A CRITICAL EVALUATION OF SAND ABSTRACTION SYSTEMS IN SOUTHERN AFRICA

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WRC Report No. 829/1/05

Water Research Commission

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PART 1: PRINTED DOCUMENT

VOLUME 1 OF 3

REPORT BODY

Report to the Water Research Commission on the Project
"Systems for the Abstraction of Water through River Sand Beds

by

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WRC Report No: 829/1/05
ISBN No: 1-77005-258-5
ISBN Set No: 1-77005-257-7

JANUARY 2005

Printed by Silowa Printers: 012 804 1164

EXECUTIVE SUMMARY

Introduction

The term sand abstraction system could be applied to a wide variety of applications and different types of abstraction systems. This research has focussed on the investigation into those systems used for abstracting water from river sand beds, be it perennial rivers or ephemeral sand rivers.

Typical advantages associated with the use of sand abstraction systems in Southern Africa are the following:

- The ability to abstract waters with high sediment loads and turbidity at relatively low costs and with fewer problems in comparison with conventional methods.
- Water could be abstracted from seasonal and sand rivers, particularly in arid and semi-arid regions where often the only source of water during the dry season is the water stored and/or flowing in the sand of surface-dry rivers.
- Sand abstraction methods are ideally suited for application in rural areas and in emergency situations where small-scale abstraction systems could be constructed by simple, labour-intensive construction methods and the use of readily available and cheap materials.
- Because of its simplicity and the filtering capability of the sand, very little operation or maintenance is normally required and operators need not be highly skilled.
- The treatment of the abstracted water is relatively simple and cheap as normally only chlorination is required.

Although sand abstraction systems offer many advantages, the behaviour of these systems were found to be somewhat unpredictable and problems with reduced yield were experienced at some of the relatively large sand abstraction systems in Southern Africa. The erratic performance of these sand abstraction systems, together with the findings of the initial investigations into the cause of the problems have led to the initiation of this research.

Purpose of this Research

This research was primarily initiated to gain more knowledge and insight into the problems and behaviour associated with sand abstraction systems in order to improve the levels of success for future installations of such systems. In addition, the lack of information available on sand abstraction systems indicated the need for the establishment of a directory of existing systems, which would cover system information and details regarding typical problems experienced with the system, the design, construction and operation of the system.

Part of the research was to investigate typical problems that occur at sand abstraction systems and to determine whether there are any significant correlations between system performance and any other external parameters that might have an impact on system performance. This information were to be presented in such a manner that it could be used for the identification of potential problems that would cause reduced system performance and the risk of occurrence of such problems under prevailing conditions.

In order to minimise and/or overcome the impacts of potential problems at sand abstraction systems it was further required to critically evaluate theoretical and practical guidelines for the design, construction and operation of such sand abstraction systems. Due to the complexity of the problems pertaining to the application of sand abstraction systems, it was agreed that emphasis should rather be placed on data collection and evaluation, and on the identification of problem areas and areas that would require further investigations, instead of the development of appropriate design and operation and maintenance guidelines for these systems.

Research Methodology

After establishing the research objectives some hypotheses regarding the failure of sand abstraction systems were formulated. These hypotheses were based on published reports and articles on the performance of sand abstraction systems and practical experience. As the research progressed some of the objectives and hypotheses were revised and modified to accommodate practical problems experienced and new information obtained on the performance of sand abstraction systems.

The next step was to conduct a literature review on the application of sand abstraction systems, which included the relevant aspects of system performance and guidelines on the design, construction and operation and maintenance of sand abstraction systems as addressed in the objectives of the research.

A comprehensive survey was also carried out to identify and log the characteristics of existing sand abstraction systems in Southern Africa. The survey methodology included aspects such as the compilation of the questionnaire, distribution of the questionnaire to the identified target group, the processing of the returned questionnaires, the setting up and conducting of site visits to the systems identified from the questionnaire and the sampling and testing of relevant system parameters at these sand abstraction systems. Where possible, interviews were conducted with the persons directly involved with the design, operation and maintenance of the abstraction system visited. The general findings and data obtained from the survey were analysed and then summarised in tabular and graphical format, which are presented in the relevant appendices of this report.

In addition to the literature and field surveys some scale model testing was conducted in a laboratory to evaluate the impacts of different parameters, such as screen types, sand density, abstraction rates and development, on the performance of a sand abstraction system. The data and test results obtained from this testing were analysed and are summarised in the relevant appendices to this report.

The research was concluded by the compilation of a comprehensive report, which includes the findings, conclusions and recommendations that resulted from the analysis and evaluation of the literature review, the data gathered and the testing results obtained. Typical qualitative guidelines based on the findings of this research and current practices for sand abstraction systems were included in the report as an aide to persons responsible for the design, operation and maintenance of sand abstraction systems.

Findings and Conclusions

Overview of Sand Abstraction Systems Surveyed

Although not all sand abstraction systems could be identified during the research project, a total number of 67 sand abstraction systems were identified, of which 39 were visited in the field. About 40% of the systems visited had vertical well points installed, whereas about 43% made use of horisontal well screens connected to a caisson or collector sump. The remainder of systems visited were mainly caissons installed in the riverbed or the riverbank.

The sand abstraction systems were mainly used for domestic water supply and in a few instances for irrigation purposes. The design yield varied from 2 l/s for a gabion type collector sump with horisontal well screens to 1020 l/s for a bank of vertical well points. About half of the systems experienced problems of low yield, while one third of them suffered from iron and manganese related problems. Only half of the systems with low yield problems also had iron and manganese related problems.

About 20% of the systems experienced some known flood damage during construction or operation of the system. Only one of these systems, the biggest well point system, with a design yield of 1020 l/s, did not suffer from a reduction in yield after the flood event.

Generally it was found that most of the sand abstraction systems were suitably designed from a structural and hydraulic point of view. However, the geohydrological aspects and the hydraulic flow through the sand formation were mostly neglected in the design of sand abstraction systems. Similarly not much attention were given to aspects such as operation and maintenance during the design phase.

Problems Experienced with Sand Abstraction Systems

Typically the problems most experienced with sand abstraction systems were that of low yield, poor quality of abstracted water and flood damage to the systems. The following parameters were found to be the main causes of the problems experienced:

- The recharge rate of an aquifer is lower than the abstraction rate of the system, resulting in over pumping and low draw down of the aquifer;
- A reduction in the permeability of the sand formation due to the accumulation or deposition of fine silt in or on the sand bed;
- The clogging of well screens by iron or manganese precipitates or by the development and accumulation of biofilm in the screens;

- The degradation or rusting of materials used for well screens and pipes, which caused either clogging of the system and or damage to pumps;
- The clogging of certain geofabrics, which in some cases resulted in a permeability of 10 times lower than when originally installed;
- A drop in the level of the water table due to low rainfall, excessive draw down or over pumping;
- The displacement or movement of well screens during fluidisation of the riverbed when floods occur;
- A change in the river course flow within the river bed over time, thereby changing the location of the system in relation to the aquifer;
- Insufficient developing of the system after installation, resulting in accelerated clogging of the system.
- Damage to the infrastructure (pipes, screens, collector wells and pumps) of the system due to flooding of the system.

A rating (1 to 5) was assigned to each of the systems visited in order to rate the typical problems experienced at each system in terms of low yield, biofouling, clogging of sand and iron and manganese concentrations. These ratings are included in the relevant appendices related to system performance.

Characteristics of Successful Abstraction Systems

The following observations regarding the design, installation and operation were made at some of the successful abstraction systems visited:

- The systems were normally located where favourable site conditions in terms of sand characteristics, water quantity and quality, geology and geography prevail.
- Innovations in the design, construction, operation and maintenance played a major role in the success of systems.
- Successful systems generally have good operational and maintenance practices in place
- The timely adaptation to any changes of the conditions that impact on the system.
- Backwashing facilities were incorporated during the design of the system.

From the literature study and the observations above it is clear that the following aspects are of critical importance for the implementation of a successful sand abstraction system:

- The location of the site – the location of the sand deposits in relation to flood levels is critical in order to minimise potential flood damage to the abstraction system and to determine the optimum layout of the system.
- The parameters of the water bearing sand formation – the thickness of the sand deposit, the grading, grain size, permeability and the specific yield are all important parameters to consider before deciding which type of abstraction system to design and implement.

- The quality of the subsurface water – sufficient testing should be carried out to determine the quality of the abstracted water, as too high treatment costs could make the abstraction system uneconomical.
- The design of the system – the system should be designed to best suit the conditions prevailing at the selected site. The individual elements such as collector wells, pipes, screens and pumps should be sized correctly to prevent over pumping, excessive draw down and high flow velocities through the system.
- The construction and installation of the system – it is very important that the construction and installation methods are suited to the site conditions and that the properties of the water bearing formation are not changed during construction of the system.
- Development of the system – it was found that the performance of a system is significantly improved if it is properly developed before being used. Several methods of development are available and the best method or combinations of methods should be employed.
- The operation and maintenance of the system – it was found that successful abstraction systems are generally operated within the design parameters and that potential problems could be detected at an early stage with regular monitoring. Corrective measures and maintenance as required would generally ensure successful performance of the system.

It was found that once problems have started to develop in a system, they would progressively become worse. It would then become much more difficult to remedy the problem if it is not dealt with as soon as possible. It is essential that the users of sand abstraction systems be open to adaptation or modification of the systems whenever required.

Correlation of System Parameters with System Performance

Water Quality

Generally it was found that the water quality parameters measured were not very good indicators of problems that could be expected at a sand abstraction system. However, it was found that the nitrate concentration in the surface water is a good indicator of the total bacteria counts in the system water and would therefore be a good indicator of biofouling problems. Similarly the turbidity is also a good indicator to estimate the total iron concentration, which could be an indication of potential problems related to iron and manganese precipitation or the presence of iron bacteria.

Graphs are included in the appendices, indicating the correlation between water quality parameters and system performance in terms of problem rating. The findings are also summarised in terms of risk (low, moderate and high) in Table A.62 of *Appendix O.1* of this report. These results could be of great value when determining the potential risk of the occurrence of a certain type of problem in a system.

Microbiological Aspects

It was found that there is a moderate risk of bacterial biofouling in most of the systems evaluated, with a high risk of bacterial biofouling occurrence in a few of the systems.

With regards to the samples drawn from the Nqutu System, it was found that bacteria was the main agent in the sample and that the black substance from the walls of the collector well was a result of bacterial fouling. The sulphate reducing bacteria (SRB) count was too low to have played any role in the biofouling that occurred in this system.

With regards to the Ulundi System, the testing results indicated that biofouling has taken place in the system and that the slime in the system was produced by bacteria and/or algae. However, it could not be determined whether bacteria or algae were the main causative agent of the slime production. The biofilm possibly formed because of the presence of algae among the sand particles, which provided a growth surface for the bacteria. It was further clear that SRB did not form part of the biofouling problem.

No conclusions could be made on the part that iron bacteria plays in the biofouling in these systems. Although SRB normally has a major effect on biofouling, it was found in this study that the number of SRB in the samples was too low to cause the biofouling. It is, however, clear that the risk of biofouling increases significantly when algae and/or high counts of bacteria are present in the system.

Sand Properties

Several sand properties were measured and compared with the problem rating at each sand abstraction site visited. The results for each system, including a photograph showing the composition of the sand, are included in *Appendix M.6* of the report. The results of the grading analyses indicated good correlations between the percentage of certain particle sizes in the sand and problems of low permeability and subsequently low yield and clogging of the sand. No significant correlation could be determined between the grading of the sand and other system problems such as biofouling and iron or manganese related problems.

There was little variation in the specific gravities of the various size fractions of the sand samples. In some instances the fines fraction had a higher specific gravity than the coarser fractions, but no particular trend or relationship was found between system performance and specific gravity.

No direct correlation could be found between the in-situ bulk density and any of the system problems such as low yield, clogging of sand, biofouling and iron or manganese related problems. However, for in-situ bulk densities higher than 1650 kg/m^3 there is a marked drop in the permeability and void ratio of sands.

Observations of particle shapes are given in *Appendix M.6* together with photographs of the respective sand, the permeability and in-situ bulk density of the sand, and the problem ratings for the systems installed in the sand. This information could be useful as a field guide for examining sands during investigations for proposed abstraction systems and could be used as an initial indicator of the potential performance of an abstraction system installed in the sand being examined.

Generally sand particles that are more rounded, not flaky and with high clay content are the most likely to present performance problems such as low yield and clogging in sand abstraction systems.

Geological Factors

Several parameters of catchment geology were measured to determine the relationship between these parameters and system performance. A reasonable correlation could be established between system yield and the size of the Drakensberg and Lebombo Group in the catchment upstream of the abstraction point. If the size of this geological Group is larger than 13% of the catchment some problems could be expected with low yield and the clogging of the sand, whereas problems of biofouling and excessive iron and manganese concentrations could be expected if the size is larger than 17% of the catchment area.

The relative size of the Basement Complex in Transvaal, Swaziland, Namibia and Rhodesia in the catchment area is another good indicator of biofouling and iron and manganese related problems. Generally, the smaller this Complex the lesser is the risk of biofouling and iron and manganese related problems. A reasonable correlation was also found between Acid and Intermediate Intrusives in the catchment area and potential biofouling problems. The smaller the size of these intrusives the lesser the risk of biofouling becomes.

Geographical Factors

Generally good correlations were found between potential biofouling and geographical parameters such as the presence of sugar cane in the catchment area, the MAP of the catchment and the size of cultivated land (land use) 50 km upstream in the catchment area. A reasonable correlation was also established between potential iron and manganese related problems in systems and other geographical parameters such as the size of tropical bush & savannah (Bushveld) and the MAR of the catchment.

It appears that geographical parameters could be used in some instances to predict problems related to biofouling and the presence of iron and manganese. It is, however, not a good indicator of potential low yield and/or the clogging of sand abstraction systems.

River Morphology

Overall it was found that the river morphology could not be considered as a good indicator of potential problems that might affect system performance.

Effectiveness and Usefulness of Sampling and Testing Techniques

Water Quality Testing

Despite several precautionary measures, difficulties were experienced in keeping samples at a constant temperature after it was taken on site and it was considered possible that samples may have undergone changes in the time between sampling and analysis. This problem was solved by using portable sampling and testing equipment for "on-site" analysis and testing. This procedure was very effective and provided more accurate results of the on-site water quality.

Another problem was that the oxidation state of the iron and/or manganese in the water samples taken from the abstraction systems probably changed in the time before the laboratory analyses were done. This problem was resolved by preserving samples specifically for iron and manganese analysis in the laboratory.

The following testing equipment was used very effectively for on-site water quality testing:

- The *HACH DR/850 colorimeter*, which could be used to test for more than 50 parameters. In this study it was used for testing Turbidity, Nitrate, Sulphate, Ferrous Iron and Total Iron.
- The *HANNA DiSTWP 3 conductivity meter*, which was used for testing the Redox Potential of the water.
- The *HANNA HI8314 pH / mV / °C meter*, which was used for testing the pH and Conductivity of the water.

The standard methods, as described by the manufacturers of the instruments were used for testing samples. It is important that samples of high turbidity should be filtered prior to testing for Iron, Sulphate and Nitrate.

Testing of Sand Parameters

At each site, where conditions permitted, general sand samples were taken for grading analysis, density tests and laboratory permeability tests. During initial site visits the taking of representative sand samples proved to be problematic due to reasons of access and the method of sampling used. Due to these problems alternative sampling methods were sought. Two samplers, a hand auger and a tube sampler, were found to work particularly well in these conditions. The samplers were relatively cheap and easy to make up, and were extremely manageable and effective.

In certain conditions, such as where the riverbed material was extremely coarse, with high pebble content, or where the river flow was too deep, these samplers could not be used. In these instances samples were excavated from the surface of the riverbed.

Another useful device, called the "directional" permeability test unit, was also used to measure the in-situ permeability of sand. This device could be used to measure the in-situ permeability of sand in a horisontal or vertical direction. A disadvantage of this sampler is that samples could only be taken from exposed surfaces.

The bulk density of sand was measured by using one or more of the following devices or methods:

- Troxler – this instrument is useful in measuring the in-situ density of sands very quickly. However, it has certain limitations in that it is a very expensive device, it has radioactive parts which could be a health risk if not operated correctly, it should be calibrated regularly for different types of sand and it could not be used in saturated or submerged conditions.
- Volumetric measurement of excavated hole – this method is very simple to use by measuring the volume of the excavated hole by means of water replacement. Unfortunately it did not provide reliable results of the in-situ density of sand and also could not be used in saturated and submerged conditions.
- Density ring – this method is based on the excavation of a known volume of sand. The density ring could be used in surface dry, saturated or submerged conditions, and in most types of sands. However, the density ring cannot easily be used in pebbly or extremely coarse materials. Disadvantages of this method include the fact that one is limited to taking samples from exposed surfaces.
- Dynamic Cone Penetrometer (DCP) – this instrument was used to determine the relative density of the sand by counting the number of blows required to drive the penetrometer a fixed distance into the sand.

Data and Testing Requirements for the Application of Sand Abstraction Systems

For successful sand abstraction systems it is essential that appropriate investigations be conducted prior to the design and installation of such a system. Existing data and information should be gathered and evaluated as far as possible before deciding on what testing is required at a specific site.

The following data and information are normally readily available in well documented areas and could be very useful when selecting sites for new abstraction systems:

- The location of the riverbed of the original river course in relation to the present river course. Generally the sand depth above the riverbed of the original river course is deeper than in other parts of the river.
- Changes in the width of the original river course over time - at Beitbridge, for example, the old river course was approximately 45 m wide, whereas the existing riverbed is approximately 330 m wide.
- The depth of the seasonal water table in the sand bed. At Beitbridge the river is usually surface dry from about April to October. During this period the depth of the water table usually varies between 1.6 m and 3.0 m below surface level.
- Typical characteristics of the sand, such as the type of sand and the percentage fines in the sand, the transmissivity and storage coefficient of the sand, which could be estimated from profiles and cross-sections of the aquifer and the permeability of the sand, which could differ depending on the depth of the sand in the riverbed.
- The extent of the alluvial aquifer upstream of the system in order to determine the effective storage volume and zone of influence of the system.
- Relevant hydrogeological information such as MAP, MAR and general geology of the catchment area upstream of the system.

In riverbeds where the above data are known and available, the only tests that should be required to determine the feasibility of a new abstraction system are tests to determine the depth and profile of the sand bed.

The typical tests required for the design and installation of sand abstraction systems are the following:

- Grading analysis of the sand.
- Bulk density of the sand
- Permeability of the sand, either through laboratory analysis or through theoretical calculations based on particle size distribution of the sand. From this the transmissivity of the aquifer could also be determined.
- Storativity and recharge of the water-bearing formation through theoretical calculations or through pumping tests such as step tests, at variable discharge rates, and/or constant discharge tests at the same rate as the abstraction rate. These tests should be carried out over extended periods in order to verify the sustainable potential yield of an aquifer.

It is good practice to install new systems in areas where it is known that the alluvial aquifer is contiguous with the alluvium of the riverbed. In these cases full geohydrological investigations should be conducted, including the drilling of test holes to determine the properties of the water-bearing formation and the execution of pumping tests to determine the recharge and storage properties of the aquifer.

Samples of the surface and sub-surface water should also be taken and tested for the nitrate concentration, the turbidity and pH, which might have significant impacts on the performance and operational and maintenance cost of the system.

Design Procedures and Considerations Relating to Design

Siting of a Sand Abstraction System

Several factors have an impact on the siting of an abstraction system. The parameters that should be taken into consideration are the following:

- *Aspects of Water Demand* - Generally the first guideline for siting a sand abstraction system is the area where the water is required, the volume that is required and for what purpose the water will be used.
- River Morphology - The nature of the river morphology upstream and downstream of a proposed abstraction site is a very important when deciding where the system should be located and what system would be most suitable at that location. Sand abstraction systems should be installed in such positions that the impacts resulting from high floods, such as bed fluidisation and damage to the structure of the system, would be minimised.

Geological and Geographical Aspects

Before deciding on a site for a sand abstraction system one should study the geological and geographical conditions of the catchment area upstream of the system. Typical parameters such as the presence and size of certain rock formations, the type of land use, the MAR and MAP of the catchment are good indicators of potential biofouling, high iron and manganese concentrations and clogging of the filter sand.

Other parameters, which could also impact on the performance of a system, are obstructions, such as weirs and bridges, and industrial and agricultural activities in the immediate vicinity of the proposed site. Most of these parameters could be obtained from regional geological and topographical maps and should be evaluated in terms of the relevant graphs summarised in *Appendix O* of this report.

Estimation of Yield

A sand abstraction system could be considered successful if it could supply water of appropriate quality at the required rate over the design lifetime of the system. For any good design the required abstraction rate should be in balance with the estimated yield from the aquifer. The yield from an aquifer is dependent on its recharge capability, which is determined by the flow conditions in the river and/or its interconnection with other aquifers.

The yield of a sand abstraction system is dependent on the hydraulic head above the point of abstraction and the permeability of the sand bed through which the water flows. Under natural conditions, the quantity of groundwater flowing through the alluvium under non-pumping conditions at the position of the abstraction point could be calculated by using Darcy's Law.

The specific yield and recharge of an aquifer could be estimated by making use of the developed equations for permeability in section 7.1.1 and Appendix M.4 of this report. The permeability is based on the grading analysis and site density of the relevant sand bed. The most accurate equation developed is based on the D_2, D_5, D_{10}, D_{15}, D_{20}, D_{50} and D_{80} range of sizes of a particular sand

Various software packages, such as AQUAWIN, are also available which could be used for modelling the behaviour of groundwater in an aquifer under pumped conditions. These models are normally difficult to set up and are not of much use if not calibrated correctly.

Design Norms

Typical design criteria that should be considered for the design of sand abstraction systems are the following:

- The infiltration rate from surface flow into the sand should be limited to about 0.4 mm/s in order to minimise the rate at which fine particles could penetrate and block the voids in the surface layer of the sand.
- The hydraulic gradient should be kept between 0.45 (fine sands) and 1.00 (coarse sands) to ensure laminar flow and the application of Darcy's equation for flow through the sand bed.

- Where well screens are used the flow velocity through the screen slots should not exceed 0.03 m/s in order to keep the hydraulic gradient within the limits required for laminar flow, and to minimise the infiltration of fines into the well screens, as well as to minimise head losses through the screen.
- Where abstraction pipes are used the flow velocity in the pipes should be kept between 0.9 m/s and 0.3 m/s in order to minimise head loss and the deposition of fine material in the pipes respectively.
- The size of the slot openings in the abstraction pipes or screens should be such that 95% to 100% of the surrounding sand is retained outside the pipe or screen.
- Provision should be made in the design for the development of the sand surrounding the abstraction pipes or well screens.
- Instead of developing the well, the installation of a filter pack around the abstraction pipe or screen could also be considered.
- Horisontal well screens, if used, should be installed as deep as possible in the sand bed, or anchored to the riverbed, in order to minimise the impacts of sand bed fluidisation under flood conditions.

Design Calculations

As a guideline typical design equations for the calculation of head losses and flows through the sand bed and collector pipes are included in *Appendix R* of this report. If necessary, similar equations should be developed for different assumptions and layouts other than that shown in the appendix.

Where conditions are different, revised flow nets should be compiled to determine the relevant flow and equipotential lines for different layouts and configuration of the abstraction system.

Standard hydraulic calculations should be used when sizing the different elements (pipes, screens, valves, pumps, etc.) of the water abstraction system in terms of flow velocity, head loss and flow capacity. The well screens should be sized in accordance with the required abstraction rate, which would determine the open area required and the maximum screen velocity for specific slot widths.

Practical Design Considerations

The following are good practical considerations for the design of sand abstraction systems:

- A factor of safety of at least 25% should be added to allow for possible clogging or encrustation of well screens.
- The use of geofabric as a filter material should be avoided where possible due to problems of clogging and reduced yield being experienced.
- Where possible corrosion resistant materials should be used to minimise maintenance and potential reduction in yield.

- Allowance should be made for backwashing facilities in the design of an abstraction system. As such non-return valves should not be used, and vacuum tanks should rather be installed.
- Systems should be designed to facilitate easy access to critical elements for the operation and maintenance of these systems.
- Well screens should be installed deep enough to allow for expected draw down of the water.
- Where possible, one should stay away from sand beds that contain clay lenses, as it could cause reduced yield of the system. In some cases these clay lenses could be successfully removed.
- The design of the system should be re-assessed whenever new developments or structures such as weirs or bridges are built in the near vicinity.
- Provision should be made for ventilation to prevent air locks in the system.
- Well points should be designed to operate individually instead of in banks. This would reduce power consumption and optimise abstraction rates if problems occur with some of the well points.
- Allowance should be made for the priming of well point pumps through the installation of vacuum tanks.
- Centrifugal pumps are more efficient than submersible pumps and mono pumps. For well point systems centrifugal pumps should ideally be backed up by submersible pumps.
- Abstraction systems should not be positioned perpendicular to the river flow due to higher risk of flood damage.
- Well points should be attached to a buried manifold with a flexible hose or couplings to provide flexibility of movement to minimise damage during flood events.

Construction Methods
It was found that construction methods may vary considerably for different types of sand abstraction systems and are also dependent on the site conditions, available technology and the cost of implementing such methods. However, it is very important to take note of the following issues when constructing sand abstraction systems:

"Traditional" Sand Abstraction Wells

- The walls of these wells should be excavated at a flatter slope to prevent stability and safety problems during rainy periods.
- The protective thorn fences around these wells should be anchored or replaced with conventional fencing to prevent the trapping of silt and finer sediments during river flows, thereby making it difficult for people to find optimum well sites in the river the following season.

Infiltration Galleries

- The primary application for an infiltration gallery is in shallow aquifers and natural barriers such as impermeable rock formations could greatly enhance well efficiency.
- In most cases the hydraulic head would be low due to limitations on the depth at which a trench laid gallery could be placed. In such cases it is imperative to position galleries in materials of high hydraulic conductivity, such as alluvial deposits.
- Collection sumps should be constructed using the open-end caisson sinking method where reinforced concrete rings are sunk into the river bed by excavating the sand on the inside until the desired depth is reached.

Infiltration Wells

- For easy access and to minimise potential flood damage to pumps and other expensive equipment the collection sump of an infiltration well should be built on the riverbank and then connected to the well.

Collector Wells

- The excavations around the caisson should not be backfilled, as problems would be experienced when trying to sink the caisson deeper.
- After placing aggregate at the base of the sunken caisson it should be covered with a sieve or mesh with suitably sized openings to prevent movement of the aggregate and disturbance of the filter material.
- After installation of the screens, each radial should be individually developed to remove the fines from the formation in the area adjacent to the screen. This normally results in a higher yield and efficiency of the well.
- The caisson should be extended to a level above the design flood level before it is fitted with a pumping house and the required controls. Unconsolidated sand should first be excavated to the level of the water table before placing the first sections of a caisson.
- Cofferdams should be provided to prevent flooding of the works during construction. Besides damage to the works and loss of production, the performance of the system could also be impaired.

Well Point Systems

- It is important that once the screens are in position they should be developed using surge plungers to remove the fines from the formation in the area surrounding the well thereby improving the permeability of the surrounding soil.
- Submersible pumps should be installed above the screens in such a position as to ensure an even suction over the full length of the screen.
- Where possible the manifold system should be buried in the riverbed to minimise possible damage during floods.

- The optimum location for a well point is in a shallow alluvial aquifer where the water levels remain close to surface throughout the year.
- A well point system should ideally be installed towards the end of the dry season when the river water is at its lowest level.
- The river sand should first be removed to the top of the water-bearing layer before a manifold is installed on the water yielding sand. Slotted pipes should then be driven at an angle into the water-bearing layer and then connected to the manifold. To complete the installation the manifold should then be connected to a suction pump on the riverbank.

Screened Tube Wells

- Drilling, driving and/or jetting methods should be used to install the tube wells.
- It is important that the well be developed on completion of the installation in order to establish a zone of high permeability in the formation around the screen.
- The bottom of the tube well should be sealed off by pouring cement through an inner pipe to form a 300 mm thick plug at the bottom of the tube.
- A concrete collar should be provided around the part of the tube extending above the average water level.

Sand Storage Dams

- For a sand storage dam to be successful it is essential that it be constructed in controlled incremental stages so that the velocities of flow through the basin are sufficiently high to transport most of the fine sediments over the dam crest.
- The objective should be to promote the deposition of coarse-grained sand deposits in the dam, which will improve both the efficiency of absorption and the yield of the sand storage dam.
- It is essential that each new stage should be constructed only after the previous stage has effectively silted up.

Operation and Maintenance of Sand Abstraction Systems

In general it was found that the operation and maintenance of sand abstraction systems in Southern Africa has not received the level of attention that it should and that much of the success or failure of such systems are related to operation and maintenance issues. Although the successful systems were not problem free, it was found that proper operation and maintenance procedures were in place at these systems and that problems were detected and remedied at an early stage, thus preventing more serious and costly problems.

Once a sand abstraction system is in operation it should be monitored closely for any signs of deterioration as the early detection of potential problems could potentially save a lot of unnecessary costs and also ensure sustainable yield from the aquifer.

Some typical remedial measures that could be implemented once a problem is identified are the following:

- Clogging of the filter – this is generally caused by the deposition and infiltration of fine silts during low flow conditions in the river. Possible remedial actions are the back-washing or high pressure jetting of the filter medium.
- Clogging of screens – this is normally caused by fine particles plugging the slots of the screen due to high entrance velocities or insufficient filter around the screen. Surge plungers, jetting or compressed air may be used to clear the screens.
- Biofouling of screens – this is generally caused by high levels of iron and manganese in the presence of bacterial slimes. Chlorination, removing and cleaning the screens with peroxide, mechanical agitation and pumping are some of the methods that could be used to break up, dissolve and remove biofouling.
- Incrustation of screens – this is caused by the precipitation of inorganic ions such as iron, manganese, calcium and magnesium. The use of acids and mechanical agitation are some of the methods that could be used to remove incrustation.
- Accumulation of silt in pipes – this problem could be caused by too high inlet velocities, too large slot sizes or an insufficient gravel filter. Flushing, surging or brushing methods could be used to suspend the fines whereafter it is pumped or drained from the well.
- Corrosion of screens – this is generally caused by aggressive water. The damaged elements should be removed and replace with screens or pipes manufactured from corrosion resistant materials.

The operation and maintenance of sand abstraction systems should, as far as possible, be taken into consideration during the design phase of such a system and not after it has been installed. For larger abstraction systems operators should be properly trained in the monitoring and operation and maintenance of such systems.

Groundwater Management

Where appropriate, a formal groundwater management programme should be developed and implemented, especially at large abstraction systems. The objectives of a formal groundwater management programme would be:

- To prevent an aquifer from being over-pumped.
- To optimise the individual abstraction rates from different parts of a system e.g. individual vertical caissons or well points.
- To prevent poor quality groundwater from entering the aquifer.
- To monitor and maintain the ecological integrity of the aquifer and the surrounding environment.

In order to effectively manage alluvial aquifers in riverbeds, the following measurements and equipment would be required:

- Flow meters should be installed at all the abstraction points or for each abstraction network. The total quantities of water abstracted from each system should be recorded on a weekly basis.

- Water level monitoring tubes should be installed at each abstraction point to record the water levels in the aquifer. A 25 mm diameter PVC pipe installed vertically at the abstraction point could be used for this purpose. The water levels inside the pipe should then be measured by using a dip meter.
- The water levels should be monitored and recorded on a weekly basis for the first 12 months of operation, whereafter it could be measured on a monthly basis. It should be indicated on the records whether the levels were recorded while the pump was switched on or off. Levels should be recorded at least four hours after the pump was switched on or off, to allow the water level to stabilise.
- Groundwater quality should be monitored on a monthly basis for the first year of operation and thereafter on a six monthly basis.
- Data collected over the period of a year should be submitted to a qualified geohydrologist for analysis and evaluation.

In terms of the new Water Services Act, the activities listed above are mandatory, and it is the responsibility of the local Water Authority to carry out the required monitoring.

Discussion of Hypotheses Posed

The outcomes of the hypotheses postulated in this report are as follows:

Hypothesis 1: Biologically Induced Fouling

Of the thirteen hypotheses postulated regarding biologically induced fouling eight of them were found to be invalid due to either insufficient results to support them or being false. However, the following five postulations were found to be valid:

- *Biologically induced fouling in the Ulundi system is caused by iron reducing/ oxidising bacteria.*
- *Although bacterial growth can be expected in all sand abstraction systems, the extent to which this growth occurs and the associated risk of clogging by biofouling will vary depending on system conditions.*
- *The level of risk of clogging of a system by biofouling is influenced by, and can therefore be indicated by the surface water quality.*
- *The level of risk of clogging of a system by biofouling is to some extent influenced by, and can therefore be indicated by upstream land use.*
- *The level of risk of clogging of a system by biofouling is to some extent influenced by, and can therefore be indicated by upstream geology.*

Hypothesis 2: Sand Properties

Of the eleven hypotheses postulated regarding sand properties three were found to be invalid due to either insufficient results to support them or being false. However, the following eight postulations were found to be valid:

- *The nature of the sand at the Ulundi sand abstraction system changed following installation of the sand abstraction system, with an accumulation of fines in the* *system, particularly at depth. This is contributing to the problem of low yield of this system.*

- *The installation and operation of sand abstraction systems will alter the nature of the surrounding sand beds.*
- *The accumulation of fines in the Ulundi sand is partly due to the presence of the weir immediately downstream of the system.*
- *In certain types of sands, if there is a weir downstream of a sand abstraction system then fines will accumulate in the sand.*
- *Sand permeability as measured in the laboratory is not necessarily a true representation of the in situ permeability, as the bulk in-situ density of the sand is not necessarily taken into account.*
- *The theoretical empirical formulae that are commonly used to estimate sand permeability based on the sand grading do not account for sands with a very fine fraction, even when this fraction constitutes a very small percentage of the sand.*
- *Depending on the particle shape, the permeability of sand is markedly affected by the presence of a very fine fraction.*
- *The permeability of the sand is affected by the upstream geology, river morphology and land use. In turn these factors can be used as indicators of potential success of sand abstraction systems.*

<u>Hypothesis 3: Iron and/or Manganese Precipitation</u>

Of the four hypotheses postulated regarding iron and/or manganese precipitation one was found to be invalid due to either insufficient results to support them or being false. However, the following three postulations were found to be valid:

- *Clogging by iron and/or manganese precipitation sometimes causes problems of reduced yield.*
- *Risk of clogging by iron and/or manganese precipitation can be indicated by immediate and upstream geology.*
- *Clogging by iron and/or manganese precipitation cannot necessarily be separated from clogging by bacteria, the two mechanisms acting in conjunction with each other.*

<u>Hypothesis 4: Screen Selection</u>

The hypothesis postulated below regarding well screen selection was found to be valid.

- *The type of screen used will affect the performance of a sand abstraction system.*

<u>Hypothesis 5: General</u>

Of the five hypotheses postulated regarding general issues two were found to be invalid due to either insufficient results to support them or being false. However, the following three postulations were found to be valid:

- *Geofabrics should not be used in sand abstraction systems.*

- *In sands with high fines content, the development of biofouling in an abstraction system will exacerbate the accumulation of fines in sand surrounding a system. The development of biofouling in a system will result in a reduced flow through the system and surrounding sand. This, in turn, will result in an accumulation of fines in the sand, as velocities are sufficient to draw the fines towards the system, but not sufficiently high to draw the fines through the system. The permeability of the surrounding sand will therefore reduce with time, the mechanisms of clogging by biofouling and clogging of the sand acting in conjunction to reduce the yield of a system.*
- *The yield of systems that are not operated regularly and/or are only operated at a fraction of their design yield will generally reduce in time. There will be an increase in problems experienced with biofouling, clogging of the sand, iron and/or manganese precipitation and high iron content of the abstracted water.*

Recommendations

Based on the findings of the research the following recommendations are made:

Database of Sand Abstraction Systems

It is recommended that the information gathered on the abstraction systems be captured on a separate database, and be continuously updated as new information and data becomes available. The data should be made available to prospective users for further analysis and evaluation as required.

Technology Transfer

As the bulk of the content of this report is not required for the design and implementation of new sand abstraction systems it is recommended that the technology be transferred by the development of reference manuals with guidelines for the design, construction and operation and maintenance of abstraction systems.

Groundwater Management

It is further recommended that, where appropriate, a formal groundwater management programme should be developed and implemented, especially for large abstraction systems.

Pilot Studies

It is recommended that pilot field studies be carried out for larger water abstraction schemes, in order to verify the specific yields of aquifers and the assumptions made for the designs of such abstraction systems. The results obtained from such studies would enable designers to optimise the designs and construction of these systems before investing large capital amounts.

Ongoing Research

The findings of this research have indicated that there is a need for further research into the behaviour of sand abstraction systems under certain conditions. It is recommended that the following research be carried out in the near future:

- Research to establish the relationship between biofouling, the presence of iron and manganese concentrations in the water, clogging of the sand and screens and the performance of the abstraction system.
- Further research into the cause and nature of the specific problems that occurred at Ulundi. This research should include the impacts of different construction methods, very low flow velocities through the sand and flooding on the performance of sand abstraction systems.
- Further research to find a more practical relationship between sieve analysis, permeability of the sand bed and the specific yield of an aquifer.

ACKNOWLEDGEMENTS

This report emanated from a project funded by the Water Research Commission entitled:

"Systems for the Abstraction of Surface Water through River Sand Beds"

The Research Manager responsible for the project was Dr I.M. Msibi. His support, assistance, advice and understanding throughout the implementation of this project are much appreciated.

BKS (Pty) Ltd, on behalf of Chunnett Fourie who has amalgamated with BKS (Pty) Ltd, wishes to thank the Water Research Commission for funding this project, as well as the Department of Water Affairs and Forestry, who undertook and funded the completion of the grading analyses and density tests of all sand samples. Their contributions are gratefully acknowledged.

We are greatly indebted to a few individuals who gave extremely generously and freely of their time, expertise and ingenuity during the course of this project. In particular we would like to thank:

- ***Mr S.M. Helm***, *Private Consultant, UK;* who came to Africa to assist us with the work required for this project. Mr Helm gave three months of his time (at no cost to the project) to work on this project. He assisted with the majority of the fieldwork and on-site testing required for the project, refined some of the on-site sampling and testing methods and generally contributed to the project through sharing his ideas and knowledge. Without Mr Helm's assistance this project could not have been completed.
- ***Mr R. Fourie***, *Geotechnical Services, Pretoria;* who took it upon himself to devise and make affordable, manageable and effective sand sampling devices for use in this project.
- ***Mrs A. Wagner***, *Microcheck Laboratories CC, Pretoria;* who completed all the microbiological work required for this project. Mrs Wagner never gave up trying to find the elusive answer to the question "What are the critters that lurk in these sand abstraction systems?" The discussion on microbiological aspects and the results of the microbiological testing has largely been contributed by Mrs Wagner.
- ***Mr C.R.H. Clanahan***, *Consulting Engineer, Nelspruit;* who donated many hours to this project, assisting with the laboratory permeability testing, the correlation analysis of the data on sand permeability, collection and collation of the geological data and with the commentary relating to geological aspects. He also contributed greatly through general discussion of the anomalies and puzzles encountered during this research.
- ***Mrs M.E.P. Clanahan***, *Nelspruit;* who generously gave many weeks of her time to the project, assisting with much of the general tedious "grind" work required for the collection of mapping data and the compilation of this report.
- ***Mr W.A. van Gruting***, *SNA, Nelspruit and SNALAB;* who generously assisted in retesting of the majority of sand samples.
- ***Letaba Lab***, *White River;* who assisted in retesting of a number of sand samples, free of charge.
- ***Mr S. Hussey***, *Dabane Trust, Zimbabwe;* who, at no cost to the project, assisted in locating the various sand abstraction systems in Zimbabwe, accompanying the research team on site visits to these system, and gathering information on these systems.
- ***Mrs L. van den Berg***, *BKS, Pretoria;* who assisted with locating contact persons, data input and general dog's body work.
- ***Mr R. Steenkamp***, *BKS, Pretoria;* who built the laboratory test units, Pederson devices and permeameters; and meticulously carried out all testing in the scale model unit.
- ***Mr A. Rix***, *BKS, Pretoria;* who collected mapping data.

The implementation of this work was largely dependent on contributions from individuals, companies and organisations throughout the water sector. We wish to thank all those who returned the phase I survey questionnaires. The names of these respondents are included in *Appendix e.C* (electronic appendices) to this report. Without their responses this work could not have proceeded.

A number of people gave freely and generously of their time by completing detailed surveys, accompanying the research team on site visits and sharing hard won information and expertise. Thanks must go to the people listed below for their contributions to this work.

Mr C. Ambler-Smith & Mr K. Knot	Nottingham Estate, Zimbabwe
Mr P.H. Beckley	Campbell Bernstein & Irving, Overport
Mr A. Botha	Bergman-Ingerop, Rivonia
Mr B. Boyers & Staff	Umgeni Water, Park Rynie
Mr E.C. Cloete & Mr E. Bosch	Ernst Cloete & Associates, Vryheid
Mr N. Dairam	Illovo Sugar, Gledhow
Mr J. du Toit	Messina Town Council, Messina
Mr R. Dwight	Ninham Shand, Cape Town
Mr G. Engelbrecht	SRK, Cape Town
Mr A.J. Fox	Fox Farm, Free Sate
Dr P.B.M. Glover	Glover Development Engineers, Nqutu
Mr D. Haasbroek & Mr J. Uys	Overberg Water, Oudtshoorn
Mr R. Hulley	Injambili Waterboard, Hibberdene
Mr S. Hussey, Mr Moyo & Mr M. Tshabalala	Dabane Trust, Bulawayo, Zimbabwe
Mr A.C. Johnstone	Groundwater Consulting Services, Rivonia
Mr B. Khumbuza	Department of Water Affairs and Forestry, Giyani
Lillian	Apel Catholic Mission, Apel
Mr P. Makuta, Mr T. Malataliana, Ms M. Koatla & Staff	Water and Sewage Authority, Maseru, Lesotho
Mr M. Manfron	Bradford, Conning & Partners, Newcastle
Mr J. Maseko	Tobatse TLC, Bothashoek
Mr P. Muller	Durban Water and Waste, Durban
Mr M. Mzelemu & Mrs Ngobese	Fairview Water Committee, Fairview
Mr B. Noko	Chisumbanje Estate, Zimbabwe
Mr R. Nyathi	Tshelanyemba Hospital, Zimbabwe
Mr J. Oosthuizen	Havercroft Mine, Northern Province
Mr S. Osborne & Mr B. Newton	Silk Kisch Peralta Engineers, Durban
Mr Posts	
Mr P. Thompson & Staff	Umgeni Water, Durban
Mr P.S.B. Wilson	Campbell Bernstein & Irving, Empangeni
Mr J. Wulff	ARDC, Lebowakgomo
Community Members	Chikwarakwara Community, Zimbabwe
Community Members	Shashane Community, Zimbabwe
Staff & Community Members	London Catholic Mission, Northern Province

We wish to thank the following members of the Steering Committee for their contributions to this research:

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In particular thanks to Mr AC Johnstone of Groundwater Consulting Services and Mr P Thompson of Umgeni Water for their enthusiasm, assistance and support.

Lastly, BKS (Pty) Ltd would like to thank the following authors of this report for their time and effort spent to assimilate and interpret the data and findings of this research project and to compile the final report:

- *Ms MJ Clanahan, BKS (Pty) Ltd, Pretoria,* who initiated and coordinated this research project and did most of the legwork required for the survey of existing sand abstraction systems, the site visits, the sampling, testing and analysis of system parameters, the scale model testing and the analysing and interpretation of the data in order to compile tables and visual graphs to be used as a design aid for future sand abstraction systems.
- *Mr JL Jonck, BKS (Pty) Ltd, Pretoria,* who completed the literature review, finalised the analyses, findings, conclusions and recommendations of the research project and completed the final report.

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1 INTRODUCTION

1.1 SAND ABSTRACTION SYSTEMS: A BRIEF OVERVIEW

1.1.1 Definition

The term "sand abstraction system" refers to systems for the abstraction of water from sand. In the broadest sense the term is applied to any system designed to abstract water from an alluvial aquifer. This would include river sand beds, beach dunes and other primary alluvial aquifers.

This research has focussed on investigations into those systems used for abstracting water from river sand beds, be it perennial rivers or ephemeral sand rivers. The research has mainly focused on those types of systems that are designed to abstract water flowing on the surface of a river through the river sand bed, or those systems designed to abstract sub-surface river flow.

Even in the context of abstraction from rivers, the term sand abstraction system is broadly applied to a wide variety of applications and different types of systems. Infiltration galleries, caisson type abstraction systems, vertical well points and horizontal screen abstraction systems can all be categorised as sand abstraction systems. Abstraction systems can differ vastly in scale and level of sophistication. In addition, the reasons for using such systems, as opposed to other abstraction methods, are numerous and varied.

All types of river abstraction systems encountered during the course of this research have been included in this study. A section through a typical river sand abstraction system of a caisson or infiltration gallery type is shown in Figure 1 below.

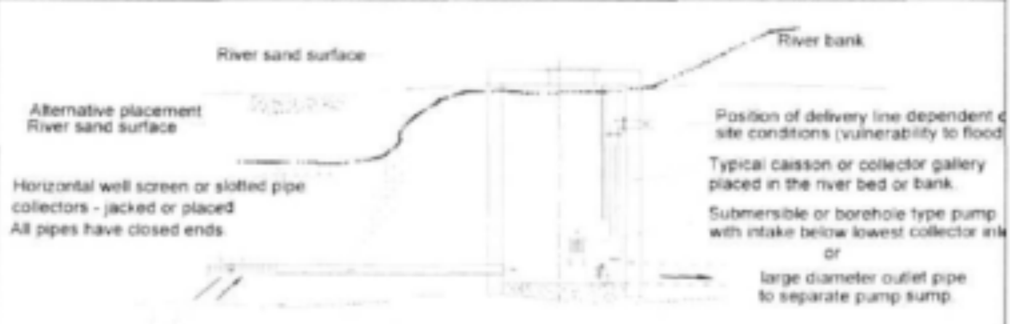

Figure 1: Typical River Sand Abstraction System

1.1.2 Advantages of Sand Abstraction Systems

Although the use of sand abstraction systems offers numerous advantages, it should be borne in mind that the advantages obtained are directly linked to the specific conditions under which these systems are operated.

1.1.2.1 *Abstraction of Waters with High Sediment Load*

A number of areas in Southern Africa have a high sediment yield. Examples of such areas include the KwaZulu-Natal region and Swaziland, where sediment yields can vary between 5 t/km^2.a to 723 t/km^2.a [Rooseboom, 1992]. In the region consisting of the upper Orange and Caledon catchments, including the south-eastern part of Lesotho, sediment yield values range from 113 to 1 382 t/km^2.a [Rooseboom, 1992]. River waters that have a high sediment load or turbidity are associated with areas such as these that have high sediment yields.

