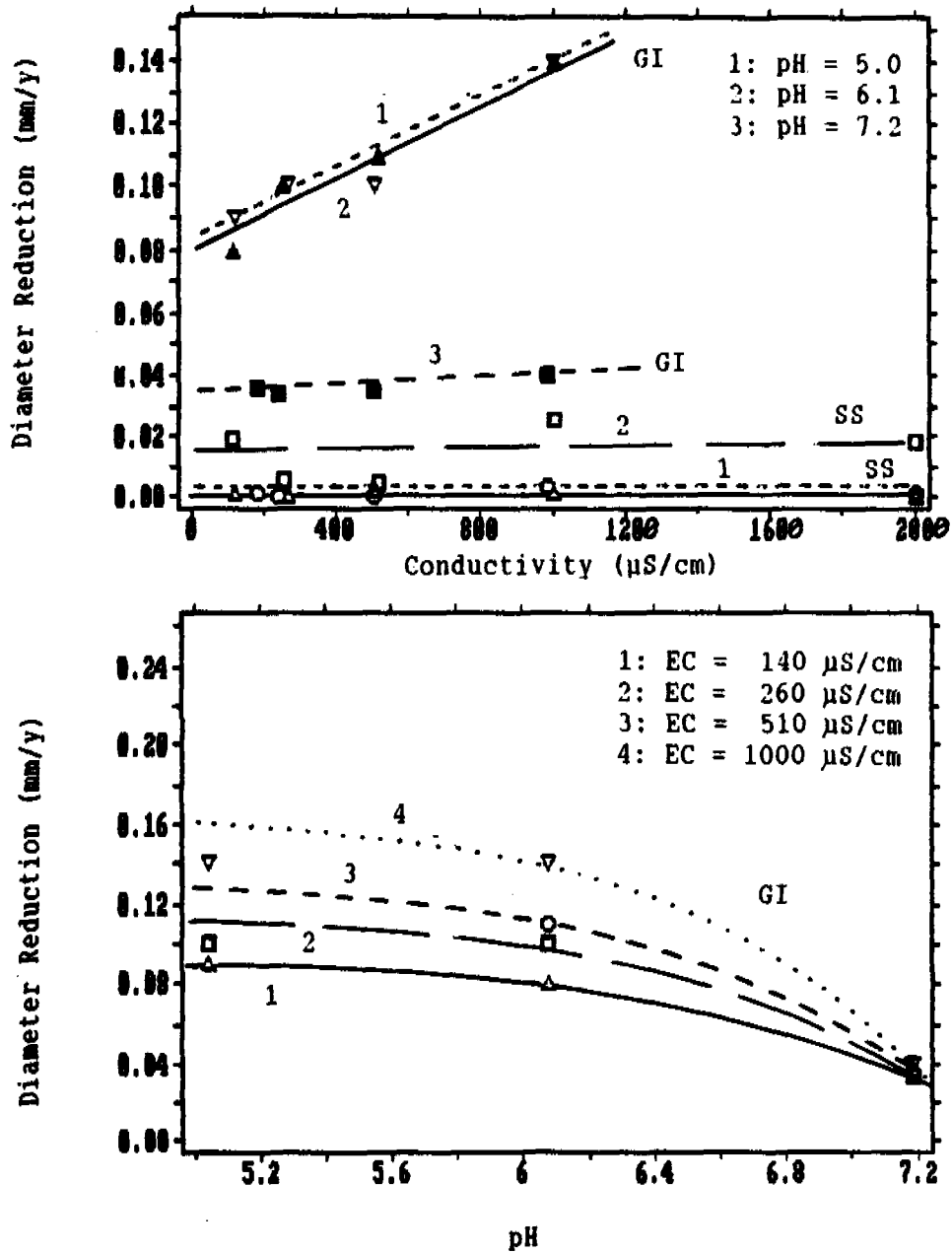
The galvanic corrosion tests were carried out with SGS-1 samples four inches long and one-half inch in diameter. The samples were screwed onto 2½-inch pistons made of brass. This combination simulated the pump rod-piston assembly in the cylinder of a reciprocating handpump in non-operating conditions. All the tests were performed in plastic buckets with a volume of about twelve liters and kept in the dark at a temperature of 26-27°C. To keep the water quality more or less constant, the water was replaced every second day in those tests where natural groundwater was used. In those tests where the pH and the conductivity (EC) were controlled, groundwater with a low pH (4.4) and a low EC (40 µS/cm) was artificially adjusted with ammonium hydroxide (NH<sub>4</sub>OH), hydrochloric acid (HCl), and salt (NaCl). The adjustments were made daily.

The main results of these tests can be summarized as follows (Fig. A.14.4 and A.14.5):

- (i) The corrosion rates (diameter reduction) in the laboratory are slower than those in the field. This may be due to the static conditions (i.e., no flowing water and no shaking of the samples).
- (ii) Galvanic corrosion rates were up to six times greater than non-galvanic corrosion rates. Under the test conditions, there was a direct relationship between the rate of galvanic corrosion and the EC until the EC increased to 500 µS/cm. That is, if the EC was low, then there was little galvanic corrosion; if the EC was high, then there was significant galvanic corrosion. Above 500 µS/cm, however, an increase in EC showed no additional influence on the rate of galvanic corrosion (at least not up to 2000 µS/cm). The pH did not have any notable influence on galvanic corrosion.
- (iii) Non-galvanic corrosion was highly dependent on pH and little to moderately dependent on EC. The corrosion rate also varied with the type of material (mild steel).
- (iv) The observed corrosion of different surface coatings indicated that: (1) the corrosion rate (diameter reduction) of mild steel surfaces (up to 0.5 mm/y) was two to three times greater than that of galvanized or electroplated mild steel,

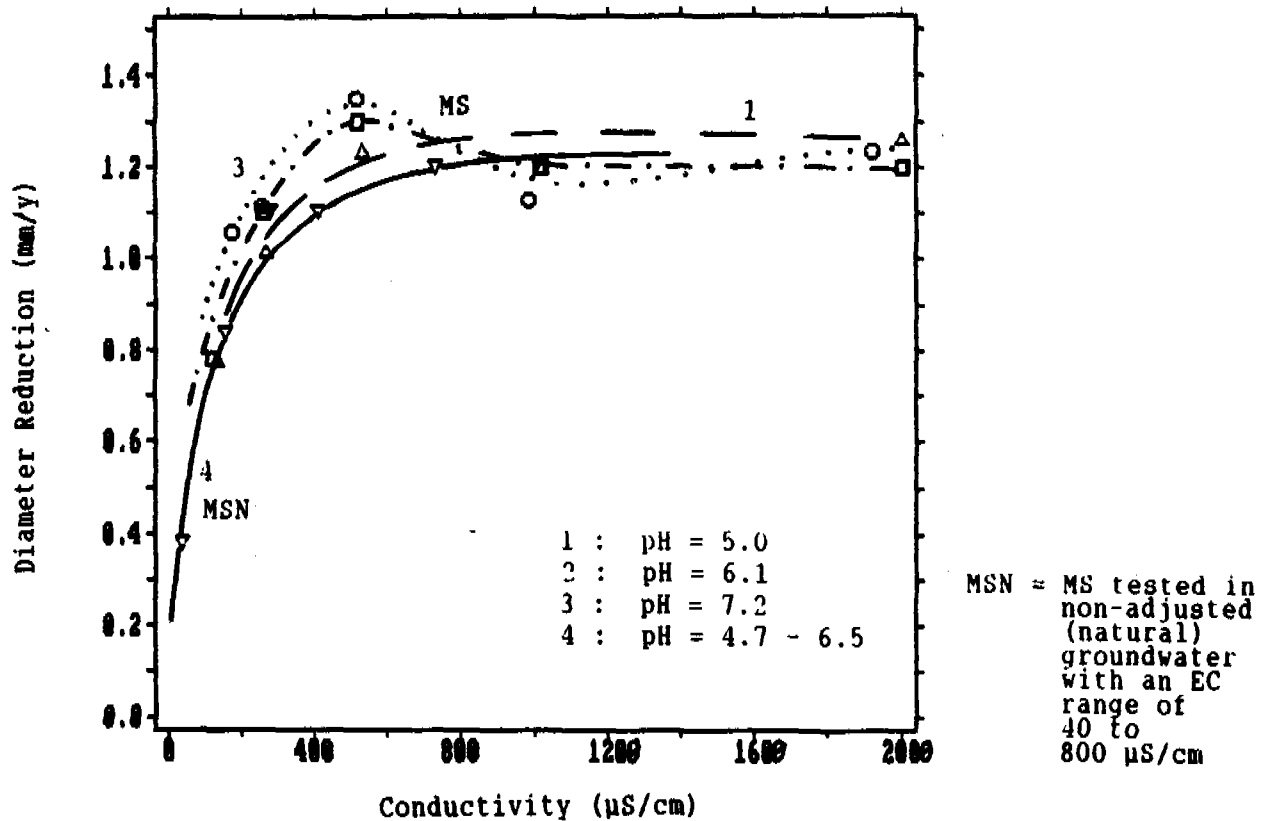
and (2) the corrosion rates of galvanized and electroplated surfaces were about equal (up to 0.15 mm/y).

- (v) The immersion tests showed good reproducibility and correspondence. The corrosion rate of different samples usually varied less than 15%.



Legend: GI = galvanized mild steel  
 SS = stainless steel

**Figure A.14.4** Corrosion rate of mild steel and stainless steel samples (under laboratory conditions) versus pH and EC after an exposure time of five days



**Figure A.14.5 Galvanic corrosion rate of mild steel samples (under laboratory conditions) versus pH and EC after six days of exposure**

### 14.3 Summary of Corrosion Rate Measurements

The results of field and laboratory corrosion rate measurements, including those performed on pump parts, are presented in Table A.14.2. Using the rating of corrosion damage in Table A.10.1 (see Appendix 10) as a reference, the measured corrosion rates of rising mains and pump rods were "moderate," with the exception of that caused by galvanic corrosion, which was "severe."

Comparison of these results indicates that the measured corrosion rates of pump rod samples in the laboratory were slower than those measured in the field. The main reason is probably that the hydraulic conditions are different; that is, a steady state in the laboratory versus a dynamic state in the field.

Also, the corrosion rate observed in functioning pump rods (which are inside the rising mains) in the field was slower than that of pump rod samples measured in the field (which are hung inside the well but outside of the rising mains). This difference is a result of the difference between internal and external corrosion (see Chapter 5).



**Table A.14.2**  
**Corrosion Rate Measurements**

Type of sample	Material	<u>Field Measurements</u>		<u>Laboratory Measurements</u>	
		pH range	Diameter reduction (mm/y)	pH range	Diameter reduction (mm/y)
<b><u>Electrochemical Corrosion</u></b>					
<b><u>Pump parts:</u></b>					
Pipes (1¼ inch)	GI	6.0 - 7.2	0 - 0.5		
Pump rods (11mm)	EI	5.8 - 6.8	0 - 0.4		
<b><u>Pump rod samples:</u></b>					
S	SS	5.8 - 6.8	0.04 - 0.05	5.0 - 7.2	0.001 - 0.03
N	MI	5.8 - 6.8	0.2 - 0.9	5.0 - 7.2	0.2 - 0.6
M	EI	5.8 - 6.8	0.1 - 1.0	5.0 - 7.2	0.04 - 0.12
A	GI	5.8 - 6.8	0 - 0.8	5.0 - 7.2	0.03 - 0.14
<b><u>Corrosion test samples (coupons):</u></b>					
SGS-1	MS			5.0 - 7.2	0 - 0.4
SGS-2	MS			5.0 - 7.2	0 - 0.4
SGS-3	MS			5.0 - 7.2	0 - 0.4
<b><u>Galvanic Corrosion</u></b>					
SGS-1	MS			5.0 - 7.2	0.4 - 1.4