Numerous problems and high costs are associated with the storage, abstraction and treatment of highly turbid waters. These problems can be alleviated, and the associated costs be reduced, if surface water is abstracted utilising sand abstraction systems as opposed to abstracting surface water directly from the river using conventional abstraction methods.

A comparison of the problems associated with abstraction and treatment of highly turbid waters using conventional abstraction methods and the potential benefits of using sand abstraction methods are given in Table 1.

Table 1 Comparison of using Conventional versus Sand Abstraction Methods for the Abstraction of Highly Turbid Waters

Conventional Abstraction Methods	Sand Abstraction Methods
Often some diversion or impoundment structure is required, with associated: • high capital costs for construction; • negative environmental impacts arising from alterations to the natural river course.	Diversion or impoundment structures are usually not required, with associated: • reduction in capital costs; • reduced environmental impacts, as it is usually not necessary to alter the natural river course at the point of abstraction.
Sedimentation of in-stream reservoirs and associated loss of storage and disruption of normal abstraction methods (e.g. through blocking of off-takes etc.)	Sand abstraction systems can be installed in reservoirs where sedimentation has occurred and conventional abstraction methods can no longer readily be used. The storage in the sand bed can be utilised, although there will only be significant storage in the sand where the sand has a reasonably high permeability and depth.
Sedimentation of off-take structures with loss of functionality and high maintenance costs associated with required cleaning.	No conventional off-take structures are required. The effective off-take structures are buried in the sand, thus further sedimentation will have no impact on the functionality of the structure.
There is no reduction in the turbidity or sediment load of raw water prior to or during abstraction. This water must pass through raw water pumps and is supplied to treatment plants.	By abstracting the surface water through the sand, the sand bed is used as a natural filter, reducing the turbidity and sediment load of the raw water during the process of abstraction. Raw water with reduced turbidity is therefore supplied to raw water pump stations and treatment plants.

cont........

Table 1 Comparison of using Conventional versus Sand Abstraction Methods for the Abstraction of Highly Turbid Waters (cont.)

Conventional Abstraction Methods	Sand Abstraction Methods
Sedimentation of raw water pump sumps, with high maintenance costs associated with cleaning of sumps.	Minimal sedimentation problems in raw water pump sumps.
Rapid wear of raw water pumps and pipework, with associated high maintenance and replacement costs.	Reduction in wear of raw water pumps and pipework, with an associated reduction in maintenance costs.
High capital costs for water treatment plants resulting from the need to design for the treatment of waters with higher turbidity. Higher capital costs arise from: • Elements of the plant required for the treatment of turbidity and high sediment loads would necessarily have a large capacity, including: ➢ primary settlers, ➢ coagulation & flocculation facilities, ➢ secondary settlers, ➢ filters, ➢ sludge removal, handling & disposal facilities. • As a result of the large time required for sedimentation, flocculation and filtration, flow rates through the water treatment plant would generally be low. The plant would therefore have to be sized larger to treat the same quantity of water on a daily basis than would be required if the turbidity of the raw water to be treated were lower.	Reduction in required capital outlay for water treatment plants, as water that must be treated will have a lower turbidity. • Elements of the plant required for the treatment of turbidity and high sediment loads could be of considerably smaller capacity than would be required if conventional abstraction methods were used: ➢ primary settlers, ➢ coagulation & flocculation facilities, ➢ secondary settlers, ➢ filters, ➢ sludge removal, handling & disposal facilities. • Reduction in the turbidity of raw water will result in a reduction in the time required for sedimentation, flocculation and filtration, with an associated increase in flow rates through the water treatment plant. The plant could therefore be sized smaller than if conventional abstraction methods were used.
High operation and maintenance costs of water treatment, arising from: • The need to clean sedimentation tanks and backwash filters more regularly, resulting in: ➢ an increase in the number of shut down periods; ➢ an increase in the amount of water lost through use for cleaning and backwashing, with an associated increase in the cost of pumping raw water to the plant. • The high cost of chemicals required for coagulation and flocculation.	Reduced operation and maintenance costs for water treatment, arising from: • Reduction in required cleaning of sedimentation tanks and backwashing of filters, resulting in: ➢ a reduction in the number of shut down periods; ➢ a reduction in the amount of water lost through use for cleaning and backwashing, with an associated reduction in the cost of pumping raw water to the plant. • Reduction in the cost of chemicals required for coagulation and flocculation.

The cost benefits associated with the use of sand abstraction systems when abstracting highly turbid waters can be demonstrated by a case study. In 1994 a study was conducted comparing the cost of utilising conventional water abstraction and treatment to the cost of using sand abstraction and treatment (ref. Chunnett, Fourie and Partners, 1994). The comparative study was conducted for planning purposes for the then KwaZulu Government (KZG) Department of Works and the Department of Water Affairs and Forestry (DWAF). The comparison was done considering demands on a relatively small, existing water treatment plant on the White Mfolozi River that supplies water to the town of Ulundi in KwaZulu-Natal.

For the period 1994 to 2015, if conventional abstraction and water treatment were used, estimates of future demands indicated that it would be necessary to augment the existing water treatment plant in the year 2004, increasing its capacity from 13 000 m^3/d to 18 000 m^3/d. In comparison, if a sand abstraction system were to be installed and water was abstracted through the sand, it would then only be necessary to install additional chlorination equipment at the plant.

Considering only the capital costs of additional work and the costs of chemicals, the present worth values of the two alternatives, for the period 1994 to 2015, were compared. The findings of the analysis are shown in Table 2.

Table 2 Present Worth Comparison of using Conventional versus Sand Abstraction Method

Method of Abstraction	Cost of Chemicals (R million)	Capital Costs (R million)	Total Cost (R million)
Conventional Abstraction	2.771	7.000**	9.771
Sand Abstraction	0.756	2.650***	3.406

Notes:

** Minimum cost for augmentation of water treatment plant.

*** Cost for sand abstraction system and additional chlorination equipment

This shows that, in this case, over a period of 20 years savings of the order of R 6.4 million could be achieved by utilising a system that abstracts water through the sand as opposed to conventional abstraction. This is not accounting for additional savings that could probably be achieved through reduction of operation and maintenance costs other than chemical costs.

The above example clearly demonstrates the cost benefits that could be gained by utilising sand abstraction systems when abstracting highly turbid waters.

1.1.2.2 *Abstraction from Seasonal and Sand Rivers*

In Southern Africa, numerous rivers are seasonal, particularly in arid and semi-arid regions such as eastern Botswana and Namibia. Where rivers are seasonal, often the only source of water during the dry season is the water stored and / or flowing in the sand of surface-dry rivers. Under such circumstances sand abstraction systems are commonly used for abstraction of water from the underlying water bearing sand. In these instances, the benefits arising from using sand abstraction systems include:

- access to continued, year-round water supply when rivers are surface-dry,
- utilisation of storage in river sand beds, particularly where sand storage dams are built specifically to trap sand and store water in the sand,
- reduced loss of water through evaporation, and
- effective pre-treatment of abstracted water as it is filtered through the river sand bed.

1.1.2.3 *Application in Rural and Emergency Situations*

In addition to the advantages mentioned above, there are numerous advantages associated with the use of small-scale sand abstraction systems.

Small-scale abstraction systems can be extremely simple in design and function. They can therefore be constructed using readily available and cheap materials, and using simple, labour-intensive construction methods, employing unskilled labour. Simplicity of function, coupled with the fact that the water is filtered through the sand river bed as it is abstracted, means that generally little operation or maintenance is required for these systems, and operators need not be highly skilled. In addition the method of treating the water once abstracted is simple and cheap, as normally only chlorination would be required.

These factors offer the following advantages, making them extremely suitable for use in rural and emergency situations:

- Local manpower can be employed for construction, thus providing employment for local people during the construction period.
- Systems can be installed at relatively short notice and relatively quickly.
- Although small-scale systems are usually not resistant to larger floods, they are cheap and relatively easy to repair. Local manpower can be employed to repair, rehabilitate, and / or upgrade such systems.
- Rural communities can easily operate and maintain their own systems, making the systems more sustainable.
- Minimal operation and maintenance requirements mean that operation costs are low. This is extremely important where rural communities are

required to pay for the operation and maintenance of their own water supply schemes, as is now the case in South Africa.

- Minimal water treatment requirements after abstraction also reduce costs and do not demand high level of skill level for operation.

1.1.3 Problems Experienced with Sand Abstraction Systems

Although sand abstraction systems offer many advantages, the behaviour of these systems has been found to be somewhat unpredictable. In particular, significant problems were experienced with a relatively large sand abstraction system installed in the White Mfolozi River at Ulundi[1], KwaZulu-Natal. Shortly after this system was commissioned, the yield of the system dropped rapidly to below the design yield. This particular problem, and the findings of initial investigations into the cause of the problem, led to the initiation of this research, which is discussed in more detail in Section 1.2 of this report.

On commencing this research the researchers were only specifically aware of problems being experienced with one other sand abstraction system, that being a system also located in the White Mfolozi River at Mpungamhlophe[2], KwaZulu-Natal. Although it was rumoured that numerous sand abstraction systems had failed, performed poorly or required extensive rehabilitation, the specific nature of problems experienced at other systems was unknown. Generally, it appeared that problems had not been investigated as systems were small and inexpensive, and the cost of further investigation was not warranted. In addition, no previous documentation was found discussing problems experienced with sand abstraction systems. Due to this lack of information, it could initially not be confirmed whether problems were commonly experienced with sand abstraction systems and what types of problems were experienced.

During the course of this research it was found that there are a number of problems commonly associated with sand abstraction systems. These include:

- low yield of sand abstraction systems i.e. where the yield of the system is considerably less than the design yield, with the design yield having been determined on what would be considered acceptable site investigations and investigations of the sand properties etc.,
- marked reduction of yield with time, where yield was initially high,
- flood damage,
- clogging of screens and pipes by what appears to be biologically induced fouling,

[1] This system is included as system number 34 in the survey of existing abstraction systems in Section 1 of this report.

[2] This system is included as system number 35 in the survey of existing abstraction systems in Section 1 of this report.

- changes in the physical properties of sand surrounding abstraction systems over time, including accumulation of fines in the sand, and reduction in the permeability of the sand,
- high iron and / or manganese content of abstracted water.

These problems have proved to be complex in nature and the reasons for their occurrence are not always evident.

1.2 EVENTS LEADING TO THE INITIATION OF THIS RESEARCH

During 1994 a sand abstraction system was constructed in the White Mfolozi River near Ulundi, KwaZulu-Natal. The system was designed to meet a peak abstraction rate of 313 l/s with an associated head loss of 0.86 m across the system.

Shortly after completion of the system, it was found that the yield of the system was considerably lower than the design yield, and the head loss across the system was extremely high. From the end of 1994 to early 1996 numerous tests were conducted to determine the cause of the problem of low yield, and various measures were taken in an attempt to improve the flow through the system. Details and findings of these investigations are discussed in "*Addendum to Report No.22: White Mfolozi River Balancing Storage – Water Abstraction from the Sand*", included as Appendix J.40.12 to this report.

The determination of the cause of the problem was, in this case, complicated by the fact that prior to the completion of the construction of the system it had been flooded, with a large amount of fine silt and rubbish being washed into the system. However, despite relatively extensive investigations, it was not possible to determine the exact cause of the problem of low yield.

Initially, the properties of the sand bed were investigated. The results of the investigations showed that there had been a marginal increase in the fines content in the sand covering the abstraction pipes, with an associated marginal reduction in the permeability of the sand. However, even with the lower permeability of the sand, as measured in the laboratory, it should still have been possible to meet the design capacity of the system with a marginally higher head loss through the sand. Indications were, therefore, that although reduced permeability of the sand could have been a factor contributing to the problem of low yield, it was not the major cause.

Results of further testing did, however, indicate that biofouling was possibly a major factor contributing to the problem. Factors that pointed to biofouling being a major contributing factor included:

- The average total bacterial counts of water samples taken from the system were of the order of magnitude of 10^6. Although by no means categorical evidence, these counts were sufficiently high to indicate a possible presence of biologically induced fouling.

- Samples of organic matter washed out of the abstraction pipes were identified as iron bacteria of the genus *Leptothrix* (refer Appendix J.40.13 – Report: "Microbiological Analysis of Ulundi Water Samples"). This is a sheath-forming bacteria that is often associated with microbiologically induced fouling. It has been documented that these bacteria are known to "grow in pipes along with deposits of iron or manganese and interfere with the passage of water in wells and filtration plants" [Dondero, 1995]. It must, however, be noted that it was not possible to culture *Leptothrix* from the water samples that were also analysed for total bacterial counts.
- A portion of one abstraction pipe was excavated for inspection. Despite disturbing the pipe extensively during excavation, it was found that the inside of the pipe was coated with a brown slime of bacterial sheaths. There was also evidence of the bacterial slime in a number of the slots on the exterior of the pipe.
- After dosing the abstraction pipes with chlorine, the yield of the system increased from about 78 l/s to approximately 228 l/s. It did, however, diminish rapidly shortly thereafter, possibly indicating a regrowth of biofilm.
- Total bacterial counts obtained from the water samples taken from the system 24 hours after the chlorine dosing were of an order of magnitude 10^7, compared to 10^5 prior to dosing. An increase in bacterial counts of this nature could indicate sloughing of biofilm from the surface of the abstraction pipes due to stress on the biofilm as caused by the chlorination.

Although these factors indicated that biofouling was possibly contributing to the problem of low yield of the system, there was insufficient evidence to state this categorically. In addition, if there was biofouling in the system, it was not possible to state what the original cause of the microbiologically induced fouling was. Further investigations were therefore deemed necessary in order to establish categorically the root cause of low yield of the system.

Based on the experience with the Ulundi system, this research into sand abstraction systems was initiated. It was strongly felt that the findings of further investigations into the Ulundi problem would be beneficial not only for the operation of that system, but would also contribute significantly to the current knowledge on sand abstraction systems in general. Equally, investigations into other sand abstraction systems could possibly shed light on the cause of the problem at Ulundi.

A fact that was, and still is, considered anomalous, is that the design of the Ulundi system was based on the same theoretical principles as the design of a similar system located in the Buffalo River near Nqutu, KwaZulu-Natal[3]. This second system, designed for a yield of 180 l/s, had successfully been in operation from 1979 to 1994, when problems were first experienced with the Ulundi system. This anomaly is indicative of the complexity of the problems experienced with sand abstraction systems.

Despite the complexity of the problem no documentation of any other investigations into similar problems were found at the time.

1.3 NEED FOR THIS RESEARCH

As discussed previously, there are numerous advantages associated with the use of sand abstraction systems. However, as evidenced by the Ulundi system, there were, and are, obvious gaps in our knowledge and understanding of the behaviour of these systems, and their performance can be somewhat unpredictable. This research was therefore initiated to gain more knowledge about the manner in which these systems operate and about the problems associated with these systems. It was hoped that such knowledge would result in an increased assurance of success with future installations of sand abstraction systems.

It was felt that an improved understanding of these systems would be extremely beneficial, as, considering the advantages of sand abstraction systems, (Section 1.1.2), it can be seen that sand abstraction systems have a potentially wide application and are particularly suitable for use in the Southern African context.

Although at least one definitive study of infiltration galleries (Helm, 1998) has been completed since the commencement of this research, at the time there was very little information about these systems available in Southern Africa. There were no standard guidelines for the design of these systems, and little documentation of systems that had been installed and were successfully in operation or of problems that had been experienced with these systems. For this reason it was felt that it would be extremely beneficial if a directory of existing sand abstraction systems in Southern Africa were to be established, covering details such as system design, method of construction, surface water quality etc.

Combining the information obtained from such a survey with information on theoretical and actual yield of the sand abstraction systems, it was hoped that it would be possible to establish what factors contribute to problems of low yield. Based on this information the intention was to establish guidelines for the design, construction and operation of sand abstraction systems. It was felt that

[3] This system is included as system number 31 in the survey of existing sand abstraction systems in Section 4 of this report. Details of this system are included in the database.

this was essential if sand abstraction systems are to be used to their full potential in South Africa.

During the course of this research, the need for the research was repeatedly reaffirmed. The initial response to the survey, the number of queries received asking for advice with regard to the design of new systems, together with the increasing application of these systems, the number of problems experienced with the systems, and the number of people reliant on them, indicated the existing and growing need for the research.

1.4 REPORT OUTLINE

This report discusses the research conducted into sand abstraction systems and the findings of that research.

Initially, research objectives and hypotheses are outlined, and the literature on various aspects relevant to the research is discussed.

Next, the survey that was conducted of existing sand abstraction systems is discussed. The methodologies implemented for conducting the survey, including aspects such as questionnaires, site visits and sampling and testing techniques are discussed. The general findings of the survey and the system data are presented, with particular attention being paid to problems experienced with sand abstraction systems.

Scale model testing that was conducted is discussed and the data from this testing is presented. This is followed by discussion of the analysis of the data from both the survey and the scale model testing. Findings and conclusions drawn from the data and data analysis are presented, with reference to the hypotheses postulated during the course of the research.

Based on the data and analysis thereof, a critical evaluation of sand abstraction systems is presented. Although no design guidelines are presented, this critical evaluation discusses aspects of sand abstraction systems that should be of assistance to persons designing and operating and maintaining sand abstraction systems.

Finally recommendations arising from this research are made. These include recommendations regarding sand abstraction systems, further research and investigations required, as well as recommendations regarding aspects such as sampling and testing techniques and developments required in this area.

2 RESEARCH OBJECTIVES AND HYPOTHESES

At the outset of the research, a number of aims and objectives were set. These are outlined in Section 2.1 below. During the course of the research, based on initial findings, and as a result of problems experienced in implementing certain aspects of the project, it became evident that it was necessary to modify these original objectives. The modified objectives, and reasons for making these modifications, are given in Section 2.2.

In addition to attempting to meet the objectives for the research, various aspects of the research were specifically conducted to investigate a number of hypotheses that were postulated during the course of this research. The hypotheses were based on prior experience, findings during the early stages of the research and on discussion in the literature. These hypotheses are presented in Section 2.3.

2.1 ORIGINAL RESEARCH OBJECTIVES

The original objectives of this research were divided into two main sections, viz.:

- those pertaining to general investigations into sand abstraction systems in Southern Africa,
- those pertaining to the specific case study of an existing sand abstraction system located in the White Mfolozi River near Ulundi, KwaZulu-Natal. As previously mentioned, relatively detailed investigations had already been conducted into the problem of low yield of this system. In addition, the information available on the theoretical design, the construction and the operational history of the system was complete. It was therefore felt that this system would be ideally suited as a case study for investigations into problems of low yield of sand abstraction systems.

2.1.1 General Objectives

- ***Aim 1*** - *To establish a directory and / or database of sand abstraction systems in Southern Africa.*

  The directory / database was to include information on aspects such as:
  - system design, including aspects such as type of abstraction pipes used,
  - construction methods,
  - system performance, including yield and problems experienced,
  - sand properties,
  - surface and abstracted water quality, including presence of bacteria, and
  - site and catchment geology and river morphology.

- **Aim 2** - To determine whether any correlation exists between system yield (specifically low yield) and / or problems experienced with sand abstraction systems, and system parameters such as those listed above.

- ***Aim 3*** *- To establish guidelines / criteria for the design, construction and operation and maintenance of sand abstraction systems.*

  These guidelines were to be based on the findings of the general investigations into sand abstraction systems, as well as on the findings of the case study of the Ulundi sand abstraction system.

2.1.2 Ulundi Case Study

The original objectives set pertaining to the specific case study of a sand abstraction system located in the White Mfolozi River near Ulundi are listed in Table 3 on the following page. A detailed study was to be conducted to investigate the problem of low yield, possibly caused by biofouling, experienced with this system. Dependent on the interim findings of the study, it was expected that the aims would change as shown in Table 3.

2.2 MODIFIED RESEARCH OBJECTIVES

At the time of setting the original research objectives, it was estimated that approximately 20 sand abstraction systems would be located in Southern Africa and included in the database of systems. However, over 50 systems were found, with 39 systems eventually being studied in detail. The scope of work regarding the development of a database of existing systems was therefore virtually doubled.

It was found that very little base information about existing systems could be obtained through surveys, as was initially intended. It was therefore necessary to visit all systems included in the detailed survey, collecting data largely through sampling and testing, visual observation of the systems, interviews with operators and users, and from sources such as maps. The extent of work required for data collection was therefore considerably increased from that initially planned.

Initial investigations also showed considerably greater variation than that originally expected in aspects such as system design and application, as well as in the problems experienced with the systems. It also became evident that, in order to obtain a reasonably comprehensive view of sand abstraction systems and the problems experienced with them, it would be necessary to investigate certain aspects in more detail than originally allowed for. This included more detailed investigations into aspects such as iron and manganese precipitation, sand properties and biologically induced fouling.

Table 3 Original Research Objectives – Ulundi Case Study

Aim 4

To determine the following with respect to the Ulundi abstraction system:

- whether microbiologically induced fouling is present in the system,
- if biofouling is present in the system, to identify the types of bacteria present in the system, and
- the extent to which the biofouling contributes to the problem of low yield of the system i.e. to determine whether biofouling was the main cause of the problem of low yield of the abstraction system, or whether it was merely a factor contributing to the problem.

If biofouling is present in the system			If there is no biofouling of the system
Aim 5a To determine the conditions which led to the development of biofouling in the system, specifically:			***Aim 5b*** To determine the cause of the low yield of the sand abstraction system.
i. To determine whether the physical parameters and operating conditions of system are suited to the development of biofouling, and to determine in what way these conditions differ from systems where biofouling is not a problem.	*ii.* To determine whether a once off condition or event (e.g. fouling of the system during flooding, no flow through the system due to river diversion or the excavation of the river sand during construction) temporarily created conditions that were suitable for the initial development of biofouling, which, once established, was maintained under normal operating conditions.	*iii.* To determine whether changes in the system, caused by factors other than biofouling (e.g. an accumulation of fines in the sand), led to the development of conditions that were suitable for the development of biofouling.	
Aim 6a To develop a method to control the biofouling.	***Aim 6b*** To develop a means of eliminating the biofouling, and prevent the recurrence of events that created conditions suitable for biofouling	***Aim 6c*** To develop a method to control the biofouling. To identify the root cause of the problem of low yield and a method to control this problem.	***Aim 6d*** If possible, to develop a method of controlling the identified cause of the problem of low yield.

The achievement of the original objectives that were set pertaining to the case study of the Ulundi system was largely dependent on gaining access to this system for an extended period of time. The access manhole to this system is located in the riverbed, and river flows must necessarily be low in order to gain access to the system.

At planning stage it was assumed that access to the system could be gained during the dry season, as had been the case during a number of years preceding the commencement of this research. Exceptionally high rainfall, however, occurred throughout the research period. This resulted in river levels being too high to permit access to the system for the majority of the research period. It was therefore not possible to proceed with detailed investigations and testing at the Ulundi system as originally planned.

Due to these problems, and based on the initial findings of the general investigations, the original research objectives were modified. It was felt that the maximum benefit would be obtained from the research if the emphasis were shifted from the case study of the Ulundi system to the development of the database of systems and to more general investigations into aspects relevant to sand abstraction systems. In addition, the analysis of data was largely to be omitted from the project, with the emphasis being placed on data collection. The data collected could then be analysed in future work.

The scope of work pertaining to the general investigations was therefore increased, with the objectives for this portion of the work being somewhat refined. Simultaneously, the scope of work pertaining to the Ulundi case study was considerably reduced, with some of the original objectives of the research being omitted.

Finally, it was considered that the problems surrounding the design, application and operation and maintenance of sand abstraction systems were far more complex than originally thought. Due to the complexity of the problem, it was felt that, based on this research, it would not be possible to develop true design or operation and maintenance guidelines or criteria for these systems. Rather, emphasis was to be placed on data collection and evaluation, and on the identification of problem areas and areas requiring further investigations. Based on evaluation of the data collected, critical observations regarding the design and application of sand abstraction systems should be presented. The modified research objectives are detailed in Section 2.2.1.

2.2.1 Modified General Objectives

- ***Aim 1*** - *To establish a directory and/or database of sand abstraction systems in Southern Africa.*

  The directory/database was to include information on the following aspects:

  - location and catchment of abstraction sites,

- system design, including aspects such as type of abstraction pipes or screens used and type of implementation,
- construction methods,
- system performance, including any problems experienced,
- sand properties, including sand grading, bulk density, particle density and permeability,
- surface and abstracted water quality, including presence of bacteria, and changes in these parameters,
- site and catchment geology, and
- river morphology.

The long-term objective of the development of the database is to establish correlations between system parameters and system performance. The establishment of such correlations would allow for the identification of parameters that could be used as indicators at planning and design stage of potential poor performance or possible problems that could be experienced with a proposed abstraction system. This would, in turn, allow for the incorporation in the design of suitable methods for the operation and maintenance of systems, or even for the selection of a more appropriate method of abstraction.

In addition, parameters could be identified that could be used as indicators of the development of problems in existing abstraction systems. By monitoring these parameters in existing systems, mitigatory measures could be taken in the early stages of the development of problems with the systems.

Considering these long-term objectives, and the fact that sand abstraction systems are often implemented in situations where development and planning costs necessarily be kept to a minimum (e.g. rural water supply), it was considered important that data be collected in a manner such that:

- sampling methods used were simple, easy to perform and would be readily accessible and affordable to the designer,
- all testing conducted to establish sand and water quality parameters be readily accessible and affordable to the designer,
- readily available data sources could be used by designers (e.g. 1:50 000 topographical maps) using simple and inexpensive methods.

Data collection was further defined by the requirement that data be collected such that it allowed for particular investigation into the following aspects:

- possible problems caused by biological fouling,
- possible accumulation of fine sand around systems and subsequent clogging of systems, and

- possible problems associated with iron and / or manganese precipitation and / or poor quality of abstracted water due to high iron content.

- **Aim 2** - *To determine whether any correlation exists between system yield (specifically low yield) and / or problems experienced with sand abstraction systems, and system parameters such as those listed above.*

  It was noted that due to the generally qualitative nature of the data collected, correlations could not necessarily be established on a statistical basis. As previously mentioned, full analysis of the data collected was not covered in the scope of the project. Correlations were to be established using simple methods such as graphical plots.

- ***Aim 3*** - *To conduct detailed investigations into various factors that will influence the performance of sand abstraction systems, and hence the design approach that should be adopted.*

  Factors to be investigated included:

  - the effect of screen type on head loss through a system, and
  - the effect of bulk density on permeability.

- ***Aim 4*** – *To present a critical evaluation of sand abstraction systems as an aid for the design, construction and operation and maintenance of abstraction systems.*

  Aspects to be considered in the critical evaluation included:

  - initial investigations and data required to aid in determining the feasibility for the application of sand abstraction systems,
  - discussion of potential problems,
  - analysis of successful applications, and
  - operating procedures implemented at successful systems

2.2.2 Ulundi Case Study: Modified Objectives

The specific aims pertaining to the Ulundi system largely fell away. Investigations into the problem of low yield and possible biological fouling that could be completed at this system were to be continued, but this system was to be treated purely as one of the systems included in the general database.

2.3 HYPOTHESES

As previously mentioned, a number of hypotheses were postulated during the course of this research. Initially the hypotheses were based largely on the experience gained at the Ulundi abstraction systems, and the results of the original testing conducted at this system. A number of hypotheses were based on the observation of major differences between the Ulundi and Nqutu systems. This was considered a basis for postulation as, even though the systems were designed on the same theoretical basis, extensive problems are experienced with the Ulundi system, while the Nqutu system has successfully been in operation for a long period. Although not necessarily substantiated by the initial investigations or the literature, hypotheses were also based on a basic understanding of sand abstraction systems and of natural river systems.

Hypotheses that were postulated with reference to the Ulundi system were extended to sand abstraction systems in general. Additional hypotheses were also postulated during the course of the research. These were based on the findings of the initial phases of this research and discussion in the literature. The hypotheses, and the basis for the postulations, are presented in Table 4.

Table 4 Hypotheses on the Failure of Systems

	Hypothesis	Basis for Postulation
1. Biologically Induced Fouling		
1.1a	Clogging of the screens by biologically induced fouling is a major cause of the reduced flow in the Ulundi sand abstraction system.	Findings of the investigations conducted prior to commencing this research indicated that biofouling could be causing the problem at this system.
1.1b	Biologically induced fouling results in clogging and reduced yield of sand abstraction systems.	Extension of 1.1a.
1.2	Biologically induced fouling in the Ulundi system is caused by iron reducing / oxidising bacteria.	Initial investigations samples taken from the system were identified as iron bacteria of the genus *Leptothrix*.
1.3a	The shape of the slots of the screens used in the Ulundi system is such that the screens are more prone to biofouling.	First principles and major difference from Nqutu system. The form of certain slot shapes may result in there being "dead" areas where flow velocities are very low, thus allowing for attachment of bacteria.
1.3b	Certain screen types are more prone to biologically induced fouling.	Extension of 1.3a.
1.4	Although the conditions at the Ulundi system may be extremely suitable for the development of biofouling it is postulated that the problem was initiated and exacerbated by events that occurred during the early life of the system.	
1.4a	The development of biofilm in the Ulundi system was initiated as a result of the flooding of the system prior to completion of construction, when a large amount of fine sand and rubbish was washed into the system. It is postulated that during this event, the system was seeded. In addition the presence of fine sand particles in the system facilitated the development of a biofilm.	First principles and literature. It is known that bacteria adhere to fine particles. If this were true, then a large amount of bacteria would have been washed into the system together with the fine sand, thus seeding the system. Under normal operating conditions these particles would largely have been removed from the water as it entered the system, as the water would have been filtered as it passed through the sand bed. The presence of the fine particles in the system would have facilitated the development of the biofilm, as the surface area for attachment would have increased considerably from what it would have been under normal circumstances.

Table 4 Hypotheses on the Failure of Systems (cont.)

Hypothesis		Basis for Postulation
1. Biologically Induced Fouling (cont.)		
1.4b	Following completion of the system the river water was diverted away from the system. This allowed for the development of a biofilm in the system.	First principles. For a biofilm to develop velocities must be sufficiently low to allow for attachment of bacteria to a surface. The diversion of the water away from the system would have resulted in a reduction in the velocities through the screens, thus facilitating the development of a biofilm.
1.5	Although bacterial growth can be expected in all sand abstraction systems, the extent to which this growth occurs and the associated risk of clogging by biofouling will vary depending on system conditions.	First principles. Initial findings of research, where it appeared that there was clogging by biofouling of some, but not all systems.
1.6	The level of risk of clogging of a system by biofouling is influenced by, and can therefore be indicated by the surface water quality.	First principles. Development of biofilm will be dependent on conditions being suitable for bacterial / algal growth. This would include nutrient levels, turbidity etc.
1.7	The level of risk of clogging of a system by biofouling is to some extent influenced by, and can therefore be indicated by upstream land use.	First principles. If postulate 1.6 holds true, then this should apply, as land use affects water quality.
1.8	The level of risk of clogging of a system by biofouling is to some extent influenced by, and can therefore be indicated by upstream geology.	First principles. If postulate 1.6 holds true, then this should apply, as geology affects water quality.
1.9	Systems where flow is mainly subsurface will be less prone to problems of clogging by biofouling.	First principles and observation. If flow is subsurface nutrient feed to the system should be less.
2. Sand Properties		
2.1a	The nature of the sand at the Ulundi sand abstraction system changed following installation of the sand abstraction system, with an accumulation of fines in the system, particularly at depth. This is contributing to the problem of low yield of this system.	Findings of the initial investigation indicated an accumulation of fines in the sand.
2.1b	The installation and operation of sand abstraction systems will alter the nature of the surrounding sand beds.	Extension of 2.1a.
2.2a	The accumulation of fines in the Ulundi sand is partly due to the presence of the weir immediately downstream of the system.	First principles. Major difference from the Nqutu system.
2.2b	In certain types of sands, if there is a weir downstream of a sand abstraction system then fines will accumulate in the sand.	Extension of 2.2a.
2.3a	The accumulation of fines at depth in the sand at Ulundi is partly due to the nature of the sand itself, with the finer particles having a higher specific density than the coarser particles. This in turn would be due to the geology of the source rock.	First principles. The accumulation of fines at depth is anomalous if purely the hydraulics of the problem are considered. This idea was postulated by a member of the steering committee based on the practice of using denser fine materials such as garnet in engineered sand filters.
2.3b	In certain types of sands the fine particles have a higher density than the coarser particles. In such sands the fine particles can accumulate at depth in the sand.	Extension of 2.3a.

Table 4 Hypotheses on the Failure of Systems (cont.)

Hypothesis	Basis for Postulation
2. Sand Properties (cont.)	
2.3c In certain geological conditions, it can be expected that fines will accumulate at depth in the sand riverbeds.	Extension of 2.3b.
2.4 Sand permeability as measured in the laboratory is not necessarily a true representation of the in situ permeability, as the bulk in situ density of the sand is not necessarily taken into account.	Findings of initial investigations. It was found that minor changes made to the compaction of the sand in a permeameter dramatically affected the measured permeability of the sand.
2.5 The theoretical empirical formulae that are commonly used to estimate sand permeability based on the sand grading do not account for sands with a very fine fraction, even when this fraction constitutes a very small percentage of the sand.	Findings of initial investigations. It was found that the calculated permeability of sands with a very fine fraction did not match the measured permeability. Modification of the empirical formulae, catering for the fine fraction, appeared to give a better correlation.
2.6 Depending on the particle shape, the permeability of sand is markedly affected by the presence of a very fine fraction.	Observation.
2.7 The permeability of the sand is affected by the upstream geology, river morphology and land use. In turn these factors can be used as indicators of potential success of sand abstraction systems.	First principles. If postulate 2.6 holds true this should hold true. Particle shape will be affected by geology and particle size will be affected by river morphology, geology and land use.
3. Iron and / or Manganese Precipitation	
3.1 Clogging by iron and / or manganese precipitation sometimes causes problems of reduced yield.	Findings of initial investigations.
3.2 Risk of clogging by iron and / or manganese precipitation can be indicated by surface water quality.	First principles. It was noted that this might not be the case due to the oxidised state of the surface water.
3.3 Risk of clogging by iron and / or manganese precipitation can be indicated by immediate and upstream geology.	First principles and findings of initial investigations. Upstream and immediate geology will affect the iron and manganese content of subsurface waters. Initial investigations indicated that the problem was prevalent in specific geographic areas.
3.4 Clogging by iron and / or manganese precipitation can not necessarily be separated from clogging by bacteria, the two mechanisms acting in conjunction with each other.	Findings of initial investigations and literature. Initial investigations showed an increase in total bacterial counts where clogging by iron precipitation was reported. It is noted in the literature that particulate matter is often incorporated in biofilms, thus appearing to be a purely chemical precipitation.
4. Screen Selection	
4.1 The type of screen used will affect the performance of a sand abstraction system.	Literature. It is reported in the literature that the screen type can have a marked effect on borehole performance, as the flow rate through the screens, as well as through the surrounding aquifer is influenced by the screens.

cont....

Table 4 Hypotheses on the Failure of Systems (cont.)

	Hypothesis	Basis for Postulation
5. General		
5.1	Geofabrics should not be used in sand abstraction systems.	First principles and observations.
5.2	The method of construction of a system may affect the performance of the system, possibly increasing the risk of biofouling of the system or alteration of sand properties.	The construction method was a major difference between the Ulundi and Nqutu systems. Members of the Department of Water Affairs and Forestry postulated this.
5.3	Ideally, systems should not be operated at velocities less than a certain minimum velocity. If velocities are lower than some (as yet undetermined) minimum velocity, fines will not wash through the sand and system, will accumulate in the sand surrounding the system and will therefore reduce the permeability of the sand.	Follows on postulates 2.
5.4	In sands with high fines content, the development of biofouling in an abstraction system will exacerbate the accumulation of fines in sand surrounding a system. The development of biofouling in a system will result in a reduced flow through the system and surrounding sand. This, in turn, will result in an accumulation of fines in the sand, as velocities are sufficient to draw the fines towards the system, but not sufficiently high to draw the fines through the system. The permeability of the surrounding sand will therefore reduce with time, the mechanisms of clogging by biofouling and clogging of the sand acting in conjunction to reduce the yield of a system.	Follows on postulate 5.3. Observations.
5.5	The yield of systems that are not operated regularly and / or are only operated at a fraction of their design yield will generally reduce in time. There will be an increase in problems experienced with biofouling, clogging of the sand, iron and / or manganese precipitation and high iron content of the abstracted water.	Observations.

3 LITERATURE REVIEW

3.1 SAND ABSTRACTION SYSTEMS

3.1.1 Introduction

In the literature review it was found that various types of sand abstraction systems are commonly in use all over the world to provide in the supply of water demand. The types of abstraction systems used were generally dependent on the volume of water required and the nature and position of the alluvial deposits.

Most of the sand abstraction systems found in the literature make use of an infiltration process to abstract the water from the sand. According to Helm (1998) the concept of using infiltration for the supply of potable and irrigation water is at least 2000 years old. Wells dug by hand in the bed of an apparently dry river was a common and probably the oldest "constructed" method employed by rural populations in arid and semi-arid parts of the world to collect water through infiltration.

3.1.2 Purpose of Sand Abstraction Systems

Hussey (1999) stated that many communities in many countries are dependent on groundwater for all their water needs. Johnstone (199_) supported this view by stating that alluvial aquifers have increasingly become a potentially viable source of water to meet domestic, commercial, mine and agricultural demand. Johnstone wrote that the main purpose of any designed water abstraction system is to yield the required volumes of water, free of sand and silt, and as efficiently as possible.

In a technical publication of the United Nations Environment Programme (UNEP) in 2000 a sand abstraction system is described as a method involving the use of slotted cast iron or PVC pipes drilled into a sand-filled river bed, connected to a mainline or manifold and a pumping system. In small-scale, domestic systems, wells or casings are usually sunk into the sandy riverbed and fitted with simple hand pumps or a bucket and windlass assembly. UNEP further stated that freshwater abstraction from sandy riverbeds is widely used in Zimbabwe and Botswana for farming and domestic supply purposes and has great potential for freshwater augmentation.

Helm (1998) stated that the initial principle of filtration through river sand beds has evolved over time to such an extent that recently entire cities, including a power station, were supplied from this source. Various abstraction systems such as perforated brick tunnels, vaulted adits and galleries were constructed during this time to access and abstract the water from the river sand beds.

3.1.3 Types of Sand Abstraction Systems

3.1.3.1 "Traditional" Sand Abstraction Wells

Burger and Beaumont (1970) stated that the principle of storing and conserving water under a cover of sand was well known to the primitive inhabitants of Southern Africa and that they used to dig shallow wells or probed for water with hollow reeds in the dry riverbeds. According to Helm (1998) hand dug wells in the bed of an apparently dry river was a common method employed by rural populations to collect water in arid and semi-arid parts of the world.

In surveys of water supplies in Zimbabwe and Botswana by Hussey (1999) and Davies et al (1995) respectively, many examples of shallow hand dug abstraction wells were found. These wells were usually dug in the river sand down to the river bed to a minimum depth of about 4.0 metres and then protected from animals by placing thorn fences around them.

3.1.3.2 Infiltration Galleries

Where "traditional" sand abstraction wells supply insufficient yield the method of infiltration galleries is often used in situations of shallow groundwater and limited depth of aquifers. Helm (1998) stated that infiltration galleries are commonly used in conjunction with surface water sources where they are either bed mounted (placed under the source) or bank mounted (placed adjacent to the source). Helm defined a typical infiltration gallery as consisting of a perforated pipe positioned within an aquifer and discharging to a sump from where the collected water is pumped or drawn. Buss (1981) described an infiltration gallery as a screen or series of screens installed in a gravel filter pack in a bed of a lake or stream along its shore.

According to Hussey (1999) the most effective way of constructing an infiltration gallery is to install perforated pipes on or below the riverbed and then to backfill with an aggregate rather than the surrounding sand particles. The perforated pipe would then drain into an offset false well on the riverbank from where water could be abstracted by either a bucket or hand pump.

A major advantage of infiltration galleries is that it is relatively inexpensive to install and that the yield could easily be increased by just adding additional collection surface area for infiltration.

3.1.3.3 Infiltration Wells

Helm (1998) defined infiltration wells as large diameter wells of typically 3.0 meter in diameter. The larger the diameter of the well the greater the surface area available for infiltration and hence the more water can be collected.

Infiltration wells are generally built as point sources in either a river bed or on a river bank, depending on the hydrogeological conditions prevailing at the site. The lower part of the well is normally constructed with porous or perforated concrete to ensure sufficient flow of water into the well.

According to Cornelissen (1970) several 3.0 meter diameter perforated concrete wells as well as two 7.6 meter diameter perforated concrete wells were successfully constructed during 1946 in the Buffels River in Namaqualand, South Africa.

3.1.3.4 *Collector Wells*

According to Helm (1998) collector wells, also known as Ranney wells in the USA, is an adaptation of infiltration galleries but operate on the same principles. The Ranney collector well is generally constructed by using the open-end caisson sinking method to form a reinforced concrete shaft that serves as the wet well or pumping station. A bottom-sealing plug is provided to make the caisson watertight. A series of lateral well screens are then projected horizontally from the caisson into the aquifer formation at one or more elevations in a variety of patterns and varying lengths. If required, artificial gravel-pack filters could be installed. The caisson is normally extended to a level above the design flood level before it is fitted with a pump house and the required controls.

The collector well can be constructed in either the river sand bed or on the riverbank depending on the specific hydrogeological conditions at the site. It is a simple process to increase the yield of a collector well by the addition of extra lateral screens.

Until recently the construction of collector wells were very expensive but due to the development of appropriate equipment and technology these wells can now be constructed at lower unit cost of water than the more traditional methods.

3.1.3.5 *Well Point Systems*

Well points are a simple and quick solution to abstract subsurface water and are generally used in cases where smaller volumes of supply are required. Johnstone (199_) defined a well point system as a group of closely spaced small diameter wells, connected to a header pipe and manifold and pumped by suction lift. Individual well points are normally positioned by driving or by jetting methods. Cashman (199_) stated that suction pumping is limited by the physical bounds of suction lift and that a multi stage well point installation should be made if more lowering of the water table is required.

Several well point systems have been installed in Southern Africa and are performing quite well. Cornelissen (1970) described the installation and use of well point systems in the Buffels River in 1947 to augment the water supply to a nearby mining company. Although yields of up to 16000 litre per hour per well point were achieved, some problems were experienced with clogging of openings by fine sand, corrosion by saline water and the need for repeated lowering of suction points as the water level dropped.

Gittens (1986) reported on the performance of a 12 well point system in the Sabie River in Zimbabwe where about 1.0 million litres per hour was abstracted from the river sands and also another 8 well system where about 0.33 million litres per hour was abstracted from a "dry" river bed in the Limpopo River

3.1.3.6 *Screened Tube Wells*

Screened tube wells are defined as large diameter PVC or steel tubes with a porous section to allow water to enter the tube and then be extracted by pumps situated in the tube well. According to Johnstone (199_) the optimum location for screened tube wells are in alluvial aquifers with a saturated thickness of more than 7.0 meters to allow for sufficient draw down after the installation of a screen and pump. The pump is installed within the tube well, which allows for greater fluctuations in water levels in the sand. Generally this is a more efficient system in terms of power requirements and water supply.

3.1.3.7 *Sand Storage Dams*

According to Burger and Beaumont (1970) the first recorded construction of a sand storage dam in Southern Africa was a weir built in 1907 near Windhoek. The weir was completely silted up by 1913 and yielded a steady supply of water at that time. Wipplinger (1958) studied the use of sand storage dams in semi-arid regions and mentioned several other successful sand storage dams in the United States of America and Germany which yielded "small but dependable" volumes of water.

In essence a sand storage dam consists of a weir-type structure placed across a watercourse behind which layers of sand are deposited by successive floods (Burger and Beaumont, 1970). The sand absorbs floodwater, which can then be withdrawn over a period of time by means of wells or drainage systems. Wipplinger (1958) stated that in small sand storage dams a well at the dam wall, surrounded by suitable filters, would provide sufficient drainage. However, in larger dams the drainage system should be specifically designed and extended upstream into the dam basin to allow for the low permeability of the silt and sand deposits.

More recently Chunnett, Fourie and Partners (1995) designed and installed a water abstraction system in the sand trapped behind a weir in the White Mfolozi River near Ulundi in the Kwazulu-Natal province of South Africa.

3.1.4 Design and Construction Guidelines

The design guidelines found in the literature is more applicable to large-scale sand abstraction systems where high volumes of water supply are required. Many design guidelines are based on practical experience and experimental results obtained in the field or in laboratories. Although not much formal design guidelines for small-scale sand abstraction systems were found in the literature survey, the principles are essentially the same as for large-scale systems.

Johnstone (199_) stated that any system designed to abstract water from sand is dependent on the following three criteria:

- The volume of water required,
- The nature of the alluvial deposits, and
- The geographic position of the sand deposits in relation to flood events.

It is obvious that the yield from sand abstraction would be insufficient if the volume required were more than the volume stored and the net recharge to the alluvial aquifer. The potential yield is further dependent on the permeability and thickness of the saturated alluvial deposit. The location of the sand deposits in relation to the river flow needs to be considered in the design of a well in order to minimise potential flood damage to the abstraction system.

In a technical bulletin published by Edward E Johnson Inc (1955) it is stated that the yield, and therefore the design, of any well in water-bearing sand is affected by the following three factors:

- The natural characteristics of the water-bearing sand,
- The elements of well design (type, layout and sizing of well) and
- The methods used in constructing and developing a well.

Although a designer has no control over the natural characteristics of the water-bearing sand, an experienced designer could at least select the site where aquifer conditions are most favourable for maximum yield. It is further within the designer's control to design an abstraction well that is best suited to the hydrological and geological conditions prevailing at the selected site. The designer or contractor could also control the third factor impacting on the yield by using appropriate methods to construct and develop the well.

Typical design and construction guidelines for the various types of sand abstraction systems are described in the following paragraphs, taking into account the factors impacting on the design of such a system.

3.1.4.1 *"Traditional" Sand Abstraction Wells*

No formal design guidelines exist for "traditional" sand abstraction wells. For generations these wells were simply dug by hand in the sand beds of seasonal rivers where subsurface water were found. The size and depth of these wells varied depending on the depth of the water level in the sand and the volume of water supply required.

A simple method of constructing small "traditional" wells is described in a paper presented by Hussey (1997) at the 23rd WEDC conference. As the water in a seasonal river drops below the surface of the sand the people excavate the sand up to the water-bearing layer and then drive a drum with no top or bottom into the wet sand. The sand is then scooped out from within the drum until a depth of about 150 mm of standing water inside the drum is achieved. A lid was then placed over the drum to protect the well from drifting sand. The wells were usually protected from access by wild animals by placing thorn fences around the perimeter of the wells.