Legend: GI: galvanized iron      MI: mild steel (with mill scale)  
 EI: electroplated iron      MS: mild steel (without mill scale)  
 SS: stainless steel

#### 14.4 Iron Uptake Tests

Iron uptake is a measure of corrosion defined as weight loss per unit area per unit time. The unit of measurement is grams per square meter per day ( $\text{g/m}^2/\text{d}$ ) or milligrams per square centimeter per day ( $\text{mg/cm}^2/\text{d}$ ). The iron uptake rate in water can be calculated from the increase in iron concentration over time using the following relationship:

$$\text{Iron increase rate} = \frac{dC_{Fe}}{dt}$$

$$\text{Iron uptake rate} = \frac{dC_{Fe}}{dt} \times \frac{V_w}{A_i}$$

Where:  $\frac{dC_{Fe}}{dt}$  = Change in iron concentration per unit time (e.g., mg/l per hour)  
 $V_w$  = Water volume  
 $A_i$  = Surface area of iron sample

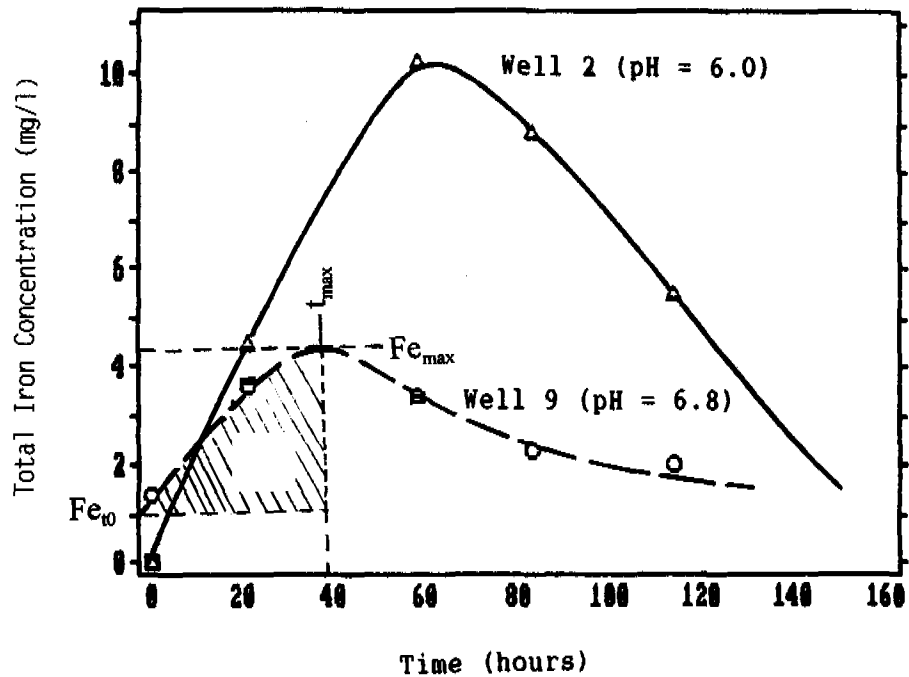
Iron uptake is that portion of the corroded iron that goes into solution in the water; it does not include the corroded iron that is precipitated as sediment or integrated into the scale (biofilm) on the iron surface. Therefore, iron uptake rates and corrosion rates are not necessarily identical, particularly where scales (biofilms) exist. The iron uptake rate is associated with the red water problem in water supply systems.

The reason for investigating the relationship between iron uptake and handpump corrosion was to quantify the corrosiveness of the water when brought into contact with iron, and to find a suitable and easily determinable parameter of water quality that could be used as a corrosion index. Iron was the most obvious parameter.

Mild steel samples (10 cm length, 14 mm diameter) from pump rods were placed in water samples that varied in quantity (1.5, 5, and 20 liters) and were of different origins (and therefore different compositions). The water samples were kept in covered plastic receptacles (e.g., bottles, jerrycans) and stored in the dark at a temperature of 26–27°C. The iron test samples were suspended in the center of the water samples by a plastic cord. These tests, carried out over several days, included daily measurement of pH, conductivity (EC), turbidity, total iron (Fe), ammonium (NH<sub>4</sub><sup>+</sup>), and nitrite (NO<sub>2</sub><sup>-</sup>) concentrations. A few analyses of nitrate (NO<sub>3</sub><sup>-</sup>) and total hardness were also performed. Two typical iron concentration versus time curves are presented in Figure A.14.6. The laboratory conditions with regard to temperature, aeration, and specific iron surface area per water volume were comparable to typical field conditions.

The curves in Figure A.14.6 have the same shape as those presented in Appendix 12, indicating that the shape and characteristic peaks of the iron concentration curves are mainly due to the development of biofilms. Because the purpose of the iron uptake tests was to obtain information on the corrosiveness of the water, and because the tests were performed under steady-state conditions (i.e., without replacing the water), only the first part of the iron concentration curves (i.e., up to their maximum levels) was used in the calculations. The iron increase rates were approximated by dividing the maximum