According to Hussey the steep walls of some of these wells created stability and safety problems during rainy periods and when the river initially starts flowing the protective thorn fences are washed into the wells and trap the silt and finer sediments. This in turn clogs up the river and makes it difficult for people to find optimum well sites in the following season.

3.1.4.2 *Infiltration Galleries*

Helm (1998) carried out extensive research in the design and construction of infiltration galleries. According to Helm the main design criteria for infiltration galleries are the following:

a) Siting of the infiltration gallery

Infiltration galleries could be installed in either the riverbed or the riverbank of perennial and ephemeral rivers. Generally the presence of phreatophytic vegetation would be a good indication of the presence of underground water and a potential site for an infiltration gallery. Other factors such as the river morphology, surrounding land use or nearby weirs all have an impact on the possible siting of infiltration galleries and should be taken into consideration during the design stage.

Buss (1981) wrote that the primary application for an infiltration gallery is in shallow aquifers and that natural barriers such as impermeable rock formations could greatly enhance well efficiency.

b) Estimation of yield

The yield of a gallery is dependent on the hydraulic head above the gallery and the hydraulic conductivity of the water-bearing formation. In most cases the hydraulic head would be low due to limitations on the depth at which a trench laid gallery could be placed. In such cases it is imperative to position galleries in materials of high hydraulic conductivity, such as alluvial deposits.

According to Helm typical values for hydraulic conductivity (k) in m^3/m^2/day is as follows:

- Fine sand 1 - 5
- Coarse sand 20 -100
- Gravel 100 - 1000
- Mixed sand and gravel 50 - 100

These values, used in conjunction with the hydraulic gradient, could be used to estimate the potential yield from an aquifer.

c) Soil testing

In order to determine the suitability of soils for infiltration galleries Helm suggested that a sieve analysis be performed on the soils. The grain size distribution curve normally provides useful information on the following material characteristics:

- Degree of sorting – this is also known as the Uniformity Coefficient (C_u), which is equivalent to the ratio D_{60}/D_{10}. A well-sorted material ($C_u < 2$) is desirable for improved specific yield.
- Effective size – normally taken as the D_{10} size, which is commonly used for the selection of slot width for well screens.
- Hydraulic conductivity – an empirical formula based on the D_{10} grain size has been developed in recent work in sand rivers in Zimbabwe. It is suggested that

$$k = 775.3(D_{10}) - 161.04$$

  be used as an approximation of the hydraulic conductivity based on a sieve analysis.
- Specific yield – Helm stated that a logarithmic relationship between specific yield and hydraulic conductivity was established for sites tested by Mutsvangwa in 1998. The suggested formula is

$$S_y = 12.426\ln(k) - 19.98$$

  where S_y is the specific yield (%) and k is the hydraulic conductivity (m/s).

d) Collection pipes or screens

Design guidelines recommended by Helm and Buss for collector pipes and screens are more of a qualitative nature and are summarised in the following paragraphs.

- Where possible the largest diameter pipe available or affordable should be used while at the same time sufficient flow is maintained in the pipe to prevent deposition of fines. In any event the minimum pipe size should not be less than 100 mm in diameter in order to facilitate cleaning of the pipe.

- Allowance should be made for potential clogging of the pipe by increasing the required length of the pipe in order to maintain supply of the design yield.
- In order to minimise head losses the gallery should be placed normal to the groundwater flow where possible.
- The spacing between individual collector pipes should be at least 3.0 metres in order to minimise hydraulic interference of collector pipes on one another.
- The flow velocity within the collector pipe should not be higher than 0.9 m/s in order to minimise turbulence and head losses and it should not be lower than 0.5 m/s in order to prevent sediment deposition.
- Pipes in gallery trenches should have a slope of 1:100 towards the clearwell.
- Where screens are used the slot widths should be based on the gravel pack or envelope available and should retain 100% of the gravel pack or envelope. The entrance velocities into the screens should be limited to 0.03 m/s in order to reduce head losses and growth of bacteria.
- Gallery collector pipes or screens should be constructed at least 0.5 metres below the dry season water level and placed on a gravel layer of minimum 0.3 metres thick. Where iron or manganese are present in the water the gallery should be placed at least 4 to 5 metres deep to reduce the presence of dissolved oxygen and the possibility of encrustation.
- In rivers prone to flash flooding and where bed fluidisation occurs the collector pipes should be placed deeper and/or anchoring of the collector pipes to the river bed should be considered.

e) Gravel backfill

A gravel backfill around an infiltration gallery is essential and serves the following functions:

- Prevention of finer particles entering the gallery.
- Provides improved hydraulic conductivity in the area between the gallery and the formation.
- Allows for the use of larger slot sizes in the gallery pipe.
- Reduces turbulent flow and consequently head loss at the screen.

According to Helm the surrounding gravel filter pack should be graded in successive layers of decreasing coarseness with increase in distance from the gallery. Sami (1998) suggested that each successive layer should consist of particles of which the D_{30} size is about 6 times greater than the D_{30} size of the adjacent filter layer. Filter layers should be at least 100 mm thick.

Mixed results have been attained in infiltration galleries where filter packs were substituted with geotextiles. Clanahan (1997) encountered several gallery systems where clogging problems occurred whereas Cansdale (1998) and Hussey (1997) reported some successes in the use of geotextiles.

f) Collection sump

Helm proposed the following general design and construction guidelines for collection sumps and clearwells:

- Collection sumps should be positioned and sized so that it is easily accessible for operation and maintenance.
- Allowance should be made for desilting of the sump and access for maintenance work on the collector pipes.
- Collection sumps are normally constructed using the open-end caisson sinking method where reinforced concrete rings are sunk into the river bed by excavating the sand on the inside until the desired depth is reached.
- A concrete plug of at least 100 mm thick should be placed at the bottom of the collection sump to seal off the sump.
- Where possible provision should be made for backwashing capability from within the sump. According to Buss (1981) the backwash rate should be twice the maximum pumping rate.

3.1.4.3 *Infiltration Wells*

Not much literature is available on the design and construction of infiltration wells. However, infiltration wells are essentially large-scale replicas of well points and the same basic design criteria as for well points could be applied to infiltration wells.

Infiltration wells are usually built as point sources in a sand bed of a river using concrete caissons and placing a porous plug in the base. The porous plug acts as a filter to prevent the entrance of silts and sand particles. Porous or perforated concrete is normally used for the lower caissons to ensure sufficient flow of subsurface water into the well.

For easy access and to prevent flood damage to pumps and other expensive equipment a collection sump is often built on the river bank and connected to the well. This collection sump is then fitted with the required pumping equipment.

Infiltration wells could also be installed in the river bank provided the hydrological and geological conditions are favourable, such as the presence of sufficient permeability between the water source and the abstraction point.

Cornelissen (1970) described the construction of several 3.0 meter diameter perforated concrete wells as well as two 7.6 meter diameter perforated concrete wells in the Buffels River in Namaqualand, South Africa, in 1946. The wells were constructed in the riverbed by casting a bottom ring on site and adding more rings as the wells were deepened. The two large diameter wells performed satisfactorily but the smaller 3.0 meter diameter wells were found to be less effective and impractical for the required large scale pumping.

3.1.4.4 *Collector Wells*

Ranney originally developed the concept of radial collector wells during the early 1920's when drilling for oil in Texas in the United States of America. The technology was later applied to water recovery systems in the early 1930's. A collector well operates hydraulically very similar to a vertical well with the difference being that lateral well screens are installed horisontally near the bottom of the water-bearing formation in order to better utilise the saturated thickness of the aquifer.

The Ranney collector well system is patented and each well is designed in accordance with site-specific environmental and operational criteria, which include the following:

- Riparian and in-stream environmental issues,
- stream flow and stage data,
- bottom and velocity profiles of the stream and
- geotechnical conditions at the intake assemblies and caisson wet well.

The information gathered from the criteria listed above is used to optimise the location of the system, the screen sizing, the entrance velocities and the construction methods best suited for installation of the system.

Typically a collector well consists of a reinforced concrete caisson which serves as the wet well or pumping station. The caisson is normally constructed in the sand bed using the open-end caisson sinking method. A bottom-sealing concrete plug is poured at the bottom of the caisson to make it watertight. The diameter of the caisson is dependent on the size of the pumps and access requirements for operation and maintenance of the system. The Swiss recommended a minimum diameter of 1.60 metre for the Fehlmann collector well (similar to the Ranney well) developed by them.

A series of lateral well screens are projected horisontally from the caisson into the aquifer formation at one or more elevations in a variety of patterns and varying lengths, depending on the characteristics of the formation, the required yield and flow restrictions within the individual pipe or screen. After installation of the screens each radial is individually developed to remove the fines from the formation in the area adjacent to the screen. This normally results in a higher yield and efficiency of the well. It is a simple process to further increase the yield or efficiency of a collector well by adding extra lateral screens and thereby making maximum use of the aquifer drawdown.

The caisson is normally extended to a level above the design flood level before it is fitted with a pump house and the required controls.

A typical example of a collector well system in South Africa is the system designed by Chunnett, Fourie and Partners (1978) in the Buffels River in the Kwazulu-Natal province. The system consists of four collector wells on the bank of the Buffels River, with four to five horizontal radials positioned into the river sand bed from each well. Typical design criteria used for this system were the following:

- Abstraction rate – a rate of 170 litres per second to provide for the initial water demand of a nearby town.
- Available yield – surface water will be abstracted through the sand bed in the river, which would act as a filter medium. During low flows the surface water would be supplemented by water released from a dam upstream of the system.
- Sand properties – test results on the sand indicated a permeability (k) of between 1.6 to 4.8 mm per second.
- Siting and layout of the system – the system was located on the river bank of the Buffels River to provide easy access during operation and maintenance of the system. Four collector wells were installed along the river bank and from each well radial well screens were horisontally positioned into the river sand by means of jacking methods. The radials were placed at a depth of 4.0 metres to minimise the impact of bed fluidisation on the system. The four wells were connected to a gravitational pipeline flowing into an abstraction tower from where the collected water would be pumped.
- Filtration rate – the filtration rate at the surface of the sand was limited to 0.4 mm per second to minimise possible clogging of the sand bed.
- Hydraulic gradient – the hydraulic gradient was limited to a maximum of 0.6 in order to maintain laminar flow and the application of Darcy's equation for flow in a porous medium.
- Screen flow velocity – the flow through the slots in the screens were limited to a maximum of 0.03 metres per second to minimise head loss and possible clogging of the slots.
- Pipe flow velocity – the flow velocity in each pipe was limited to between 0.5 and 0.9 metres per second to prevent deposition of fine materials inside the pipe and to minimise head losses.

- Width of slot openings – the width of the slot openings in the screens was selected as 0.15 mm to retain at least 80% of the surrounding sand outside the screens.
- Collector wells – the diameter of the collector wells was 3.50 metres to provide sufficient access for the installation of the radial screens. The wells were also provided with ventilation pipes to prevent the formation of air pockets and subsequent reduced flow inside the system.

The design equations and flow nets used to determine the flows, head losses and the H-Q curves for one radial cover with 4.0 metres of sand are included in the design report by Chunnett, Fourie and Partners (1995).

During construction it was necessary to build cofferdams to prevent flooding of the works. After completion of the excavations to the required levels the reinforced concrete wells were built in-situ and backfilled. The horisontal radials were then drilled through the sandstone formation into the river sand bed. After this the well screens were installed by means of a steel casing that was jacked into the sand formation up to the required length. During construction the system was flooded and since completion of the construction problems were experienced with reduced yield.

3.1.4.5 *Well Point Systems*

Not much design guidelines specifically aimed at well point systems were found in the literature survey. According to Hussey (1997) the most important aspect for the design of a successful well point system is the sizing of the individual parts or members of the system.

Hussey further stated that the required yield and the velocity of water in each part of the system should determine the number of well points required, the size of the manifold, the size of the piping to the river bank and the type and size of pump required. The layout and configuration of a well point system at a particular site could therefore be optimised by using standard hydraulic design formulae for the sizing of individual parts of the system.

Practical design guidelines regarding the siting of the well points, the type and the size of screen slots are important issues to be considered for maximum yield. Gittens (1986) reported on a project where a 12 metre thick water bearing formation was located by means of a preliminary geophysical survey. Eight wells, with 152 mm stainless steel continuous slotted screens, were installed at 18 metre intervals in this formation. The continuous slots were wedge shaped and had a width of 0.075 mm in order to hold back at least 60% of the fines in the water bearing formation. Once the screens were in position they were developed using surge plungers to remove the fines from the formation in the area surrounding the well thereby improving the permeability of the surrounding soil.

The wells were then tested at a pumping rate of twice the required yield whereafter submersible pumps were installed above the screens in such a position as to ensure an even suction over the full length of the screen. The entrance velocity into the screens was limited to 0.03 metres per second in order to prevent excessive movement of silt in the area surrounding the screen. The submersible pumps were then coupled to a manifold leading into a single 254 mm diameter pipe that feeds a large reservoir from where the water is pumped for further use. The manifold system was buried about 3.0 metres deep in the riverbed for protection against damage during floods.

In a related article about well points Cashman (199_) stated that extra care is required to prevent abstraction of fines when installing well points in silty soils. He advised that it might be necessary to install multi-stage well points in cases where greater lowering of groundwater levels are required, especially in low permeability soils with a highly stratified structure. According to him the optimum location for well points is in a shallow alluvial aquifer where the water levels remain close to surface throughout the year.

Hussey (1997) gave some general guidelines for the construction and operation of well point systems in Zimbabwe. He mentioned that a well point system should have a sufficiently low velocity of water at the abstraction point in order to prevent sand from being drawn into the system. According to him a well point system should ideally be installed towards the end of the dry season when the river water is at its lowest level. The river sand should first be removed to the top of the water-bearing layer whereafter a manifold should be installed on the water yielding sand. Slotted pipes should be driven at an angle into the water-bearing layer and then connected to the manifold. To complete the installation the manifold should then be connected to a suction pump on the riverbank.

3.1.4.6 *Screened Tube Wells*

As for any other type of well the first step towards the design and installation of a screened tube well is the selection of the most favourable site. Generally coarse-grained sand provides a better rate of flow and deep sand provides a high column of water.

According to Cornelissen (1970) the size and number of screened tube wells to be installed in an aquifer depend on the volume of water required. The required yield should be in balance with the volume of water that is available in the water-bearing formation.

The bottom portion of tube wells should either be perforated by slots of specifically designed width and length or fitted with slotted screens with sufficient slot size to prevent the abstraction of fines from the formation around the well. Drilling, driving and/or jetting methods could be used to install the tube wells. As the casing is lowered additional lengths are added to the column until bedrock is reached. Johnstone (199_) stated that it is important that the well be developed on completion of the installation in order to establish a zone of high permeability in the formation around the screen. Once this is done the bottom of the tube well should be sealed off by pouring cement through an inner pipe to form a 300 mm thick plug at the bottom of the tube. The installation is then completed by providing a concrete collar around the part of the tube extending above the average water level and the installation of a suitable pump.

Cornelissen (1970) described the installation of several steel casings similar to screened tube wells in the Buffels River since 1957. According to him these wells have proved to be the most effective method of water withdrawal from deep sands. Initially twelve 508 mm diameter casings were installed from which about 675 to 1800 litre per minute was abstracted. These casings were slotted in the bottom portion over a length equal to the average height of the water column in the sand and were positioned using driving and jetting methods until bedrock was reached. The bottom was sealed of with cement and a concrete collar was constructed around the portion of casing extending above the average water level. It took about one week to install a 508 mm casing in 12 metres of sand.

3.1.4.7 Sand Storage Dams

According to Wipplinger (1958) the basic principle for developing a successful sand storage dam is to construct it in controlled incremental stages so that the velocities of flow through the basin are sufficiently high to transport most of the fine sediments over the dam crest. The objective is to promote the deposition of coarse-grained sand deposits in the dam, which will improve both the efficiency of absorption and the yield of the sand storage dam. In practice silt beds and lenses do occur when silt is deposited during small floods. However, subsequent floods of higher magnitude would normally scour part or most of the deposited silt.

Sand storage dams are therefore constructed in stages, with the height of each stage carefully controlled and each new stage constructed only after the previous stage has effectively silted up (Burger and Beaumont, 1970). Wipplinger recommended that a flow velocity of 0.5 metres per second near the dam wall be adopted as a limiting condition for the design of stages of a sand storage dam. Wipplinger further stated that the additional pressure caused by the sand deposits needs to be taken into account when designing the dam wall.

Further guidelines regarding the grading of successive layers of filter material around the abstraction well is also proposed by Wipplinger. Based on standard sieve analyses the D_{15} size of successive filter layers should not be coarser than four times the D_{85} size of the adjacent layer of material and the slot size of the well screen should be equal to the D_{60} size of the filter layer nearest to the well screen.

More recently Chunnett, Fourie and Partners (1995) designed and installed a water abstraction system in the sand trapped behind a weir in the White Mfolozi River near Ulundi in the Kwazulu-Natal province of South Africa. The system consisted of a reinforced concrete gallery installed parallel to the river on the river bank with a series of collector pipes positioned at right angles from the gallery into the river sand deposited behind the weir. Typical design criteria used for this system were the following:

- Abstraction rate – a rate of 313 litres per second, based on peak demand during emergencies was applicable.
- Filtration rate – based on sand samples tested a maximum filtration rate of 0.4 mm per second was allowed at the surface of the sand in order to minimise clogging of the voids in the surface layer.
- Hydraulic gradient – the maximum hydraulic gradient was found to be in the range of 0.84 to 0.96 for the in-situ sand at the weir site. By removing the portion of sand finer than 0.30 mm the hydraulic gradient of the sand was improved to between 1.04 and 1.33. It was therefore decided to remove the fraction of sand finer than 0.3 mm and to limit the hydraulic gradient to 1.0 near the abstraction pipes.
- Coefficient of Permeability (k) – the effective coefficient of permeability of the river sand was determined as 1.20 mm per second.
- Screen flow velocity – the flow through the slots in the collector pipes were limited to a maximum of 0.03 metres per second to minimise head loss and possible clogging of the slots.
- Pipe flow velocity – the flow velocity in each pipe was limited to between 0.5 and 0.9 metres per second to prevent deposition of fine materials inside the pipe and to minimise head losses.
- Width of slot openings – the width of the slot openings in the pipes was sized to retain at least 95% of the surrounding sand outside the pipes. For the system 150 mm diameter PVC Soloflo wedge pattern screens with 0.25 mm slot width and 2.67% open area were selected.
- Bed fluidisation – the minimum installation depth of the collector pipes to minimise the impacts of bed fluidisation was estimated at 2.50 metres.
- Gallery – the gallery was provided with ventilation to prevent the formation of air pockets.
- Sizing of individual structures and pipes – the gallery, outlet pipe and individual pipes and screens were all sized in accordance with the design criteria and the associated head loss when abstracting the design yield of 313 litres per second.

Part of the design of the abstraction system was to optimise the placing of the collector pipes. In order to do so flow nets with equipotential lines were compiled for various depths and intervals between the collector pipes. Darcy's equation for laminar flow through a porous medium was used to calculate the flow through the sand bed. The design equations used to determine the flows, head losses and the backwater curve in the gallery and pipes are included in the design report by Chunnett, Fourie and Partners.

3.1.5 Development of Wells

The way in which a well is drilled and developed has an important bearing on its yield and efficiency. According to Johnson Inc. (1959) the development of a well could be defined as the removal of the silt, fine sand or gravel around the well screen in order to produce a natural filter of coarser and more uniform sand or gravel. The purpose of development is to create a coarse filter around the well screen in order to have the greatest possible amount of open space for water to flow through.

A further advantage of development is that the grading of the material in the water-bearing formation around the well screen is "stabilised", thereby making the formation safe against failure regardless how heavily it may be pumped.

In Bulletin No. 1033 of December 1959, Johnson Inc. gave a detailed overview of the various methods available to develop a well. The three methods of well development described by Johnson Inc. are the following:

1. <u>Developing Wells with Surge Plungers</u>

   According to Johnson Inc. surge plungers are well known for their effectiveness and simplicity to develop sand wells. Generally two types of surge plungers are used in the development of a sand well. The two types are the following:

   - Solid surge plunger – this plunger is operated up and down in a well casing for the purpose of exerting more or less equal force on the inward and outward movement of the water through the screen. The repeated application of this surging force will tend to shift the sand particles and change the entire arrangement of the water-bearing formation around the screen. As a result the formation will have both a higher porosity and a higher permeability.

     It is very important that the screen slots have a sharply receding opening (such as a wedge shape) to prevent any clogging during the development procedure.

   - Valved surge plunger – this plunger is normally used in wells where the formation has a weak yield. It works on the principle of producing a greater in-rush than out-rush of water through the screen and formation. It is operated in the same way as the solid surge plunger and provides excellent results in developing obstinate wells in sand and gravel provided the well is properly screened and the plunger is operated correctly.

When the screen is filled about 65% with sand the surging operation should be stopped and the sand first removed before continuing with surging.

2. Developing Wells with Compressed Air

The use of compressed air to develop a well could be very rapid and effective if the correct equipment and methods are used. The two methods generally in use are the following:

- Back-washing Method – the principle of this method is to force the water back out of the well, through the screen, into the water-bearing formation by means of compressed air after sealing off the top of the casing. In order to prevent "air-logging" of the formation special provision is made to prevent the air from entering the formation. Normally a 3-way valve is used to release the compressed air from the well when required.
- Open Well or Surging Method – for this method it is essential to have the correct equipment to develop the well and at least 60% of the air-line in the well needs to be submerged for this method to be efficient. This method is based on the principle of combined surging and pumping. A strong surge is produced in the formation by means of the sudden release of large volumes of compressed air in the well and pumping is done as with an ordinary air lift. In many cases this method has been used successfully in conjunction with the surge plunger method.

3. Developing Wells with Over-pumping and Back-washing

According to Johnson In. the simplest and most common method of developing a well ending in sand and gravel is by means of "over-pumping". This is done by pumping the well at a much higher rate than the normal operating rate, thereby creating a higher draw-down and subsequently a higher head in the water-bearing formation.

However, there are generally the following three objections against this method of development:

- Over-pumping does not improve the yield of a well significantly.
- Over-pumping tends to cause the sand to "bridge" in the formation, which could later lead to clogging of the well.
- Over-pumping often requires larger pumping equipment than is conveniently available.

Some of the problems with "bridging" could be overcome by keeping the water as agitated as possible by pumping intermittently. However, this method is not recommended where "bridging" problems are foreseen or where large development of a well is required.

Back-washing is based on the principle of surging or agitating the formation at the well-end with the purpose to prevent "bridging" of the sand particles and to remove a large portion of the finer material by using either hydraulic or water pressure. It is recommended by Johnson Inc. that back-washing be used in conjunction with other methods for efficient development of a well.

3.1.6 Operation and Maintenance of Wells

In his research report Helm (1998) stated that the operation and maintenance of sand abstraction systems is the most deficient aspect of water supply programmes in developing countries and that much of the success or failure of such systems are related to operation and maintenance issues.

Several authors advocate that operation and maintenance issues of sand abstraction systems should be taken into consideration during the design phase of such a system. Once a sand abstraction system is in operation it should be monitored closely for signs of deterioration. The early detection of potential problems could save the owner of the system a lot of money and also ensure sustainable yield from the aquifer. Helm (1998) identified the following parameters worthwhile of monitoring:

- Water turbidity – relative increases in turbidity could be an indication of deteriorating filter performance.
- Water quality – sudden deterioration in water quality may be an indication of a source of pollution into the aquifer. The pollution could be from chemical (iron content) or bacterial (coliform) sources.
- Water quantity – changes in pumping rates could be an indication of a drop in the water table, insufficient recharge to the aquifer, clogged screens or loss of pump efficiency.

The following potential problems and possible solutions were identified by Helm:

- Clogging of the filter – generally caused by the deposition and infiltration of fine silts during low flow conditions in the river. Possible remedial action is back-washing, jetting and use of compressed air.
- Clogging of screens – this is caused by fine particles plugging the slots of the screen due to high entrance velocities or insufficient filter around the screen. Surge plungers, jetting or compressed air may be used to clear the screens.
- Biofouling of screens – this is generally caused by high levels of iron and manganese in the presence of bacterial slimes. Chlorination, mechanical agitation and pumping are some of the methods used to break up, dissolve and remove biofouling.
- Incrustation of screens – this is caused by the precipitation of inorganic ions such as iron, manganese, calcium and magnesium. The use of acids and mechanical agitation are some of the methods used to remove incrustation.

- Accumulation of silt in pipes – this could be caused by too high inlet velocities, too large slot sizes or insufficient gravel filter. Flushing, surging or brushing methods are used to suspend the fines whereafter it is pumped or drained from the well.
- Corrosion of screens – generally caused by aggressive water. Replace with screens or pipes manufactured from corrosion resistant materials.

It should be borne in mind that no single treatment is suitable for all types of wells and that a combination of different treatment methods are often used in some problematic situations.

3.2 BIOLOGICALLY INDUCED FOULING

3.2.1 General

Biologically induced fouling, or biofouling, is the phenomenon whereby surfaces in contact with water are colonised by micro-organisms, which are ubiquitous in our environment (Costerton and Bovin, 1987). The accumulation of unwanted organic materials in an environment, either natural or man-made is generally referred to as biofouling (Wolfaardt, 1990).

Micro-organisms distinguish themselves from other water contaminants by their ability to utilise available nutrient sources, reproduce, and generate intra- and extracellular organic and inorganic compounds in water (Wolfaardt, 1990). This normally results in biofilm formation.

Biofilm formation is a consequence of the activity of micro-organisms, of which two distinct populations are found in water systems: planktonic (free-floating) micro-organisms present in the bulk fluid and the more predominant sessile (surface attached) micro-organisms growing in biofilms (Schapira, 1988). Micro-organisms most commonly involved in biofilm formation are the coliform bacteria, the pseudomonad, fungi (moulds and yeasts), and algae. These organisms grow on available surfaces, initially as adherent micro-colonies and eventually as a confluent layer (Costerton, 1984).

The development of biofilms occurs as follows (Lynch and Edyvean, 1988):

1. Immediately upon immersion, dissolved organic material is adsorbed onto the surface to form a conditioning film.
2. This is followed by the adhesion of microbial cells to the conditioned surface. Bacteria, diatoms and algae are probably carried to the substratum in association with suspended organic debris.
3. Then, if conditions are suitable, growth of the attached organisms occurs. These produce copious amounts of extracellular polysaccharides, resulting in the characteristic slime associated with biofilms. Growth continues until nutrient limitation occurs at the base, leading to death of some organisms and a sloughing in parts of the biofilm.

3.2.2 Parameters Affecting Biofilm Development

The formation of biofilms is affected by a number of parameters such as:

3.2.2.1 *Temperature*

Micro-organisms have a characteristic optimal growth temperature at which they exhibit their highest growth rates and metabolic activities. Biofilm development is affected by both ambient temperature (related to season, day length etc.) and system temperature. The closer temperatures get to the optimal growth temperatures of the micro-organisms involved, the higher the rate of biofilm development. This is due to increased rates of accumulation of new cells on surfaces as well as increased rates of cell growth (Fera *et al.*, 1989).

3.2.2.2 *Water Flow Rate*

Schapira (1988) stated that an increase in flow rate causes an increase in biofilm thickness. He further stated however, that this might also increase shear forces, thus reducing microbial attachment and removing attached biomass.

3.2.2.3 *Nutrient Availability*

Since nutrients are concentrated at the solid-water interface, motile bacteria display a positive chemotactic response to the surface. A low nutrient availability can also stimulate biofilm development since some bacteria adhere to surfaces as a strategy to survive low nutrient conditions (Marshall, 1985).

3.2.2.4 *Concentration of Inorganic Particles*

Inorganic particles can become entrapped and so provide additional attachment sites (Costerton and Irvin, 1981).

3.2.3 Organisms Involved in Microbially Influenced Corrosion

3.2.3.1 *Sulphate Reducing Bacteria (SRB)*

During dissimilatory sulphate reduction, sulphate is reduced to hydrogen sulphide, which is a corrosive agent. Dissimilatory sulphate-reduction is carried out by a specialised group of anaerobes: the sulphate reducing bacteria (Cloete *et al.*, 1994).

SRB have been isolated from the anaerobic regions of marine and estuarine sediments as well as from saline ponds and non-saline environments such as anaerobic mud and sediment of freshwater. Although these bacteria are strictly anaerobic, their presence has been detected in many aerobic regions (Cloete *et al.*, 1994). SRB are identified as the single most causative micro-organisms responsible for corrosion under anaerobic conditions. Algae and fungi are also indirectly involved in corrosion as these organisms are involved in biofilm formation (Wolfaardt, 1990).

3.2.3.2 Iron Bacteria

In a special topic report Stuart Smith (1997) states that iron bacteria, also known as iron biofouling, consists of biofilms which include living and dead bacteria, their sheaths, stalks, secretions and other leavings, and embedded metal oxihydroxide particles.

Iron bacteria aerobically oxidise dissolved ferrous ions to insoluble ferric salts. These may be deposited in a covering sheath, or produce a stalk-like filamentous form (Tatnall, 1981). It has been suggested that these bacteria alter the environmental pipe surfaces, encouraging the growth of chemo-organotrophic bacteria (Poulton, 1993).

According to Smith (1997) iron bacteria often acts as a preliminary iron filter in wells and therefore can serve a positive function as well. Generally iron bacteria causes side effects such as sulphide odour, red water and pitting-type corrosion of iron and steel.

3.2.4 Biofouling Control in Water Systems

3.2.4.1 Biofilm Monitoring

A recent approach for biofilm monitoring has been the development of replaceable sampling surfaces. These allow more detailed observation of relatively undisturbed portions of the biofilms. Pederson (1982) developed a method for the study of biofilms in flowing-water systems. In this method, microscope slides, placed in flow cells, parallel to the direction of flow through the cells, provide the test surfaces.

3.2.4.2 Estimation of Microbial Numbers

Several methods have been used to determine microbial numbers in water. The most common are the different culture techniques where several dilutions of each sample are grown on growth media. Agar plates allow the isolation of pure strains and the enumeration of colonies arising from individual viable cells. It is therefore also referred to as colony counts. The most generally used methods include the following techniques:

- Pour plates
- Spread plates
- Thin-layer plates
- Layered plates
- Membrane filter methods

In biofouling related studies it may often happen that only a limited amount of information is gathered with these techniques since:

- Numbers of planktonic organisms are usually determined which provide little information as to what is occurring on the surface because there is often no relationship between sessile and planktonic numbers (Wolfaardt, 1990).

- The media employed for the counting of micro-organisms normally have an efficiency of less that 10% (Steyn and Cloete, 1989) for the recovery of bacteria.

Scanning electron microscopy (SEM) techniques are sometimes employed to quantify the extent of biofouling on surfaces. However, since a large amount of expertise and sophisticated equipment are needed to obtain results with these techniques, they are not suitable for routine monitoring of biofouling (Wolfaardt *et al.*, 1990).

A possible solution to this problem lies in the use of 4'6-diamino-2-phenylidole (DAPI), a highly specific DNA stain used to detect bacterial cells (Wolfaardt, 1990). When excited by light at the right wavelength (365nm), the DAPI-DNA complex produces a bright blue fluorescent glow in direct proportion to the cellular content. The unbound dye molecules and DAPI bound to material other than DNA may fluoresce a pale yellow.

3.3 IRON AND MANGANESE

High iron and/or manganese content in abstracted water is one of the problems commonly associated with sand abstraction systems. An article by Global BioSciences Inc (2003) confirms that chemical and biological incrustation are major causes of decreased well performance and eventual failure. GBI further states that iron and manganese bacteria not only produce accumulations of slimy material (biofouling) but that they also precipitate dissolved iron and manganese. This process, together with oxide and hydroxide depositions, is generally the cause of well screen clogging and failure. This correlate with the statements of Smith (1997) and the findings of the Northern Territory Government of Australia (2002) that iron bacteria is generally the catalyst for iron and manganese precipitation in abstraction wells.

Iron and manganese precipitation typically occurs when oxygen or another oxidising agent such as chlorine is introduced. In a technical report Armstrong reported on the use of the Vyredox Method (Hallberg and Martinell, 1976) to remove iron and manganese from a clogged up well in Massachusetts. The Vyredox Method is primarily applicable to shallow sand and gravel aquifers and involves the injection of oxygenated water into the ground around a supply well. According to Armstrong the activity of certain beneficial bacteria are stimulated through this process resulting in the precipitation of iron and manganese, which are retained within the aquifer.

According to Vance (2002) the inorganic oxidation processes whereby iron and manganese are precipitated in the presence of dissolved oxygen in groundwater are the following:

- Iron oxidation

  $O_2 + 4Fe^{+2} + 4H^+ \Rightarrow 4Fe^{3+} + 2H_2O$
- Manganese (II) oxidation

  $O_2 + 2Mn^{2+} + 2H_2O \Rightarrow 2MnO_2 + 4H^+$
- Iron sulphide oxidation

  $15O_2 + 4FeS_2 + 14H_2O \Rightarrow 4Fe(OH)_3 + 8SO_4^{2-} + 16H^+$

When using the Vyredox Method to precipitate iron and manganese in groundwater, Armstrong also found indications of a mineral transformation from amorphous limonite Fe(OH) H_2O to hematite, Fe_2O_3, having hexagonal crystals.

Vance (2002) also stated that ferric hydroxide ($Fe(OH)_3$) is the direct result of ferrous iron oxidation and precipitation and that, with time, ferric hydroxide is mineralised in the following principal forms:

- amorphous hydrous ferric oxide (Fe_2O_3 XH_2O),
- maghemite (gamma-Fe_2O_3),
- lepidocrocite (gamma-FeOOH),
- hematite (alpha-Fe_2O_3) and
- goethite (alpha-FeOOH).

The above iron oxides are listed in order of decreasing solubility, which also reflects increasing crystallinity. According to Vance the time required for ferrous iron to undergo oxidation to the ferric state is dependent on many factors, with the dominant being pH; temperature; dissolved oxygen level; and the presence of other soluble ions.

In an article by Sedin (2002) of Swedish EPA it is stated that the redox conditions of groundwater affect the concentration and solubility of many substances contained in it. A low redox potential (water devoid of oxygen) indicates several risks, including precipitates of iron and manganese and difficulty in reducing the water's concentration of these metals in soluble form. According to David Finger (200_) results of tests performed on infiltration through sediments of riverbeds indicate that microbiologically mediated dissolution of manganese and ferrihydrite involving organic matter (bacteria) occurs at low redox potential as follows:

- dissolution of manganese

  CH_2O $106(NH_3)$ $16(H_3PO_4) + 212MnO_2 + 438H^+ \Rightarrow 106CO_2 + 16NH_4^+ + HPO_4^{-2} + 318H_2O + 212Mn^{+2}$ and
- dissolution of ferrihydrite

  CH_2O $106(NH_3)$ $16(H_3PO_4) + 424Fe(OH)_3 + 862H^+ \Rightarrow 106CO_2 + 16NH_4^+ + HPO_4^{-2} + 1166H_2O + 424Fe^{+2}$

Conversely, in groundwater with a high redox potential (high presence of dissolved oxygen) the manganese and iron would then be oxidised and precipitated as shown before.

In a study of the kinetics of Fe(II) oxidation and well screen encrustation by Applin and Zhao (1989) it was concluded that the greatest rate of oxidation occurs when pumping from the well is stopped and the remaining water in the well gradually becomes oxygenated after exposure to atmospheric O_2. They also found that precipitation would continue until $Fe(OH)_3$ production ceases.

3.4 SAND PROPERTIES

3.4.1 Grading Analysis

The standard sieve analysis is generally used to determine the grading or size distribution of particles in sand. Wipplinger (1958) and Helm (1998) used the following grain sizes to determine the relative suitability of various types of sand:

- The effective size D_{10} – the grain size of the 10% finer fraction (D_{10}) is normally used for the selection of the slot widths of well screens. According to Helm it could also be used in the following formula to estimate the hydraulic conductivity of the material:

  $$K = 775.3(D_{10}) - 161.04$$

  where K is the hydraulic conductivity (m/day) and D_{10} is the effective size (mm).

- Uniformity coefficient $C_u = D_{60}/D_{10}$ – this gives an indication of the degree of sorting of the alluvial material. The lower C_u, the better the sorting of the material and the higher the hydraulic conductivity.

- The D_{15} and D_{85} sizes are important parameters for the design of filters around well screens. Generally the D_{15} of a filter layer should not be coarser than 4 times the D_{85} of the adjacent filter layer.

3.4.2 Porosity

Porosity is the ratio of the pore volume to the total volume of a representative sample of the material. According to Wipplinger (1958) the porosity of a material is largely dependent on the size and shape of grains, the uniformity of grain size and the compaction of the material.

Fine sands tend to have a higher porosity than coarse sands because of their more uniform grain size. This is confirmed by Lu et al (1993) who showed that the mean value of porosity varies from 0.43 for fine sand to 0.28 for coarse gravel. However, where fine and coarse sands have the same porosity the coarse sands will have a higher specific yield due to the larger grain size of coarse sand.

3.4.3 Hydraulic Conductivity and Permeability

According to Yu et al (1993) and many other authors the hydraulic conductivity of a soil is a measure of the soil's ability to transmit water when submitted to a hydraulic gradient. It is often referred to as K (m/s), as in Darcy's equation for flow through a porous media (Hillel, 1971). The hydraulic conductivity K can be expressed as follows (Bear, 1972):

$$K = \frac{k \rho g}{\mu}$$

where k, the intrinsic permeability of the soil depends only on properties of the solid matrix, and $\rho g/\mu$, the fluidity of the liquid, represents the properties of the percolating fluid. When the fluid properties of density and viscosity are known, the above equation can be used to experimentally determine the intrinsic permeability k, and the hydraulic conductivity K. For water, $\rho g/\mu$ can often be assumed as a constant value, with the result that k is directly related to K.

The hydraulic conductivity is dependent on the soil grain size, the structure of the soil matrix, the type of soil fluid, and the relative amount of soil fluid (saturation) present in the soil matrix (Yu et al). The most important properties relevant to the solid matrix of the soil are the pore size distribution, the pore shape, the tortuosity, the specific surface and the porosity. Hillel (1971) stated that the mean size of the pores, rather than the total porosity, has the largest influence on hydraulic conductivity.

It is evident that certain properties of alluvial sand have a direct impact on the yield of a water-bearing formation. Measuring and analysing these properties could provide valuable information regarding the yield of water-bearing formations. Yu et al (1993) provided some tables with typical values of the saturated hydraulic conductivity, and subsequently the permeability, of different soils based on the soil type, the soil texture, the grain size, the degree of sorting and the silt content.

3.4.4 Bulk Density

The soil bulk density (dry density) is the ratio of the mass of the solid phase of the soil (dried soil) to its total volume (solid and pore volumes together). Bulk density is dependent on the structure of the soil matrix (or its degree of compaction) and the soil matrix's swelling/shrinkage characteristics. Yu et al (1993) listed the following typical values of the bulk density of soils, based on soil texture type:

Soil type	Dry Density (g/cm^3)
Sand	1.52
Sandy loam	1.44
Loam	1.36
Silt loam	1.28
Clay loam	1.28
Clay	1.20

The common method used in the field to classify a soil is the "feel" method where the soil is rubbed between the thumb and fingers (Brady, 1984). A more accurate, but time-consuming method to classify soil is by means of a sieve analysis in the laboratory.

3.5 WELL SCREENS

3.5.1 Definition and Purpose

The Ohio Department of Natural Resources (fact sheet 93-7) defines a well screen as a filtering device that allows ground water from unconsolidated or semi-consolidated aquifers to enter the well while at the same time keeping the majority of sand and gravel out of the well and out of the pump.

Other important purposes of well screens are to support the aquifer material and to prevent the well from collapsing. Jackson (1983) added that well screens also need to be resistant to corrosion to prevent the collapse and the subsequent pollution of a well and that well screens should minimise the loss of head when water enters the well.

3.5.2 Types of Well Screens

A number of different well screen types are available in the market. These screens are normally manufactured using non-corrosive materials such as plastic, glass reinforced plastic, stainless steel and galvanised mild steel. The screens are manufactured using different slot construction techniques, different slot sizes, different slot shapes and different percentages of open area. The manufacturing processes normally used to form the desired sizes and shapes of slots are machining, drilling, pressing and the winding of wire around a set of vertical rods. The various types of screens can therefore broadly be classified in terms of the configuration of their slots.

According to the Ohio Department of Natural Resources (1993) the three most common screen types used in Ohio are the continuous slot screens; slotted PVC screens and slotted or perforated pipe screens. During his research on well screen performance Jackson (1983) tested various types of screens, which included screens with continuous, slotted, mesh, and shutter (louver) types of slots. Clark & Turner (1981) carried out several experiments to assess the hydraulic efficiency of well screens. The well screens tested by them included screens with continuous, slotted and bridge types of slots.

3.5.3 Performance of Well Screens

The hydraulic performance of various types of well screens was evaluated by several researchers in terms of the slot characteristics of the screens. Jackson (1983) and Clark and Turner (1981) investigated the impact of the type of slot, the slot size, the slot shape and the percentage of open area on well screen performance.

Both research findings showed that the head loss over all the types of screens tested was very small (less than 5mm), except for the wire mesh type of slot (25mm for coarse mesh to 400mm for fine mesh), and could be considered negligible.

Jackson (1983) also evaluated the head losses in the formation surrounding the well for each of the various screens. The measured formation losses was approximately the same for the wire mesh and shutter (louver) type of screens, while the comparative losses for the continuous and slotted type of screens were about 20% to 100% higher. The results further indicate that the slot width, rather than the percentage of open area, has a major impact on the head losses through the formation. It appears that there is an optimum slot width for each type of screen, which is dependent on the characteristics of the formation surrounding the well. Clark and Turner (1981) also found that there was no significant improvement in the hydraulic performances of well screens, irrespective of design, provided the open area of the screen exceeded 10%.

The Ohio Department of Natural Resources (1993) stated that continuous slot screens are often the best choice for use in unconsolidated sand and gravel aquifers because the design allows small particles to pass completely through the screen without becoming wedged in and clogging the screen. The Department also stressed the importance of selecting the proper slot size (width), which would allow water to freely enter the well while holding back the majority of the aquifer material.

3.5.4 Design of Well Screens

According to Lightfoot of Basic Mineral Engineering (Pty) Ltd in South Africa the successful design of a well screen is dependent on the following parameters:

- The amount of water available in the aquifer – enough holes should be drilled to determine the volume of water available in the aquifer.
- The position of the aquifer – the optimum aquifer should be determined from the borehole drilling log information.
- The size distribution of particles – the drilling information should provide information on the size distribution of particles i.e. fine sand, coarse sand, gravel etc.
- The permeability of the aquifer – in general the better the sorting of the grains, the coarser the average grain size, the looser the packing and the lesser the cement there is between the grains, the higher the permeability would be. The permeability of an aquifer could be increased by a factor of three to five times by providing a suitable artificial gravel pack or by proper development of the aquifer.
- The yield from the screen – the screen should be sized in accordance with the required abstraction rate, which would determine the open area required and the maximum screen velocity for specific slot widths.

- The specific capacity of the aquifer – the aquifer should have sufficient capacity and depth to accommodate the expected drawdown and the required length of screen. It is good practice to have a pumping test done to ensure that the required yield does not exceed the capacity of the aquifer.

Well screens should be selected in terms of the type of slot, the slot size, the length and diameter of the screens, any fittings that may be required and the construction conditions prevailing at the water abstraction site.

4 SURVEY OF SAND ABSTRACTION SYSTEMS: METHODOLOGY

As stated in Section 2.1.1, the first objective of this research was to establish a database of existing sand abstraction systems in Southern Africa. To this end a survey of existing sand abstraction systems was conducted. This chapter discusses the implementation of the survey, the types of data collected, methods of data collection and problems experienced with data collection.

The survey of existing sand abstraction systems was conducted in two phases. The purpose of the first phase of the survey was to find as many sand abstraction systems in Southern Africa as possible, and to determine whether problems of low yield had been experienced with any of these systems. The purpose of the second phase of the survey was to gather detailed information and data about those systems that were found during the first phase of the survey.

4.1 SURVEY – PHASE I

In order to locate sand abstraction systems in Southern Africa, a questionnaire was drawn up for distribution throughout the water sector. The questionnaire included a letter that briefly described the research project and the objectives of the research. The questionnaire itself was kept extremely brief, in the hope that this would result in a better response. A copy of the questionnaire is included in the electronic appendices to this report as *Appendix e.A*.

The questionnaire was posted to as many role players in the water sector in Southern Africa as possible. This included:

- all consulting civil engineering companies listed as water engineers in the directory of the South African Institute of Civil Engineers (all branches of each company were sent a questionnaire),
- irrigation boards,
- water boards,
- manufacturers and suppliers of well screens,
- engineering, microbiology, agricultural and environmental departments of universities and technicons,
- institutions and associations, including the Water Institute of South Africa and the Borehole Water Association of South Africa, and
- government departments, including the various offices and divisions of the Department of Water Affairs and Forestry, South Africa.

In total, 745 survey questionnaires were posted to the various groups.

4.2 SURVEY – PHASE II

The purpose of the second phase of the survey was to gather detailed data and information about the systems located during Phase I of the survey. The type of data collected, and the manner in which it was collected, were determined by the objectives set for the project as defined in Section 2.2.1. In addition data was collected to allow for investigation of the validity of the various hypotheses postulated during the course of the research.

4.2.1 Detailed Questionnaire

It was initially intended that detailed information about the design, construction and operating history of each system be gathered mainly by means of a questionnaire. Where data was incomplete, it was then intended that sites of the abstraction systems would be visited and interviews would be conducted to obtain additional information.

A detailed questionnaire was therefore drawn up and posted to all persons given as contacts for each of the systems found during Phase I. A copy of the detailed questionnaire is included in the electronic appendices to this report as *Appendix e.B*.

The response to the detailed questionnaire was, however, extremely poor. In retrospect the poor response can be attributed to three main factors, viz.:

- The questionnaire was too long.
- The questionnaire was designed based on the research team's own experience with sand abstraction systems. At the time this was limited to infiltration galleries that incorporated horizontal well screens. Questions about system design were therefore relatively specific to these types of systems, and did not actually cater for the wide variety of systems encountered during the research.
- It was assumed that the contact persons would have a reasonably good knowledge of the abstraction systems. This was rarely the case.

4.2.2 Site Visits and Interviews

Due to the poor response to the detailed questionnaire, it was necessary to use alternate methods to gather detailed information about the systems. Therefore, where possible, the sites of the sand abstraction systems were visited. The purpose of these site visits was to:

- Interview designers, operators and / or owners of the systems. Aspects that were discussed during these interviews included:
    - ➢ purpose of the system e.g. community water supply, irrigation etc.,
    - ➢ system design and arrangement, including design principles, materials used, testing done during the design phase etc.,
    - ➢ sand properties,
    - ➢ water quality,
    - ➢ method of construction and problems experienced during construction,
    - ➢ operating history of the system, including general operation and maintenance aspects, system yield etc., and

- problems experienced with the system,

- Make observations regarding aspects such as system location, layout and design, as well as river morphology, land use and vegetation in the immediate vicinity of the system
- Take water samples for on-site and laboratory analysis (see Section 4.2.3).
- Take sand samples for on-site and laboratory analysis (see Section 4.2.4).

As far as possible, the sites of all systems located during Phase I of the survey were visited. Some of systems were, however, not visited. Reasons for this include:

- The geographic locations of the systems were such that it was prohibitively expensive to visit these sites e.g. systems located on the West Coast.
- Systems had been washed away and / or were no longer in operation.
- Owners of the systems refused permission for the research team to visit the sites.
- Appointments to visit systems were broken by the owners of the systems, and systems were too distant to allow for a second visit.
- During the period when systems were being visited the owners of the systems could not be contacted, or were not available.
- Owners and / or systems could not be located when site visits were being planned.

In most instances, due to the paucity of information available about them, systems that were not visited by the research team were excluded from the detailed survey.

In addition to conducting site visits, individuals and companies who had relatively extensive experience with sand abstraction systems were visited and interviewed. Aspects discussed during these interviews include those outlined above.

4.2.3 Water Sampling

At all sites, water samples (grab samples) were taken for water quality analysis and microbiological analysis. Water samples were taken for a number of reasons. These included:

- Comparison of the surface water to the abstracted water at each system. Such comparisons would in turn allow for:
  - The determination of the effective filtration achieved by using different types of sand abstraction systems.
  - Investigation into the possible problems of biologically induced fouling, as changes in various water quality parameters occurring as water

passes through an abstraction system could possibly be used as indicators of biofouling.

- ➢ Investigation into the problems of iron and / or manganese precipitation and the problems associated with high iron and / or manganese concentrations in some of the abstracted waters

- The determination of any correlation between surface water quality and the various problems experienced with sand abstraction systems. If such correlations could be established, then surface water quality could be used during the planning and design phase of sand abstraction systems as an indicator of the possible problems that could be experienced with a proposed system. This would in turn allow for adequate planning and design for the operation and maintenance of a system in order to manage potential problems, or even for the selection of an alternative abstraction method as more appropriate for the given river conditions.
- The determination of any correlation between abstracted water quality and problems experienced with abstraction systems, as well as any correlation between the change in water quality between the surface water and the abstracted water at any given system. If such correlations could be established, then surface and abstracted water quality could be used as indicators for the early detection of developing problems in existing sand abstraction systems.

Generally, two sets of water samples were taken at each site viz.

- samples of the surface water, and
- samples of the water abstracted through the sand abstraction system, prior to treatment.

Where possible and appropriate, each set of samples included:

- a sample for on-site water quality testing,
- an unpreserved sample for laboratory water quality testing,
- a preserved sample (preserved using nitric acid) for laboratory testing of iron and manganese content,
- a sample for microbiological analysis.

In some instances it was only possible to take one set of samples e.g. where rivers were surface dry, and/or the systems were not in operation. In other cases, where it was felt that useful information could be gleaned from additional testing, additional sets of samples were taken e.g. during backwashing of a system.

Details of water samples taken, water sample handling, reasons for the selection of the water sampling and handling methods, and discussion of some problems experienced with water sampling, are included in Appendix B.

4.2.4 Sand Sampling and On-Site Testing

It is broadly accepted that the properties of the sand in which a sand abstraction system is bedded have a significant effect on the performance of the system. It was therefore considered of particular importance that sand properties be established for each system, thus making it possible to determine any correlation between these properties and system performance. Sand samples were therefore taken at each site for laboratory testing.

In addition, as listed in Table 4, a number of hypotheses regarding sand properties were postulated during the course of this research. Sand sampling and testing were therefore also conducted to allow for testing of the validity of the various hypotheses postulated.

At each site, where conditions permitted, the following samples were taken:

- general samples,
- a sample for a directional permeability test, and
- a sample for a bulk density test.

Tests, using a hand held Dutch Cone Penetrometer (DCP), were also conducted at each site.

In a few cases not all the sand samples were taken, and in one instance no samples were taken. Conditions where this occurred included:

- where the river sand was too coarse to permit taking "contained" samples as required for the directional permeability sample and the bulk density test sample,
- where the river flow conditions were too high to allow for all the samples to be taken without undue risk of drowning (e.g. Save River), and
- where the risk of becoming crocodile dinner was particularly high (e.g. Limpopo River).

The sand sampling methods used are briefly discussed below. Details of the sand sampling methods, sand sample handling, reasons for the selection of the sand sampling and handling methods, and discussion of some problems experienced with sand sampling, are included in Appendix C.

4.2.4.1 General Sample

Using a hand augur, tube sampler or simple excavation, sand samples were taken for conducting sand grading analysis, particle density tests and permeability tests. Where possible sample were taken at different depths, so that some distinction between the sands located at different depths could be determined.

4.2.4.2 *Sampling for Directional Permeability Tests*

It was postulated that laboratory permeability test do not necessarily give a true representation of the in-situ permeability of the sand (Hypothesis 2.4). In order to compare laboratory permeability measurements to actual in-situ conditions, some measurement of in-situ permeability was required. Ideally in-situ permeability would be measured by means of pump testing. However, due to the number of sites included in this research pump testing was not a viable option, as it would have been prohibitively expensive.

In his book on sand storage dams, Wipplinger recommends the use of a device for taking "undisturbed" sand samples and then measuring the permeability of the sample without transferring the sample (Wipplinger, 1958). Permeability tests conducted using a device of this nature are advantageous as they can be considered to give a reasonable representation of the in-situ permeability of the sand.

Based on Wipplinger's device, a permeability sampling and test unit was made and used for obtaining some indication of in-situ permeability. This unit was called the "directional" permeability test unit as it can be used to take samples in a specific direction (vertical or horisontal) in the sand and thus test the permeability in that direction. Details of the device, and the use thereof are given in <u>*Appendix C.2*</u>.

Wherever possible directional permeability samples were taken below the water table, at the same surface depth at which the tube, augur or hand dug samples were taken.

4.2.4.3 *Sampling for Bulk Density Tests*

As discussed, it was postulated that the permeability of samples measured in the laboratory is not necessarily a true representation of the in-situ permeability, as the in-situ bulk density of the sand is not taken into account (Hypothesis 2.4). To determine the validity of this hypothesis, it was necessary to obtain some measurement of in-situ bulk density of the sand at the different sites.

Different methods for measuring in-situ density of sand, and problems and advantages associated with the different methods are discussed in <u>*Appendix C.3*</u>. For this study, a simple method, based on first principles, was adopted to measure the in-situ density of the sands. The method used is referred to as "the density ring". Wherever possible samples were taken below the water table, at the same surface depth at which directional permeability and the tube, augur or hand dug samples were taken.

4.2.4.4 *Dutch Cone Penetrometer (DCP)*

As stated previously, a measurement of the in-situ bulk density of the sands was required. A number of penetrometer-type tests have been used by engineers to determine various parameters of in-situ soils, including relative density. Cone penetrometer tests are, however, limited in accuracy, and it is recommended that they be used in conjunction with information from other methods and evaluations (Cernica, 1982). They are not recommended for cohesive soils, and are also not used in saturated and submerged conditions.

As the use of penetrometer tests to determine relative density of soil strata is an established practice, it was decided to conduct penetrometer tests at all sites in conjunction with the ring density tests. When commencing this research it was not known whether these tests would give an indication of relative density in saturated or submerged conditions. It was known that it would be likely that the test would not be effective in saturated or submerged conditions, as instantaneous shearing of the soil structure can occur and such conditions. The test would then not give any indication of the density of the soil.

The penetrometer tests were, however, included in the testing programme in order to determine whether, in riverbed conditions, there is any correlation between bulk density and/or permeability and the results of these tests. The tests are cheap and easy to conduct, and should such a correlation be shown, the implementation of such a test would be extremely valuable when conducting preliminary investigations for the installation of sand abstraction systems.

A hand held Dutch Cone Penetrometer (DCP) was used for the penetrometer tests. Details of the DCP and its use are given in *Appendix C.4*.

DCP tests were conducted at all sites, except in extremely pebbly material. The tests were started at the same surface depth at which the directional permeability, the ring density and the tube, augur or hand dug samples were taken.

4.2.5 Ulundi System: Pederson Device

In addition to the standard investigations that were conducted at all other sites, more detailed investigations into the possible problem of biofouling were conducted at the Ulundi sand abstraction system. As part of these more detailed investigations, Pederson devices and modified Pederson devices were built and installed in the abstraction screens of the Ulundi system.

Pederson devices are designed to allow for the growth of biofilm in a system on a substrate e.g. a glass slide, which can be removed from the system. A relatively undisturbed sample of biofilm can thus be obtained from a system, facilitating the investigation of the sessile, as opposed to the free floating, bacterial population in the system.

Three different types of devices were made and installed in the screens of the Ulundi abstraction system. These included:

- a slide unit,
- a screen section unit, and
- a screen section unit with sand.

Details of the devices used are given in *Appendix D*.

Three sets of units were installed in the abstraction screens of the Ulundi abstraction system. Two sets of units included slide units and screen units with no sand, whilst the third set included a screen unit without sand and one with sand. The sets of units were installed in the separate screens as far apart from each other as possible, at approximately 10 m into the screens from the screen outlets.

It was initially intended that the units be installed in the Ulundi abstraction system and sampled at a maximum of one-week intervals, thus allowing for monitoring of the progressive development of any biofilm. Access to the Ulundi system was, however, limited due to the extremely high rainfall experienced during the research period, and it was not possible to take samples from the units at regular intervals.

The units were installed in the system on 16 October 1998. They were left in the system until 24 April 1999, when access could once again be gained to the system. The units were then removed from the system and stored, with ice packs, in water taken from the system for transportation to the laboratories.

4.2.6 Water Quality Testing

The water samples taken from the systems included in the survey were analysed for a number of different water quality parameters. As discussed in Section 4.2.3, water quality was analysed in order to investigate several of the problems associated with sand abstraction systems and to determine whether any correlations exist between water quality and system performance. Parameters that could be used as possible indicators of biological fouling and iron or manganese related problems were therefore selected for analyses. Water quality parameters for which analyses were conducted are listed in *Appendix E*.

Both laboratory and on-site testing of water quality was conducted. All water quality laboratory testing was conducted by Waterlab Research (Pty) Ltd, Pretoria.

Ideally water samples should be delivered to a laboratory for testing as soon after sampling as possible. This would ensure that there are no, or minimal, changes to the water quality of the sample, through biological activity, oxidation etc. prior to testing.

Due to the remote location of a number of the sites visited, and the extended periods that the research team were in the field, it was not possible to deliver water samples to the water laboratory shortly after sampling. Samples were kept refrigerated (at 4°C as far as possible) and were shipped or delivered to the laboratory in ice packs generally within a week of sampling. There was still, however, concern that changes could have occurred to the water quality of the samples prior to laboratory testing. Two measures were therefore taken to assess whether any such changes in the water quality of the samples had occurred. These included:

- Preserving one set of samples with nitric acid. This would prevent changes from occurring in the total iron and manganese concentration of the samples. These preserved samples were analysed by Waterlab Research.
- Conducting on-site water quality testing.

Methods used for on-site water quality testing are discussed in Appendix E.1

4.2.7 Microbiological Analyses

As part of the investigations into biologically induced fouling, various microbiological analyses were conducted on the water samples taken from the abstraction systems. Microcheck Laboratories CC conducted all microbiological analyses.

Details of the microbiological analyses conducted are discussed in Chapter 3 of Microcheck's report "*Microbiological Analyses of samples from Sand Abstraction Systems*", and is included as Appendix F.1 to this report. Microbiological analyses conducted included the following:

4.2.7.1 *Total Bacterial Counts in Water Samples.*

Total bacterial counts were conducted on all water samples to determine the planktonic (free floating) bacterial population in the samples. Although biofouling is caused by sessile populations of bacteria i.e. bacteria attached to a surface as biofilm, it was generally not possible to obtain samples of biofilm from any of the abstraction systems. It was therefore necessary to determine the planktonic bacterial populations in the abstraction systems, as this can give some indication of the sessile bacterial population in a system. Nutrient agar was used for the total bacterial counts. This medium is used for the enumeration, isolation and cultivation of less fastidious micro-organisms.

4.2.7.2 *Enumeration of Sulphate Reducing Bacteria (SRB)*

As previously discussed, Sulphate Reducing Bacteria (SRB) are commonly associated with biofouling and biologically induced corrosion. In order to identify whether SRB were contributing to fouling of abstraction systems, enumeration of SRB was initially included in the microbiological testing regime. Testing for SRB was, however, discontinued, as initial testing of samples from a number of systems indicated extremely low or zero counts of SRB. The Modified IS medium was used. This medium is used for the isolation and enumeration of sulphate reducing bacteria.

4.2.7.3 *Scanning Electron Microscopy (SEM)*

Scanning Electron Microscopy (SEM) was conducted on water samples from the Ulundi and Oshoek systems, as well as on the slides taken from the Pederson device installed in the Ulundi abstraction system: Electron microscopy was not performed on the samples from the Ulundi and Nqutu systems containing large agglomerations of biofilm, due to the density of the material present in the sample. The personnel at the electron microscopy unit advised us that in order to be able to take any meaningful photographs of the material, it would have to be diluted several times. This could render unrepresentative results. SEM was not performed on other samples due to the high cost.

4.2.7.4 *Light Microscopy*

Light microscopy was performed on the samples that came from systems appearing to have problems with deposits and/or slime formation. Wet preparations as well as Gram staining was performed on these samples.

4.2.7.5 *DAPI Staining*

The slides from the Pederson device installed in the Ulundi abstraction system were stained with DAPI to detect bacterial cells on the slides.

4.2.7.6 *Culturing of Iron Reducing / Oxidising Bacteria:*

Iron reducing / oxidising bacteria are commonly associated with biofouling. In addition, tests conducted on samples from the Ulundi system, prior to the commencement of this research, showed the presence of iron reducing bacteria. Culturing of iron reducing / oxidising bacteria was therefore initially performed on some of the water samples.

Several media were used in attempts to culture and/or isolate iron bacteria, i.e.: Iron-oxidising medium, Iron bacteria isolation medium, and Iron sulphite medium. Initial attempts were, however, unsuccessful. Due to the lack of success experienced in culturing iron bacteria, this testing was discontinued.

It must, however, be noted that the failure to culture iron bacteria did not, necessarily mean that there were no iron bacteria present in the samples. In the past a lot of difficulty has been experienced in culturing iron bacteria, probably due to the fastidious nature of these bacteria. An example of similar problems was communicated to Ms Wagner of Microcheck by researchers from SASOL who also had no success in culturing these organisms. It also has been noted that media for the culturing of micro-organisms usually have an efficiency of less than 10% for the recovery of bacteria from their natural environment (Steyn and Cloete, 1989).

4.2.8 Sand Testing

Testing of sand samples was conducted to determine various parameters of the sand from the different sites. Sand testing was conducted by various soils laboratories as well as by the research team.

4.2.8.1 Soils Laboratory

Testing conducted at solids laboratories included:

- *Sand grading analyses*

  It stands to reason that the grading of a sand will affect the permeability of the sand, and hence the performance of a sand abstraction system. Parameters determined from sand grading analysis are traditionally used for the calculation of the theoretical permeability of sand.

  Sand grading analyses were therefore conducted on all sand samples, with the exception of samples taken using the density ring and site permeameter. It was assumed that the gradings of these samples would be similar to those of the samples taken using the short tube sampler or hand dug at the surface of the riverbed. Grading analyses were conducted on samples taken at different depths in the sand bed to determine whether there were any changes in the sand properties through the bed.

- *Specific gravity of the entire sample:*

  Specific gravity (SG) analyses were conducted on the entire samples. The SG was determined, together with the bulk density of the sand, to be used for the determination of the void ratio of the sand.

  Although not normally used for the determination of the theoretical permeability of the sand, it was hypothesised that the SG and bulk density of the sand, or equivalently the void ratio of the sand, would have an effect on the permeability of the sand. The SG results were therefore used in the analyses conducted to determine correlations between sand parameters and permeability of the sand.

- *Specific gravity on fractions of the sample*

  Initial grading analyses conducted on samples taken at the first sites visited indicated that at some sites there was an increase in fines content of the sand with increasing depth in the sand bed. Considering the normal settlement of sand in rivers, this is anomalous. It was therefore decided to conduct specific gravity (SG) analyses on several of the sieved fractions of the samples e.g. the SG of the fraction of sample retained on the 1.18 mm sieve. Specifically, the SG of those fractions containing the D_{80}, D_{50}, D_{10} and D_2 particle sizes was determined (where the D_{80} is the particle size corresponding with 80% passing on the grading curve, the D_{50} is the particle size corresponding with 50% passing on the grading curve etc.).

These tests were conducted to determine whether the SG of the finer fraction was greater than that of the coarser fraction of the sample. If this was found to be true, this could, to some extent, explain the anomaly of the accumulation of fines at depth. The fraction SG's could also be used in the analysis to determine correlations between sand parameters and permeability of the sand.

All testing conducted at soils laboratories was conducted according to SABS standard methods. Soils laboratories where testing was conducted included:

- Matrolab, Pretoria
- Department of Water Affairs and Forestry Soils Laboratory, Pretoria
- Letaba Lab, White River
- SNALab, Nelspruit

4.2.8.2 *Bulk Density Tests*

The in-situ bulk density of the sands was determined using the samples taken using the density ring. Bulk densities were measured for use in the determination of the void ratio of the sand. The bulk densities determined were also used during the permeability tests, as discussed below. The method used to determine the bulk densities of samples is discussed in *Appendix G.1*.

4.2.8.3 *Permeability Tests*

Constant head permeability tests were conducted on all samples taken using the directional permeability unit (as described in *Appendix C.2*) and on at least one representative sample (typically the long tube sample) from each system visited using a constant head permeameter. At least two constant head permeability tests were done for each sample tested. These included:

- *Permeability test done at "normal testing" density*
  The first permeability test conducted on each sample was done with the sample at what has been referred to as "normal testing" density. By "normal testing" density it is meant the density at which the sample would naturally settle in the permeameter without any compaction. This is the

manner in which constant head permeability tests are normally conducted, hence the name used: "normal testing" density.

- *Permeability test done at "site" density*
  After completing the permeability test at "normal testing" density, the sample was tested at "site" density. The sample is compacted such that its bulk density is equivalent to that determined for the in situ sand (determined using the "density ring" sampler).

Permeability tests were conducted at the two densities in order to establish the effect of the bulk density of the sand on the permeability, and to determine whether it is necessary to alter normal testing practice, preparing the sample such that its bulk density in the permeameter is equivalent to that of the in situ sand.

In some instances additional permeability tests were done. Where it was evident that fines were accumulating in layers in the sample, or the sample became more compacted during the course of the test, then the sample was backwashed for an extended period. The sample was backwashed by reversing the flow through the system. After backwashing of the sample, the permeability tests were repeated. This allowed for determination of the effect of backwashing on the permeability of the sample.

Permeability testing procedures are described in Appendix G.2.

4.2.8.4 *Particle Shape*

Photographs were taken of representative samples from each system and observations of the particle shape and general appearance of the sand were made.

Particle shape will affect the packing of the sand, with more angular particles generally being more loosely packed, while more rounded particles will be more tightly packed. Flat or flaky particles will affect the permeability of the sand in that the permeability in one direction (usually the horizontal direction, depending on the orientation of the particles) will generally be much higher than that in another direction.

Observations of particle shapes were made in order to determine whether the general particle shape of sand has an impact on the performance of a sand abstraction system. In addition, if general visual observations of dry sand can be used as an indicator of the potential success or failure, this would be extremely useful during initial site investigations being conducted for the development of a new sand abstraction system.

The manner in which the particle shape and general appearance of the sand were defined is given in Appendix G.3.

Observations of particle shapes are given together with photographs of the respective sand, the permeability and in-situ bulk density of the sand, and the problem ratings (as described in Section 4.3.1) for the systems installed in the sand. This can be used as a field guide for examining sands during investigations for proposed abstraction systems, and can be used as an initial indicator of the potential performance of an abstraction system installed in the sand being examined.

4.2.9 Geographical and Geological Aspects

Geographical and geological aspects of the catchment upstream of a sand abstraction system would probably have an effect on the performance of a system. This is due to the fact that water quality and sand parameters are determined by the geology and geography of the catchment. Aspects that could affect system performance include:

- *General catchment geology*

  All sediment in a river is derived from the base rock in that catchment. The base geology of a catchment will therefore largely determine the nature of the sand in rivers in that catchment. Parameters of the sand that could be affected by the geology include:

  - particle shape,
  - particle density,
  - particle size and sand grading curves,
  - mineralogy.

  The base geology of a catchment will also affect the water quality of a river.

  Other factors that would impact on the nature of rivers in a catchment are in turn influenced to some extent by the base geology of an area e.g. rainfall-runoff response, natural vegetation cover and land use activities.

- *River morphology*

  River morphology, or the shape and slope of the river and its catchment, will influence the development of sand in a catchment as well as the manner in which the sand is deposited in the riverbed. Examples of how river morphology could affect sand in rivers include:

  - sands developed in steep valleys will differ from those developed in flat broad plains, and
  - the deposition of sand in meandering rivers would differ from the deposition of sand in rivers with a relatively straight flow path.

- *Land use*

  Land use will affect both the development of sand in a catchment, as well as the water quality of a river. This would include aspects such as agricultural, urban and forestry developments in the catchment, and the development of impoundments on rivers.

Other geographical parameters that could possibly be related to the performance of a sand abstraction system through their impact on the river catchment include:

- rainfall, runoff and evaporation parameters,
- soils,
- sediment yield,
- natural vegetation

Considering the above, geographical and geological data about the river catchments upstream of the abstraction systems was collected from various sources.

4.2.9.1 *1:50 000 Topographical Maps*

Data about the reach of river 50 km upstream of the system, (or to the head of the catchment, whichever was the shorter) and the associated catchment, was gathered from 1:50 000 topographical maps. Types of data gathered from these maps included river morphology, land use and settlements.

A 50 km reach was studied, as it is probable that the effects of land-use etc. in more distant parts of the catchment would have minimal effect on the performance of the system. In instances where the catchment is extremely large e.g. the Limpopo and Olifants Rivers (Northern Province), the entire catchment for the 50km reach was not studied, but the area that was assessed to have the most impact on the system was considered.

Details of the data extracted from the 1:50 000 maps are given in <u>*Appendix H.1*</u>.

4.2.9.2 *"Surface Water Resources of South Africa 1990 – Map Books"*

Data about the entire system catchment was extracted from the maps in *"Surface Water Resources of South Africa 1990. Book of Maps"*, (Ref. 0). Types of data gathered from these maps included land cover, precipitation and sediment parameters, geology and soil types. Generally the data was extracted as percentage areas of each system catchment falling within a specific data category.

Unfortunately these maps do not cover Zimbabwe or Botswana. It was therefore not possible to collect the relevant data about the Zimbabwe systems, nor about the entire catchments of the systems located on the Limpopo River.

Details of the data extracted from the maps of *"Surface Water Resources of South Africa 1990. Book of Maps"* are given in Appendix H.2.

4.2.9.3 *Geological Maps*

As no geological information could be gathered for the Zimbabwe systems from the *"Surface Water Resources of South Africa 1990"* maps, geological data was also extracted from geological maps covering all of Southern Africa. The geological map used was *"Figure 167 – Geological Map of Southern Africa (Scale: 1:6 000 000)"* from A.B.A. Brink's *"Engineering Geology of Southern Africa"* (Ref. 0). The stratigraphic terminology used in this map is as recommended by the South African Committee on Stratigraphy, 1977). This map was used as opposed to standard 1:250 000 geological maps as it was the level of complexity of the geology shown on the 1:250 000 maps was too great to allow for interpretation of the data with respect to derived sand types and sand abstraction system performance. The stratigraphy shown on Brink's map is a simplified version of that shown on the 1:250 000 maps.

Percentage areas of each different type of stratigraphic formation in each system catchment were determined. This data was then interpreted to give a general description of the derived sand that could be expected in each catchment.

An example of a typical geological map extracted from Brink's map, with the catchment defined, is shown in Appendix H.3.

4.3 DATA ANALYSIS

4.3.1 Rating of Abstraction Systems

Following the site visits and collection of data regarding the performance of the abstraction systems, each system was given a rating relative to the problem of low or reduced yield from the system. The systems were rated from 0 to 5, where 0 indicated no problems of low yield experienced and 5 indicated severe problems. The systems were also given a rating relative to the problems of possible clogging of the sand, possible microbiological fouling of the system and problems related to iron and manganese (e.g. high iron concentrations in the abstracted water, precipitation of iron in the system).

It must be noted that the ratings given each system are relatively subjective, being based on the understanding of the research team of the various systems and the problems associated with them.

Ratings for each system were plotted against the various parameters for each system; including water quality, sand, geological and geographical parameters; in order to determine the relationship of each parameter to system performance, or to the problems associated with abstraction systems. Correlations between parameters and system performance were determined visually using these plots.

4.3.2 Correlation of Sand Parameters with Laboratory Measured Permeability

Correlation analyses were conducted to determine the relationship between sand parameters and laboratory-measured permeability of sand samples. Sand parameters considered in the analysis included:

- Sand grading analysis.

  The sand grading analyses were included in the correlation analyses by incorporating the various D sizes of the samples in the equation. The D size is the particle size at a given percentage passing on the grading curve e.g. the D_2 is the particle size corresponding with 2% passing on the grading curve. The D sizes were calculated by means of linear interpolation of the $\log_e$ of the particle size between the percentages passing measured for the standard sieve sizes.

- Bulk site density.

  The correlation analysis was done to develop an equation for the theoretical calculation of permeability, and to determine whether the inclusion of the bulk density of the sand as a parameter in the equation would give better correlation than the existing equations used to calculate permeability.

Correlation coefficients were determined by comparing the calculated sand permeability, using the developed equations, with the measured permeability of the different sands. These were compared with the correlation coefficients obtained when comparing the calculated sand permeability, using existing equations, with the measured permeability of the sands.

The existing equation used for calculating permeability was:

$$k = \frac{\left(e^{7.96} \times D_{50}^{1.87}\right)}{\left(1 + \ln\left(\frac{D_{60}}{D_{10}}\right)\right)}$$

The results of the analyses are shown in *Appendix M.3* of this report.

5 SCALE MODEL TESTING

A scale model test unit to simulate a typical horisontal well point was constructed to evaluate the impacts of specific variables on the performance of the well point. The aims, methodology and the test results are discussed in more detail in the following sections.

5.1 AIMS OF SCALE MODEL TESTING

The aims of the scale model testing were:

- To determine the flow patterns and head loss through the sand bed and well screens in a horizontal well point type abstraction system.
- To compare the performance of two different types of well screens, namely:
  - Plastic moulded Soloform screen with wedge shaped slots, 0.25 mm slot size (2.66% open area, 150 mm internal ø.
  - Stainless steel wedge wire screen, with profile wire head width 1.5 mm, slot size 0.25 mm.
- To determine whether the different types of screens affected the flow paths and head loss through the sand.
- To determine the effect of developing the sand around the screen on system performance.
- To determine the effect of a small percentage of clay in the sand on the performance of the system.
- To determine the effect of the sand profile relative to the screen on the performance of the system.

5.2 METHODOLOGY

5.2.1 Test Unit

Details of the layout of the scale model test unit are shown in Figure 2.

Essentially the test unit consisted of a perspex box, 590 mm wide x 220 mm deep x 960 mm high. The unit incorporated:

- A half section of well screen, installed at the bottom of the unit against the sidewall. Outlets and valves for a scour drain, air release valve and outlet were incorporated in the side of the unit from the inside of the screen section.
- Openings for piezometer tubes with 5 mm ø piezometer tubes. The piezometer tubes were installed in a grid pattern in the front face and side of the unit. Smaller diameter tubes were not used as suitable fittings for the connection of the tubes into the walls of the unit could not be obtained.
- An overflow weir at the top of the unit. This was incorporated so that a constant head could be maintained in the unit at all times.

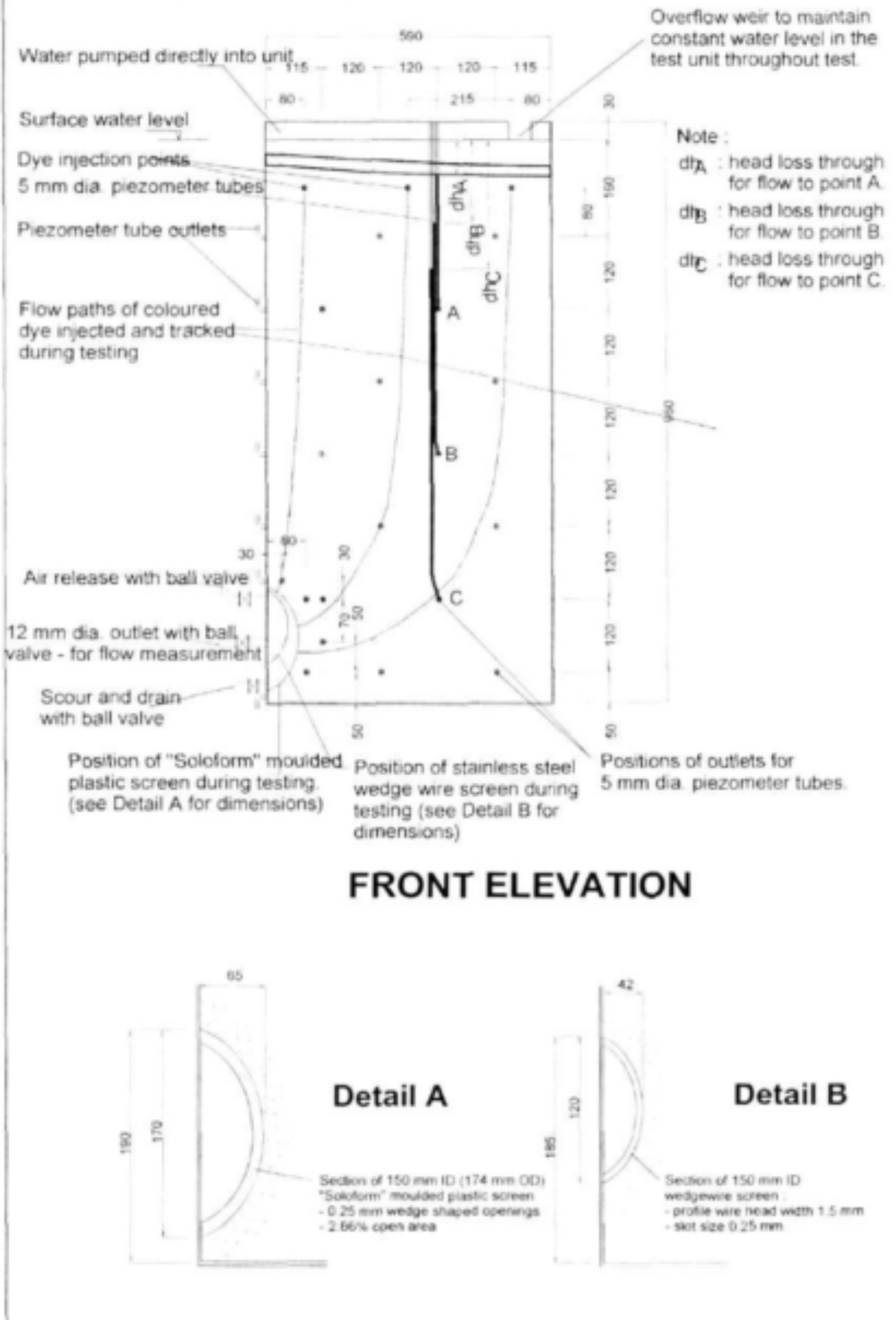

Figure 2: Scale Model Test Unit
Sheet 1 of 2

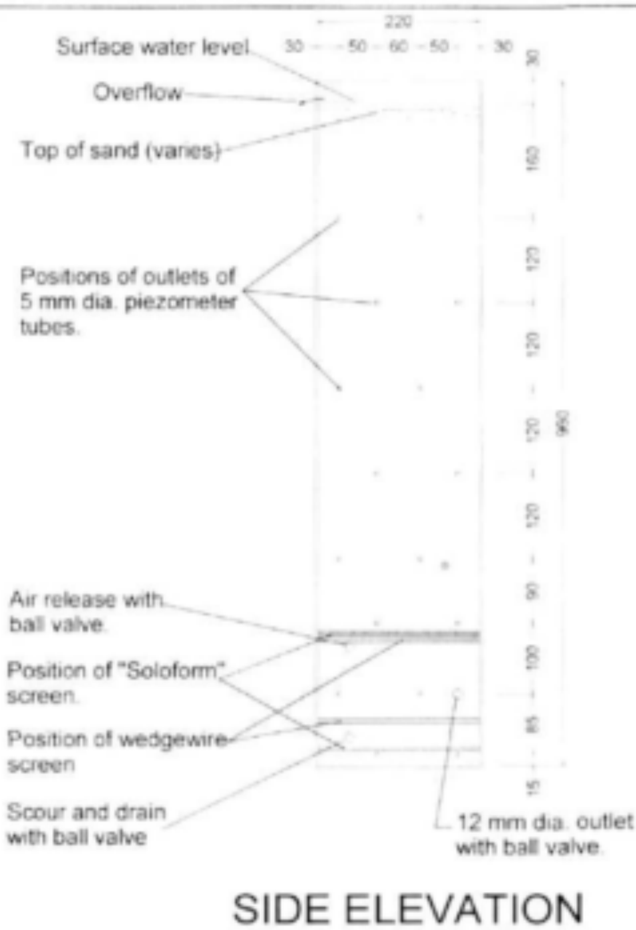

Figure 2: Scale Model Test Unit
Sheet 2 of 2

5.2.2 Testing Method

The method of testing was carried out as follows:

- The unit was filled with sand. Throughout the process of filling the sand was kept submerged to prevent air from being trapped in the sand.
- Water was pumped into the top of the unit, being allowed to overflow the weir to maintain a constant head in the sand. Water flowed out of the unit through the outlet inside the well screen section. Trapped air was released through the air release valve installed inside the screen section.
- The unit was left for some time to allow for the stabilisation of the flow through the sand bed. The system was considered stable when the water levels in the piezometer tubes remained constant.

- The water levels in all the piezometer tubes were then read. This gives a measurement of the head loss through the sand from the surface to the depth of the piezometer tube.
- Coloured dye was then injected into the sand bed, at three points across the sand bed. The time of flow and position of the flow path of the coloured dye was tracked and recorded.
- Five main variables were altered through the testing regime. These included:
    - Screen type: All tests changing the other variables were conducted using both the Soloform and wedge wire screens.
    - Sand: Sand from two systems was used in the testing. Sand from the Nqutu system (system 31) and the Ulundi system (system 34) were tested. All tests changing the other variables were conducted using both sands. Sand from these two particular system was used for the following reasons:
        - There is large amount of information available on both systems, including details of design procedures, construction methods and operational history.
        - The systems are in adjacent catchments, are of similar design and were designed based on the same principals. The Nqutu system performs extremely well, with problems of low yield only occurring 23 years after installation, while the Ulundi system has never performed adequately. It was thought that use of the sand from these two systems could possibly provide some insight into the reasons for the difference in performance of the two systems.
    - Development of the sand: Tests were conducted without developing the sand, and then repeated with developing the sand.
    - Addition of clay to the system: Some tests were conducted after a small quantity of fines was added to the system.
    - Surface profile: Tests were conducted varying the surface profile from level, to sloping up away from the screen section, to sloping down away from the screen section. This was done in order to determine whether the profile of the surface of the sand bed relative to the screen would affect system performance.

In addition to changing these variables, the flow rate was changed with tests being conducted at high and low flow rates. The flow rates were adjusted by throttling the outlet valve.

In total, 99 tests were conducted. A breakdown of the variables tested is shown in Table 5. An index of all tests conducted is included in *Appendix P*.

Table 5 Variables in Tests Conducted in Scale Model Unit

Test Parameters / Variables			Number of Tests	Total Number of Tests
Sand	Ulundi		54	99
	Nqutu		45	
Screen	Soloform		57	
	Johnson's		42	
Development of sand by backwashing system	Not Developed		33	
	Developed		66	
Clay / silt added	Yes		7	
	No		92	
Sand surface profile relative to screen	Level		36	
	Sloping	Up from screen	32	
		Down from Screen	31	

5.3 TEST RESULTS

Overall a total of 99 tests were conducted in the scale model test unit. A typical test in progress is shown below in Plate 1. Details of the scale model test results are included in the electronic Appendix e.H. A summary of the test results is shown in Table 6.

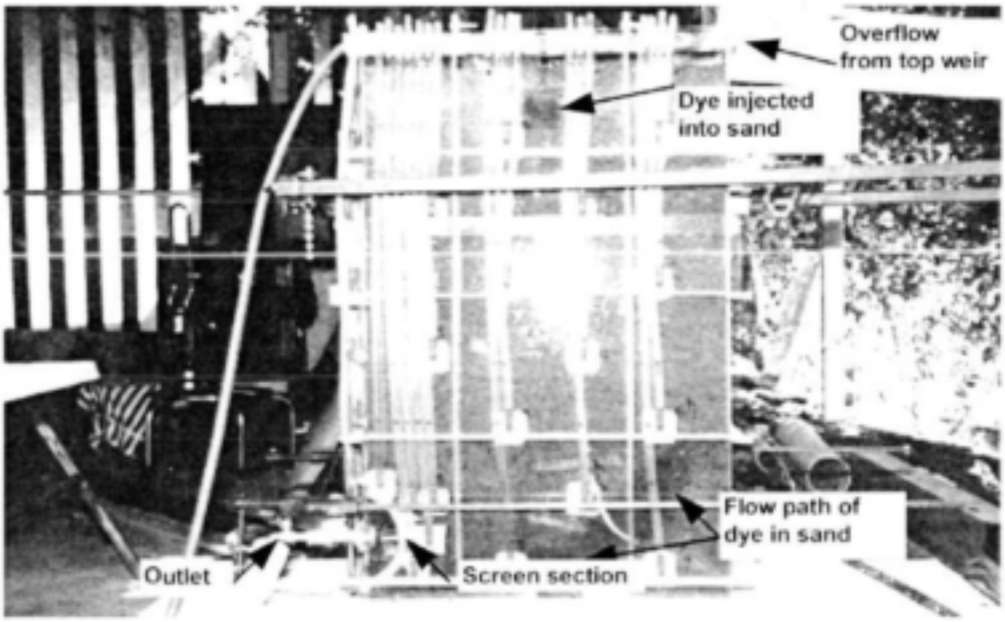

Plate 1: Flow Paths in Scale Model Test Unit

Some important results from these tests include the following:

- The average permeability for a specific sand is higher when using stainless steel wedge-wire screens than when using the plastic moulded Soloform screens (same slot size). The effect of the screen appears to be more marked with sands of higher permeability. This cannot, however, be stated categorically without testing additional sand samples. A difference of as much as 26% in the permeability of the sands was measured when using the two different screens.

- Normally, by developing the sand, there was an increase in the permeability of about 22% to 39%. When developing the sand in the "Nqutu Soloform" tests, there was not, however, always an increase in the permeability of the sand. The effects of developing on the sand can be seen in Plate 2. This photograph was taken shortly after backwashing or developing of the system was started. It can be seen that the fines have been washed out of the wedge of sand immediately over the screen.
- Considering the profile of the surface of the sand relative to the screen, in most cases, the permeability was highest when the surface was sloping up, away from the screen (i.e. shallowest part of sand bed over the screen), and lowest when the surface was sloping down away from the screen (i.e. deepest part of sand bed over the screen).
- The addition of a small amount of clay to the sand resulted in an average reduction of the permeability of 23%. This indicates the impact the fines fraction of a sand has on its permeability. It is therefore very important to consider the fines fraction when designing a system.
- The head loss across the screen was measured during the testing. This was done by monitoring and recording the water levels of piezometer tubes installed on either side of the screen. To compare the head loss at different flow rates, the head loss was divided by the square of the flow rate. Ideally the velocity should be used, but the percentage open area of both screens was not known. The $\frac{dh}{Q^2}$ varied markedly for any one particular set of tests conducted for a given screen type and a specific sand. The average $\frac{dh}{Q^2}$ for the tests were:

  - Nqutu Soloform 10
  - Nqutu Johnson's 11
  - Ulundi Soloform 16
  - Ulundi Johnson's 19

  Considering these results, it appears that the head loss through the screen is more dependent on the sand, rather than the screen type.

Table 6 Summary of Results of Scale Model Unit Tests

Test	Average for Tests		
		Permeability	
	Dry Density (kg/m^3)	Gross Average Permeability (mm/s)	Gross Square Mean Root Permeability (mm/s)
All **"Nqutu Soloform"** Tests	1407	4.87	4.69
Not Developed	1409	5.06	4.96
Developed	1406	4.76	4.54
Not Developed - Level Surface	1376	5.26	5.14
Not Developed - Surface Sloping Up from Screen	1424	5.20	5.11
Not Developed - Surface Sloping Down from Screen	1428	4.72	4.62
Developed - Level Surface	1406	4.55	4.35
Developed - Surface Sloping Up from Screen	1409	5.37	5.15
Developed - Surface Sloping Down from Screen	1398	4.41	4.17
All **"Nqutu Johnson's"** Tests	1406	6.14	5.68
Not Developed	1383	5.04	4.77
Developed	1418	7.03	6.54
Not Developed - Level Surface	1321	4.45	3.97
Not Developed - Surface Sloping Up from Screen	1430	4.51	4.33
Not Developed - Surface Sloping Down from Screen	1399	5.26	5.02
Developed - Level Surface	1395	7.88	6.90
Developed - Surface Sloping Up from Screen	1419	7.06	6.82
Developed - Surface Sloping Down from Screen	1439	5.88	5.71
All **"Ulundi Soloform"** Tests	1408	3.39	2.89
Not Developed	1396	2.97	2.92
Developed	1415	3.62	2.92
Not Developed - Level Surface	1367	3.09	3.06
Not Developed - Surface Sloping Up from Screen	1424	2.87	2.82
Not Developed - Surface Sloping Down from Screen	1418	2.87	2.80
Developed - Level Surface	1436	3.40	2.87
Developed - Surface Sloping Up from Screen	1402	3.97	2.92
Developed - Surface Sloping Down from Screen	1404	3.64	3.04
All **"Ulundi Johnson's"** Tests	1478	3.43	2.91
Not Developed	1454	2.97	3.00
Developed	1485	3.80	3.28
Developed - Clay / silt added	1483	2.94	1.95
Not Developed - Level Surface	1439	3.03	2.90
Not Developed - Surface Sloping Up from Screen	1474	3.09	3.80
Not Developed - Surface Sloping Down from Screen	1449	2.84	2.71
Developed - Level Surface	1501	4.58	4.20
Developed - Surface Sloping Up from Screen	1467	3.56	3.09
Developed - Surface Sloping Down from Screen	1489	3.25	2.55
Developed - Clay or silt added - Level Surface	1493	3.28	1.89
Developed - Clay or silt added - Surface Sloping Up from Screen	1483	2.99	2.13
Developed - Clay or silt added - Surface Sloping Down from Screen	1484	2.90	1.77

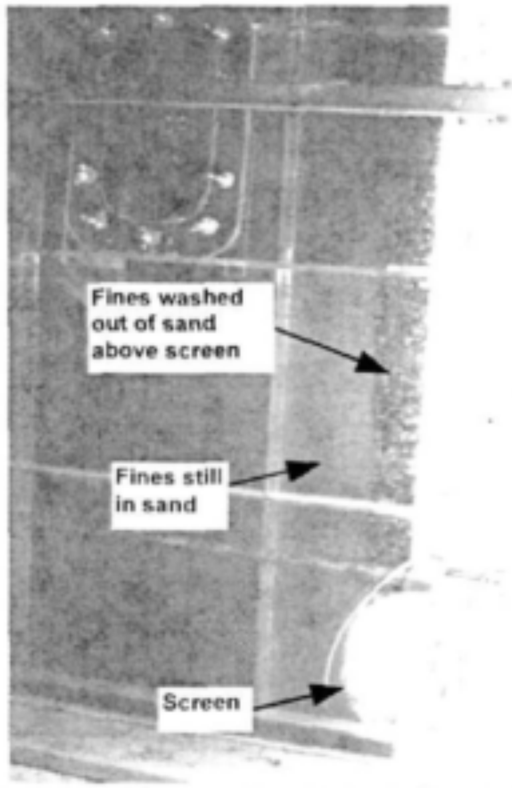

Plate 2: Effect of Backwashing in Scale Model Test Unit

- The flow paths were plotted for all tests. For similar tests using different screens, it was found that the flow paths through the sand differed. An example of this is shown in the following graphs in Figure 3. This is an indication that the screen type does have an impact on the flow through the entire sand bed.