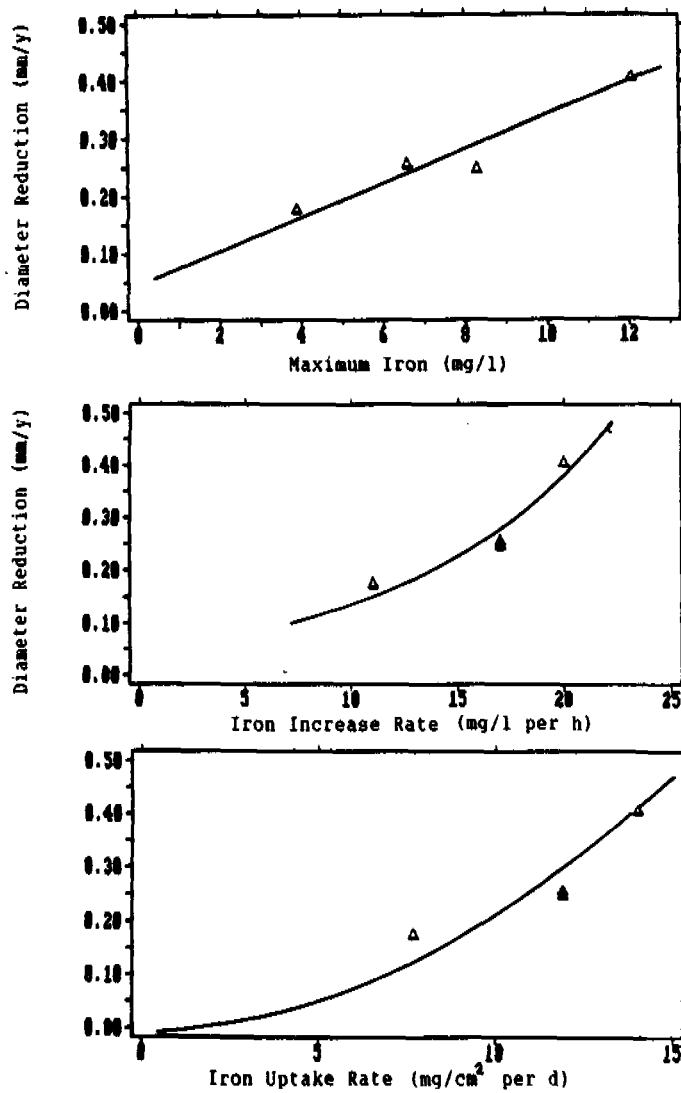
iron concentration ( $Fe_{max}$ ) and  $(Fe_{max}) - (Fe_{t_0})$ , respectively, by the time at which  $Fe_{max}$  was reached ( $t_{max}$ ); that is,  $(Fe_{max}) \div (t_{max})$ . The iron uptake rates were computed on the basis of the definition given above.



Legend:  $Fe_{t_0}$  = iron concentration at  $t_0$  (start of test)  
 $Fe_{max}$  = maximum iron concentration  
 $t_{max}$  = time at  $Fe_{max}$

**Figure A.14.6 Total iron concentration versus time**

The comparison of the results of the iron uptake test and the corrosion rates from the field are shown in Figure A.14.7.



**Figure A.14.7 Results of iron concentration and uptake measurements versus corrosion rates (also see Figure A.14.6)**

#### 14.5 Comparison of Corrosion Tests, and Conclusions

The results of the various indexes and corrosion tests considered in this report can be summarized as follows:

- (i) The corrosion indexes and corrosion tests showed a strong correlation.

- (ii) There is a strong relationship of the results of the corrosion indexes and corrosion tests with the corrosion rates observed in the field.

The applied corrosion indexes, apart from the Riddick Index (RI), do not indicate a specific rate of corrosion, but only whether corrosion is likely to occur. This information is usually sufficient for determining the requirements for water treatment in the water industry, but for handpumps, details on corrosion rate are desirable and useful for estimating the severity of mechanical failures of pump parts, which may result in breakdowns (breakage of pump rods and damage to rising mains and pumping elements).

The results of corrosion indexes and corrosion tests used for this report were correlated with a modified version of the adjective rating of corrosion damage that appears in Table A.10.1 (Table A.14.3). The modification of the adjective rating of corrosion damage is suggested for use with handpumps. Although this classification is only indicative in nature (due to the small sample size of corrosion measurements in the field and the limited range of groundwater quality taken into consideration), it might be useful for estimating corrosion rates of downhole components of handpumps with corrosion indexes and corrosion tests.

As to the practical application of the results for handpumps the following points must be taken into account: (1) the classification presented in Table A.14.3 is valid for mild steel, and (2) the behavior of zinc (galvanization) regarding corrosion is different from that of mild steel.

Field and laboratory investigations indicated a high corrosion rate of mild steel in the low pH range ( $\text{pH} < 6.5$ ), with a gradual decrease at high pH levels (up to pH of about 8). In contrast to mild steel, zinc showed a rather constant corrosion rate at low pH levels ( $\text{pH} < 7$ ) and a relatively rapid decrease in corrosion rate at pH in the proximity of 7.

At  $\text{pH} < 7$  the corrosion rate of mild steel was about two to four times higher than that of zinc; at  $\text{pH} > 7$  the rate was about six times higher than that of zinc.

With regard to the application of galvanized downhole components for handpumps, the results indicate that protection against corrosion by galvanization is only effective when the  $\text{pH} > 7$ . Below this range the corrosion of zinc is rather constant at 60–200  $\mu\text{m}/\text{y}$  penetration rate, which explains the rapid removal of zinc coatings on rising mains observed in the field (see Section 4.2).<sup>4</sup> The fact that the corrosion of zinc shows a strong relationship to pH when  $\text{pH} \approx 7$  also indicates that the pH is a useful indicator of corrosiveness as to the application of galvanized downhole components for handpumps. The relationship between corrosion indexes and pH and between corrosion tests and pH is shown in Figure A.14.8.

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<sup>4</sup> According to ASTM and DIN standards, the average thickness of the zinc coating of galvanized steel is about 50–80  $\mu\text{m}$ .