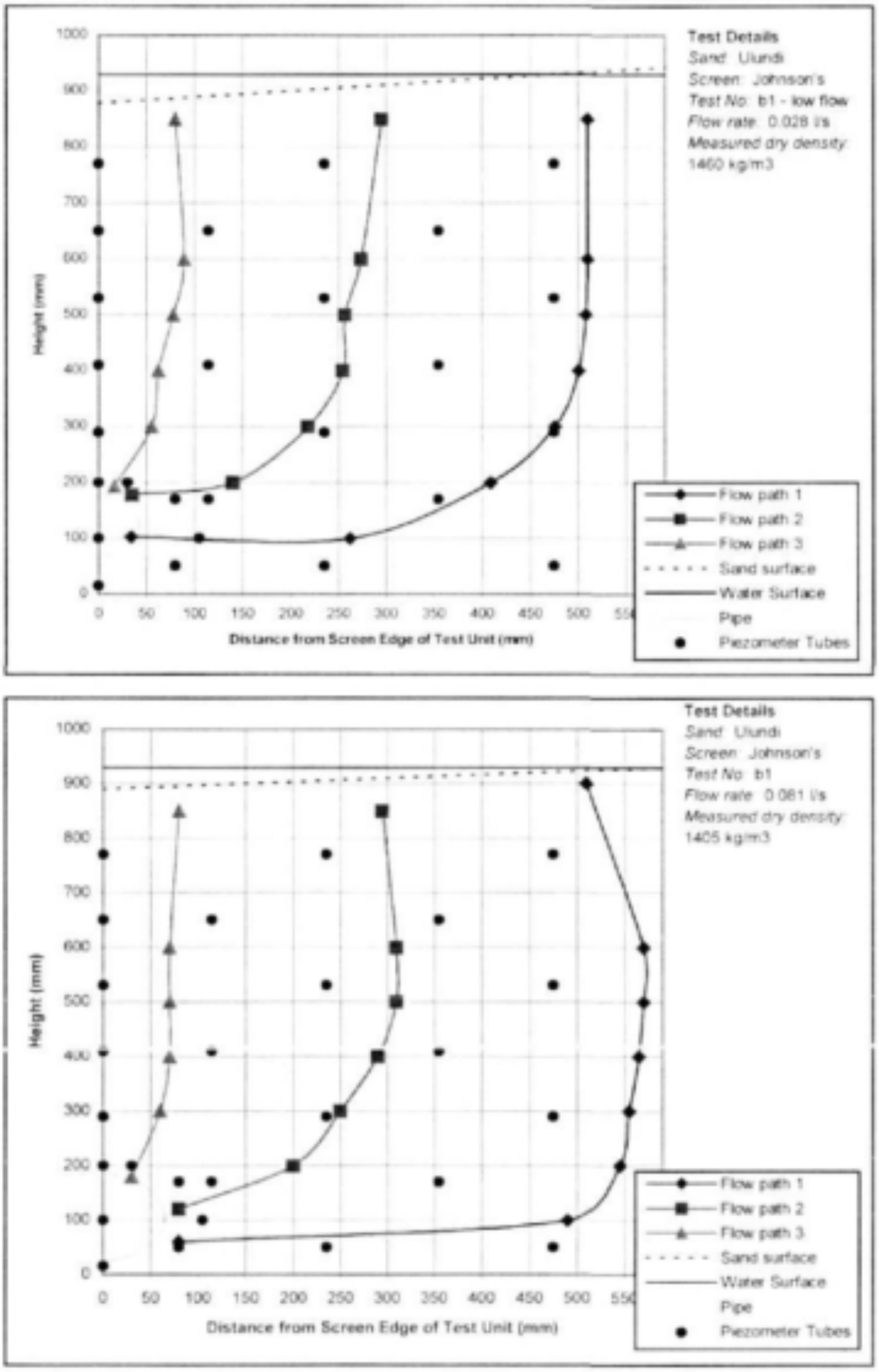

Figure 3: Examples of Flow Paths, Scale Model Tests

6 SURVEY OF SAND ABSTRACTION SYSTEMS: DATA AND FINDINGS

6.1 SURVEY – PHASE I

A total of 745 survey questionnaires were distributed to relevant parties in the water sector in Southern Africa. The initial response to the surveys is shown in Table 7.

Table 7 Response to Survey - Phase I

	Number	Percentage
Questionnaires distributed	745	100%
Questionnaires returned	130	17.4% response rate
Questionnaires giving information about an abstraction system	51	39.2% of questionnaires returned
Actual number of abstraction systems found from survey	34	66.7% of questionnaires indicating knowledge of an abstraction system

6.2 SURVEY – PHASE II

In addition to those systems found through Phase I of the survey, another 33 systems were found during the course of the second phase of the investigations, giving a total of 67 systems that were found. This is only including those systems of which the existence, either past or present, could be confirmed. Numerous rumours of other systems were also "collected" during the course of the research, but if these could not be confirmed they have not been reported on.

6.2.1 Systems not Visited

Of the systems found, 28 systems were not visited. Reasons for not visiting the systems included the following:

- The system no longer existed, having been destroyed in floods, or having been replaced by an alternative system.
- The system was no longer utilised. These were generally systems that were extremely problematic.
- The systems had been installed for emergency water supplies during severe drought periods and had then been abandoned.
- The owners of the systems could not be contacted, or would not permit the research team to visit the system.
- Systems were too remote to be visited within the budget available to the research team.
- Responses to the survey were received after all site visits were complete. Some responses to the survey were received up to three years after the initial surveys were distributed.

Where possible, people were interviewed to collect information about the systems that were not visited. This included interviews with the design engineers and operating authorities. Alternatively information was gathered through the distribution of a detailed questionnaire. Details of the systems not visited are included in *Appendix K*.

The geographical distribution of the location of the systems was as follows:

- Zimbabwe: 8
- Botswana: 1
- Swaziland: 1 (scheme including a number of systems)
- Lesotho: 1
- South Africa: 18, located in the following regions:
  - Northern Province: 8
  - Northern Cape: 3
  - Free State: 1
  - KwaZulu-Natal: 6

In discussions with a number of people systems in Mpumalanga were mentioned, and information promised. Despite follow up on these discussions, specific details about systems in Mpumalanga could not be obtained.

6.2.2 Systems Visited

A total of 39 systems were visited during the course of the research. Details of each system visited are given in the System Information Sheets included in *Appendix J*. Where information was available it has been included in these system information sheets. Details discussed for each system include the following:

- Locality and catchment maps.
- Details about the system location, system owner and source of information.
- Purpose of the system.
- Testing and investigations during the design and feasibility phases.
- Design procedures.
- General description of the system.
- The construction methods used.
- The operational history of the system, including problems experienced.
- Remedial measures taken to improve the performance of the system.
- Photographs and drawings or sketches of the system.

A summary of the details of the systems visited is given in Table 8.

Table 8 Systems Visited – Summary Information

System Number	System Name	River	Country	Province	Purpose	Type of system	Design Capacity (l/sec)	Problems of Low Yield	Problems Associated with Iron or Manganese	Problems with Flood Damage
1	Dysselsdorp	Olifants	South Africa	Western Cape	Domestic water supply	Vertical well point	10.8	No	No	Yes
2	Laingsburg 1	Wilgehout	South Africa	Western Cape	Domestic water supply	Caisson & horizontal collector channel	12	Yes	No	No
3	Laingsburg 2	Buffels	South Africa	Western Cape	Domestic water supply	Caissons	22	No	No	No
4	Melkbosstrand	Sout	South Africa	Western Cape	Irrigation - golf course	Caisson & horizontal well screen	10	No	No	No
5	Fox Farm	Caledon	South Africa	Free State	Irrigation & farm domestic water supply	Vertical well points	35 per well point	Yes	Yes	Yes
6	Peka	Caledon	Lesotho		Domestic water supply	Bank of vertical well points	Unknown	Yes	Yes	No
7	Hlotse	Hlotse	Lesotho		Domestic water supply	Bank of vertical well points	3.89 for one well point	Yes	Yes	No
8	Teyateyaneng	Puthiatsana	Lesotho		Domestic water supply	Bank of vertical well points	Unknown	Yes	Yes	Yes
10	London Catholic Mission	Molomathlapi Tributary	South Africa	Northern Province	Domestic water supply	Caisson	Unknown	No	No	No
11	Giyani	Klein Letaba	South Africa	Northern Province	Domestic water supply	Caisson & horizontal well screen	20	No	No	No
12	Bothashoek	Steelpoort	South Africa	Northern Province	Domestic water supply	Caisson	37.5	No	No	No

Table 8 Systems Visited – Summary Information (cont.)

System Number	System Name	River	Country	Province	Purpose	Type of system	Design Capacity (l/sec)	Problems of Low Yield	Problems Associated with Iron or Manganese	Problems with Flood Damage
13	Messina	Limpopo	South Africa	Northern Province	Domestic water supply	Vertical well points	110 to 340	Yes	No	Yes
14	Chikwarakwara	Limpopo	Zimbabwe	Masvingo	Irrigation	Vertical well points	22.2	Yes	No	No
15	Nottingham Estates	Limpopo	Zimbabwe	Matabeleland South	Irrigation & farm domestic water supply	Bank of vertical well points	166.7	Yes	Yes	Yes
16	Chisumbanje	Save	Zimbabwe	Masvingo	Irrigation & farm domestic water supply	Bank of vertical well points	1 020	No	No	Yes
17	Shashe	Shashe	Zimbabwe	Matabeleland South	Irrigation	Bank of vertical well points	38.2	No	No	No
18	Whuwana	Manzanyama	Zimbabwe	Matabeleland	Irrigation - market gardens	Horizontal well screen - hand pumped	hand pump	No	No	No
19	Shashani	Shashane	Zimbabwe	Matabeleland South	Domestic water supply - Hospital	Bank of vertical well points	4.2	Yes	No	No
20	Mambali	Shashe	Zimbabwe	Matabeleland South	Irrigation	Bank of vertical well points	40	No	No	No
21	Shangani	Shangani	Zimbabwe	Midlands	Irrigation - market gardens	Horizontal well screen - hand pumped	hand pump	No	No	No
22	Umgeni Water - Mtwalume	Mtwalume	South Africa	KwaZulu-Natal South Coast	Domestic water supply	Bank of horizontal well screens	28.9	Yes	Yes	No
23	Umzinto	Mzinto	South Africa	KwaZulu-Natal South Coast	Domestic water supply	Bank of horizontal well screens	69.4	Yes	Yes	No

Table 8   Systems Visited – Summary Information (cont.)

System Number	System Name	River	Country	Province	Purpose	Type of system	Design Capacity (l/sec)	Problems of Low Yield	Problems Associated with Iron or Manganese	Problems with Flood Damage
24	Umkomaas	Mkomazi	South Africa	KwaZulu-Natal South Coast	Domestic water supply	Bank of horizontal well screens	28.9	No	Yes	No
25	Mtwalume School	Mtwalume	South Africa	KwaZulu-Natal South Coast	Domestic water supply - Boarding School	Gabion type collector sump and horizontal well screen	2	No	No	No
26	Fairview	Mzumbe	South Africa	KwaZulu-Natal South Coast	Domestic water supply	Vertical well points	5.6	Yes	Yes	No
27	Pungashe	Mhlabatshane	South Africa	KwaZulu-Natal South Coast	Domestic water supply	Gabion type collector sump	10	No	No	No
28	Umvoti - Illovo Sugar	Mvoti	South Africa	KwaZulu-Natal North Coast	Industrial - Sugar mill	Horizontal well screens	Unknown	No	Yes	No
29	Umdloti	Umdloti	South Africa	KwaZulu-Natal North Coast	Domestic water supply	Horizontal well screens, packed in gabions	Unknown	No	No	No
30	Glover	Mona	South Africa	KwaZulu-Natal Interior	Domestic water supply	Gabion type collector sump and horizontal well screen	4	Yes	No	No
31	Nqutu	Buffels	South Africa	KwaZulu-Natal Interior	Domestic water supply	Caissons with radial horizontal well screens	170	Yes	No	Yes
32	Makhosine	Mpembeni	South Africa	KwaZulu-Natal Interior	Domestic water supply	Horizontal collector chamber	3.3	No	No	No

Table 8 Systems Visited – Summary Information (cont.)

System Number	System Name	River	Country	Province	Purpose	Type of system	Design Capacity (l/sec)	Problems of Low Yield	Problems Associated with Iron or Manganese	Problems with Flood Damage
33	Opuzane	Nsingane	South Africa	KwaZulu-Natal Interior	Domestic water supply	Horizontal well screen, with horizontal collector chamber and no-fines concrete sump	8.25	Yes	No	No
34	Ulundi	White Mfolozi	South Africa	KwaZulu-Natal Interior	Domestic water supply	Horizontal well screens off gallery	310	Yes	No	No
35	Mpungamhlophe	White Mfolozi	South Africa	KwaZulu-Natal Interior	Domestic water supply	Horizontal well screens, packed in selected aggregate cages	10.8	Yes	No	Yes
37	Havercroft Mine	Lower Olifants	South Africa	Northern Province	Mining	Caissons	16.5	Yes	No	No
39	Apel Mission	Olifants	South Africa	Northern Province	Domestic water supply	Caisson	Unknown	Yes	No	No
45	Hibberdene	Mzumbe	South Africa	KwaZulu-Natal South Coast	Irrigation - sugar cane	Vertical well points	45.8	Yes	Yes	No
46	Mtubatuba	Mfolozi	South Africa	KwaZulu-Natal North Coast	Domestic water supply	Vertical well points	99	No	Yes	No
47	Nondweni	Nondweni	South Africa	KwaZulu-Natal Interior	Domestic water supply	Vertical well points	Unknown	No	No	No

6.2.3 Types of Systems

Numerous different types of systems were encountered during the course of the research. The main types of systems are discussed below.

6.2.3.1 Caisson Type Systems

Numerous caisson type systems were found. These systems incorporate a large diameter vertical caisson installed in the sand of the riverbed or the riverbank. The level of sophistication of caisson type systems varies from simple systems constructed using precast hollow blocks or even large perforated steel drums to structures constructed using precast manhole rings, reinforced concrete or no-fines concrete.

Provision needed to be made for the infiltration of water into the caisson. Various methods, including the following were used:

- The use of no-fines concrete for the construction of the caisson. No-fines concrete is permeable, thus allowing water to infiltrate into the system through the entire caisson surface.
- The inclusion of slots or openings in the caisson walls. Some slots were covered with a screen or mesh to prevent the ingress of sand into the caisson. A typical caisson with slot openings is shown in Figure 4.
- Selected aggregate or stone were used to construct the floor of the caisson. This allows for infiltration of water through the floor of the caisson. Some of the floors were covered with a screen mesh to prevent the ingress of fines into the system and to retain the aggregate in place. Where caissons have both slot openings in the wall and an aggregate floor, it has been found that the majority of water infiltrates through the floor of the caisson. It was evident that caissons performed better if they were constructed with either a packed aggregate or no-fines concrete floor.
- Horisontal well screens connected to the caisson were positioned in the sand bed surrounding the caisson. Water infiltrating the well screens then flow through the screens into the caisson. Multiple screens were generally installed radially from the caisson. A typical system of this type is shown in Figure 5.

Caissons lend themselves to the installation of submersible pumps making it possible to pump the collected water directly from the caisson to a storage or treatment facility. Alternatively, outlet pipes are installed in the bottom of the caisson, connecting the caisson to the wet well of a pumping station, or the outlet pipes are connected to the suction pipe of a centrifugal or mono-type pump. Where more than one caisson is installed at a site, a common collector pipe is normally used to discharge the water collected from the caissons into a sump at the pumping station.

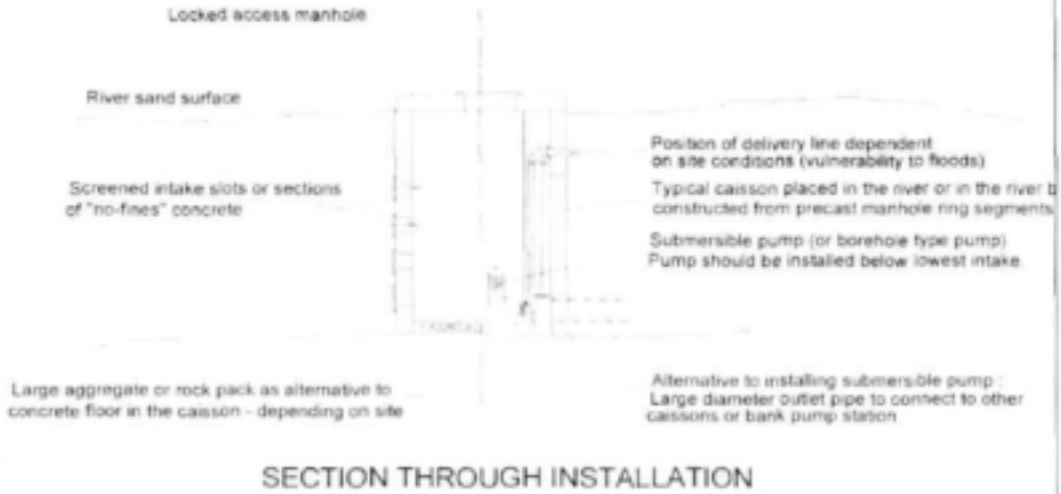

Figure 4: Caisson with Intake Slots or Sections

Where possible caissons should be founded on bedrock and anchored to the rock by means of rock dowels or similar. Where not possible, it might be necessary to construct the floor of the caisson in submerged conditions.

Numerous successful applications of caissons were encountered. It was, however, found that caissons with slot openings are not ideally suited to conditions where there are high percentages of fines in the river sand. Fines tend to enter the caisson and there is a build up of sludge in the bottom of the caisson under these conditions. Caissons with horisontal well screens with appropriate slot sizes would be more suited to these conditions.

Caissons are also not ideally suited to installation in rivers where relatively high flood flows with associated bed fluidisation of the sand occurs at depth. Caissons could then begin to "float" within the sand and could be overturned. Caissons installed in the riverbank are less susceptible to flood damage. However, the parameters of the alluvium in the riverbank should be carefully investigated to ensure that sufficient infiltration could be achieved if the caisson is to be installed in the riverbank.

Caisson type systems are most suited to conditions where:

- The depth of the sand bed varies between 3 and 5 m. This gives sufficient depth for infiltration into the caisson, and allows for founding the caisson on the bedrock.
- The fines content of the river sand is not high, unless horisontal well screens are to be used.

A disadvantage of caisson type systems is that they do not lend themselves to backwashing or development of the sand around the caisson.

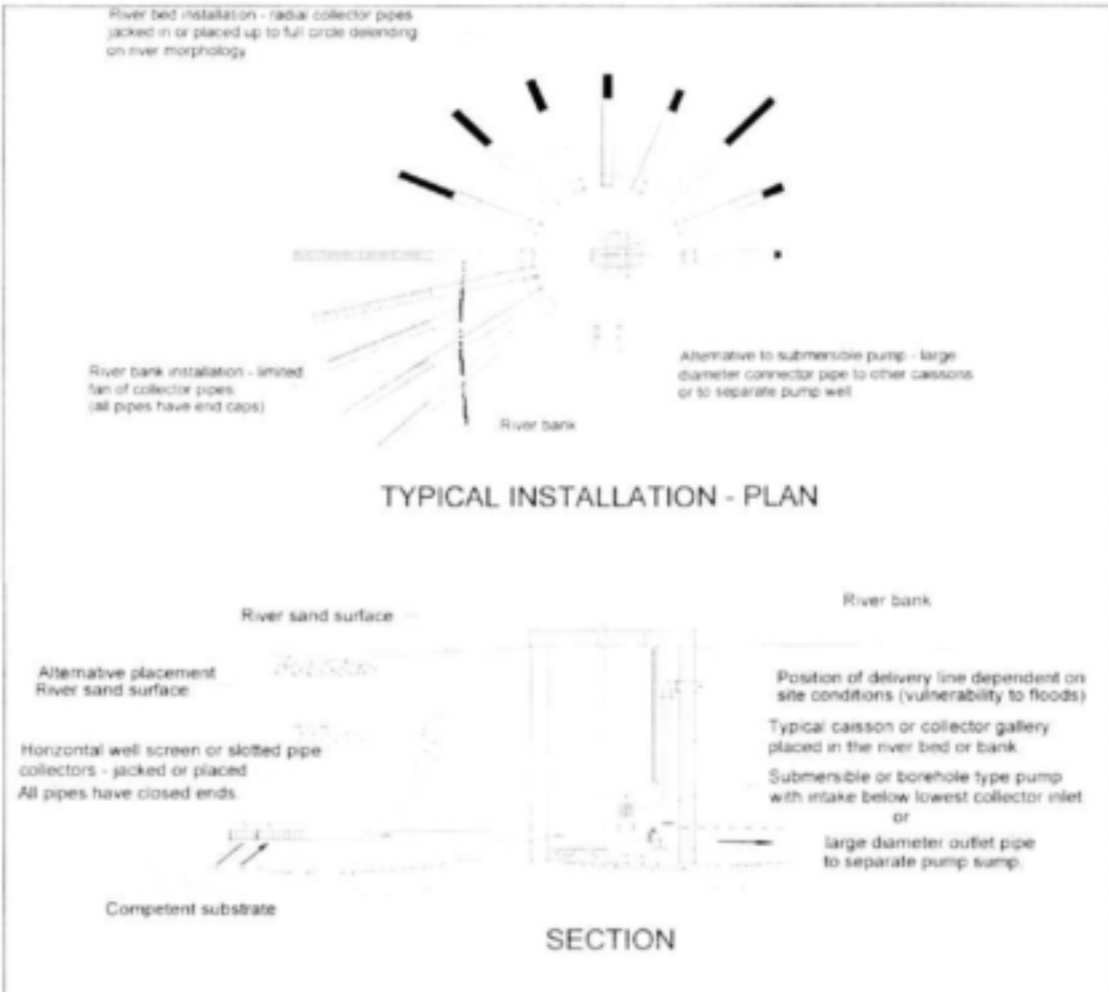

Figure 5: Caisson with Radial Horisontal Well Screens

6.2.3.2 Infiltration Galleries with Horisontal Well-Screens

Infiltration galleries with horisontal well screens incorporate a horisontal gallery installed in the riverbed or riverbank. Horisontal well screens are connected to the gallery, near the invert of the gallery. These well screens project into the riverbed. The well screens are normally parallel to each other, although screens can be installed in the ends of the gallery, projecting perpendicularly to the screens installed in the sides of the gallery. A typical infiltration gallery with horisontal well screens is shown in Figure 6.

The length, diameter and slot size of the well screens will be determined by the parameters of the sand, and the required yield of the system. The screen diameter is also governed by the need to minimise head loss for flow through the screen pipe.

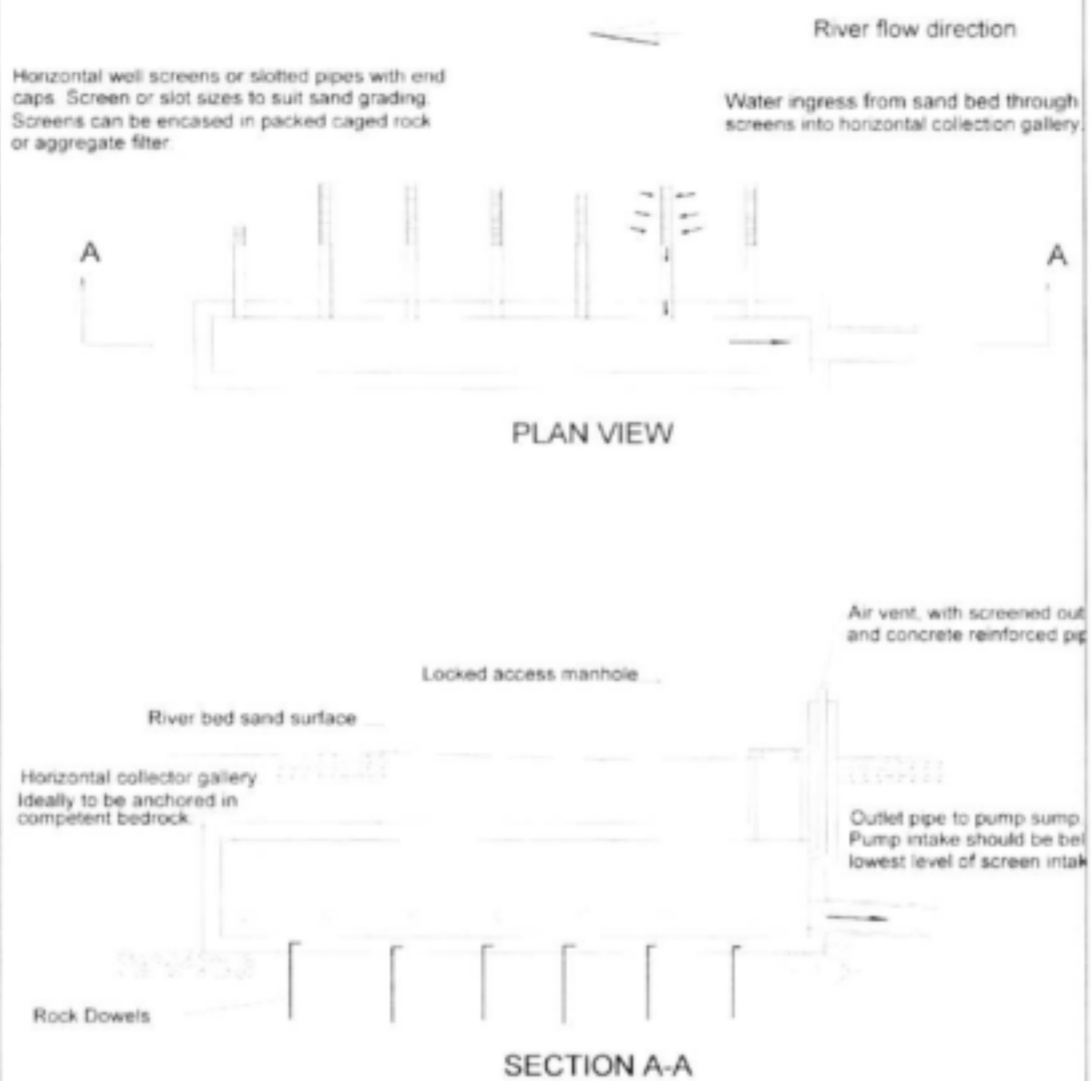

Figure 6: Collector Gallery with Horisontal Well Screens

The collector gallery would normally be constructed from reinforced concrete, but other construction materials such as blockwork could also be used. The gallery should be founded on bedrock, with the gallery being anchored to the rock by means of rock dowels or similar.

Construction of these types of systems can be lengthy, and when compared to other systems, costly. Systems with a collector gallery and horisontal well screens are therefore more suited to applications where demand is relatively high, and higher capital costs can be justified. For systems where demands are lower, other types of systems would be more suitable.

These systems are less susceptible to flood damage than are banks of vertical or horisontal well screens. This is generally because the well screens could be installed at greater depth than systems where the wells screens are connected to a manifold. The collector gallery also provides some anchorage under flood flow conditions.

Similarly to caissons, these systems lend themselves to the installation of submersible pumps. Water could then be pumped directly from the collector gallery to a storage or treatment facility. Alternatively, an outlet pipe could be installed in the bottom of the gallery, connecting the gallery to the wet well of a pump station, or being connected to the suction of a centrifugal or mono-type pump.

A disadvantage of infiltration galleries with horisontal well screens is that they do not lend themselves to the incorporation of a facility to backwash the screens, or to the development of the sand around the screens at the time of construction. It is possible to develop the sand by isolating each screen independently, but it is far easier to develop the sand when installing banks of vertical or horisontal well screens connected to a manifold.

6.2.3.3 *Horisontal Well Screens Connected to a Manifold*

Banks of horisontal well screens are generally installed in the water-bearing formation with all the screens connected to a common manifold. The manifold could then be connected either directly to the intake of either a centrifugal or mono-pump, or water could flow under gravity to the wet well of a pumping station. A typical horisontal well screen type system is shown in Figure 7.

The banks of screens could be installed in either the riverbed or riverbank. In general, although more susceptible to flood damage, yields will be better when screens are installed in the riverbed instead of in the riverbank.

When installing systems of this type, it is good practice to install the manifold on the riverbank. It would then be possible to incorporate isolating valves at the head of each well screen, so that each screen could be isolated from the rest of the system. However, this would not always be possible, particularly when the riverbed is extremely wide and the main flow of the river (surface or subsurface) is not close to the riverbank.

The length, diameter and slot size of the well screens are determined by the parameters of the sand, and the required yield of the system. The screen diameter is also governed by the need to minimise head loss for flow through the screen pipe.

The well screens should be connected to the manifold by a length of flexible pipe (helical) to allow for some movement of the well screens within the sand bed, thereby preventing shearing of the screens at the manifold.

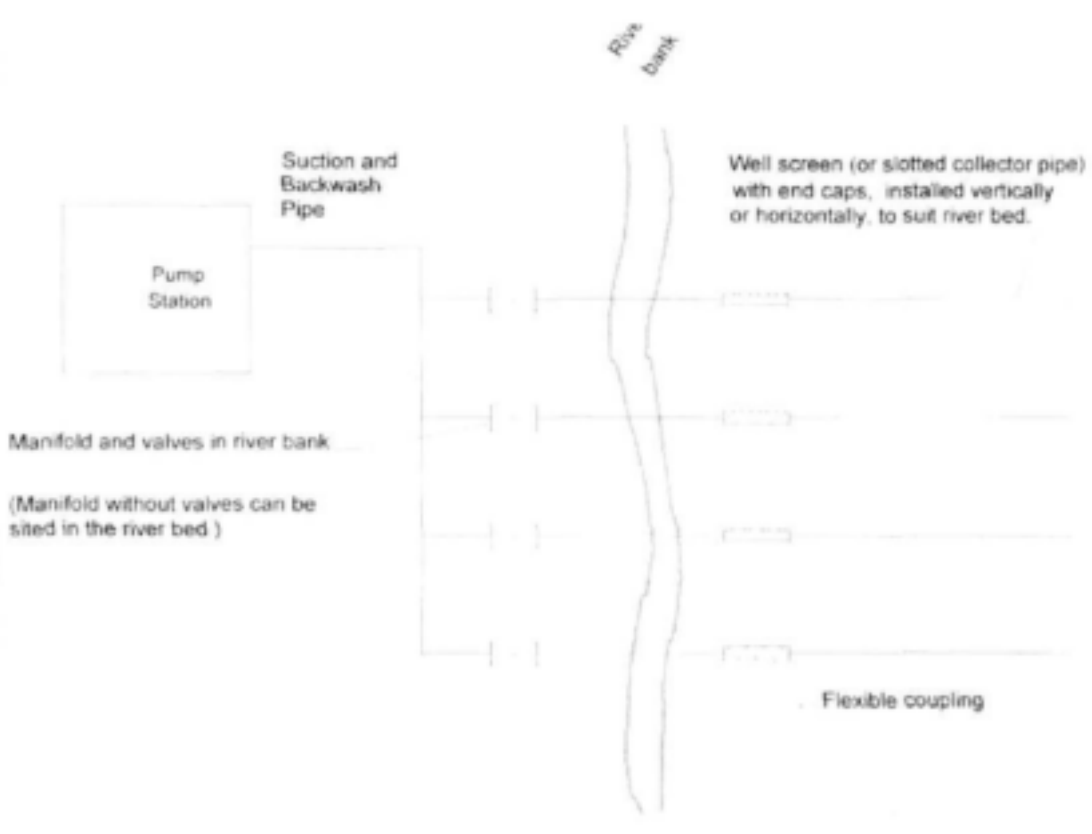

Figure 7: Horizontal/Vertical Well Screen System off Manifold

It has generally been found that the performance of systems that are backwashed regularly as part of normal operation procedures is better than that of systems that are not backwashed. Backwashing of the screens will remove any fines that have accumulated in the screens and will assist in breaking down and controlling the development and build up of scale and/or biofilm in the screens.

Where possible, the system should therefore be designed to accommodate backwashing facilities. This could be done by either incorporating a return flow from the storage tanks, with a bypass around the pumps, or by incorporating a circular return system, whereby water abstracted from one screen is pumped back into another screen to backwash it. The former system is however, preferred. In case of the latter system, problems could arise if fines and biofilm etc. being washed out of a particular screen is sucked into the screen that is being used to abstract the water for backwashing. This could lead to clogging of the screens.

If possible, only one screen should be backwashed at a time. If the entire bank is backwashed simultaneously, the backwash water will follow the path of least resistance, flowing out of the cleanest screens, and not effectively backwash those screens that require backwashing the most.

Well screens are susceptible to flood damage, particularly when the screens are installed at relatively shallow depths in the sand. Sufficient measures should therefore be taken to protect the screens against flood damage. Alternatively, one could simply accept that the screens would occasionally be damaged or lost, replacing them only if required. The latter approach has often been found to be more economical, particularly where the operating body has the skill to rapidly and easily replace the screens. This approach would not, however, be suited to schemes where the operating body do not have the skills to replace the screens, or are not likely to have the capital resources to pay for replacing lost screens e.g. large community water supply schemes.

The following typical methods and measures have been implemented to protect horisontal well screens:

- Installing the screens at the greatest possible depth, just above bedrock level.
- Tying the screens to anchor blocks buried in the sand.
- Encasing the screens in gabions or packed rock.
- Laying the screens on a mass concrete foundation, and encasing them in aggregate enclosed in a mesh cage, which is bolted to the concrete foundation. The cage is then covered with rock. This system, designed by Bradford, Conning and Partners, Newcastle, was implemented at Mpungamhlophe (system 35) when the damaged system was replaced. The system is relatively expensive to construct when compared to other horisontal screen systems, but it is believed that this system will remain successfully in operation for many years. The design has the added advantage of incorporating a graded filter around the screens. Problems of low yield are also therefore less likely to occur at this system. Details of this system are given in *Appendix J.41*.
- Attempts have also been made to anchor the well screens to the bank by means of a chain connected to rings on the end of the well points. This has, however, not been very successful.

6.2.3.4 *Vertical Well Points*

Vertical well points are either installed independently, or in banks connected to a manifold.

Well points that are installed independently are similar to normal boreholes. They could be installed in the riverbed, or the alluvium of the riverbank. Generally they incorporate a well screen installed vertically in the sand bed. The entire well point need not be screened. Normally the upper section of a well point consists of a steel or PVC casing whereas the lower section below the water table is screened.

In most cases submersible borehole type pumps are installed in independent vertical well points. The depth to which the well point is installed will thus depend on the drawdown level in the sand when water is being abstracted. The well point should be installed in such a manner that the pump intake is always below the water table during operation.

Banks of vertical well points connected to a manifold are installed in a manner similar to that in which banks of horisontal well points are installed. The well points are normally installed at an offset from the manifold by incorporating straight lengths of pipe, which are installed horisontally from the manifold to the well point.

Most of the times it is not possible to install the manifold in the riverbank. Valves for isolating each well point are therefore also not normally incorporated in the system. The manifold is usually buried in the sand, at sufficient depth to have some protection during floods. The manifold is generally directly connected to the intake of either centrifugal or mono-type pumps installed in a pumping station on the riverbank.

When using centrifugal pumps care should be taken in making provision for priming of the pumps. This is particularly important when the water level in the river drops below surface level. Non-return valves should not be incorporated on the intake side of the pumps, as it would prevent easy backwashing of the pumps. Problems were also experienced with the sealing of non-return valves because of grit being trapped in the valve.

The priming of pumps could be provided for by incorporating a vacuum tank on the intake side of the pump. The vacuum tank should have a volume equivalent to about 2½ times the volume of the pipework to the vertical well points. This tank should be connected to the delivery pipe of the pumps by a small diameter bypass with an isolating valve. Before starting the pumps, the vacuum tank should be filled with water from the delivery pipe of the pumps in order to facilitate the priming of the pump.

Alternatively, a small mono-type pump could be installed to pump water into a storage tank for priming the centrifugal pump. A system of this type is used at Chisumbanje (system 16). Photographs of this pump installation are shown in *Appendix J.19.8*.

Vertical well point installations are suited to conditions where the sand bed is very deep, and where the river is often surface dry. The largest system found in Southern Africa is the one at Chisumbanje, Zimbabwe. It consists of three banks of vertical well points installed in the river sand of the Save River and has a yield of 1 020 litres per second.

6.2.3.5 *Gabion Type Systems*

Gabion type sand abstraction systems generally incorporate a sump constructed out of gabions (rock packed in wire baskets). The sump is normally installed in the riverbed near the bank and is founded on bedrock, on packed rock or on concrete. The sump is covered with a concrete slab with an access manhole, and a submersible pump is installed in the sump. Water flows through the gabion walls into the sump, from where it is directly pumped. A typical gabion type system is shown in Figure 8.

The system could be augmented by the inclusion of horisontal well screens connected to the sump. These well screens could either be buried in the sand of the riverbed or be encased in gabions.

In all systems of this type that were visited, the gabions had been wrapped in geofabric. Both the design engineers recommended the use of Kaytech geofabrics as opposed to bidum. The systems are located in river sections where the turbidity of the river is low and where there are very low percentages of fines in the river. Up to the time of inspection no problems were experienced with the use of geofabric in these systems. The geofabric has, however, shown signs of reduced permeability. It was evident that this type of system would rapidly clog under conditions where there are a large percentage of fines in the sand.

A typical gabion type system was developed by Silk Kisch Peralta Engineers (SKP), Durban. This system is called the "Hydrochamber" and has been patented by SKP. Details of the "Hydrochamber" are shown in Appendices J.29.9 and J.29.10. A similar system has been installed by Glover Development Engineers near Nongoma (system 30) (Appendix J.36).

Gabion type systems are ideally suited to applications where:

- The water demand is low.
- It is necessary to keep construction costs to a minimum.
- Operation and maintenance should be as simple as possible.

This system is therefore ideal for use in rural water supply schemes. In addition, the system are suited to conditions where:

- The surface water is relatively clean.
- The alluvium of the riverbed is coarse.
- Flood levels are not very high.

These conditions normally occur at the head of a catchment.

Reference Drawing:

Province of KwaZulu-Natal Department of Education and Culture

Additions to Mthwalume Secondary School Water Supply and Sanitation System Upgrade

Drawing Title: Gabion Pump Chamber at River Addition of Subsurface Inlet

Drawing No.: 4407B-119 *Date:* March, 1997

Design By: **Silk Kisch Peralta (SKP) Engineers, Durban**

Drawing By: Liebenberg & Stander, Durban

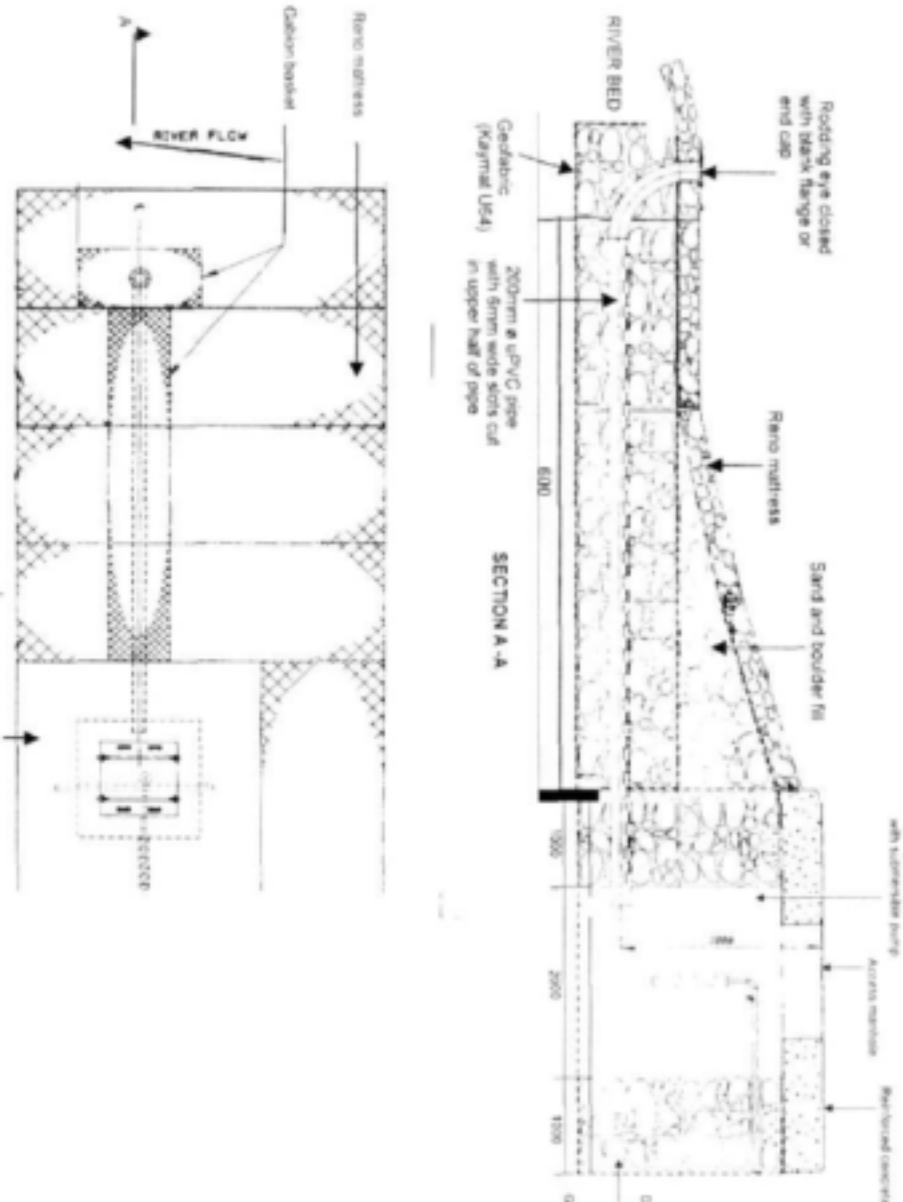

Figure 8: Gabion Type Collector Sump

6.2.3.6 *Abstraction Chambers*

In addition to the caisson type abstraction chambers, horisontal abstraction chambers were also visited.

These are generally long, narrow sumps that are relatively shallow. The sump is installed in the riverbed. Provision is made for the flow of water into the sump either through the inclusion of screened openings in the sump walls, or through the use of no fines concrete. A pipe connects the sump to the wet well of a pump station installed in the riverbank. The invert level of the pump station wet well should be such that the water can gravitate from the sump to the wet well of the pumping station. Submersible pumps or normal centrifugal pumps are normally installed in the pumping station.

The chamber should ideally be founded on bedrock and anchored to the bedrock by means of rock dowels or similar.

A typical horisontal abstraction chamber is shown in Figure 9. This system was designed by Ernst Cloete and Associates in Vryheid, and has been successfully implemented at Makhosine (system 32) and Opuzane (system 33).

Horizontal collector chambers are ideally suited to applications where:

- The water demand is low.
- Operation and maintenance should be as simple as possible.
- A reasonable level of filtration is required.

This system is therefore ideal to be used in rural water supply systems, where the water is not treated (except for chlorination) prior to use. In addition, the system are suited to conditions where:

- The surface water is relatively clean.
- The alluvium of the riverbed is relatively shallow.
- Flood levels are not very high.

These conditions normally occur at the head of a catchment.

Reference Drawing:

Zululand Regional Council

Makoseni Water Project

Drawing Title: Details of Abstraction Chamber at Mpembeni River

Drawing No.: 96-19/13 *Date:* December 1997

Design By: **Ernst Cloete and Associates, Vryheid**

Drawing By: **Ernst Cloete and Associates, Vryheid**

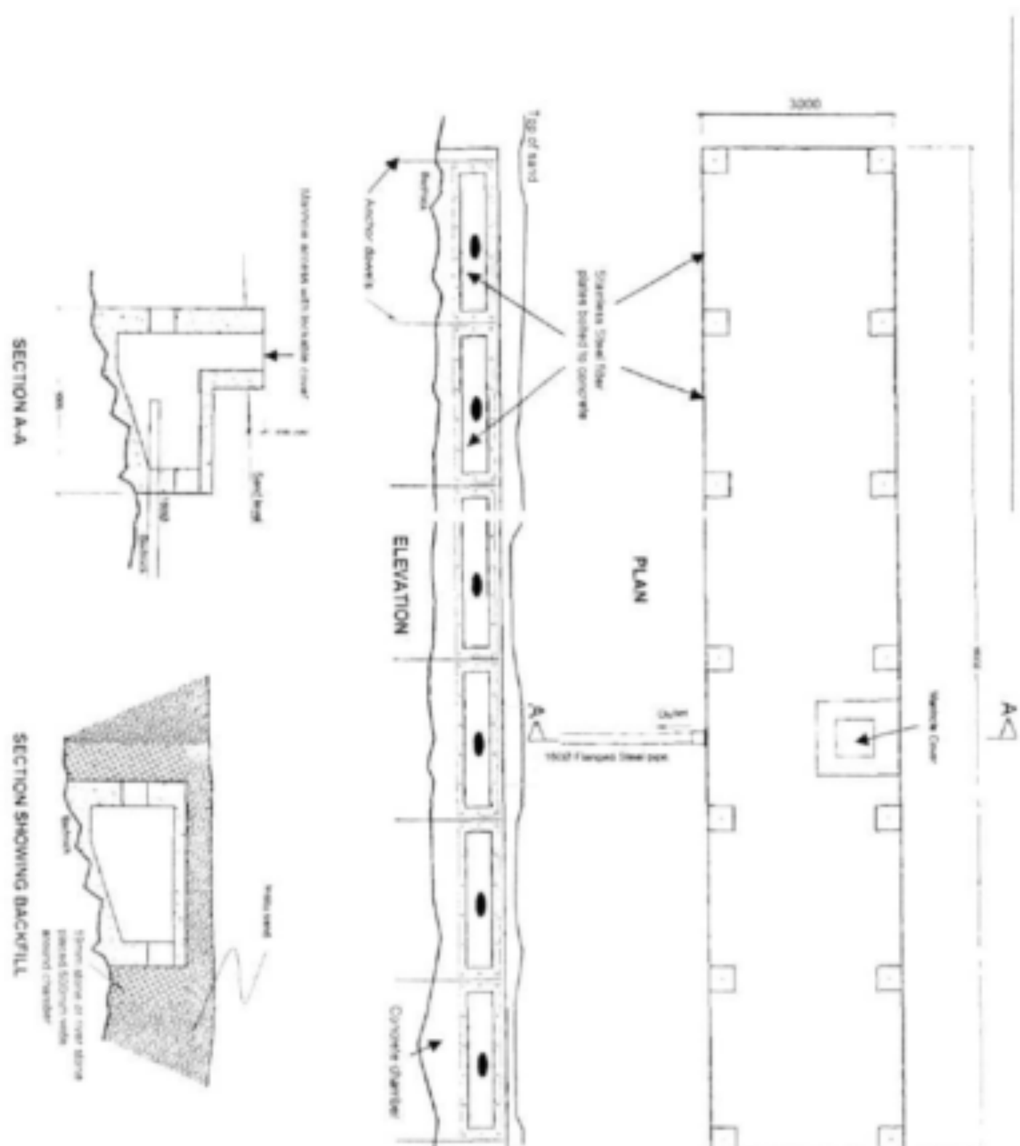

Figure 9: Horizontal Collector Chamber

6.2.3.7 *Small-Scale Systems*

For many rural applications small-scale, low technology systems are often more suitable than larger more sophisticated systems. A simple hand-pumped sand abstraction system has been developed by Dabane Trust in Zimbabwe and successfully implemented for water supply for community market gardens.

This system incorporates a short well screen that is installed in the riverbed, at an angle to the surface. The well point is connected to a Rower pump (hand pump) installed on the riverbank just above the flood line. Water from the Rower pump is discharged directly into a concrete or sealed blockwork sump installed in the riverbank.

If it is necessary to pump the abstracted water to a higher elevation, a second pump is installed. This pump, a Joma hand pump, is installed further up the embankment. This pump is used to draw water from the sump, which is filled using the first Rower Pump, and then pumping it further up the embankment to where it is discharged into a reservoir from where it is distributed for domestic water supply or for irrigation.

With the simplicity of this system, women can easily operate and maintain this system. As the major water users and collectors in rural communities, this is particularly important. It was noted by Dabane Trust that women quickly learned to undertake all basic maintenance and repair work to the pump. The women have cited the sustainability and low operation and maintenance costs, in addition to increased self-reliance, as reasons for their preference for using this system.

The design of these systems is simple, and the systems, including the pumps, can be built using commonly available materials. It is therefore possible to teach rural communities to construct and install systems of this type themselves.

These systems are ideally suited to applications where:

- The water demand is low.
- Simple appropriate technology is required.
- Operation and maintenance should be low cost and simple.
- Electricity or fuel supplies are not readily available.

In addition, the system are suited to conditions where:

- The river is often surface dry.
- The alluvium of the riverbed is either shallow or deep.

Other small-scale systems include temporary systems that can be used for localised or emergency supply. An example of such as system is a trench dug across a surface dry riverbed. Seepage water is collected from the trench either by hand or with the use of a small submersible pump. Farmers in the Karoo commonly use systems of this type.

6.2.3.8 *Other Systems*

Other types of systems that do not fall into any specific category were found during the survey. These included the system installed at Laingsburg on the Wilgehout River (system 2), a collector channel, and the system installed in the Olifants River at Olifantspoort, Northern Province (system 38), and a "buried culvert" system

The collector channel, at Laingsburg, is installed in the streambed, near a spring source. It is constructed from cement hollow blocks (390 x 190 x 140 mm), oriented such that the openings of the hollow blocks connect the surrounding sand to the inside of the channel. The channel is covered with precast concrete slabs.

The Olifantspoort system was constructed in a stratified alluvial aquifer of 9 m depth. The horisontal culvert type system incorporated a 90 m long box culvert, constructed by using 400 x 400 mm increasing to 900 x 900 mm precast culvert sections. The culvert was installed in an 800 to 1 000 mm thick layer of 19mm stone. The effective abstraction length of the culvert was approximately 60 m. The culvert was installed immediately upstream of a weir, running parallel to the weir. Details of this system are given in *Appendix K.1*.

Although this system has never performed efficiently, this design has the potential to render high yields if successfully implemented. Indications are that factors other than the design of the system have caused the problems of low yield experienced at the system. During installation the bedding aggregate was wrapped in geofabric, which could be the cause of the reduced yield of the system.

During construction the system was also flooded, resulting in a large amount of fines, silt and organic matter being washed into the system. It was found that the yield of a number of systems that have been flooded in a similar fashion during construction has been low from the time of commissioning, reducing rapidly once in operation. In these cases the systems were never used continuously and were not given a chance to be developed or flushed. Although not substantiated, it appears that flooding of this type might "seed" a system, causing rapid development of biofouling in the system.

Experience, mostly gathered since the installation of this system, has also shown that severe problems of low yield have been experienced at the majority of the systems installed in the Olifants River in the Northern Province. A number of factors could be contributing to this, including problems of fouling associated with iron and manganese precipitation, and the sealing of the sand through the ingress of clay.

6.2.4 Typical Tests and Investigations Carried Out

It was found that often very little testing and investigations were conducted during the feasibility and design phases of sand abstraction systems. It is anomalous that in some instances, where no preliminary investigations were conducted, the system worked well, while in other instances, where extensive and comprehensive testing had been done, the system failed, with the yield of the system reducing rapidly with time.

A summary of the testing conducted for different types of systems is given below. It must be noted that the tests for both surface dry and surface flow conditions are discussed. Appropriate tests were implemented at the different systems depending on the river flow conditions.

6.2.4.1 General Types of Data and Information Required.

Whether obtained through on-site testing, desktop studies or from previous experience with a particular site or river reach, the following general information was normally obtained for use in selecting sites and for the design of new systems:

- The profile of the riverbed, including the depth and average saturated depth of the alluvium.
- The various horisons within the alluvium, in particular, any clay lenses or silt layers.
- In larger rivers, knowledge of where the original river course lies beneath the present riverbed. The sand depth above the original river course is generally deeper than that in other parts of the river.
- The depth of the water table in the sand during periods when the river is surface dry. This varies with the seasons.
- The characteristics of the sand, including:
  - The sand type and percentage fines in the sand.
  - Transmissivity and storage coefficient of the sand.
  - Permeability of the sand.
- The extent of the alluvial aquifer upstream of the system (effective storage volume).
- The characteristics of the catchment area upstream of the system (effective recharge area) and average precipitation for the catchment, as well as no-flow (i.e. no recharge) periods.

6.2.4.2 *Common Tests and Investigations for all Types of Sand Abstraction Systems*

Certain tests were commonly conducted for virtually all types of systems. These tests included the following:

- Determination of cross-sectional profiles of the riverbed, including the depth of the alluvium, horizons in the alluvium, depth of the water table and the profile of the bedrock beneath the alluvium. This was done by means of one or a combination of the following tests:
  - ➢ Depth probes using steel probes done in a grid pattern in the area where the system was to be installed.
  - ➢ Vertical electrical and resistivity soundings.
  - ➢ Where possible, drilling and sampling of test holes.
  - ➢ Where possible, digging, inspection and sampling of test pits.
- Determining the extent of the alluvial aquifer upstream of the system by means of the following method:
  - ➢ The distance the alluvial aquifer extends upstream of the system can be estimated from a study of topographical and geological maps.
  - ➢ The width of the alluvial aquifer can be estimated from a study of topographical and geological maps, together with the cross-sectional profiles of the river, established as discussed above.

6.2.4.3 *Tests for Caissons*

The installation of new systems:

In some cases, particularly Havercroft Mine (system 37) extensive testing and investigations were conducted during the feasibility study and design phases, including the following:

- The aquifers were investigated by means of jetting to determine the depth of the sand bed and the grain size of the sand particles. A dual type method of jetting was used, where a 1" pipe inside a 2" pipe was jetted into the sand. The smaller pipe was then removed, a PVC pipe was placed in the larger pipe, and the larger pipe was removed. During the jetting process, sand returns in the water were logged and sampled, allowing for the evaluation of the alluvial aquifer in terms of its thickness and grain size. Sites of active erosion were avoided.
- Sand grading analyses were conducted for samples taken at different depths and locations.
- Aquifer pump tests were conducted, determining drawdown levels in piezometer tubes located at varying distances from the well point from which water was being pumped. Based on the results of aquifer pump tests the following parameters were determined:
  - ➢ The transmissivity of the aquifer.
  - ➢ The sand storage coefficient (based on the cross sectional area of the aquifer and the storage coefficient).

- The zone of influence around an abstraction point was estimated.
- Considering the zone of influence around an abstraction point and the storage coefficient of the sand, the volume of water that is held around an abstraction point for utilisation was estimated.
- Based on the cross-sectional area of the aquifer, the hydraulic gradient in the aquifer and the permeability of the sand, the through flow rate through the sand were estimated.

- The digging of test pits and taking of "core" samples to determine the profile of the alluvium.

Testing done at existing systems:
Where it was necessary to augment the water supplied from existing systems, through either the installation of new sand abstraction systems, or modifications to the existing systems, testing was conducted taking the existing systems into account. Testing of this nature was conducted at both the Laingsburg systems (systems 2 and 3).

In general, tests for augmenting systems incorporated the following:

- Investigations to determine whether the existing systems were abstracting all available sub-surface flow, and whether the efficiency of these systems could be improved.
- Geophysical investigations to determine the thickness of the alluvium and the storage capacity or yield potential of the alluvium.
- The installation of piezometer tubes around the existing caissons, or other types of sand abstraction system. These were monitored during pump tests and normal system operation to determine the flow patterns of the subsurface water.
- When installing the piezometer tubes, core samples were taken. The various types of horizons and depths of these horizons were determined by examining the core samples.
- Extended (24 to 36 hours) pump test were conducted, pumping at a constant rate from the existing system. Where other systems were located near the system at which the pump test was being conducted, these were operated at normal abstraction rates throughout the pump test, to monitor the combined effect of the two systems on the water flow in the alluvium. During these pump tests observations were made of the following parameters:
  - Water levels in the abstraction system.
  - Water levels in the piezometer tubes.
  - Flow rates into the existing abstraction system to identify the presence of any blockages or restrictions to flow.

- Multiple rate discharge or step tests were carried out to determine the performance characteristics of the abstraction system, which is influenced by the geometry of the system (e.g. vertical well or caisson diameter and depth, the arrangement and depth of wells screens etc.) and the nature of the aquifer material. The quantity of groundwater available for abstraction and the amount of groundwater flowing through the alluvium at the well is generally determined by step tests as follows:
  - During a step test, the abstraction system or well is pumped at increasing abstraction rates (Ref. 0). Drawdown rates and levels are monitored for each discharge rate.
  - When pumping is stopped, water levels in the aquifer rise to their pre-pumping levels. The rate at which the water level rises to the pre-pumping levels (the rate of recovery) provides a means of calculating the hydraulic conductivity and storage potential of the aquifer.
  - The difference between pre-pumping and post-pumping water levels is an indication of aquifer dewatering.
  - The data from multiple rate discharge tests is then used to estimate the sustainable yield of the abstraction system.
  - Well or abstraction system efficiency could also be determined from the results of step tests (Ref. 0). A positive linear correlation between discharge and drawdown is an indication that the well is functioning efficiently.
- In some instances it was recommended that constant discharge tests be conducted after installation of the caissons. These tests need to be done over a period of 7 days in order to confirm the sustainable potential yield of the aquifer.

6.2.4.4 *Tests for Infiltration Galleries and Caissons with Horizontal Well Screens*

Prior to the installation of infiltration galleries or caissons with horizontal well screens, the following tests were done:

- The 1:100 year flood levels were determined using normal hydrological methods. This was done to allow for an estimation of the depth of bed fluidisation during floods. When the sand bed is fluidised, movement will occur in the bed, both as suspended load and as bed load.
- Investigations of the sand bed over a long reaches of the river in order to identify the best site for the system. These investigations were conducted during low flow periods. Riverbed profiles were determined based on the assumption that the bedrock would be relatively close to the surface of the sand where there was still surface flow in the river.
- At the site selected for the installation sand samples were taken on a grid pattern at various depths in the sand bed. Grading analyses were conducted on the samples to determine the uniformity of the material in

the sand bed and to identify any clay lenses present in the sand bed. The results of these tests were used to verify whether the assumption of a constant permeability through the sand bed was correct.

- Laboratory permeability tests were also conducted on the sand samples.
- Pumping tests were conducted in the riverbed.
- Further tests were conducted during construction, including the following:
  - Detailed profiling of the bedrock.
  - Grading analyses were conducted on sand samples taken from sand removed from the well screens casings.
  - Water samples were taken regularly and tested throughout the construction period.

6.2.4.5 *Tests for Horizontal Well Screens Connected to a Manifold*

No details of tests conducted during the design and feasibility phases were given for any of the systems that incorporate horizontal well screens connected to a manifold.

6.2.4.6 *Tests for Vertical Well Points Installed in the Riverbank*

Sites for new vertical well points to be installed in the river bank were selected in areas where it was known that the alluvial aquifer in which the well points were to be installed was contiguous with the alluvium of the riverbed.

Common tests conducted as part of the investigations for the installation of vertical well points in the alluvium of the riverbank included:

- The drilling of exploration holes in the alluvial aquifer of the riverbank. This was done to:
  - Determine the blow yield of the test holes.
  - Determine and define the profile of the alluvium, including the vertical and lateral extent of saturated potential aquifer horizons represented by coarse sands and gravels.
  - Determine the water quality of the groundwater in these alluvial aquifers.
- The drilling of production holes in areas where the physical structure of the aquifer was suitable for the installation of a vertical well point, or where a test hole had a suitable blow yield.
  - The production hole was equipped, whereafter piezometer tubes were installed around the production hole for observation of the water table during pump testing.
  - Hydrological and production pump tests were then conducted at the production hole.

- In some instances, based on the findings of the pump tests conducted at the production hole, additional production holes were drilled and the wells were equipped.
- A well field monitoring programme was then implemented. This incorporated:
  - ➢ Weekly monitoring of water levels, including piezometric levels.
  - ➢ Monthly monitoring of production yields. This was done to:
    - o Determine whether pumps were producing at recommended rates.
    - o Calibrate recharge volumes.
  - ➢ Water quality monitoring.
  - ➢ Monitoring and recording of flow periods and water levels in the river, as this is when there recharge to the aquifer. This allows for the calculation of the effective recharge extent and period.
- Using the results of the monitoring programme, recharge rates, the amount of water available for abstraction, and aquifer parameters were determined.

6.2.4.7 *Tests for Vertical Well Points Installed in the Riverbed*

Prior to installing vertical well points in riverbeds, tests were conducted to investigate the alluvial aquifer associated with the river. Investigations included the following:

- In some instances (Chisumbanje – system 16) shallow sand samples were taken and it was assumed that the finer sands would not be encountered with depth. It must be noted, that on studying sand samples from numerous systems, this assumption should generally not be made. In many instances fine sand accumulates at depth in the riverbed.
- The drilling of exploration holes in the alluvium. This was done to:
  - ➢ Inspect samples during drilling to determine particle size and nature and bed depth.
  - ➢ Install small diameter piezometer tubes for the collection of samples for water quality testing.
  - ➢ To determine the depth and saturated depth of the alluvium.
- The drilling of production holes in the alluvium:
  - ➢ The production holes were equipped with screens and casings for pump testing.
  - ➢ The results of the pump testing were used to determine the hydraulic properties of the sand, potential yield and associated drawdown.
  - ➢ Samples were taken for water quality testing.

- At Chisumbanje, the production holes were used as a pilot scheme, which was operated for a number of months, through an extreme dry period. Based on the operation of this pilot scheme, the larger system was then developed.

6.2.4.8 *Tests for Gabion Type Systems, Abstraction Chambers and Small-Scale Systems*

Generally, for the installation of gabion types systems, abstraction chambers and small-scale system, no testing was done other than to determine the depth of the sand bed and the normal level of the water table. This is appropriate, as:

- These are low cost systems and the cost of detailed investigations would not be justified when installing these systems.
- Abstraction chambers and gabion type systems were generally installed in shallow sand beds (0.5 m to 2.0 m depth), and were installed be excavating the sand bed. Any anomalies in the sand would therefore be quickly identified during the early stages of construction.
- The volumes of water abstracted using these systems are so small, that it is highly unlikely that any stress will ever be placed on the aquifer.

In the case of the small-scale hand pumped systems, it may, however, be advisable to take sand samples using a sampler similar to the tube samplers used by the research team. This should be done to identify clay lenses. It was found that when using the tube sampler, clay lenses that occurred within the sampling depth (up to approximately 2.0 m) could be identified.

6.2.5 Design Procedures

For most systems it was found that the structural design and hydraulic design (for flow in pipes and pump design) of systems was generally implemented using normal methods. It was, however, found that with respect to the geohydrology and the hydraulics of the flow through the sand and into the system, systems were seldom designed. Rather, the approach of "install it and see if it works and how much water we get" was often taken.

Various design procedures that were implemented for the design of some of the systems are discussed below. General aspects noted during interviews with persons with extensive experience with abstraction systems are also included.

6.2.5.1 *General Aspects Relating to Design*

Discussions were held with a number of people, including Mr A.J. Fox (Fox Farm, system 5), Mr J. du Toit (Messina, system 13) and Mr C. Ambler-Smith (Nottingham Estate, system 15) who have many years experience with the installation and operation of sand abstraction systems. During these discussions, a number of important points were noted regarding general design principals and the use of sand abstraction systems. These included:

- The success of sand abstraction systems cannot necessarily be based on "scientific or engineering design", although good design does contribute to the success of a system. It is essential that lessons be learned from experience with these systems, and that the users of the systems be open to adaptation, modification or upgrading of the systems if required.
- Sand abstraction systems should never be considered as systems that require low maintenance and management. On a daily basis, maintenance requirements are low, but the production/yield of any system should be monitored and steps taken to alleviate any problems that may occur with systems as and when they do arise. Once problems start developing in a system, if they are not dealt with as soon as possible, the problems will rapidly become worse and are then extremely difficult and costly to remedy.

6.2.5.2 Design of Caissons

The design and sizing of caissons was generally based on the results of pump tests and geophysical investigations. Data obtained from the pump tests was used to determine the transmissivity and storage coefficient of the alluvium, as well as the estimated zone of influence of an abstraction point.

- *Calculations used for determining the quantity of groundwater available for abstraction from the alluvium or aquifer potential:*
  - There must be a balance between the water being drawn from an aquifer and the water entering the aquifer or recharge into the aquifer. Recharge to the aquifer can be through ingress of surface water (surface water flow or precipitation), or from other interconnected aquifers. Using this water balance, the amount of water that can be abstracted from the aquifer, without exhausting it, was determined.
  - The quantity of groundwater available for abstraction from the alluvium over a year was calculated by estimating the saturated thickness of the alluvium, the average width of the alluvium in the river bed, the length or distance the alluvium extends upstream of the well, and the storativity of the alluvium.
  - The storativity of the alluvium is defined as the volume of water released from storage per unit surface area of the aquifer per unit decline in hydraulic head. Storativity is a dimensionless quantity, as it is a volume of water stored per volume of alluvium.
  - The quantity of groundwater available for abstraction from the alluvium was calculated as:

$$\text{Volume} = t \times b \times l \times s$$

where: t =saturated thickness of alluvium
b = average width of alluvium

l = length of alluvium upstream of abstraction point
s = storativity

This volume of water is considered the upper limit of water available for abstraction. The lower limit of water available for abstraction was determined by the amount of water that can actually flow through the alluvium and reach the abstraction system. Under natural conditions, the quantity of groundwater flowing through the alluvium under non-pumping conditions at the position of the abstraction point was calculated using Darcy's Law:

$$Q = kiA$$

$$\text{or } Q = k\frac{dh}{dl}A$$

where:
- Q = flow rate (measured at the abstraction point)
- A = cross sectional flow area perpendicular to the direction of flow.
- i = hydraulic gradient
- dl = distance between two observation points
- dh = change in piezometric level between the two observation points.

These two results give the upper and lower estimates of the quantity of groundwater available for abstraction, but neither gives an accurate reflection of the water available for pumping. Rather, they provide a scenario of natural groundwater conditions that can be used for modelling the effects of pumping.

- *Calculation of recharge of aquifers from surface water flow:*
  - Recharge to the alluvium in a riverbed occurs whenever the river flows. Annual flow data for the river was therefore considered when determining production pumping rates for a system, in particular extended low flow periods were noted.
  - Where a system was installed in a river that is surface dry for a period of the year, the longest no flow period recorded was noted and the system was designed to be operated such that it would dewater the aquifer in a period longer than this no-flow period e.g. if the river is surface dry for a period of 4 months, with no surface flow to recharge the aquifer, then the pumping rates were set such that the system would dewater the aquifer over a period of say six months. This would give a factor of safety in the use of the aquifer during extended dry periods.
  - Where systems were dependent on surface flow, the abstraction rates of the system were set not higher than the normal low flow levels in the river.

- Various software packages are available which can be used for modelling the behaviour of groundwater in an aquifer under pumped conditions. These include AQUAWIN. Modelling of the aquifer and groundwater flow at the systems was conducted. Computer simulations were used to estimate:
    - The amount of water that could safely be abstracted from the system.
    - Whether the capacity of the abstraction system would be governed by the recharge rate into the catchment and the storage capacity of the aquifer, or by the transmissivity of the aquifer i.e. the ability of the aquifer to convey the water to the abstraction points.
    - The time period with nil recharge, but continued use of the abstraction system at a given rate, that would result in the aquifer being completely dewatered.

  The various computer programmes developed to model groundwater, are adaptable and powerful. Setting up of data for the models is time consuming, particularly if three-dimensional models are being used. Good quality data is also required to get useful answers from the modelling process, and adequate data is rarely obtainable. In particular, good historical data is needed to calibrate the models. When historical data is not available, and the models cannot be calibrated then results from the models can only be used as indicators of the behaviour of the groundwater in the aquifer.

  If facilities, or finances, were not available for modelling the system, it was generally considered safe to assume a pump rate equivalent to that determined using Darcy's Law i.e. the lower limit of water available for abstraction.

- Based on the results of the pump tests and modelling, pumping rates were set for each caisson dependant on the available head in the caisson. Pump rates were set to maintain a minimum head over the pump. Pumps were throttled using vales to give the required pumping rate.

- When setting pumping rates consideration was made of legislation requiring the maintenance of a base groundwater flow for environmental purposes. The National Water Act, 1998, requires that a certain quantity of groundwater be conserved to maintain the ecological integrity of the aquifer and the surrounding environment. This is referred to as the environmental reserve. The Act also requires that all large-scale groundwater abstraction be monitored to avoid over-pumping of an aquifer and damaging the surrounding environment. To gain accurate estimates of groundwater reserve requirements requires extensive and costly hydrogeological and environmental impact assessment of the given study area. This could be avoided by adopting a conservative approach, allowing a large amount of the groundwater to be allocated to the environmental reserve. This approach was taken when establishing suitable pumping rates for the systems at Laingsburg, where 50% of the available water was allocated to the reserve and the remaining 50% was considered available for exploitation.

6.2.5.3 *Design of Infiltration Galleries and Caissons with Horizontal Well Screens*

The following design norms were adopted for the design of these systems:

- A maximum infiltration rate (into the sand from surface flow) of 1.5 $m^3/m^2/hr$ was set. This was required to minimise the rate at which fine particles can penetrate and block the voids in the surface layer of the sand.
- A maximum hydraulic gradient of 0.45 (fine sands) to 1.0 (coarse sands) was allowed. The maximum hydraulic gradient occurs in the system as the flow enters the abstraction pipes. This was done to ensure laminar flow into the system. Darcy's equation for flow through a porous medium could then be used to calculate the flow through the sand bed.
- Based on information obtained from the distributors of Johnson's well screens, the following design norms were adopted for the flow in the horizontal well screens.
  - ➢ Maximum flow velocity through the screen slots: 0.03 m/s.

    This was done to:
    - o Maintain the hydraulic gradient in the sand surrounding the pipe within limits for laminar flow.
    - o To minimise the infiltration of fines into the well screens.
    - o To minimise head losses through the screen.
  - ➢ The maximum flow velocity in the well screens: 0.8 to 0.9 m/s
  - ➢ Maximum head loss in the well screen: 0.3 m
  - ➢ Slot size selection such that 80 to 100% of the surrounding sand is retained outside the screen.

  It is necessary to adopt these design norms to:
  - ➢ Retain the fine fraction of the sand outside the screen.
  - ➢ To keep any fines that do migrate into the screen in suspension, so that they are washed out of the well screens and do not accumulate in the screen, thus blocking the screen.
  - ➢ To keep head loss in the well screens to a minimum.
- In order to maintain the design norms as the flow in the well screen increased, it was recommended that the diameter of the screens be changed along the length of the screen.

- The depths at which the screens were installed in the riverbed were determined by the profile of the bedrock. The screens were installed as deeply as possible in the sand bed. This was done as it is difficult to determine the depth of bed fluidisation under flood flow conditions, and it is considered prudent to install the screens as deeply as possible.
- The size of the caissons and infiltration gallery were generally determined by the construction method e.g. where the horizontal screens were jacked into the sand from the caissons it was necessary to size the caissons such that the necessary equipment for installation of the screens could fit into the caissons.
- The collector pipe or collector gallery were sized to keep head losses in the pipe to an absolute minimum. This would ensure that the heads against which the different caissons were operating would be virtually identical, and would ensure that all the caissons connected to the pipe would be used to their full potential. The maximum allowable head loss from the furthest caisson to the intake tower was therefore set at 0.1 m.
- The permeability of the sand was determined both through permeability tests and using Casagrande's equation.

Design equations developed and used for the determination of flow through the sand and screens, and the associated head loss in a system with parallel horizontal well screens and a collector gallery are included in *Appendix R*. Similar equations can be developed from first principals for horizontal well screens installed in different configurations e.g. a radial configuration.

6.2.5.4 *Design of Well Screens Connected to a Manifold in the Riverbed*

Mr C. Ambler-Smith of Nottingham Estate (system 15) has had more than 20 years experience with the installation and use of abstraction systems. In an interview with him the following points were noted regarding the general design of sand abstraction systems, with particular reference to well point type systems:

- A factor of safety should be allowed for in the design of systems, with the systems generally being ±25% over-designed. This should be done to cater for the risk of clogging of well screens through rust (steel screens), the accumulation of fines, siltation and / or the build up of salts or biofilm in the screens.
- The systems should be designed for abstraction at relatively low velocities. Mr Ambler-Smith recommended that:
  - Velocities in the well points are kept to below ±3 ft./s (0.914 m/s).
  - Velocities in the mainlines or manifolds are kept to below ±5 ft./s (1.52 m/s).

Velocities in the systems should be kept low for a number of reasons, including:

- To minimise the ingress of fines into the well points.
- To reduce the friction losses with flow into the well points. It was found that there is approximately a one third greater power requirement (based on the volume water pumped and delivered pressure) for pumping from sand abstraction systems than for pumping from surface flow. This is attributed to friction losses in the sand and as the water flows into the well screens. By minimising the flow velocities in the system, these friction losses can be reduced.
- Higher entrance velocities into the well screens result in more abrasion on the slots of the screens.
- When using positive displacement or mono pumps, unless operating at low velocities, vibrations develop in the system and the wear on the pump rotor and stator are increased.

6.2.5.5 *Design of Vertical Well Points*

Generally vertical well points were designed based on findings from test holes drilled and the hydrological and production pump tests conducted.

The following norms were applied when designing vertical well point systems:

- The well points were spread over a large distance to minimise the draw down in the alluvium.
- In sands with a relatively high percentage of fines, it was recommended that well points of smaller diameter e.g. 50 mm be installed. Very high levels of drawdown were experienced during dry periods when using well points of large diameter. This in turn resulted in an increased suction head against which pumps were operating and increased power requirements for pumping.
- In larger rivers that are surface dry, the well points were sited such that they were installed in the main subsurface flow channel in the riverbed.
- The configuration of the well points was varied, depending on the position of clay lenses relative to the system.
- Where conditions were suitable, the well points were installed below clay layers in order to abstract water of better quality. Clay layers in the alluvium can seal out saline water from the lower portion of the sand bed, where the water quality is less saline.
- Experience has shown that a greater slot area is required the greater the distance of the well point from the pump.

- Where possible well points should be anchored to the bedrock. Alternatively well points should be tied to stakes or concrete beams driven into the riverbed.
- Non-return valves were not incorporated in the systems, as the systems were designed such that the well points could be backwashed.
- Generally centrifugal pumps were used to pump the well point systems. Centrifugal pumps were preferred to mono-type pumps for the following reasons:
  - Positive displacement or mono pumps can cause vibrations in the system, and wear on the pump rotor and stator can then be rapid.
  - Submersible pumps have been found to be up to ten times more efficient than non-submersibles, but the pumps generally do not allow sufficient flexibility in adjusting flow rates.

  Ideally, a system should be equipped with a centrifugal pump, with a submersible pump as backup.
- System alignment relative to the river was varied. It was, however preferred not to install the systems directly perpendicular to the flow of the river, as systems installed in this fashion are more likely to be washed away during flooding.

6.2.6 Construction Methods

Construction methods implemented varied considerably. Methods used for installing different types of systems are discussed below. Although requested by the Project Committee, the specific ratio between the cost of construction and the performance of the system could not be determined, as details of cost and specific performance were generally unknown.

6.2.6.1 Caissons

The most commonly used method for installing caissons is described below:

- At the site of the caisson, the unconsolidated sand was excavated to the level of the water table.
- The caisson rings were placed in the excavation. The excavations around the caisson were NOT backfilled at this time. This is important to note as it was found that if the excavations were backfilled at this stage then problems were experienced with getting the caisson to settle/drop into further excavations.
- Sand and clay inside the caisson was then excavated to bedrock level, and the caisson rings were allowed to drop as the sand was excavated.
- Wet sand in the caissons used to form a slurry, which was pumped out of the caisson using a slurry pump.
- Clay layers, and larger stones or small boulders that were encountered were removed manually.

- Once the caisson was founded on bedrock, aggregate was tremmied onto the floor of the caisson and levelled at a suitable depth. The aggregate was then covered with a sieve or mesh with suitably sized openings.

6.2.6.2 *Infiltration Galleries and Caissons with Horizontal Well Screens*

Various methods were implemented to install infiltration galleries or caissons with horizontal well screens. In general, the installation of these types of system proved to be the most problematic, costly and time consuming. This may, however be the impression given as these systems are generally installed where larger yields are required.

For all methods implemented to install these systems, excavations were dug for the installation of the caissons or galleries, and the caissons or galleries were constructed using normal methods of construction for reinforced concrete.

The most commonly used method for installing the well screens is described below:

- The systems were installed by excavating the sand bed to the required depth for the laying of the horizontal well screens. For the installation of single well screens deep wide trenches were excavated, while for the installation of a bank of well screens, the entire area in which the screens were to be installed was excavated to the appropriate depth.
- The screens were then laid in the excavated trenches. Where systems incorporated graded filters, the selected aggregates or sand were then packed around the screens prior to backfilling.
- It was normally necessary to dewater the sand continuously throughout the installation of the horizontal well screens.

In most cases problems were experienced during the laying of the horizontal well screens in this manner. These included:

- Problems were experienced with excavation plant sinking into the sand bed. This occurred when the sand bed was not sufficiently dewatered prior to excavation. In one instance (Melkbosstrand – system 4) this problem was resolved by dewatering the bed prior to continuing with excavations. Vertical well points were jetted into the sand, and water was pumped from these continuously, thus dewatering the aquifer. It took an average of 3 to 4 days to sufficiently dewater an area to allow for continued excavation.
- General problems were experienced with continuous dewatering of the excavations.

- In a few cases problems were also experienced with flooding of the works prior to completion of the system. This resulted in a large amount of silt and debris being washed into the systems. This included rocks, clay and even a small dewatering pump. Indications are that a large amount of fines washed into these systems prior to completion has a significant negative impact on the system from the time it is commissioned.

An alternative method of installing these types of systems involves the jacking of the well screens into the sand from the caisson or gallery. This method, as implemented at Nqutu (system 31) is described below:

- The work commenced with the installation of the collector pipe and caissons.
- The excavations for the caissons and collector pipe were protected and kept dry using cofferdams. The cofferdams were constructed using sand bags and cement.
- Initially the first sections of the horizontal holes for the well screens were drilled from the caissons through the sandstone and shale (300 mm ø).
- The remainder of the holes for the horizontal screens (300 mm ø) were formed by jacking a casing with a steel drive point into the sand. The drive point of the casing was connected to a pipe inside the casing, which allowed for the removal of material from the shaft, thus facilitating jacking.
- The abstraction pipes were installed in the casing and the casing was removed.
- During construction once installation of a well screen was completed, it was sealed with a screwed sewer plug. This was done to keep the water levels in the caissons sufficiently low to allow for the installation of all the horizontal well screens.
- On completion of installation of the well screens, each well screen was developed by jetting pulsed flows at high pressure into the screens.
- The construction of the caissons was relatively expensive, as they were installed in hard weathered sandstones and shales. It was, however, believed that the additional expense was justified, considering the improved stability of the caissons that would be achieved, particularly during floods. In addition, the accessibility of the system during flood flow conditions would also be improved by installing the system in the rocky bank. The system has now been operated for twenty-three years without sustaining any major damage during floods.
- Typical problems experienced during construction when using this method included:

- ➢ Problems with the sealing of the first sections of the horizontal holes that were drilled through the sandstone and shale. The caissons were often flooded with sand and water form these holes.
- ➢ The works were flooded five times during construction.
- ➢ During installation of the well screens, problems were experienced with sealing installed well screens to allow for continued work in a caisson. Problems were also experienced with aspects such as installing screens/casings skew.

6.2.6.3 *Horizontal Well Screens Connected to a Manifold Installed in the Riverbank*

The installation of these systems was generally relatively easy and low cost when compared to the installation of other types of systems. The installation method used for the majority of the system s operated by Umgeni Water (Mtwalume, Umzinto and Umkomaas) is described below.

- Normal construction methods were generally used for the installation of the pipe manifold and isolating valves and of the pump station on the riverbank.
- The horizontal well screens were then connected to the manifold and laid on the surface of the riverbed. The screens were then simply allowed to settle into the sand with time. This was possible as the screens are attached to the manifold by a section of flexible helical piping.

Some innovative measures implemented when constructing the pumping stations for these types of systems, included the use of brickwork as shuttering for the concrete work for the pump station. This helped to prevent the ingress of water into the works when pouring concrete, and is generally more aesthetically pleasing than a plain concrete structure. This was done at Umdloti (system 29).

6.2.6.4 *Vertical Well Points Installed in the Riverbed*

Virtually all vertical well point systems installed in the riverbed were installed in the same manner. The following methods were generally used:

- The systems were normally installed during the dry season.
- These systems were generally installed using a bulldozer, dewatering pumps and a simple cable tool drilling rig.
- Where well points were connected to a manifold, the sand bed was excavated to the level of the water table, and the manifold was laid in the sand bed at this level. Excavations were either done manually (smaller systems) or using a bulldozer
- The vertical well points were then either jetted or driven (hammered) into the sand of the riverbed from the level of the excavations. Where single well points were installed the well points were installed from the surface

level of the sand bed. Typically, jetting the screens into the sand involved:

- ➢ The use of small diameter jetting pipes to wash a temporary casing into place. The temporary casing had an internal diameter larger than the outside diameter of the casing and screens that were to be installed. The hole was washed through the sand by the water that emerges from the jetting pipe.
- ➢ When the casing was installed to full depth, the jetting pipe was removed and the casing was flushed clean.
- ➢ The screen and casing were then installed in the temporary casing, and the temporary casing was manually removed.

- Each well point was developed separately to remove fines from the vicinity of the well point, effectively creating a graded filter. This was done by hand surging the well points or by back washing them, using both water and compressed air. Development of the well points is essential for efficient functioning of the systems.

  In some instances development was done using the jetting tool, typically a small diameter tool with multiple nozzles that discharge water at high velocities. Clean water from the previous well point installed was used to develop the next well point.

- During connection of the pipework it was found advantageous to lay the pipe "uphill" to facilitate bleeding any air out of the system.
- The entire system was then connected to the suction end of a pump, which was installed in the riverbank.

6.2.6.5 *Vertical Well Points Installed in the Riverbank*

When installing vertical well points in the riverbank, normal procedures for installing a borehole were usually followed.

- The vertical wells/boreholes were drilled in the alluvial aquifer of the riverbank. Drilling techniques used included direct circulation mud rotary drilling with biodegradable drilling fluid flush.
- A casing of PVC or steel was then installed in the borehole, with the lower section of the casing being a well screen or perforated pipe.
- In most instances, the casing was surrounded by a selected aggregate gravel pack.
- In some cases, the upper section of the casing and gravel pack were enclosed in a steel sleeve, which was cast in concrete. This was done for protection against damage during flooding.
- The wells were then developed for the following reasons:

- To repair the damage to the formation caused by the drilling of the well hole.
- To alter the physical characteristics of the aquifer near the well such that water will flow freely into the well.
- To achieve sand free water and the highest possible well efficiency.

Wells were developed by:

- Air lifting for to discharge drilling fluid and induce ground water flow.
- Backwashing and surging. A column of water was lifted above the pumping water level and allowed to fall back into the well point. This has a rinsing action in the screen, gravel pack and formation around the screen.
- High velocity jetting and airlifting. Chlorinated water was used with simultaneous airlift pumping.

Development time can vary between 12 and 48 hours. Once the wells were developed, submersible borehole pumps were installed.

6.2.6.6 *Gabion Type Systems*

Installation of the gabion type systems is generally simple and is as follows:

- The riverbed was excavated to the required depth for the installation of the gabions.
- A level surface was created on the bedrock of the riverbed. This was done by packing rocks to create a level platform.
- Concertina gabion boxes were used to form the sump and the gabions were packed with stone.
- In some cases (Pungashe – system 27) plastic pipes were installed vertically in the gabions, for the full height of the sump. These pipes were filled with concrete and reinforcing steel. The cover slab was anchored to the concrete and steel in these pipes.
- Reno mattresses were also often installed around the systems to prevent local erosion.

6.2.6.7 *Abstraction Chambers*

Standard construction methods were used for the installation of these systems, with the necessary excavations being dug in the riverbed and bank for the installation of the system.

6.2.6.8 *Small-Scale Abstraction Systems*

For small-scale abstraction systems such as the hand pump systems developed by Dabane Trust (Whuwana, system 18 and Shangani, system 21) a typical installation involved:

- The well screen was jetted into the sand. This was done using a potable diesel driven pump.
- The sump and trenches for the pipework for the Rower Pump and Joma pump were hand excavated.
- The Rower and Joma Pumps were manufactured by Dabane Trust, using normal plastic pipe and pipe fittings.
- All sumps and other structure were constructed using reinforced concrete, blockwork or stonework.

6.2.7 Problems Experienced with Systems

Numerous and varied problems were experienced with sand abstraction systems. With the exception of the smaller systems, virtually none of the abstraction systems investigated were problem free. It must, however, be noted that although problems are experienced at a system, it does not mean that the system is not a successful application of sand abstraction methods. Many systems are well managed, operated and maintained, and measures are taken to prevent and remedy problems that occur in the systems. Thus, successful systems are not necessarily problem free systems, but are generally those systems that are properly managed and operated.

The main types of problems found to occur with abstraction systems are:

- Problems of low yield, where the system does not meet the design yield, or there is a decrease in system yield over time.
- Poor quality of abstracted water, specifically with respect to high iron and manganese concentrations.
- Flood damage.

These and other problems experienced at sand abstraction systems, and the probable causes of these problems, are discussed below. Remedial measures, both successful and unsuccessful, that have been taken to alleviate these problems are discussed in Section 6.2.8.

6.2.7.1 Low Yield, Other Causes

Problems of low yield were experienced in at least 20 of the 39 systems visited (51%). Generally, problems of low yield have not occurred at the smaller scale systems with low demands. In some instances insufficient information was available to state where problems of this nature had occurred at the system. The main causes of problems of low yield were identified as either one or a combination of the following factors:

- Reduction in the permeability of the sand, through the accumulation of fines in the sand bed or on the surface of the sand.
- Clogging of the well screens by iron or manganese precipitate.

- Clogging of the screens by the development and accumulation of biofilm in the screens.

These causes of problems of low yield are discussed in further detail in the sections following. Other causes of problems of low yield include:

- *Degradation of Materials*

  In some instances piping and well screens have degraded, resulting in either clogging of the well screens through rusting, or the development of operational problems caused by holes in piping, damaged or worn pumps etc. This is particularly prevalent in older systems, which were constructed prior to the advent of the variety of plastics and other corrosion resistant materials. Examples of this include:

  - Chikwarakwara (14)

    Well points for the original system were fabricated in 2" galvanised steel pipe, with longitudinal slots cut with an oxy-acetylene torch. High tensile steel galvanised wire was wound around the pipe over the entire length of the slots, with the ends welded in place. This was done on a slow moving lathe. The wire surfaces were, however, in contact with each other. This resulted in the aperture being very narrow, and the screens were rapidly clogged, either through rusting or the accumulation of fine sediments, salts etc.

  - Chisumbanje (16)

    In 1992 a severe drought was experienced in Southern Africa. At this time problems were experienced with priming the pump of the system installed in 1983. This was due to corrosion of the pump.

  - Shashani (19)

    Problems were experienced with clogging of the screens with rust.

  - Umkomaas (24)

    Problems were experienced with holes in the sections of helical piping connecting the well screens to the manifold.

- *Clogging of Geofabrics*

  In general, where geofabrics have been incorporated in an installation, it has been found that they clog, resulting in a reduction in the permeability of the geofabric and associated reduction in yield of the system. Clogging of geofabrics is not as severe when used in systems that are installed in very coarse sands and in rivers that do not have high turbidity. Clogging of geofabrics with an associated reduction in yield has occurred at the Messina (13), Mpungamhlophe (35), Opuzane (33), Mtwalume School (25) and Glover (30) systems.

  - Opuzane (33)

    The horizontal well screen was wrapped in Bidum U34. Although the bidum has not been inspected, clogging of the geofabric can be virtually the only reason for the reduction in yield of this part of the combined type abstraction system.

- Mtwalume School (35)
  Samples of the geofabric (Kaymat U64) were taken from the geofabric around the gabions approximately two years after the system was installed. The permeability of the samples was tested, and it was found that the permeability had reduced by a factor of ±10. The permeability was measured as 10 000 ℓ/m²/hr or 2.778 mm/s.

- *Induced Stress on the Aquifer*
  At Messina, it was found that if the aquifer was stressed through over pumping, then the recharge rates decreased. It has been found that if the water level is drawn down too far, then a wedge of dry / unsaturated sand is formed in the riverbed, and the recharge rate into such a wedge is very low. The system is now operated such that the alluvial aquifer is not stressed. The use of the abstraction points is rotated, with blocks of about 7 to 8 abstraction points being used for short periods. This is done to prevent excessive drawdown in the sand around the abstraction points.

- *Drop in the Level of the Water Table*
  It is relatively self-explanatory that the yield of a system will decrease when there is a drop in the level of the water table. The level of the water table will drop if:
  - Low rainfall, and hence low recharge rates, is experienced.
  - The abstraction and use of the water in the upstream catchment has increased.
  - The abstraction system is being over pumped, stressing the aquifer such that water levels do not return to the original level.

  At the Wilgehout (2) caisson, it was found that the level of the water table dropped around the caisson after many years of use of the caisson. This occurred shortly after the abstraction system upstream of the caisson was improved, and a borehole in the catchment upstream of the caisson was commissioned. It is likely that the drop in water level at the caisson could be attributed to the increased efficiency of the abstraction system upstream of the caisson. In addition, with the borehole in the upstream catchment being brought into production, it is possible that some of the recharge that would normally have fed into the abstraction system catchment is now recharging the borehole aquifer.

  Other systems where declining water levels have resulted in reduced yield of the system include Nottingham Estate (15), Shashani (19)

- *Movement of Well Screens Within the Riverbed*

  At some systems, it has been found that well screens move within the river bed during periods of high flow. This occurs most frequently when well screens have been installed attached to a manifold by means of a section of flexible piping. In some cases the well screens settle in the sand at a level above the level of the water table in low flow periods. It is possible that this has occurred at Shashani.

- *Change of the Course of Flow of the River Within the Riverbed*

  With systems that are designed for the abstraction of surface water flow, problems are often experienced during low flow periods, when a river changes its normal flow course within the riverbed and the surface flow is no longer near the abstraction system. It then becomes necessary to divert the stream flow, using sand bags or similar such that it is flowing over the well screens. This problem has been experienced at systems including Mtwalume (Umgeni Water) (22) and Apel Mission (39).

6.2.7.2 *Rapid Loss of Yield after Commissioning*

At three systems it was found that the system yield reduced rapidly after commissioning, the system performance finally stabilising at a yield of approximately ⅓ of the design yield. This occurred at Ulundi (29), Havercroft Mine (37) and Olifantspoort (48 - not visited).

At Havercroft Mine, a multiple caisson system installed in the riverbank, it was also found that the influence of adjacent caissons on each other increased markedly with time. When the system was first installed (1997), the extent of interference was negligible. In 1999, the yield from the total system remained virtually the same whether one or three caissons were in use, indicating that the extent of interference between the caissons had increased considerably from the time of installation. The yield from the caisson located closest to the river is, however, greater than that from the other caissons.

For all three systems comprehensive testing and investigations were conducted during the feasibility and design phases, and the design of the systems was based on the findings of these investigations. At all three systems potential yields were calculated based on the parameters of the sand, or production yields were recommended based on the results of pump tests. It is therefore difficult to explain the rapid drop in the yields of these systems. Indications are that the installation and use of the abstraction systems have impacted on the alluvium in which they are installed, rapidly altering the characteristics of the alluvium and decreasing the transmissivity or permeability of the surrounding sands.

Both the Ulundi and Olifantspoort systems were flooded prior to the completion of construction. In both cases fine silt, clay and organic matter were washed into the collector system (gallery and well screens at Ulundi and "culvert collector" at Olifantspoort). It may be that the initial ingress of fines into these systems has contributed to the rapid decline in the performance of the systems.

Reasons that have been identified as probable causes of low yield at these systems are discussed in the sections following.

6.2.7.3 *Biofouling*

Biologically induced fouling, or biofouling, is the phenomenon whereby surfaces in contact with water are colonised by micro-organisms, which are ubiquitous in our environment (Costerton and Bovin, 1987). The mechanisms of biofouling are discussed in Section 3.2. Essentially a slimy matrix is formed in the well screens, clogging the slots of the screens and thus resulting in reduced yield of the system.

Biofouling is difficult to identify in sand abstraction systems, as it is usually not possible to inspect the abstraction points or well screens. An indication of possible biofouling can be obtained from the total numbers of planktonic (free floating) bacteria in the water of the system. This however is only an indicator of biofouling, as numbers of planktonic organisms may provide little information as to what is occurring on the surface because there is often no relationship between sessile (attached) and planktonic numbers.

Despite the difficulties associated with identifying biofouling, there are indications of biofouling at a number of systems listed below.

- *Umzinto (23):*
  - ➢ Problems have been experienced with the accumulation of organic slime on the screens.
  - ➢ At the time of the site visit in 1999, the sand riverbed had been excavated to the levels of the screens. It was noted that at the level of the top of the excavations (approximately 1 m below water level) a thick black granular slime had accumulated. Tests of this slime indicated both a very high fines content, as well as high total bacterial counts. It is speculated that this is a combination of bacterial growth, probably iron reducing bacteria, and iron precipitate. This could well be causing the low yield problems experienced at the system.
  - ➢ It has been noted that there is development of iron bacteria against the upstream face of the weir downstream of the system.

- *Umvoti (Illovo Sugar) (28)*

  There was evidence of bacterial growth (possibly iron reducing / oxidising bacteria) in water samples taken from the system during the site visits in 1998.

- *Nqutu (31)*
  - In 1999, at the time of the site visit, Bradford, Conning and Partners, Newcastle were conducting investigations, into problems of low yield being experienced at the system. These problems had commenced in about June 1998.
  - Indications were that the screens were clogged by a combination of biofilm and/or iron precipitate, and the ingress of clay particles into the screens. This was evidenced by:
    - All the abstraction pipes were found to be coated with a granular, black slimy material. In some of the screens the layer of this material inside the screen was up to 10 mm thick.
    - A thin layer of clay was present in the bottom of the well screens.
    - The screens with the thickest coating of black slimy matter had the least amount of clay in them, but had the highest flows. The screens with the largest amount of clay in them had the lowest flows.
  - At the time of the site visit a magnetic flow meter had been removed from the intake to the water treatment plant. Discrepancies had been found in the flows measured entering the plant and leaving the plant and the meter had been removed to service it. It was found that the meter was thickly coated with a similar black slimy granular substance to that coating the abstraction pipes. The coating of this substance was so thick inside the meter that the flow velocity through the meter had increased, thus affecting the measured flows.
  - Tests conducted on the black matter removed from the screens and the flow meter showed high bacterial counts (2.5×10^7 cfu/ml). This clearly indicates that bacteria are contributing to the fouling of the system.
  - It was unfortunately not possible to test the substance for iron content. Light microscopy performed on the samples did, however, show large quantities of granular debris in the sample.
  - Considering these results, it is speculated that biofilm develops on the inside of the screens and pipe fittings, trapping particulate matter in the biofilm. Iron precipitation may also be occurring, with the precipitate being caught in the biofilm. This will lead to clogging of the screens.
  - As was noted, where the black film on the inside of the screens was the thickest, the least clay occurred in the screens. It is possible that the biofilm prevents the ingress of clay into the screen, but this may in turn result in a build of clay in the sand immediately surrounding the screen.