**Table A.14.3**

**Classification of Different Corrosion Indexes and Corrosion Tests for Mild Steel (Based on the Modified Adjective Rating of Corrosion Damage)**

Rating	Corrosion rate (mm/y)		Range of values of corrosion indexes		
	Diameter reduction	Metal penetration	SI	SI <sub>m</sub>	I
Negligible	< 0.1	< 0.05	> 0	> 0	< 5
Mild	0.1 to 0.4	0.05 to 0.2	0 to -2.5	0 to -1	5 to 11
Moderate	0.4 to 1.0	0.2 to 0.5	-2.5 to -3	< -1	11 to 12
Severe	1.0 to 2.5	0.5 to 1.25	< -3		> 12
Extreme	> 2.5	> 1.25			

	Corrosion rate (mm/y)		Range of values of corrosion indexes			
	Diameter reduction	Metal penetration	DFI	RI	pH	Eh (mV)
Negligible	< 0.1	< 0.05	> 1	< 75	> 7	< 10
Mild	0.1 to 0.4	0.05 to 0.2	1 to 0.15	75 to 200	7 to 6	10 to 100
Moderate	0.4 to 1.0	0.2 to 0.5	< 0.15	200 to 350	< 6	
Severe	1.0 to 2.5	0.5 to 1.25		> 350		
Extreme	> 2.5	> 1.25				

	Corrosion rate (mm/y)		Range of values of corrosion tests		
	Diameter reduction	Metal penetration	Iron uptake tests		
			Fe <sub>max</sub> (mg/l)	Fe <sub>inc</sub> (mg/l/h)	Fe <sub>up</sub> (mg/cm <sup>2</sup> /d)
Negligible	< 0.1	< 0.05	< 2	< 5	< 7.5
Mild	0.1 to 0.4	0.05 to 0.2	2 to 12	5 to 20	7.5 to 15
Moderate	0.4 to 1.0	0.2 to 0.5	> 12	> 20	> 15
Severe	1.0 to 2.5	0.5 to 1.25			
Extreme	> 2.5	> 1.25			

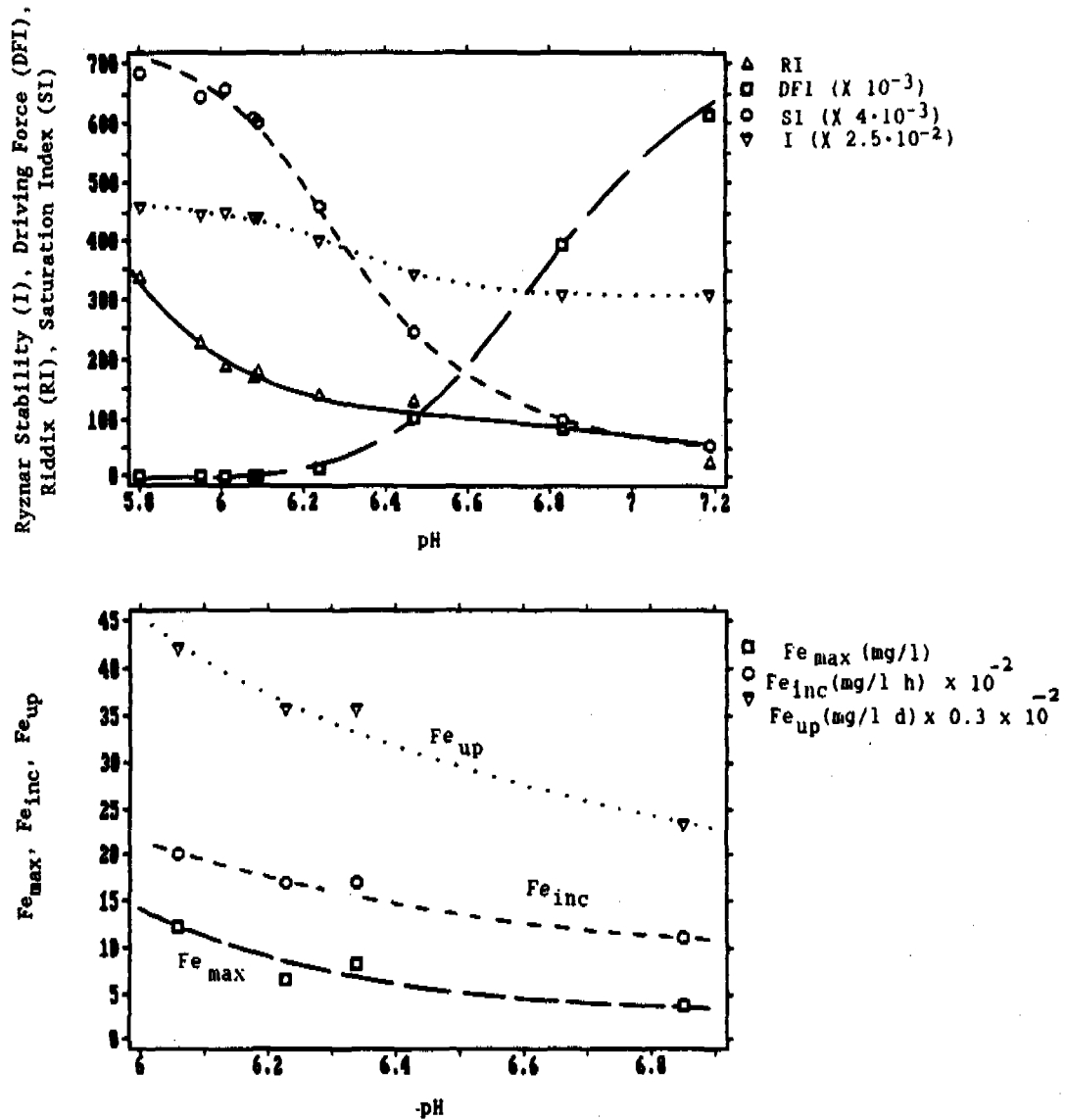
Rating	Corrosion Rate (mm/y)		Immersion Test	
	Diameter reduction	Metal penetration	Diameter reduction (mm/y)	Metal penetration (mm/y)
Negligible	< 0.1	< 0.05	< 0	< 0
Mild	0.1 to 0.4	0.05 to 0.2	0 to 0.15	0 to 0.075
Moderate	0.4 to 1.0	0.2 to 0.5	> 0.15	> 0.075
Severe	1.0 to 2.5	0.5 to 1.25		
Extreme	> 2.5	> 1.25		