- *Ulundi (34)*

  Numerous and detailed investigations have been conducted to determine the cause of the problems of low yield. The results of these investigations are discussed in a report by Chunnett Fourie, enclosed as Appendix J.40.12. In summary, the actual cause of the problems of low yield could not be identified, but a number of factors are thought to contribute to it, including microbiological fouling. There are numerous factors that indicate that there is biofouling in this system, including:

  - High total bacterial counts, (of the order of > 1 x 10^6, to > 1 x 10^7) in water samples taken from the system. Water samples taken from the system at intervals from 1995 to 2000 showed high total bacterial counts. Findings of the analyses conducted on water samples taken from the system are discussed in Appendix J.40.13: Report, Microbiological Analysis of Ulundi Water Samples and Appendix F.1: *"Report: Microbiological Analyses of Samples from Sand Abstraction Systems"*
  - Bart tests (tests used to identify iron, sulphate and slime forming bacteria) showed insignificant growth of slime forming bacteria, but aggressive growth of iron reducing and sulphate reducing bacteria.
  - Samples of biomass taken from the system were identified as iron bacteria of the genus *Leptothrix* (also called sheath-forming bacteria). This is discussed in Appendix J.40.13. The identification of the bacteria present in the system as sheath-forming bacteria is a strong indication that the problem of low flow through the abstraction works is caused by biofouling. It has been documented that these organisms are known to "grow in pipes along with deposits of iron or manganese and interfere with the passage of water in wells and filtration plants."[4].
  - Other samples of biomass were identified as black algae, as discussed in Appendix F.1.
  - A section of well screen was excavated and removed from the system. The inside of the pipe was coated with a brown slime of bacterial sheaths and there was evidence of similar slime in a number of the slots on the exterior surface of the pipe.
  - Test units (Pederson devices, (as described in Section 4.2.5 and Appendix D) were installed in the screens of the system, and left in the system for a period of approximately 6 months. On removal of the test units from the system, it was found that the slides and screen sections in the test units were covered with biofilm. This is shown in Appendix J.40.10. Slides from the test units were studied using scanning electron microscopy (SEM) techniques. The SEM showed that algae, bacteria and slime were present in the samples, with the dominant substance on the slides being the slime matrix (polysaccharide slime), which could be produced by both the bacteria and/or the black algae present in the biofilm. It was found that the

thickness of the biofilm on the slides was such that it could cause clogging of the screens. Photographs of the biofilm taken using SEM, together with discussion of the findings of the microbiological investigations are discussed in *Appendix F.1*.

It is probable that biofouling may often be associated with problems related to high concentrations of iron and manganese in systems. Based on the findings of this research it is, however, difficult to test this hypothesis. This is due to number of reasons, including lack of data:

- At many of the systems where there are reported problems with high iron concentrations, it has been difficult to obtain samples from the systems. These systems are either not in operation or only used in emergencies (Fairview (26), Umvoti (28), Mtubatuba (46) and Hibberdene (45)).
- Many of the other systems, where problems associated with high iron concentrations are reported, are backwashed regularly at high pressures (Mtwalume (22), Umzinto (23) and Umkomaas (24)). During backwashing operations at high heads, biofilm would be disturbed and broken off the screens.

6.2.7.4 Reduction in Sand Permeability

Reduction in the permeability of the sand following the installation of the abstraction system has occurred at many sites. This occurs either through the ingress and accumulation of fines in the sand bed, or through the natural deposition of fines on the surface of the riverbed during low flow periods.

- *Deposition of Fines on the Surface of the Sand*
  - Laingsburg 1 and 2 (2 and 3)
    Fine sediments deposited on the surface of the riverbed dry out and form an extremely hard layer on the surface. During site visits, This layer could not be penetrated using hand augurs and it was necessary to first excavated a hole in the river bed prior to taking augur samples. Similar problems were experience by members of the CSIR when conducting tests at these sites.
  - Fox Farm (5)
    The development of a caked silt layer on the surface of the sand occurs. This silt layer effectively seals the sand.
  - Umkomaas (24)
    Problems of low yield are caused by the accumulation of silt, or clays in the system and on the surface of the riverbed. This becomes severe during low flow or drought periods when there is not sufficient surface water flow to wash away the silt deposited on the surface of the sand. The silt layer effectively seals the surface of the sand.

- Apel (39)

  Considering the sand bed, although the sand in the river is generally coarse, there is a layer of clay and silt that has built up just beneath the surface layer of coarser gravels and sand. This may be a factor contributing to the low yield of the system, causing clogging of the sand around the abstraction system.

- *Accumulation of Fines in the Sand Bed*

  In many cases reduction in the permeability of the sand has occurred where, during construction or site investigations, clay lenses were found in an otherwise generally coarse alluvium with relatively low fines content. Indications are that through the installation and operation of an abstraction system in the sand bed, fines are drawn into the sand around the system, accumulating and reducing the permeability of the sand in the vicinity of the abstraction systems.

  Clogging of screens by some agent (biofouling, precipitation or fines) and the accumulation of fines in the sand surrounding an abstraction point appear to be interactive. It is speculated that with clogging of abstraction points, flow into the abstraction point is reduced, with an associated reduction in the velocities in the surrounding sand. Fines therefore can be drawn to the system, but velocities in the bed are not high enough to draw them through the sand into the abstraction point. This leads to an accumulation of fines in the sand and an associated reduction in the flow through the sand reaching the abstraction point. There is then a reduction in the flow velocities entering the abstraction point and a reduction in any scouring effect of flow into the slots of the abstraction point. Clogging material can thus accumulate more rapidly. This is very much a circular "chicken and egg" situation. This interaction could explain why, once problems do develop in a system, the extent of the problem increases extremely rapidly.

  - Fox Farm (5)

    Reduction in yield of vertical well points at Fox Farm was first attributed to clogging of the screens by iron and manganese precipitation. The screens were therefore removed and cleaned before being reinstalled in the riverbed at the same sites where they were originally installed.

    Although the yield of the system increased once the screens were cleaned, it was still lower than the original yield achieved when the well points were initially installed. Backwashing the well points at high pressures for an extended period (i.e. developing the sand around the system) resulted in an improvement in the yield. This indicates that there was a reduction in permeability of the sand around the well point, probably through the accumulation of fines in the sand around the well points.

- Teyateyaneng (8)

  This system was abandoned due to poor yields. The sand had a high percentage of fines. It may therefore be possible that clogging of the sand bed itself has occurred.

- Nottingham (15)

  Low yield problems are sometimes caused by the accumulation of fines in the sand. It has been noted that after operating one system virtually continuously for a period of a year, there was a high level of accumulation of fines in the system. The system was then backwashed. Subsequent to this, however, it was found that there was significant fines accumulation within a period of about a month.

- Chisumbanje (16)

  Problems were experienced with clogging of the system installed at Chisumbanje in the 1970's. Reasons for the clogging of the system were not established, but it is likely that the following factors may have contributed to the problem:

  - The system was not properly developed.
  - The system was installed at a relatively shallow depth in the riverbed, possibly resulting in the ingress of fines from the surface of the riverbed.

- Mtwalume (22)

  Problems are experienced with accumulation of fines in the sand. The system is, however, designed to be backwashed at high pressures. As part of normal operation procedures the system is backwashed approximately 4 times per week, or more often if required.

- Umzinto (23)

  It was noted by the design engineer, that when this system was installed, the clay fraction in the sand was less than in the sands at any of the similar systems constructed for Umgeni Water (Mtwalume (22), Umkomaas (24)). A clay lens was, however, encountered in the sand bed when the system was first installed. This is important to note, as of the three systems, Umzinto has proven to be the most problematic, particularly with respect to clogging of the system by accumulated fines. This may well be linked to the presence of the weir immediately downstream of the abstraction system.

- Umkomaas (24)

  It is believed that some of the problems can be attributed to disturbance of the sediment through sand winning operations on the opposite bank and just downstream of the system. Sand winning upstream of the system may, however, benefit the system, as sediment is removed from the river prior to reaching the system.

- Nqutu (31)
  Investigations into problems of low yield at Nqutu showed that the low yield was likely caused by a number of factors, including accumulation of fines in the sand and clogging of the screens, partly by the ingress of clay particles into the screens. This was evidenced by:
  - A thin layer of clay was present in the bottom of the well screens.
  - The screens with the thickest coating of black slimy matter had the least amount of clay in them, but had the highest flows. The screens with the largest amount of clay in them had the lowest flows.
  - A reduction in permeability of the sand around the well screens, as a result of the ingress of clay into the sand bed.
- Havercroft Mine (37)
  An important observation made during the site visit was the evidence of the sand being sealed, probably by clays. A small hole was dug in the riverbed, where the bed was surface dry, immediately adjacent to the surface flow in the river. The water level in the hole was approximately 15 cm below the level of the water flowing on the surface of the sand bed, approximately 30 cm from the hole. The water level in the hole did not rise above the observed level. The only possible explanation for this is that the sand is sealed, with no flow between the surface flow and the hole. Should a similar phenomenon occur deeper in the sand bed, this could possibly explain the reduction in yield of the caissons.

- *Accumulation of Fines at Depth*
  It has been at a number of systems that there is an accumulation of fines in the sand bed at depth. The percentage fines in the sand decreases from the surface of the bed, and then increases to a maximum at greater depths, either at the level of the horizontal well screens (if present in the system), or just above the bedrock.

  This was found at Ulundi (34), Mpungamhlophe (35) and Umzinto(23). When the Mpungamhlophe system was excavated prior to replacing the system, a layer of silt and fines was found at the bottom of the sand bed around the screens. Similarly, the screens of the Umzinto system were excavated in an attempt to increase the yield of the system, and a layer of fines and a black slimy material was found at the depth of the screens. Sand samples were taken from the sand bed at Ulundi at various depths. The accumulation of fines was identified from the grading analyses conducted on these samples.

These three systems have two main factors in common. They were the only systems visited that were installed immediately upstream of a concrete weir. They are also all systems that incorporate banks of horizontal well screens.

With the banks of horizontal well screens, water will be drawn vertically down through the sand bed over a relatively large area. Fines will therefore also be drawn into the bed over the same area. It is likely that the obstruction caused by the weir in the riverbeds impacts on the accumulation of fines at depth. With the weir, there would be no horizontal flow of water through the sand at depth, and any fines drawn into the sand by the abstraction system would remain in the sand. At other systems these fines would be washed out of, or through the sand under higher flow conditions.

Posing this as a possible cause of this phenomenon, one would then ask why similar problems are not experienced with systems such as the sand dams constructed in Namibia. There are a number of differences between sand dams and the three weirs at the systems discussed above.

- Sand dams are constructed in phases, with the sand dam wall being raised progressively over time as the dam fills with sand. The height of each lift of the dam wall is determined such that the flow velocities through the dam are sufficiently high to keep the fines fraction of the sand load in suspension. Coarse sand is therefore accumulated in the sand dam. The weirs at the three systems discussed above were all constructed in a single phase, and were all rapidly filled with sand during one or two flood events. Fine sand would therefore have been deposited in the dams.
- Sand dams are normally constructed in rivers that are surface dry for a large percentage of the year. The three abstraction systems are installed in rivers where there is virtually continuous flow, and the rivers generally have a very high turbidity.
- Abstraction systems installed in sand dams are normally of the caisson or vertical well point type. Fines would therefore not be drawn into the sand to the same extent as with the banks of horizontal well screens.

6.2.7.5 *Problems Associated with High Iron and Manganese Concentrations*

Problems associated with high iron and manganese concentrations have been found in numerous systems, particularly on the KwaZulu-Natal Coast, and in the Northern Province. Two main problems are associated with high iron and manganese concentrations in the water in the alluvium in which sand abstraction systems are installed. These include:

- High iron concentrations in abstracted water.

- The precipitation of iron and manganese in the abstraction system, resulting in clogging of the system. Clogging caused by this precipitation will be worse when associated with significant biofilm development, as particulate matter will be trapped by the biofilm, resulting in rapid clogging of the screens etc.

Typical examples of systems where iron and manganese problems were experienced are the following:

- *Fox Farm (5)*
  It was initially found that delivery lines (LDPE pipes) were being clogged by iron and manganese precipitation. This indicated that similar clogging of the well points themselves could be occurring. In 1999 / 2000 a number of the vertical well points were removed from the riverbed. It was found that the screens were clogged with a black substance, possibly iron and manganese precipitate with some biofilm.

- *Teyateyaneng (8)*
  One reason for the failure of the system could be clogging of the screens by manganese precipitation. On removing screens it has been found that the screens are encrusted with manganese oxide.

- *Mtwalume (Umgeni Water) (22)*
  Problems have been experienced with the accumulation of iron salts and scale in the system, clogging the screens.

- *Fairview (26) and Hibberdene (45)*
  The Hibberdene (45) system is located adjacent to the Fairview system, and virtually identical problems are experienced at both systems.

  At both systems severe problems are experienced with extremely high iron concentrations in the abstracted water. Similar problems are not experienced if water is abstracted from the surface flow.

  In the Hibberdene pumping station, there was evidence of severe corrosion of the centrifugal pumps, and the walls of the pump station were stained orange from water that had obviously been sprayed on the walls when priming the pump.

  During the site visits, although the systems were not in operation, the storage tank of the Fairview system was inspected. The water in the tank was bright orange in colour, with large clumps of biomass floating in the water (hairy in appearance and orange in colour). This could be colonies of iron bacteria. Bacterial counts from the water storage tank were high.

  Samples were taken by members of the Fairview Water Committee when the system was brought back into operation in November 1999. Samples were taken just after starting the pumps and then about 20 minutes after the pumps had been started. The first sample taken was bright orange in colour and had extremely high total iron concentrations. The quality of the water had improved by the time the second sample was taken, but still had high iron concentrations.

There has been a reduction in the yields of both of these systems. Considering the problems experienced with high iron concentrations in the systems, it is possible that this is caused by clogging of the well points either through iron precipitate or through iron bacteria.

- *Nqutu (31)*
  Water samples were taken regularly throughout the construction period. Initially these samples contained high concentrations of iron and manganese, but dropped to within acceptable norms for domestic consumption after water had been flowing through the screens for an extended period of time. This, however, indicates a source of iron and manganese in the catchment, indicating the potential for the development of problems associated with iron and manganese.

- *Apel (39)*
  The array of horizontal well screens is no longer delivering water to the caisson. The screens have become clogged with iron oxide.

- *Mtubatuba (46)*
  Severe problems are experienced with extremely high iron concentrations in the abstracted water. Similar problems are not experienced if water is abstracted from the surface flow. The water abstracted from the well points is otherwise of very good quality, but the cost of treating the abstracted water (for iron removal) is higher than the cost for treating surface water with very high turbidity. The well point system is therefore only used for water supply in emergencies.

  Problems have been experienced with corrosion of the borehole risers. It has been necessary to replace the risers. It is not known whether this problem is related to the high iron and manganese concentrations in the abstracted water.

  It is not known whether there is iron or manganese precipitation occurring in the screens, forming scale in the screens.

6.2.7.6 *Flood Damage*

All systems are at risk to flood damage, but in many instances have proven to be surprisingly resilient under flood flow conditions. Only 9 of the 39 (23%) systems visited have been damaged during floods. Of these 9 systems that were damaged, three have been in place for longer than 20 years (Messina (13), Nottingham (15), Nqutu (31)). Examples of systems damaged during floods include:

- *Chisumbanje (16)*
  A system installed at Chisumbanje in the 1970's was destroyed by floods.

- *Umvoti (28)*
  Some problems have been experienced with flooding of the pumping station, as it is located well within the flood plain of the river and the manhole access to the pumping station is only approximately 2.4 m above the level of the riverbed.

- *Nqutu (31)*
  All the screens in caisson 1, the most downstream caisson, were broken in about 1997, 19 years after installation. Shortly before the screens were broken, sand-winning operations commenced in the riverbed just downstream of the system. It is believed that these operations may have resulted in a rapid shift of the sand bed, as sand moved to replace the sand being excavate from the system. This could have been a major factor contributing to the damage of the screens in caisson 1. One screen in caisson 2 is also broken.

6.2.7.7 *Operational Problems*

Problems have been experienced in training, or persuading, operators to use sand abstraction systems.

Mr Fox (Fox Farm, 5) noted he experienced problems with operators refusing to work if at any time it became necessary for them to go into the river. This would be necessary, if for example, pumps were to be removed to protect them from flood damage.

At Ulundi (34) problems were experienced in training the water treatment plant and pumping station operators how to use the abstraction system. The problem arose in that the operators could not see the water flowing into the pumping station intake works. The outlet from the abstraction system was connected to an existing intake works. Surface water abstracted from the river by conventional abstraction methods flowed from a channel off-take, over screens into this intake works. Previously the operators had been taught not to turn on the pumps when they could not see water flowing over the screens. With the installation of the abstraction works, the water delivered to the pump intake works did not flow over the screens, and pump operators adamantly refused to switch on the pumps. Even when all manholes were opened and they were shown the subsurface flow from the abstraction works, they still refused to start the pumps.

It is believed that the non-operation of the Ulundi system has contributed to the problems of low yield experienced there, as the system and sand bed has never been flushed. Attempts were made to persuade the water treatment plant staff to operate the system on a daily basis, but this was not done and the system has not been in use. This was possibly partly due to the fact that switching from the conventional abstraction system to the sand abstraction system required the opening and closing of a number of valves and sluice gates.

Aspects such as these are important and should be addressed when designing a sand abstraction system. They are, however, difficult to control.

6.2.7.8 *Administrative Problems*

Administrative problems were experienced at some of the abstraction systems installed for community water supply in rural areas. These types of problems are not unique to sand abstraction systems. However, in one instance the poor quality of the abstracted water may have contributed to the administrative problems, which have resulted in the system not being used and standing idle. This, in turn, has exacerbated the problems experienced with the sand abstraction system.

Typical examples of administrative problems experienced at systems are the following:

- *Fairview system (26)*

  Problems have been experienced at the Fairview System (26) with respect to non-payment of the necessary tariffs for water. The Water Committee has then been unable to pay electricity accounts (for running the pumps) and the system has not been operated for extended periods.

  This non-payment by the community can, in part, be attributed to the poor quality of water received from the system. The abstracted water has a very high iron concentration, and community members do not feel it is justified paying tariffs for water that is bright orange in colour, stains their clothes when used for washing and is generally of poorer quality than water abstracted directly from the river.

  It is possible that by letting the system stand idle, a build up of iron and iron bacteria was created in the system, resulting in the subsequent problems experienced with the system.

- *Glover system (30)*

  The Glover system had not really been used at the time of the site visit due to administrative problems. During the initial stages of the project the community signed an agreement as to how they would operate and maintain the scheme. Several problems were experienced with the implementation of this agreement.

Problems were also experienced with the removal and vandalism of standpipes in the village reticulation system. It was then the community's responsibility to replace the standpipes, and the scheme would not be operated until such time as the standpipes had been replaced.

With the system standing idle, fine silt and clay has accumulated in the system, evidenced by the high turbidity inside the gabion sump. It is likely that this could affect the performance of the system in the future.

6.2.7.9 *Other Problems*

Some other problems experienced at sand abstraction systems are described in the following paragraphs:

- *Nottingham (15)*
  - ➢ The development of airlocks in the sand. This situation could be remedied by surging of the system.
  - ➢ High groundwater salinity. It would be necessary to test the salinity of the water on a monthly basis.
  - ➢ The occurrence of siltation inside the well screens.
  - ➢ Pump suction problems.
- *Umvoti (28)*

  The total dissolved solids concentration (TDS) of the abstracted water was found to be quite high, causing other problems when used in the sugar mill. Because of these problems, a well was dug directly in the riverbed and water was abstracted from there. It was found that the high TDS concentration was somewhat reduced when using this well.
- *Makhosine (32)*

  Some problems were experienced with the accumulation of sludge in the wet well of the pumping station. The problem was resolved by cleaning and removing the sludge from the wet well.

6.2.8 Remedial Actions

Although systems are sometimes abandoned when problems are experienced with them, many different types of remedial actions have been implemented to improve the performance of systems. Remedial actions can either be preventative or curative. Actions taken and the level of success achieved by implementing are discussed below.

6.2.8.1 *Fox Farm (5)*

- A layer of silt developed on the surface of the sand, partly sealing the sand and reducing the system yield. The problem was solved by simply herding cattle into the river, thereby breaking up the silt layer.

- In 1999/2000 a number of the vertical well points were removed from the riverbed. It was found that the screens were clogged with a black substance, possibly iron and manganese precipitate with some biofilm. The problem was remedied by removing and cleaning the screens with peroxide. The screens were reinstalled in the riverbed at the same sites where they were originally installed.

- Although the yield of the system increased after the screens were cleaned, it was still lower than the original yield achieved when the well points were initially installed. Backwashing the well points at high pressures for an extended period (i.e. developing the sand around the system) resulted in an improvement in the yield.

6.2.8.2 *Nottingham (15)*

Low yield problems were attributed to the accumulation of fines in the river sand. The system was subsequently backwashed to improve the yield of the system. However, soon after this significant fines accumulation occurred again within a period of about a month.

6.2.8.3 *Mtwalume (22)*

- Problems were experienced with the accumulation of iron salts and scale in the system, resulting in the clogging of the screens. The screens were removed form the riverbed, acid cleaned and then reinstalled.

- Problems were also experienced with accumulation of fines in the river sand. To resolve the problem the system was backwashed at high pressures. Today part of the normal operation procedures is to backwash the system approximately 4 times per week, or more often if required.

  Backwashing of two of the screens was observed during the site visit. The sand bed around the screens is rapidly fluidised during backwashing. Black flaky particles could clearly be seen being washed from the sand, and possibly the screens, during the backwashing process. Backwashing of the system as part of the normal operation of the system has been successful in maintaining the yield of the system at high levels.

6.2.8.4 *Umzinto (23):*

- Problems were experienced with the accumulation of organic slime on the screens. The screens were removed form the riverbed and acid cleaned before being reinstalled. At the time of the site visit in 1999, some of the screens has just recently been excavated and cleaned.

- Problems were also experienced with the accumulation of fines in the river sand. To resolve the problem the system was backwashed at high pressure by releasing water from the storage reservoir at a pressure head of some 50 metres. Today part of the normal operation procedures is to backwash the system approximately 4 times per week, or more often if required. Despite these backwashing measures, problems are still experienced with reduced flow in the system.

6.2.8.5 *Nqutu (31)*

Following the investigations conducted in 1999, the following remedial actions were implemented in an attempt to improve the yield of the system.

- Water containing 50% peroxide was pumped into the well screens in order to kill any biofilm that had developed in the system. Peroxide was used because it is rapidly diluted by water and should not cause any harm to the natural environment once washed out of the system.
- Following the use of peroxide in the screens, there was a slight increase in the flow from the screens. This indicated that there had been some effect of sloughing of bacteria from the biofilm. However, the bulk of the biofilm, although no longer viable, remained attached to the screens.
- A few days after dosing the system with peroxide, the screens were jetted at high pressures. Roto Rooter was employed to do this work, using equipment that is normally used for cleaning sewers. As the screens were jetted, the flow into the system increased so rapidly that the screens that had already been cleaned had to be isolated. Sufficient flow to meet the demand could be obtained from one caisson. The system has been used successfully since this remedial action was taken.

It is possible that the jetting of the screens may have been successful without dosing the system with peroxide. Similar jetting of the screens was, however, undertaken at the Ulundi System without dosing the screens with peroxide. There was very little improvement in the flow from the Ulundi system following the jetting of the screens. Further evidence would be required to be able to state categorically whether both dosing with peroxide and jetting should be implemented simultaneously to successfully improve the yield of a system.

Considering the success of the remediation measures taken, it appears that the reduction of flow is caused by two factors:

- Clogging of the screens through the development of biofilm and through the ingress of clay into the screens.
- Reduction in the permeability of the sand around the screens through accumulation of fines.

This is similar to what has occurred at Fox Farm (5). These processes are likely to be interactive, with the one exacerbating the other.

6.2.8.6 *Ulundi (34)*

A number of remedial actions were attempted prior to the commencement of this research, none of which were effective. These are discussed in more detail in the report included as *Appendix J.40.12*. The measures include jetting air into the sand, rodding the sand, and dosing the system with HTH.

- In 1995 it was decided to dose the entire abstraction system with chlorine in an attempt to kill the bacteria. A total of 200kg of HTH was therefore pumped into and distributed over the abstraction pipes. The weir reservoir was filled approximately 7 days after this was done. The pipes were sealed for 24 hours after dosing. Water and bacterial samples were taken from the abstraction system before dosing the pipes, and half an hour after opening the pipes samples were taken. Further samples were taken an hour after opening the pipes.

  Bacterial counts obtained from the samples taken before dosing and half an hour after opening the pipes were of the same order of magnitude, being in the region of 1 to $8x10^6$. Depending on the system in which the bacteria are found this is considered an average to high bacterial count. It was found that the counts obtained from the samples taken half an hour after opening the pipes were an order of magnitude larger than those obtained from the other sets of samples. This result can possibly be attributed to the sloughing of bacteria from the biofilm due to the environmental stress created by the chemical dosing. It is indicative that there is biofilm development in the abstraction pipes, and that the biofilm was affected by the chemical dosing. The bacteria were not, however, killed by the chemical dosing, having only been stressed to the point where portions of the biofilm sloughed off the pipe surface.

  Initially the dosing appeared to be effective in improving the yield. Shortly after dosing the system the yield improved to ±228 litres per second. However, the capacity of the abstraction system diminished rapidly and within one week had dropped to ±78 litres per second.

  It is highly probable that the rapid reduction in the capacity of the system, after the marked improvement after dosing of the system, could be attributed to the re-establishment of the biofilm in the abstraction pipes. It has been recorded that biofilms can rapidly re-establish after chemical dosing if the bacteria in the film have only been stressed, and not killed. In some instances the biofilm will develop to a greater extent than prior to chemical dosing, as the less resistant bacteria are killed, resulting in selection of the more resistant bacteria.

- Since the commencement of this research, the only remedial action that has been taken at this system was in October 2000. Roto Rooter was employed to jet the well screens of the abstraction system. The screens were individually jetted at a pressure of 16 bar. This was done following the success of jetting of the screens in the Nqutu abstraction system. The screens were not, however, dosed with peroxide prior to jetting, as was done at Nqutu.

The jetting of the screens was not successful in restoring the yield of the system. There was only small increase in the flow from the system following the jetting of the screens. It must be noted that it was not possible to jet any of the screens for an extended period, or to jet all the screens, as flow in the riverbed increased and it was necessary to leave the gallery before it was submerged.

6.2.9 System Performance

As noted previously, problems of low yield have been experienced at 51% of the systems visited. Many of these systems are, however still being effectively utilised through good management and the implementation of remedial actions to improve the yield of the systems.

In general, the performance of small-scale systems is good, with the exception of problems occasionally being experienced with high iron concentrations in the abstracted water. This can be attributed to the fact that small-scale systems do not stress the alluvial aquifer in any way.

The performance of larger systems is varied, with no specific type of system appearing to perform better than others. The extent of problems experienced tends to vary with geographic location. Fewer problems are experienced with systems in Zimbabwe, whilst problems are experienced with virtually all medium to large-scale systems found on the KwaZulu-Natal Coast, in Lesotho, and in the Northern Province.

Problem systems are also associated with particular catchments, notably the Olifants River in the Northern Province, the White Mfolozi River in KwaZulu-Natal, and the Caledon River on the border of the Free State and Lesotho. Problems of a similar nature can also be linked with geographic regions.

As discussed in Section 4.3.1, systems were rated according to the extent of problems experienced at the system. This rating does not necessarily give an indication of the success or failure of a system, because, as previously mentioned, in many instances the problems are contained through good operational and management practices.

The ratings given to systems for the various types of problems that can typically be experienced are shown in Table 9.

Table 9 System Problem Rating

System Number	System Name	PROBLEM RATING			
		Reduced Yield	Probable Biofouling	Probable Clogging of Sand	Problems Related to High Iron / Manganese Concentrations
		0 (None) to 5 (Severe)			
1	Dysselsdorp	1	0	1	0
2	Laingsburg 1	1.5	0	1	0
3	Laingsburg 2	1	0	1	0
4	Melkbosstrand	1	2.5	1	0
5	Fox Farm	4	4	4	4
6	Peka	4	4	4	4
7	Hlotse	4.5	4	4.5	4
8	Teyateyaneng	5	4	5	4
10	London Mission	1	0	3	0
11	Giyani	0	0	0	0
12	Bothashoek	1.5	1	2	0
13	Messina	4	2.5	4	0
14	Chikwarakwara	4	2.5	4	0
15	Nottingham	4	2.5	4	0
16	Chisumbanje	1	0	0.5	0
17	Shashe	2	1	2	0
18	Whuwana	0	0	0	0
19	Shashani	2	1	2	0
20	Mambali	2	1	2	0
21	Shangani	0	0	0	0
22	Mtwalume - Umgeni	4	4	4	4
23	Umzinto	5	5	5	5
24	Umkomaas	4	4	4	4
25	Mtwalume School	1	1.5	1.5	0
26	Fairview	3	4	3.5	5
27	Pungashe	0	0	0	0
28	Illovo Sugar	3	4	3	5
29	Umdloti	1.5	3	1.5	1.5
30	Glover	4.5	4.5	5	4
31	Nqutu	3.5	4.5	4	3.5
32	Makhosine	0	0	0	0
33	Opuzane	1	1	1	0
34	Ulundi	4.5	5	5	3
35	Mpungamhlophe	5	5	5	3
37	Havercroft Mine	4.5	3	5	2.5
39	Apel Mission	1	0.5	0.5	0
45	Hibberdene	4	5	4	5
46	Mtubatuba	2.5	3	2.5	5
47	Nondweni	1	0	0	0

6.2.10 Water Quality at Systems

As previously discussed water samples were taken at each system for testing to determine various system parameters. Details of the samples taken and the results of the tests conducted are included in the electronic appendices, as Appendix e.D.

6.2.11 Microbiological Aspects

The results of all microbiological analyses conducted are included in Appendix F.1 and Appendix F.2.

6.2.11.1 *Ulundi System: Pederson Device*

The Pederson type devices that were installed in the Ulundi System were removed from the system some 6 months after they were installed.

All the devices were entirely covered with a black slimy, slightly granular substance, with the exception of the surfaces of the screens abutting the sand in the sand unit. One of the units removed from the system is shown in Plate 3 below. The devices were stored in river water in a cooler box for transportation to the laboratory. During transportation, some of the biofilm on the units was sloughed off, leaving the water black in colour.

Detailed results of the tests conducted on the samples obtained from the Pederson type devices and the water in which they were stored for transportation are given in Appendix F.1. In summary, the following results were found:

- Total bacterial counts: 1.63×10^6 to 2.00×10^6 cfu/mℓ.
- Sulphate Reducing bacteria: < 10 cfu/mℓ
- Gram staining: Gram negative and gram positive bacteria present, with gram negative bacteria dominant.
- Light Microscopy: Brown algae and bacteria identified.
- Scanning electron microscopy: Showed algae (possibly black algae), bacteria and slime present in the samples, with the dominant substance on the slides being the polysaccharide slime matrix

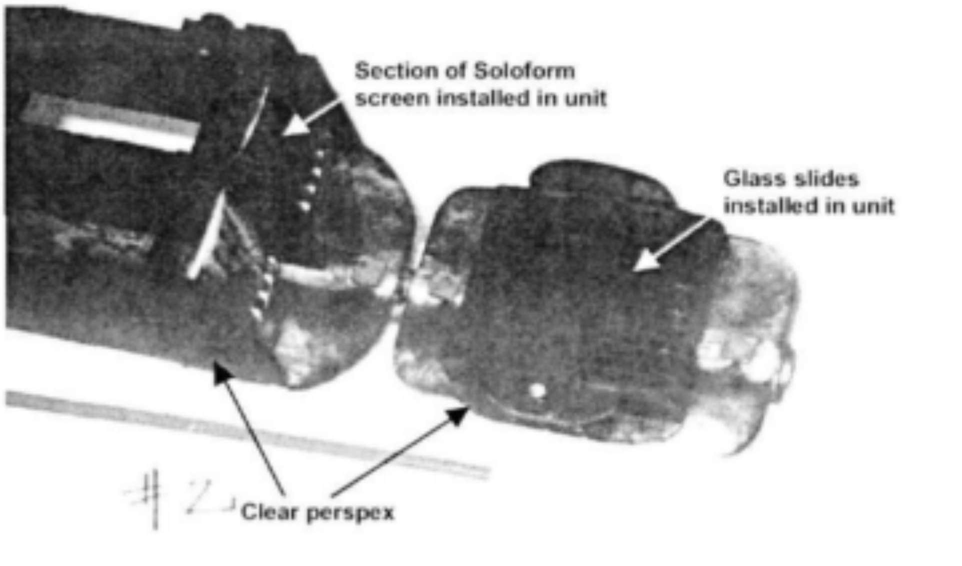

Plate 3: Pederson Type Device Removed from Ulundi System
Note: The units are constructed from clear perspex.

6.2.12 Sand Properties

As previously discussed, sand samples were taken at each system for testing to determine various system parameters. Details of the samples taken and the results of the tests conducted are included in the electronic appendices, as Appendix e.F.

Some problems were experienced with discrepancies in the testing results obtained from the laboratories. This was particularly the case with the specific gravity tests done on the various size fractions of the samples. These results have therefore not been used in the correlation analysis conducted to determine the relationship between sand parameters and permeability.

Full grading analyses were also not conducted on some samples, with the fraction of the samples > 6.7 mm being discarded. Where additional sample was available full grading analyses were conducted on these samples. The correlation analysis conducted to determine the relationship between sand parameters and permeability was therefore conducted on two sets of data, one using full grading analyses, and one using the partial grading analyses. As shown in Section 7.1.1, this proved to be fortuitous, as better correlations were obtained using the partial grading analyses. This indicates that the larger fractions of the sand have minimal impact on the permeability of the sand.

The following points can be noted about the sand data:

- For any one sample, there was little variation in the specific gravities of the various size fractions of the samples. In some instances the fines fraction had a higher specific gravity than the coarser fractions, but there was no particular trend in this.

- The specific gravity of all samples taken in the Olifants River (Northern Province) catchment are high, being in the order of 3 200 kg/m^3. Severe problems of low yield have been experienced at most of the systems installed in this river, even when comprehensive testing and investigations have been done for design purposes (Havercroft Mine (37)).

6.2.12.1 Permeability Tests

The detailed results and charts of the permeability tests are included in the electronic *Appendix e.F.5*.

As discussed in *Appendix G.2* permeability tests were conducted at two densities, namely "normal testing" density and site density. The "normal testing" density is the density that the sample naturally assumes in the permeameter without compaction, while the site density is the density equivalent to the in-situ bulk density measured for that sand.

In general, it was found that the "normal testing" density was lower than the site density, with an associated higher permeability. The maximum difference between the two densities was 17% relative to the normal density, with the average difference being 5%.

There was up to a 95.6% decrease in the permeability measured at "normal testing" density and that measured at site density. The average decrease in the permeability measured was 29.8%. Generally, it was found that the difference in the permeability of the two densities was lower for sites that have shown fewer problems associated with reduction in permeability of the sand.

For each test, the permeability was measured in the surface layer (k_1) of the sample, as well as in the body of the sample (k_2). As would be expected, the k_1 value was always higher than the k_2 value. The permeability at the surface tended to decrease rapidly after the tests were started.

Tests were run over an extended period of time (up to 2 days). The flow was increased in steps, and then decreased in steps. In some cases, the sample in the permeameter was backwashed, and then permeability tests were resumed. The sequence of permeabilities measured was then plotted for each test. Examples of these plots are shown in Figure 10 to Figure 13. Some interesting trends in the sequence of permeabilities were observed. These included:

- Permeabilities measured remained relatively constant throughout the testing sequence for systems where problems associated with reduction in permeability of the sand. An example of this is shown in Figure 11, the test results for Mambali (20).

- The permeabilities measured for systems where problems are experienced with reduction in permeability of the sand either varied considerably throughout the testing period (Figure 10, Peka (6)) or continued to decrease throughout the testing period (Figure 13, Ulundi (34)).
- The effects of backwashing can clearly be seen in Figure 10, Figure 12 and Figure 13, where there is always an increase in permeability after backwashing.
- In samples from some of the more problematic systems, it was also noted that the surface permeability, k_1, continued to decrease throughout the testing regime. This is shown in Figure 13. In some instances this could be attributed to a build up of clay on the surface of the sample (the test water was recycled), but in other cases there was no obvious reason for this.

Another interesting phenomenon that was observed during the tests was the development of stratification within the sample during the test. This can be seen in Plate 4 and Plate 5. This usually occurred in samples that have high fines content, and a generally low permeability.

Plate 4: Permeameter with Sample from Glover System (30)

Plate 5: Permeameter with Sample from Laingsburg 1 System (2)

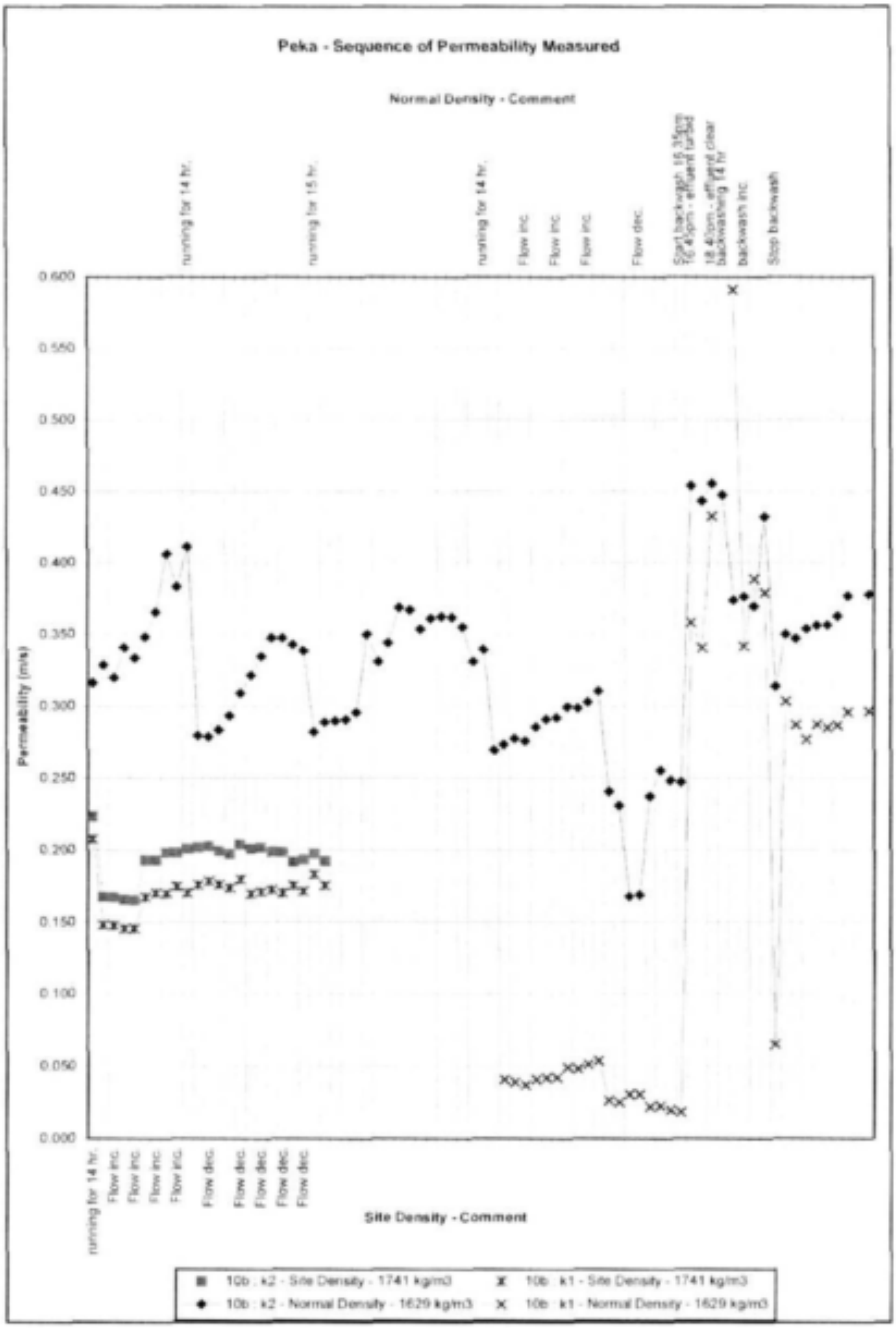

Figure 10: Peka – Permeability Test –Sequence of Permeabilities Measured

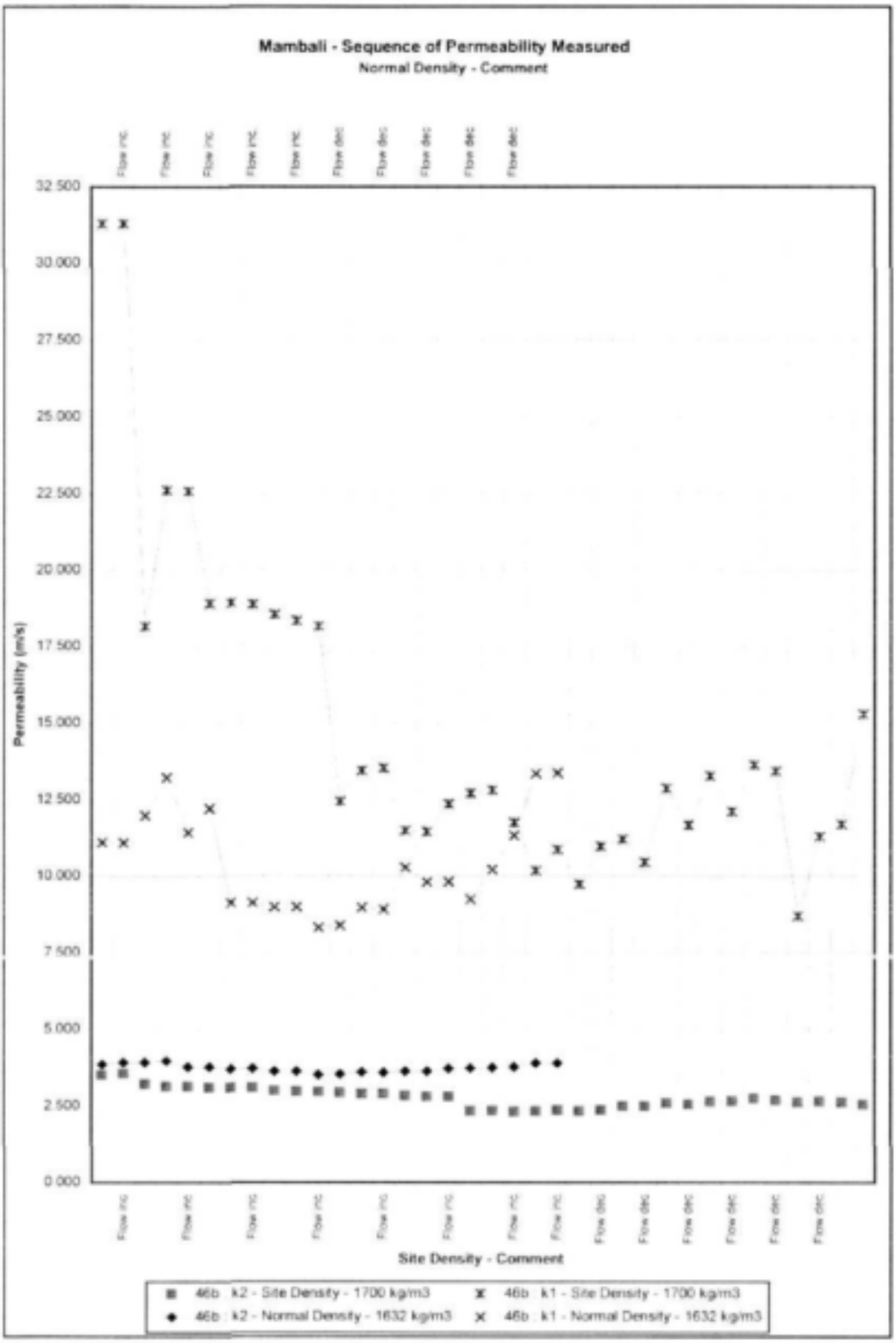

Figure 11: Mambali – Permeability Test –Sequence of Permeabilities Measured

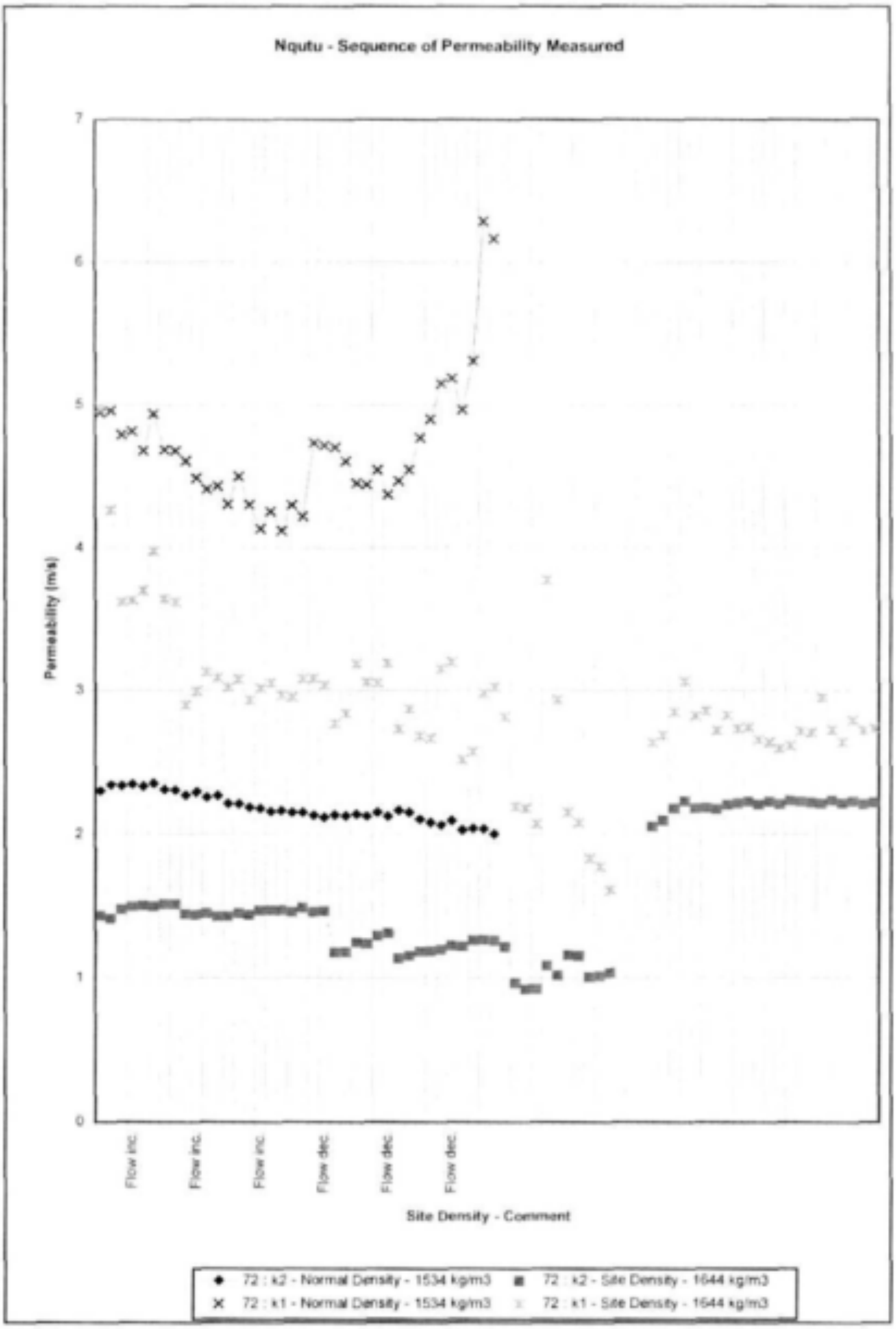

Figure 12: Nqutu – Permeability Test –Sequence of Permeabilities Measured

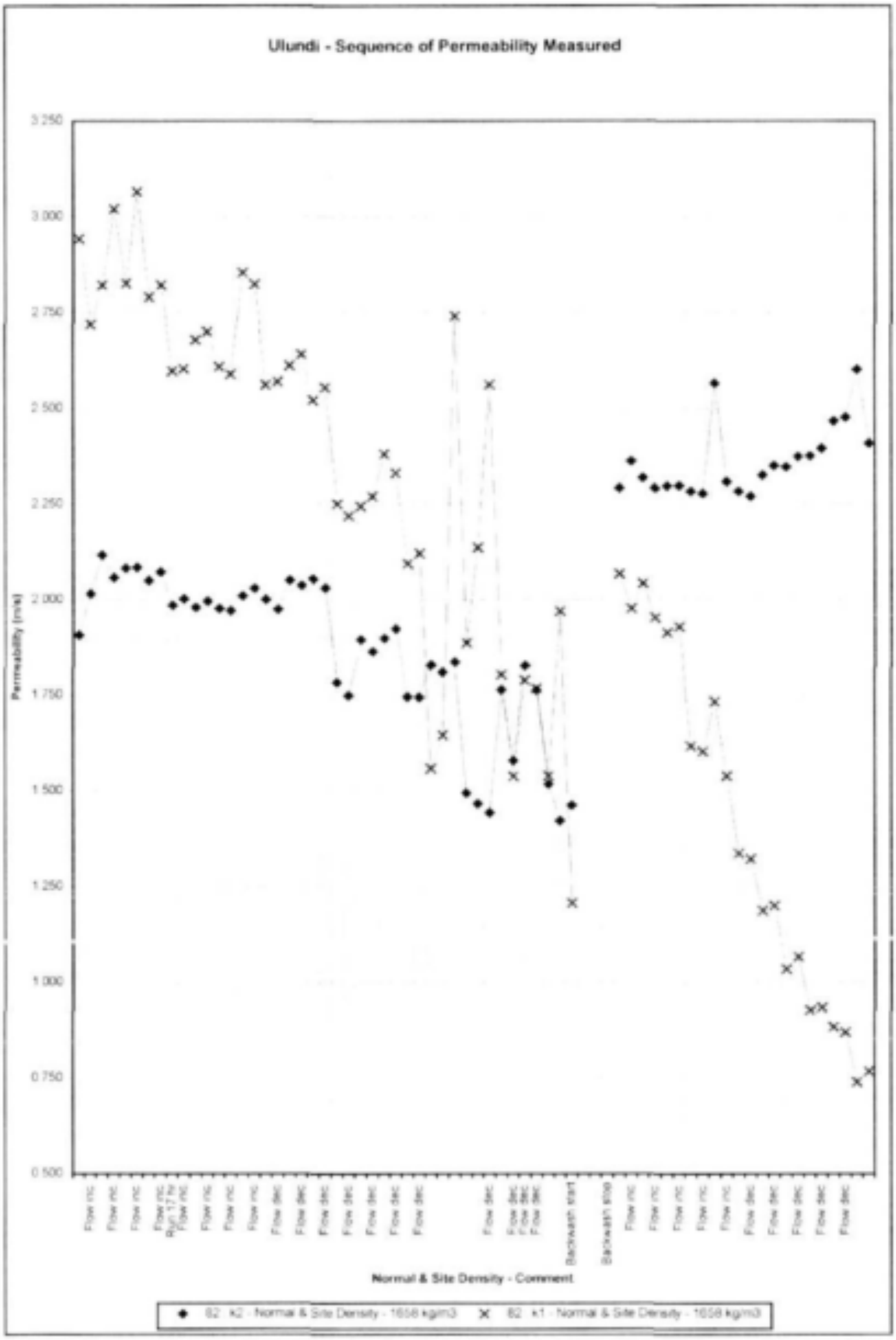

Figure 13: Ulundi – Permeability Test –Sequence of Permeabilities Measured

6.2.12.2 *Sand Data Collected from Other Sources*

Sand data was obtained from other sources such as design engineers and other researchers. This included data of tests conducted at the time of construction. Where possible this data was compared to data gathered during the course of this research.