Legend:

SI	=	Saturation Index (mean value of SI determined according to Langelier, graphical method, Larson)
SI <sub>m</sub>	=	measured SI (marble test)
I	=	Ryznar Stability Index
DFI	=	Driving Force Index
RI	=	Riddick Index
Eh	=	Redox Potential
Fe <sub>max</sub>	=	maximum iron concentration
Fe <sub>inc</sub>	=	Iron increase
Fe <sub>up</sub>	=	Iron uptake

Based on the results obtained, it is obvious that there are no significant differences between the corrosion indexes and corrosion tests regarding their application to predict corrosiveness of the different types of groundwater presented in Table A.13.1 (see Appendix 13). The amount of data necessary to perform the different indexes and tests, however, is quite variable. For example, the pH is a single measurement while the Riddick Index (RI) is based on eight different parameters. There is also a significant difference in simplicity between computing the SI and determining it graphically.

Taking into account the good correlation of the results from the various indexes and tests regarding the prediction of handpump corrosion, it is evident that a simple corrosion index such as the pH or the Saturation Index (SI) fully meets the requirements to be expected. This does not mean that all other indexes and tests described previously should not be recommended when the necessary means and expertise are available. In fact, it is common practice to apply more than one index or test. Different corrosion indexes and tests usually complement each other and, if their results correspond, increase the confidence in the reliability of the measurement, or, in the case of non-correspondence, may indicate the necessity for further investigations.



**Legend:**

- SI = Saturation Index (mean value of SI determined according to Langelier, graphical method, Larson)
- $SI_m$  = measured SI (marble test)
- I = Ryznar Stability Index
- DFI = Driving Force Index
- RI = Riddick Index
- Eh = Redox Potential
- $Fe_{max}$  = maximum iron concentration
- $Fe_{inc}$  = iron increase
- $Fe_{up}$  = iron uptake

**Figure A.14.8 Relationships between corrosion indexes and pH, and between corrosion tests and pH**



The electrical conductivity (EC) is also of importance regarding corrosion. Although its effect on electrochemical corrosion is generally negligible, it does have a significant effect on galvanic corrosion. Therefore, galvanic or bimetallic corrosion should be avoided, or at least minimized, by the selection of appropriate materials for downhole components of handpumps. pH, on the other hand, plays an important role in electrochemical corrosion, but has a negligible effect on galvanic corrosion (see Appendix 14.2).

There are two main problems associated with corrosion: its effect on water quality (high iron concentration) by the removal of the protective zinc coating, and subsequent dissolution of iron, and mechanical damage to pump equipment that results in breakdowns. The effect on water quality is primarily the result of electrochemical corrosion; that is, of the more or less uniform removal of the galvanization of rising mains and pump rods. To predict the severity of this type of corrosion, any of the indexes or tests described in the preceding appendixes are useful. The simplest is the one based on pH (see Appendix 13, Section 13.5). In order also to consider mechanical failures caused by galvanic corrosion, which is usually concentrated in small areas near the contact between different types of materials (e.g., pump rod-piston, rising main-pump cylinder), it might be useful to complement the pH-based corrosion index with an EC-based galvanic corrosion index. The galvanic corrosion index is of indicative value only because galvanic corrosion depends not only on the EC, but also on the types of metals coupled, their dimensions, and their geometry. An EC-based index for galvanic corrosion is presented in Table A.14.4.

**Table A.14.4**  
**EC-Based Corrosion Index for Galvanic Corrosion of Mild Steel Coupled with Brass**  
**(Based on Results of Laboratory Tests and Field Observations, and on the Modified**  
**Adjective Rating of Corrosion Damage)**

EC ( $\mu\text{S/cm}$ )	Laboratory Measurements		Field Measurements	
	Diameter reduction (mm/y)	Rating of corrosion damage	Diameter reduction (mm/y) <sup>a</sup>	Rating of corrosion damage
EC $\leq$ 50	< 0.4	mild	< 0.8	moderate
50 < EC $\leq$ 100	0.4 to 0.6	moderate	0.8 - 1.2	moderate to severe
100 < EC $\leq$ 250	0.6 to 1.0	moderate	1.2 - 2.0	severe
250 < EC $\leq$ 500	1.0 to 1.2	severe	2.0 - 2.5	severe
EC > 500	1.2	severe	> 2.5	severe (to extreme)

<sup>a</sup>Approximated results (diameter reduction measured in the laboratory multiplied by 2 based on field experience).

## Appendix 15. Acronyms, Abbreviations, Units, Conversion Factors

### 1. General Acronyms

APHA	American Public Health Association
ASTM	American Society for Testing and Materials
AWWA	American Water Works Association
DIN	Deutsche Industrie Norm (German Standards)
EAWAG	Swiss Federal Institute for Water Resources and Water Pollution Control
GWSC	Ghana Water and Sewerage Corporation
IDC	International Drilling Consultants
INT	Interregional
ONAREM	Office Nationale des Ressources Minières
SGS	Société Générale de Surveillance
UNDP	United Nations Development Programme
USA	United States of America
WHO	World Health Organization
WPCF	Water Pollution Control Federation

### 2. Technical Acronyms

DFI	Driving Force Index
DO	Dissolved Oxygen
EC	Electrical Conductivity
GI	Galvanized Iron
GW	Groundwater
HD	Hardness
I	Ryznar Stability Index
MF	Membrane Filtration
PVC	Polyvinyl Chloride
RI	Riddick Index
SI	Saturation Index
SS	Stainless Steel
TDS	Total Dissolved Solids

### 3. Chemical and Technical Abbreviations

Al, Al <sup>3+</sup>	Aluminum, Aluminum ion
Alk	Alkalinity
Al <sub>2</sub> O <sub>3</sub>	Aluminum oxide
Ca, Ca <sup>2+</sup>	Calcium, calcium ion
CaCO <sub>3</sub>	Calcium carbonate
CO <sub>2</sub>	Carbon dioxide
CO <sub>3</sub> <sup>2-</sup>	Carbonate ion
cH <sup>+</sup>	Concentration of H <sup>+</sup> ion

Cl, Cl <sup>-</sup>	Chloride, chloride ion
e <sup>-</sup>	Electron
Eh	Redox potential
Fe	Iron
FeCO <sub>3</sub>	Iron carbonate (siderite)
Fe(OH) <sub>2</sub>	Iron (II)-hydroxide
FeOOH	Iron (III)-oxyhydroxide (goethite)
Fe <sub>3</sub> O <sub>4</sub>	Iron oxide (magnetite)
H, H <sup>+</sup>	Hydrogen, hydrogen ion (proton)
HCl	Hydrochloric acid
HCO <sub>3</sub> <sup>-</sup>	Bicarbonate
H <sub>2</sub> O	Water
K, K <sup>+</sup>	Potassium, potassium ion
log	Logarithm to the base 10
Mg, Mg <sup>2+</sup>	Magnesium, magnesium ion
N	Nitrogen
NaCl	Salt (sodium chloride)
NH <sub>4</sub> <sup>+</sup>	Ammonium ion
NO <sub>2</sub> <sup>-</sup>	Nitrite ion
NO <sub>3</sub> <sup>-</sup>	Nitrate ion
NH <sub>4</sub> OH	Ammonium hydroxide
O <sub>2</sub>	Oxygen
OH <sup>-</sup>	Hydroxyl ion
SiO <sub>2</sub>	Silica
S, SO <sub>4</sub> <sup>2-</sup>	Sulphur, sulphate ion
Zn	Zinc

#### 4. Units

cm	Centimeter
cm <sup>2</sup>	Square centimeter
°C	Degree centigrade (Celsius)
d	Day
g	Gram
h	Hour
km	Kilometer
km <sup>2</sup>	Square kilometer
l	liter
m	meter
m <sup>2</sup>	Square meter
m <sup>3</sup>	Cubic meter
mm	Millimeter
mm <sup>2</sup>	Square millimeter
mg	Milligram
mg/l	Milligram per liter
m <sup>3</sup> /h	Cubic meter per hour

mils	Milliinches
mpy	Milliinches per year
NTU	Nephelometric Turbidity Unit
$\mu\text{m}$	Micrometer
$\mu\text{S/cm}$	Unit for conductivity at 25°C ( $1 \mu\text{S/cm} = 1 \mu\text{mhos/cm}$ )
y	year

## 5. Metric-English Unit Conversion Table

**Length:**  
 1 meter (m) = 39.37 inches = 3.28 feet = 1.09 yards  
 1 kilometer (km) = 0.62 miles  
 1 millimeter (mm) = 0.03937 inches  
 1 centimeter (cm) = 0.3937 inches  
 1 micrometer ( $\mu\text{m}$ ) =  $3.937 \times 10^{-5}$  inches

**Area:**  
 1 square meter ( $\text{m}^2$ ) = 10.764 square feet = 1.196 square yards  
 1 square kilometer ( $\text{km}^2$ ) = 0.386 square miles = 247 acres  
 1 square centimeter ( $\text{cm}^2$ ) = 0.155 square inches  
 1 square millimeter ( $\text{mm}^2$ ) = 0.00155 square inches

**Volume:**  
 1 cubic meter ( $\text{m}^3$ ) = 35.314 cubic feet = 1.3079 cubic yards  
 1 cubic centimeter ( $\text{cm}^3$ ) = 0.061 cubic inches  
 1 liter (l) = 1.057 quarts = 0.264 US gallons

**Mass:**  
 1 kilogram (kg) = 2.205 pounds  
 1 gram (g) = 0.035 ounces = 15.43 grains  
 1 milligram (mg) = 0.01543 grains

### Volumetric flow rate

1 cubic meter per second ( $\text{m}^3/\text{s}$ ) = 15,850 gallons (US) per minute = 2.119 cubic feet per minute

1 cubic meter per hour =  $57.06 \times 10^6$  gallons per minute = 7,628.4 cubic feet per minute

1 cubic meter per day ( $\text{m}^3/\text{d}$ ) = 0.183 gallons per minute

1 liter per second (l/s) = 15.85 gallons per minute

**Viscosity:** 1 poise =  $1.45 \times 10^{-5}$  pounds seconds per square inch

1 centipoise = 0.01 poise =  $1.45 \times 10^{-7}$  pounds seconds per square inch

**Temperature:** degrees Celsius ( $^{\circ}\text{C}$ ) =  $\frac{5}{9} (\text{^{\circ}\text{F}} - 32)$

degrees Fahrenheit ( $^{\circ}\text{F}$ ) =  $(\frac{9}{5} \times \text{^{\circ}\text{C}}) + 32$

# References

- Akiti, T. T. (1982). Nitrate Levels in Some Granitic Aquifers from Ghana. In *Impact of Agricultural Activities on Groundwater*. International Symposium IAH. Prague.
- Arlosoroff, S. et al. (1987). *Community Water Supply—The Handpump Option*. Washington, D.C.: The World Bank.
- APHA-AWWA-WPCF (1980). *Standard Methods for the Examination of Water and Wastewater*. Fifteenth edition. Springfield, Va.: Byrd PrePress.
- ASECNA, Service météorique (1979). *Le climat de la Côte d'Ivoire*. Abidjan, Côte d'Ivoire: Ministère des Travaux Publics, des transports, de la construction et de l'urbanisme.
- AWWA (1987). *External Corrosion—Introduction to Chemistry and Control. Manual of Water Supply Practices M27*. Denver, Colo.: American Water Works Association.
- AWWA-DVGW (1985). *Internal Corrosion of Water Distribution Systems*. Cooperative Research Report by the AWWA Research Foundation/DVGW-Forschungsstelle am Engler-Bunte-Institut der Universität Karlsruhe (TH). Denver, Colo./Karlsruhe, Federal Republic of Germany: American Water Works Association Research Foundation.
- Babut, M. (1984). *Eaux d'alimentation en zone rurale ivoirienne*. Thèse de doctorat de 3ème cycle. Université de Lille, France.
- Chilton, P. J. and Lewis, W. J. (1989). The Impact of Plastic Materials on Iron Levels in Village Groundwater Supplies in Malawi. *Journal IWEN*, no. 3, February.
- Clarke, F. E. (1980). *Corrosion and Encrustation in Water Wells. A Field Guide for Assessment, Prediction and Control*. FAO Irrigation and Drainage Paper 34. Rome: Food and Agriculture Organization of the United Nations.
- De Lorenzi, G. and Volta, C. (1987). *Projet eau potable. Rapport final, année 1986*. Ouagadougou, Burkina Faso: Bulletin de liaison du Comité Interafricain d'Etudes Hydrauliques, no. 70, octobre.
- Driscoll, F. G. (1986). *Groundwater and Wells*. 2d ed. St. Paul, Minn.: Johnson Division.
- Faust, S. D. and Aly, O. M. (1983). *Chemistry of Water Treatment*. Boston, London, Sydney, Wellington, Durban and Toronto: Butterworth.

- Der Fischer Weltatmanach 91.* (1991). Frankfurt am Main: Fischer Taschenbuch Verlag GmbH.
- Groen, J., Schuchmann, J. B. and Geirnaert, W. (1988). The occurrence of high nitrate concentration in groundwater in villages in northwestern Burkina Faso. *Journal of African Earth Sciences* 7(7-8):999-1009.
- GWSC-IDC (n.d., ca. 1986). *3000 Well Drilling Programme in Southern and Central Ghana.* Final Report. Accra, Ghana: Ghana Water and Sewerage Corporation (GWSC) and International Drilling Consultant.
- Höll, K. (1970). *Wasser, Untersuchung, Beurteilung, Aufbereitung, Chemie, Bakteriologie, Biologie.* Fifth edition. Berlin: Walter De Gruyter.
- Jong, S. J. and Kikietta, A. (1980). *Une particularité bien localisée, heureusement présence d'arsenic en concentration toxique dans un village près de Mogtedo (Haute-Volta).* Bulletin de Liaison du Comité Interafricain d'Etudes Hydrauliques, Septembre-Décembre 1980, No. 42-43. Ouagadougou, Burkina Faso.
- Langenegger, O. (1981). High nitrate concentration in shallow aquifers in a rural area of central Nigeria caused by random deposit of domestic refuse and excrement. In *Studies in Environmental Science.* Vol. 17 of *Quality of Groundwater, Proceedings of an International Symposium.* Amsterdam: Elsevier.
- Langenegger, O. (1988). Groundwater Quality in Rural Areas of Western Africa. In *Proceedings of the Sahel Forum on the State-of-the-Art of Hydrology and Hydrogeology in the Arid and Semi-Arid Areas of Africa,* Ouagadougou, Burkina Faso: UNESCO/IWRA.
- Langenegger, O. (1988). The impact of handpump corrosion on water quality. In *Proceedings of the Sahel Forum on the State-of-the-Art of Hydrology and Hydrogeology in the Arid and Semi-Arid Areas of Africa,* Ouagadougou, Burkina Faso: UNESCO/IWRA.
- Langenegger, O. (1989). Groundwater quality—An important factor for selecting handpumps. In *Groundwater Economics, Selected Papers from a United Nations Symposium, Barcelona, Spain, 1987.* Amsterdam, Oxford, New York, Tokyo: Elsevier.
- Langenegger, O. (1989). Hydrogeological mapping of groundwater quality under particular consideration of corrosiveness and salinity of aquifers in western Africa. Abstracts, Vol. 2. 28th International Geological Congress, Washington, D.C.
- Mallevalle, J. and Suffet, I. H. (1987). *Identification and treatment of tastes and odors in drinking water.* American Water Works Association/Lyonnaise des Eaux. Denver, Colo.: American Water Works Association.

- Mathis, A. (1983). *Analyses physico-chimique des eaux souterraines des cercles de Bougouni, Yanfolila et Kolondieba (République du Mali). Projet de Forages Hydrauliques, Zone Mali-sud.* HELVETAS/DNHE.
- Merck, E. *Die Untersuchung von Wasser.* 9th ed. Darmstadt, Federal Republic of Germany: Ref. Truesdale, Downing, and Lowden, *J. Appl. Chem.* 5 (1955): 53.
- Nene Schweizer Bibliothek. (1958). *NSB Universal Lexikon.* Zürich: Schweizer Druck und Verlagshaus AG.
- Prevost, C. P. (1987). *Corrosion Protection of Pipelines Conveying Water and Wastewater.*
- Sawyer, C. N. and McCarty, P. L. (1967). *Chemistry for Sanitary Engineers.* 2d ed. New York: McGraw-Hill.
- WHO (1984). *Guidelines for Drinking-Water Quality, Vol. 1, Recommendations.* Geneva: World Health Organization.





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