- *Nqutu (31)*

  Grading curves were obtained from tests done during the feasibility study for this system, and during the construction of the system. Bradford, Conning and Partners, Newcastle, also made available results of grading tests conducted on samples during the investigations they conducted into the problems of low yield of this system. The results of grading analyses conducted on sand samples from the Nqutu system are shown in *Appendix J.37.8*. These results show that there has been little change in the characteristics of the sand between 1978 and 1999. All tests conducted in 1999 fall between the finest and coarsest gradings measured in 1978.

- *Ulundi (34)*

  Grading curves were obtained from tests done during the feasibility study for this system, and during the construction of the system, as well as for tests conducted during earlier investigations into the problems of low yield at this system. Comparing these grading analyses of the sand, as well as grading analyses conducted as part of this research, it has been found that there has been an increase in the fines content of the sand. This is particularly noticeable at depth, where the fines content near the screens is higher than anywhere else in the sand bed.

- *Whuwana (18) and Shashani (19)*

  Mr S.W. Hussey of Dabane Trust is currently conducting studies into small-scale sand abstraction systems. As part of his investigations, Mr Hussey took sand samples at different depths in the riverbed at Whuwana and Shashani. Results of grading analyses conducted on these samples are shown in *Appendix J.21.8* and *Appendix J.22.8*. Unfortunately the depths at which samples were taken and the depth of the water table at the time were not given.

  It can be seen from the results that the coarsest sand occurs in the central depths of the sand bed, with the gradings of the sand at the top and bottom of the sand bed being very similar. The sand at the bottom of the bed has a slightly higher percentage of fines than does the sand at the top of the bed. This may vary depending on the size, intensity and duration of the last flood event in the river.

6.2.13 Geographical and Geological Aspects

Geographical and geological data collected are included in electronic *Appendix e.G*. This includes data collected from the 1:50 000 topographical maps, the "*Surface Water Resources of South Africa – Map Books*", ABA

Brink's geological map, as well as long and cross-sections of the river valleys upstream of the systems.

On plotting the valley cross-sections, an aspect that clearly became evident, was that the cross-sectional valley form, particularly in the reaches approximately 40 km upstream of the system, appears to be a good indicator of problems of clogging of the sand bed. This can be explained in that, depending on the geology of the catchment, more erosion, and hence more fines, could be expected in a steeper catchment. Typical cross-sections for a system where problems of clogging of the sand are not experienced (Chisumbanje (16)) and for a system where problems of clogging of the sand are experienced (Mtwalume (22)) are shown in Figure 14. The cross sections are plotted on the same horizontal and vertical scales.

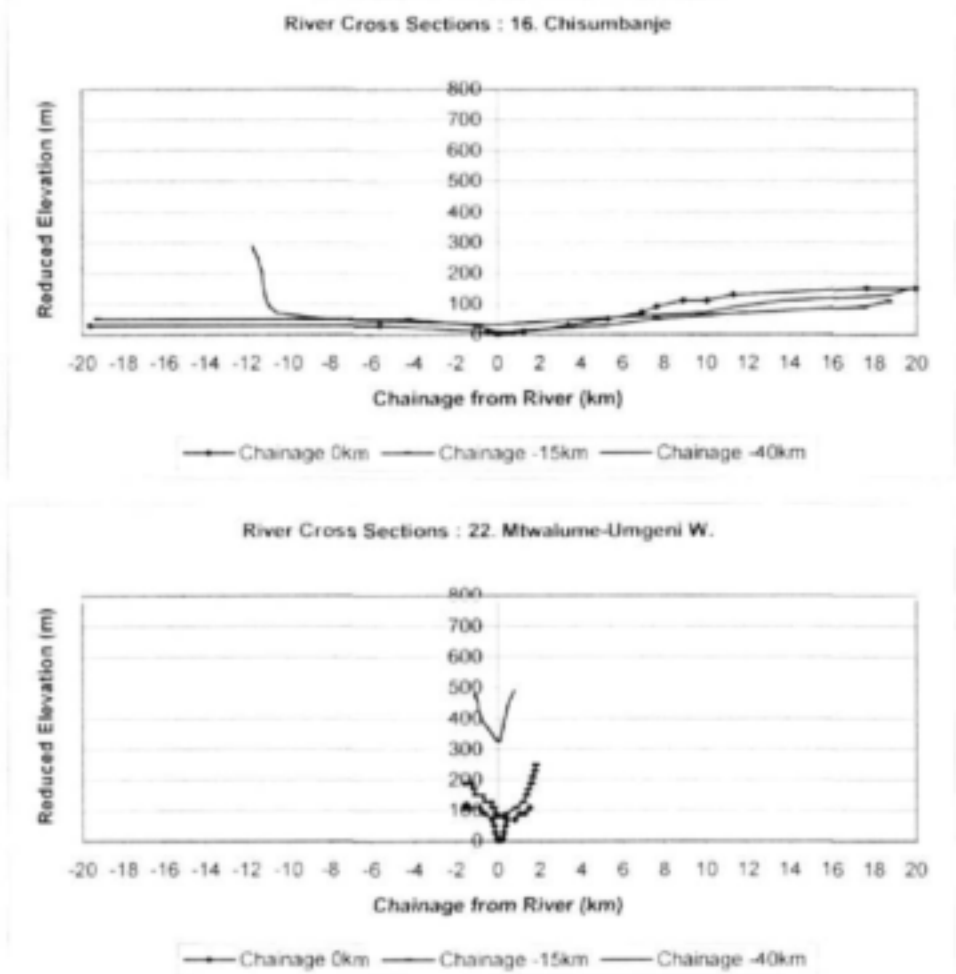

Figure 14: Typical Valley Cross-Sections for Systems

7 DATA ANALYSIS

7.1 SAND PARAMETERS

7.1.1 Correlation between Laboratory Measured Permeability and Other Sand Parameters

Various standard equations are currently being used for the calculation of the permeability of sand. However, these equations have been found to give extremely unreliable results in some instances. This could possibly be attributed to the fact that the existing standard equations for the calculation of the theoretical permeability generally only take into consideration up to three D_x sizes (the nominal sieve sizes passed by x% of the sand sample) of the sample. Factors such as the bulk and specific density, compaction of the sand, particle shape and in-situ void ratio, are not taken into account.

It would therefore be extremely useful if a more reliable method of predicting the permeability of sands, without conducting permeability tests, could be developed. Ideally a reasonable prediction of permeability should be obtained using only the results of sand grading analyses and density tests (bulk and specific densities). These tests are relatively simple and easy to conduct at relatively low cost, and could be useful for the prediction of the permeability of sand in the early stages of any investigations into the feasibility of a sand abstraction system.

In order to develop an equation that would give a more reliable estimate of the permeability of a given sand, some correlation analyses were performed to determine the relationship between the measured permeability of a given sand and various other sand parameters.

The complex and somewhat intuitive correlation found between permeability and other sand parameters was initiated by recognising that the density and mechanical clogging of sand beds would be the most important factors in assessing the physical capability of water flow through the sand bed. Biophysical factors such as bacterial infestation would also affect the permeability of sands. However, these type of factors were not taken into account because they are often difficult and expensive to measure, and the need to conduct complex and expensive testing in order to predict the permeability of a sand would negate the usefulness of any theoretical equation for the prediction of permeability.

The density of a sand bed is most likely linked to particle size relationships, which appear to be best analysed in terms of particle volume. It was found that irregular sand particle shapes, rather than spherical or cubic shapes, are the norm and that the cube of the particle nominal dimension would therefore not be a correct comparative measure.

In carrying out the correlation analysis, the equations were set up to enable iterative determination of particular factors, such as particle size exponents.

The D_2, D_5, D_{10} etc. values are factors that are easily determined through common laboratory grading tests and are therefore the most useful basic information to use in the prediction of the permeability of a sand.

A number of factors were varied during the correlation analyses. Typical variations in the data sets and parameters used, and the basis of the developed equation included the following:

- The inclusion or exclusion of the bulk dry density of the in-situ sand (as measured using the samples taken with the "density ring") as a parameter in the equation. The size of the data set used was usually smaller when the bulk site density was included as a parameter, as bulk site densities had not been measured for all samples tested.
- The use of either full or partial sand grading analysis results, and the associated D_x values as parameters in the equations.
  - ➢ Full grading results: The grading analysis of the entire sample was used, including the fraction of the sample > 6.7 mm.
  - ➢ Partial grading results: The grading analysis of the fraction of the sample < 6.7 mm was used, where 6.7 mm was taken as 100% passing.

  Full and partial grading analyses were conducted for the following reasons:

  - ➢ Firstly, when laboratory tests were carried out on a number of the samples, the fraction larger than 6.7 mm was inadvertently discarded. Where sufficient sample volumes remained, the samples were retested and full gradings were obtained for them. It was thought that a more comprehensive data set could be used if the partial grading analyses proofed to be adequate for the correlation analysis.
  - ➢ Secondly, it was done in order to determine whether the larger fraction of the sand had a marked influence on the permeability or not.
- The equations were varied by using natural logs and/or base 10 logs and by calculating the k (permeability) or $\log_{10}k$ values.
- For some analyses smaller sample sets were used; excluding samples that were known not to be representative of the entire sand bed (e.g. samples of clay plugs were excluded).
- The fineness modulus (f_m) was incorporated in the equations. Variations of the fineness modulus, that effectively weighted different particle sizes, were also used. The modified fineness moduli used are shown in *Appendix M.*
- The number of parameters included in the equations was varied, and parameters such as the in-situ void ratio and in-situ bulk dry density were either included or excluded.

Due to a lack of reliable grain density (specific density) data on a large enough range of samples for analyses to be meaningful, no correlation of permeability was done against grain density, although it would probably have a significant effect on the accuracy of the prediction equation.

The correlation coefficient was determined by comparing the calculated permeability, using the developed equations, with the measured permeability at site density. These results were compared with similar results obtained when using the following standard equation for the calculation of permeability:

$$k = \frac{e^{2.99}(D_{50})^{1.87}}{1 + \ln\left(\frac{D_{90}}{D_{10}}\right)}$$

Numerous equations were developed, varying the above-mentioned parameters. Details of the range of correlations investigated are summarised in Appendix M.4.

Seven of the developed equations have been selected to demonstrate the effects of the variation of parameters in the correlation analyses. The equations and the results of the correlation analyses are included in Appendix M.3. A summary of the variations in the equations and the correlations obtained are shown in Table 10. Details of the equations and correlation analyses of equations 6 and 7, for which the best correlations were achieved, are shown in Sections 7.1.1.1 and 7.1.1.2. It should be noted that the scatter of the calculated permeabilities for these two equations was considerably reduced.

Despite a number of problems experienced in data and information collection, the calculated correlation coefficient (R^2) of between 70% and 90%, as shown in Table 10, is considered a good result. Particular indication of poor permeability has been achieved, which is also important, as an indicator that can predict a poor to very poor yield is a useful tool. Avoiding expending time, cash resources and energy on installations that could be predicted to be barren, is even more important than predicting good yields.

The equations developed are somewhat cumbersome to use, but the degree of accuracy that can be achieved to estimate the permeability with data obtained from low cost testing would generally justify the use of these equations.

Table 10 Summary of Calculated Permeability Correlation Analysis

Equation number	Size of data set	Full or partial gradings	Exclusion of less representative samples	Fm used	Inclusion of bulk site density as a parameter	Natural log or Log_{10}	k or $log_{10}k$	Correlation coefficient (R^2)	Correlation coefficient using standard equation for calculating permeability (R^2)
1	163	partial	No	$Fm_{6.7}$	no	Log_{10}	k	0.7455	0.4772
2	163	partial	No	$Fm_{6.7}$	no	Natural	k	0.7396	0.4772
3	163	partial	No	$Fm_{6.7}$	no	Natural	$Log_{10}k$	0.7101	0.4772
4	143	full	Yes	Fm	no	Log_{10}	k	0.7640	0.5495
5	133	partial	Yes	$Fm_{6.7}$	yes	Log_{10}	k	0.6833	0.2658
6	133	partial	Yes	$Fm_{6.7}$	yes	Log_{10}	$Log_{10}k$	0.8971	0.2658
7	133	partial	Yes	$Fm_{6.7}$	yes	Natural	$Log_{10}k$	0.8995	0.2658

7.1.1.1 *Equation 6: Correlation of Calculated and Observed Laboratory Permeability (k_t)*

Analysed against part grading results, i.e. including only material < 6.7 mm, and site dry density, with 30 sites excluded for lack of density data or on inspection of sand samples and gradings.

$$\log_{10} k_t = C_1 10^{m1} + C_2 10^{-m2} + C_3 10^{-m3} + C_4 10^{-m4} + \ldots + C_8 10^{-m8} + C_9 10^{m9}$$

where: $m1 = (1/(Fm_{6.7}))^{10}$			$C_1 = 3.01876$
$m2 = 10^{-n1}$	and	$n1 = (D_2)^{2.31}$	$C_2 = -4.0946$
$m3 = 10^{-n2}$	and	$n2 = (D_5)^{2.31} + 2.35\,n1$	$C_3 = 2.0792$
$m4 = 10^{-n3}$	and	$n3 = (D_{10})^{2.31} + 2.35\,n2$	$C_4 = -0.11473$
$m5 = 10^{-n4}$	and	$n4 = (D_{15})^{2.31} + 2.35\,n3$	$C_5 = -1.99977$
$m6 = 10^{-n5}$	and	$n5 = (D_{20})^{2.31} + 2.35\,n4$	$C_6 = 2.42089$
$m7 = 10^{-n6}$	and	$n6 = (D_{50})^{2.31} + 2.35\,n5$	$C_7 = -5.20487$
$m8 = 10^{-n7}$	and	$n7 = (D_{80})^{2.31} + 2.35\,n6$	$C_8 = 8.8554$
$m9 = (1500/(cd))^{-1.5}$; cd = comparative (site dry) density			$C_9 = -0.01394$

and where

D_2, D_5, D_{10} … are the computed threshold sizes for 2%, 5%, 10%… of the sand sample; and

$Fm_{6.7}$ is the standard Fineness Modulus of all material < 6.7 mm only.

For a sample of 133 calculated permeabilities, the correlation coefficient (R^2) achieved was 0.8971. The corresponding correlation coefficient for the "Standard Permeability" was 0.2658.

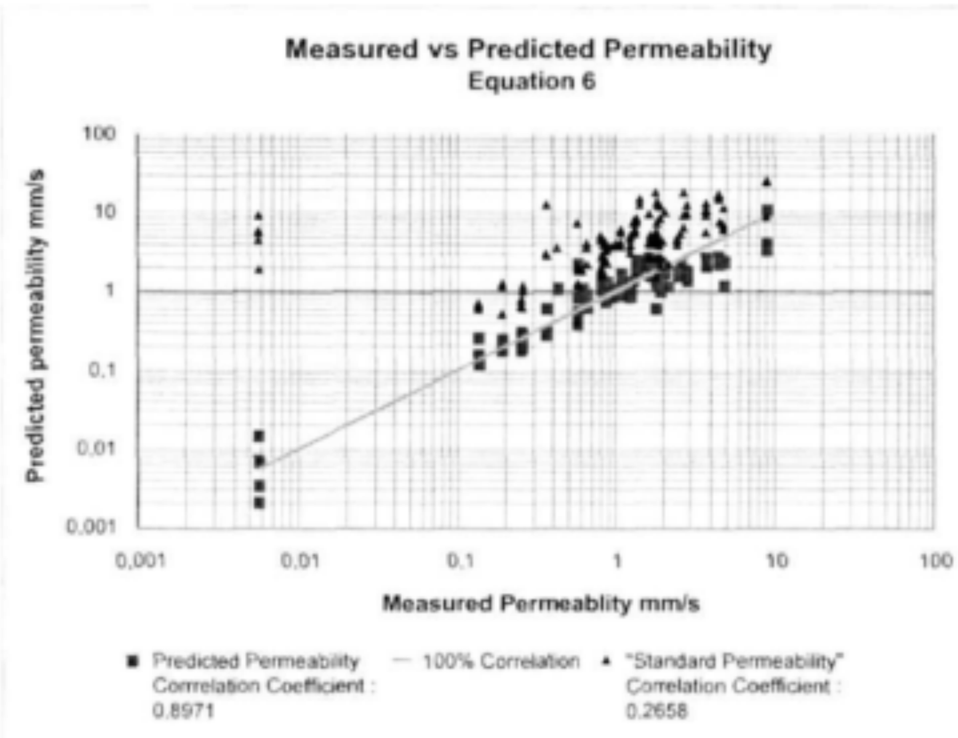

Figure 15: Plot of Measured Versus Predicted Permeability, Equation 6

7.1.1.2 *Equation 7: Correlation of Calculated and Observed Laboratory Permeability (k_l)*

Analysed against part grading results, i.e. including only material < 6.7 mm, and site dry density, with 30 sites excluded for lack of density data or on inspection of sand samples and gradings.

$$\log_{10} k_l = C_1 e^{m1} + C_2 e^{-m2} + C_3 e^{-m3} + C_4 e^{-m4} + \ldots + C_8 e^{-m8} + C_9 10^{m9}$$

Where:

$m1 = (1/(Fm_{6.7}))^{10}$			$C_1 = 4.8217$
$m2 = e^{-n1}$	and	$n1 = (D_2)^{2.11}$	$C_2 = -6.8218$
$m3 = e^{-n2}$	and	$n2 = (D_5)^{2.11} + 1.62\ n1$	$C_3 = 3.8566$
$m4 = e^{-n3}$	and	$n3 = (D_{10})^{2.11} + 1.62\ n2$	$C_4 = -0.3149$
$m5 = e^{-n4}$	and	$n4 = (D_{15})^{2.11} + 1.62\ n3$	$C_5 = -2.3603$
$m6 = e^{-n5}$	and	$n5 = (D_{20})^{2.11} + 1.62\ n4$	$C_6 = 2.1029$
$m7 = e^{-n6}$	and	$n6 = (D_{50})^{2.11} + 1.62\ n5$	$C_7 = -3.9321$
$m8 = e^{-n7}$	and	$n7 = (D_{80})^{2.11} + 1.62\ n6$	$C_8 = -0.0628$
$m9 = (1500/(cd))^{-2.11}$; cd = comparative (site dry) density			$C_9 = -0.1183$

and where

D_2, D_5, D_{10} ... are the computed threshold sizes for 2%, 5%, 10%.. of the sand sample; and

$Fm_{6.7}$ is the standard Fineness Modulus of all material < 6.7 mm only.

For a sample of 133 permeabilities, the correlation coefficient (R^2) achieved was 0.8896. The corresponding correlation coefficient for the "Standard Permeability" was 0.2658.

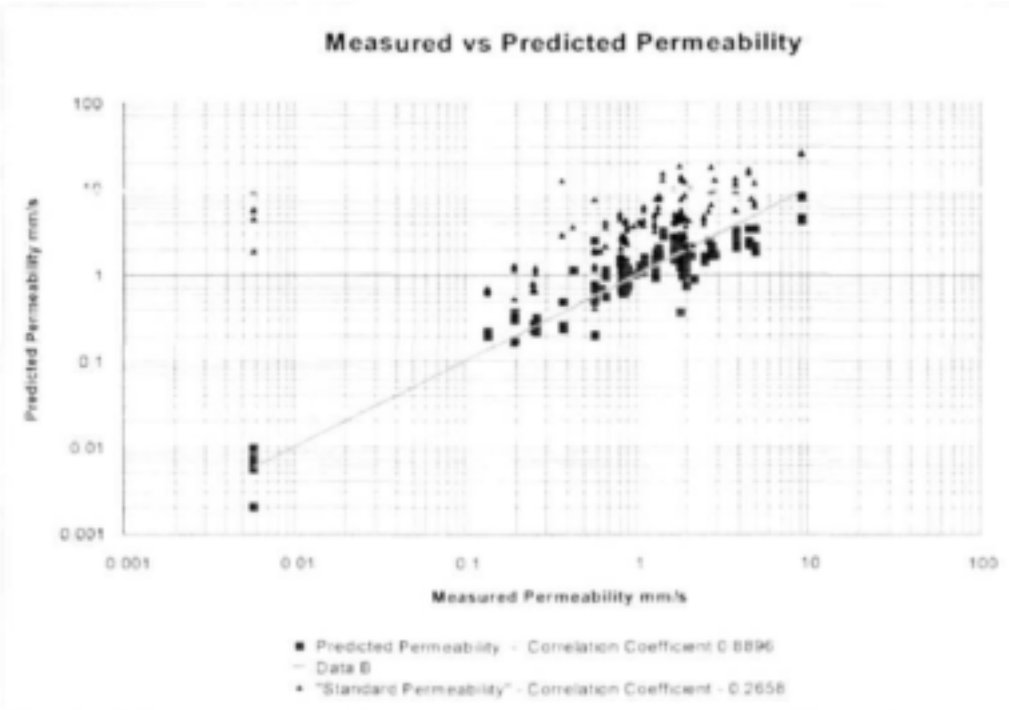

Figure 16: Plot of Measured Versus Predicted Permeability, Equation 7

7.1.2 Correlation of Sand Parameters with System Performance

All of the sand parameters and various permutations of the sand parameters were plotted against the system rating parameters set for the problem types identified i.e.

- Low yield.
- Biofouling
- Clogging of the sand
- Problems related to high iron and manganese concentrations in the system water.

Typical examples of these comparative plots are shown in Figure 17 below. All charts that show a correlation between system performance and sand parameters are included in *Appendix M*. All other charts are included in the electronic *Appendix e.F*.

In general, where there is a correlation between sand parameters and system performance, these are "wedge-shaped" relationships. By this is meant that for either the minimum or maximum limit of the problem rating, the value of the parameters measured cover the full range of parameter measurements (minimum to maximum). For the other limit of the problem rating, only a small range of the parameter measurements are covered, usually near the minimum or maximum of the parameter measurements.

For example, considering the plot of

$$\% \frac{\text{ABS (Permeability } k_2 \text{ - Permeability } k_1)}{\text{Permeability } k_2} \text{ versus low yield problem rating}$$

in Figure 17, and ignoring the outlier at 430%, it can be seen that for systems with low problem ratings of 0.5 to 2.0, the percentage difference between the body and surface permeability ranges from 0 to ±40%. For systems with higher problem ratings between 3 and 5, the difference between the body and surface permeability ranges from 0 to ±180%.

This type of relationship cannot be used to necessarily predict the performance of the system, but can be used as an indicator of potential problems. Numerous system parameters, including water and geographical and geological parameters, exhibit relationships of this type with system performance. All can be used as indicators of potential problems, and when considered in combination, a fair assessment can be made of the possibility of problems developing at a system. It can actually not be expected that any single, or even a combination of a few, parameters, could be used to predict system performance. System performance is dependent on numerous interactive factors, each of which is defined by a number of parameters.

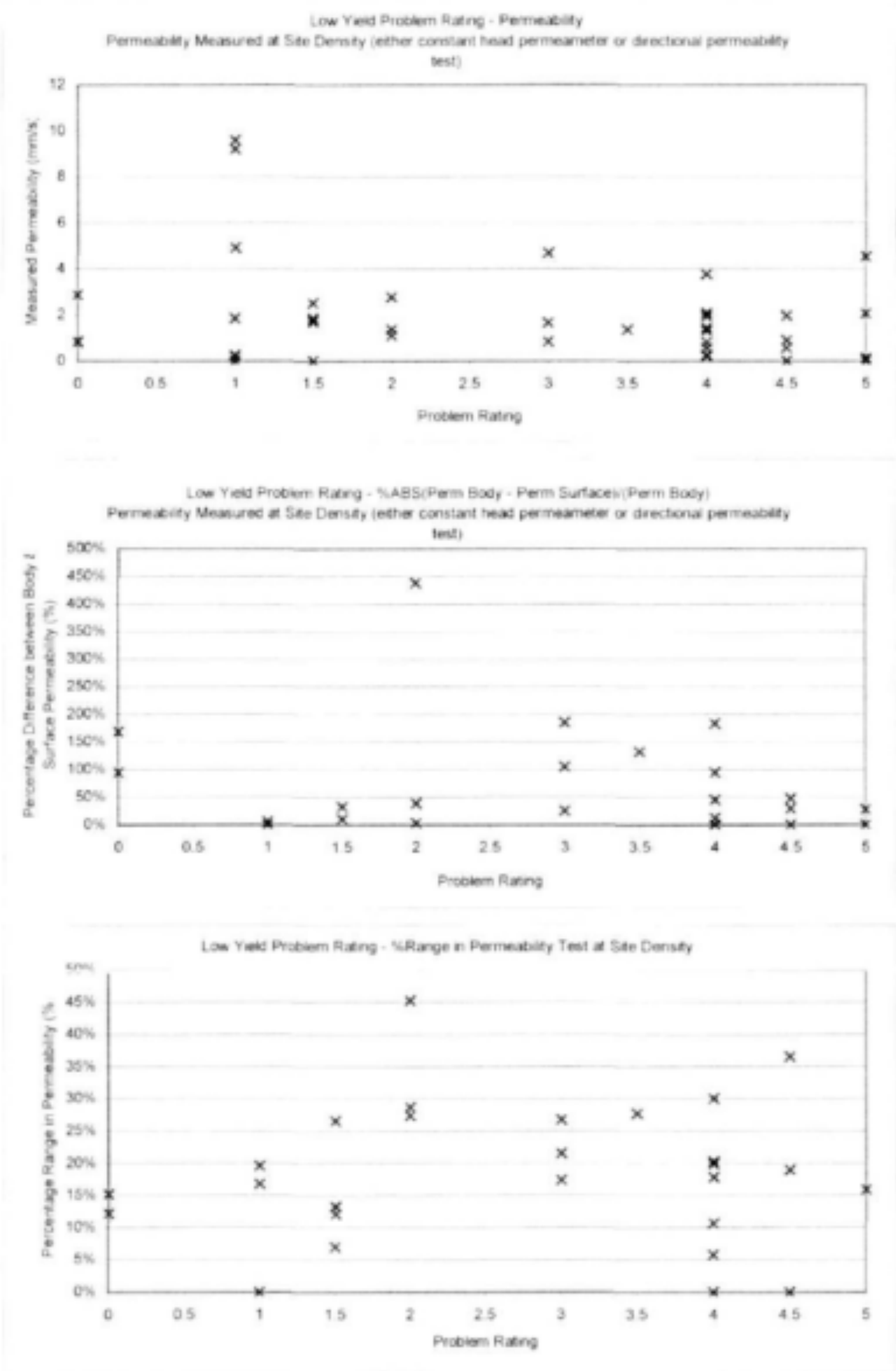

Figure 17: Typical Charts of Sand Permeability Parameters vs System Low Yield Problem Rating

7.2 WATER QUALITY

7.2.1 Correlation of Water Quality Parameters with System Performance

Various system parameters, including surface (river) water and abstracted (system) water quality parameters, were tested to determine whether these could be used as indicators of problems experienced in sand abstraction systems or of sand abstraction system performance, either potential or actual. The results of these tests are summarised in *Appendix L.1* of this report for each system. The water quality parameters evaluated were the following:

- Total bacteria counts,
- Total iron concentrations,
- Ferrous iron concentrations,
- Nitrate concentrations,
- Manganese concentrations,
- Conductivity,
- Sulphate concentrations,
- Turbidity,
- Sulphide concentrations,
- pH,
- Total Dissolved Solids,
- Sulphate Reducing Bacteria and
- Redox Potential

The water quality parameters were plotted and grouped together by type of problem actually experienced in the abstraction systems in order to determine whether there were any trends in these parameters relative to the different types of problems. The resultant plots are shown in *Appendix L.2* of the report.

Typically it was found that the nitrate concentration in the surface water is a good indicator of the total bacteria counts in the system water. The relationship as shown in Figure A.70 in *Appendix L* could be used to estimate the total bacteria counts in the system. Similarly the turbidity is also a good indicator to estimate the total iron concentration in a system. The equations shown in Figures A.85 and A.86 could be used to estimate the total iron concentration in the abstracted water.

Selected graphs were also compiled to determine whether there are any correlations between water quality and the following parameters:

- The type of problem experienced,
- The geographical region of a system,
- The total bacteria count in a system,

- The total bacteria count resulting from a change in water quality parameters as water move from the surface to the system and
- The total iron concentration in abstracted water.

The results are shown in *Appendix O.1* (Figures A.176 to A.199). The correlation between water quality parameters and system performance are shown in terms of risk (low, moderate and high) in Table A.62 of *Appendix O.1* of this report. These results indicate that a number of surface (river) water quality parameters could be used as indicators of a system being at either high or low risk of the occurrence of a certain type of problem.

Similarly, it was found that various abstracted (system) water quality parameters could be used as indicators of the development of different types of problems in existing systems.

7.3 GEOGRAPHICAL AND GEOLOGICAL ASPECTS

7.3.1 Geological Interpretation

Interpretation of the effects of catchment geology on potential river abstraction installations was done as a low level task, using "Engineering Geology of Southern Africa", (Brink A.B.A, Re 0). This book, in four volumes, discusses the engineering properties of rock and derived soils from each geological Group or Supergroup.

This was considered to be a simple procedure, which could be followed by most people interested in or designing an installation. The main indicators sought were the range of sand grain shape and size, as well as the probable content of very fine clay and silt particles. These indicators would then give a very rough basis of assessing the degree of mechanical clogging and compaction that will probably occur.

A rough guide to derived sands based on interpretation of the geology of the catchment was developed. Derived sands would also be markedly influenced by other factors such as the size, slope, vegetation, MAR, land use and farming practices in the catchment, both as to overall sand-grading and transmissivity or permeability. This should be taken into account when using this guide. The assumed river sand characteristics derived from geological strata occurring in the catchment are shown in Table 11 below.

Using this rough guide, the geology of each system catchment was interpreted. Based on the percentage area of the various types of geological strata occurring in the catchment, the types of sands that would likely occur at the abstraction system were defined. The results of this interpretation are shown in *Appendix N*.

Table 11 Assumed River Sand Characteristics Derived from Geological Strata Occurring in the Catchment

Mapping Description (Groups)	Interpreted Rock Types	Assumed Derived Sand
As noted in the Key of the geological mapping used for extraction of data on catchment geology.	*From descriptions of engineering properties in "Engineering Geology of Southern Africa". Brink. A.B.A. (Ref. 0)*	*A rough guide to derived sands based on interpretation of the geology of the catchment. Derived sands will also be markedly influenced by other factors such as the size, slope, vegetation, MAR, land use and farming practices in the catchment, both as to overall sand-grading and transmissivity or permeability*
Basement Complex in Namaqualand & Natal	granites / gneisses etc.	Moderately hard cubical grains of medium sized fractions – becoming rounded in larger catchments. Very fine fractions generally absent or low percentage.
Basement Complex in Transvaal, Swaziland, Namibia & Rhodesia	granites / gneisses etc. with lavas, greywacke etc.	As above, with harder smaller angular grained sands derived from the lavas and greywacke.
Beaufort Group	mudrocks, sandstones	Fine grained rounded hard particles from sandstone, with very fine particles derived from mudrocks. Generally prone to clay and / or mechanical clogging.
Bokkeveld Group / part Cape Super Group	slatey mudrocks	Harder mudrocks giving rise to flaky and rounded angular particles, probably with lower vertical than horizontal transmissivity. Clays and silts could cause problems.
Chuniespoort & Wolkberg Group	Limestone & dolomites	Giving rise to irregular graded sands (if any) from the dolomites and cherts – tending to be angular and hard.
Drakensberg & Lebombo Groups	basalt, lava, agglomerates	Harder smaller angular grained sands derived from the lavas, with basalt contributing the same or finer round particles, depending on basalt type. Agglomerates would contribute more rounded medium sized grains. Variable transmissivity.
Ecca Group & Dwyka Formation	mudrocks, tillite	Tillite should give rise to medium grained hard cubical to rounded sand grains, while the mudrocks would contribute silt / clays to the matrix.
Kuibis Sub Group	shale, sandstone, quartzites etc.	These should give rise to hard angular to rounded with angular flaky medium fine to medium grain.
Lebowa Granite & Rashoop Granophyre Suites	granites	Moderately hard cubical grains of medium sized fractions – becoming rounded in larger catchments. Very fine fractions generally absent or low percentage.
Malmesbury, Gariep, Swakop & Otavi Groups	hard shales etc. fine grained	Fine-grained sands – larger particles flaky, with smaller particles cubical to rounded. Even grading but low to medium transmissivity.
Molteno, Elliot & Clarens Formations	fine sandstone, mudstone, gritstone	Medium to coarse angular to cubical particles with high percentages of finer fractions, silts and clays. Poor transmissivity in larger catchments.

Table 11 Assumed River Sand Characteristics Derived from Geological Strata Occurring in the Catchment (cont.)

Mapping Description (Groups)	Interpreted Rock Types	Assumed Derived Sand
As noted in the Key of the geological mapping used for extraction of data on catchment geology.	*From descriptions of engineering properties in "Engineering Geology of Southern Africa". Brink. A.B.A. (Ref. 0)*	*A rough guide to derived sands based on interpretation of the geology of the catchment. Derived sands will also be markedly influenced by other factors such as the size, slope, vegetation, MAR, land use and farming practices in the catchment, both as to overall sand-grading and transmissivity or permeability*
Molteno, Elliot & Clarens Formations	fine sandstone, mudstone, gritstone	Medium to coarse angular to cubical particles with high percentages of finer fractions, silts and clays. Poor transmissivity in larger catchments.
Pretoria Group	Shales and quartzites	Fine-grained sands – larger particles flaky, with smaller particles cubical to rounded. Even grading but low to medium transmissivity.
Rooiberg Group	felsitic granites	Very hard angular to flaky, coarse to medium grain sized. Should have good transmissivity.
Rustenburg Layered Suite	gabbro / norite, mafic etc.	Hard angular to cubic medium to medium-fine grained sands. Should give good transmissivity.
Soutpansberg Group	quartzite / sandstone / shales	Fine-grained sands – larger particles flaky, with smaller particles cubical to rounded. Even grading but low to medium transmissivity.
Swaziland Super Group & Basement Complex	granites / gneisses etc.	Moderately hard cubical grains of medium sized fractions – becoming rounded in larger catchments. Very fine fractions generally absent or low percentage.
Table Mountain Group	shales, sandstone	These should give rise to hard cubic to rounded smaller fractions with angular flaky medium fine to medium grain sizes.
Table Mountain Group / part Cape Super Group	quartzitic sandstone + minor mudrock	Fine to medium fine sands, cubic to rounded, but with medium to low transmissivity due to mudrock derivatives.
Ventersdorp Super Group	lavas, agglomerates	Hard angular medium to fine grained sands with varied grading from agglomerates and variable transmissivity.
Waterberg Group	sandstone / mudrocks	Fine to medium fine rounded sands, with medium to low transmissivity due to mudrock derivatives.
Witteberg Group / part Cape Super Group	slatey mudrocks micaceous shales, sandstones, quartzites, grits, siltstones, conglomerates	Fine to medium fine sands, flaky to angular to cubic to rounded, with lower vertical than horizontal transmissivity and prone to problems due to mudrock and siltstone derivatives. Difficult.
Witwatersrand Super Group	Shales, quartzites, conglomerates	Fine to medium grained sands – larger particles flaky, with smaller particles cubical to rounded. Even grading but low to medium transmissivity.

7.3.2 Correlation of Catchment Geology with System Performance

In order to determine whether there are any correlations between system performance and the specific geology of the catchment within which a system is situated the following readily available data and maps were used:

- 1:50 000 topographical maps,
- Maps from "*Surface Water Resources of South Africa 1990*" and
- Geological maps from A.B.A. Brink's "*Engineering Geology of Southern Africa*".

With respect to the geology, maps were developed using the "*Surface Water Resources of South Africa 1990*" geological maps as base maps. The catchment of each system was defined, with the catchments being divided into sections upstream and downstream of large and medium dams. The catchments were divided in this way, as sediments would be trapped in dams upstream of the system, with mainly only the very fine sediments from the portions of the catchments upstream of the dams reaching the abstraction systems. Each section of the catchment was then divided into upper, middle and lower catchment portions. Typical maps showing the catchments and geology as defined for the data collection are shown in Figures A.3, A.4 and A.5 in *Appendix H*.

It was endeavoured to establish a possible relationship between system performance and catchment geology. The evaluation was based on the catchment geology and the size of the catchment, which was compared to the probability of occurrence of the four main problem types identified earlier. The results are summarised in Table A.64 and A.65 in *Appendix O.3* of the report.

In some instances it was found that the size and type of catchment geology could be a reasonable good indicator for the occurrence of system problems but overall the relationship between system performance and catchment geology was poor.

Generally it was found that the problem of low yield increases with an increase in size of catchments consisting of formations of the Drakensberg and Lebombo Group (Figure A.224 in *Appendix O*). On the other hand, the iron/manganese problem decreases with an increase in size of catchments consisting of formations of the Basement Complex in Transvaal, Swaziland, Namibia and Rhodesia (Figure A.231). From Figure A.239 it can be seen that the biofouling problem would decrease with an increase in the size of catchment comprising of Acid and Intermediate intrusives.

7.3.3 Correlation of Geographical Parameters with System Performance

The same topographical and geological maps listed in the previous section were used to determine whether there are any correlations between system performance and the geographical parameters of the catchment within which a system.

The different categories and sub-categories of data extracted from the 1:50 000 topographical maps are shown in Table A.3 in *Appendix H* of the report. The areas in the system catchments, relative to the system, for which the data was extracted, are also shown. A distinction was made between the areas immediate to the river and the general catchment in order to determine whether the areas immediate to the river had a larger impact on abstraction system performance than the catchment as a whole.

The different categories and sub-categories of data extracted from the *"Surface Water Resources of South Africa 1990"* maps are shown in Table A.4 of *Appendix H*. The data was extracted for the entire system catchment upstream of the system.

In order to establish a relationship between system performance and geographical parameters of a catchment the following indicators were evaluated in some detail as shown in Table A.66 in *Appendix O*:

- Catchment area,
- Vegetation,
- Soils,
- Land cover and
- Sediment characteristics,
- Precipitation,
- Land use upstream and in the immediate vicinity of the system.

Generally poor to moderate correlations were obtained for the use of geographical parameters as a means to predict system problems. However, reasonably good correlations were established in the following cases:

- Biofouling could become a problem when increasing the area of land use by cultivating (Figure A.253 and A.261);
- The higher the MAP from the catchment area upstream of the system, the higher the risk of biofouling becomes (Figure A.258);
- Similarly, the higher the MAR from the catchment area upstream of the system, the higher the risk becomes for iron and manganese related problems (Figure A.259);
- Iron and manganese related problems appear to be reduced when the area upstream of the system comprises of trees and bushes instead of cultivated land (Figure A.262).

From the results it appears that geographical parameters do not have a direct impact on system problems such as clogging of sand and low yield.

7.3.4 Correlation of River Morphology with System Performance

The river morphology up to a distance of 50 km upstream of the system and in the immediate vicinity of the system was also evaluated in an attempt to find a correlation between system performance and specific characteristics of the river. The following characteristics of the river were analysed:

- The number and length of straight sections in the river;
- The meandering of the river in plains and in valleys;
- The number of horseshoe bends;
- The number of rapids;
- The number of major and minor tributaries;
- The number of bridges;
- The number of impoundments;
- The total number of obstructions in the river and
- The valley shape where the system is installed.

Although the correlation factors between system performance and the river characteristics listed above were found to be somewhat low (less than 0.10), some of the characteristics do give an indication of whether problems could be expected or not. Typical risks of failure (low, moderate and high) for each river characteristic and potential system failure are summarised in Table A.67 in *Appendix O.5* of this report.

8 CONCLUSIONS

8.1 OBSERVATIONS REGARDING SAND ABSTRACTION SYSTEMS IN SOUTHERN AFRICA

8.1.1 Overview of Sand Abstraction Systems Surveyed

Although not all sand abstraction systems could be identified during the research project, a total number of 67 sand abstraction systems were identified, of which 39 were visited in the field. Although most of the systems were found in South Africa and Zimbabwe (26), it is a large enough number of systems to be considered a representative sample of all types of systems currently in operation within the borders of Southern Africa.

About 40% of the systems visited had vertical well points installed, whereas about 43% made use of horisontal well screens connected to a caisson or collector sump. The remainder of systems visited were mainly caissons installed in the riverbed or the riverbank.

The sand abstraction systems were mainly used for domestic water supply and in a few instances for irrigation purposes. The design yield varied from 2 l/s for a gabion type collector sump with horisontal well screens to 1020 l/s for a bank of vertical well points. About half of the systems experienced problems of low yield, while one third of them suffered from iron and manganese related problems. Only half of the systems with low yield problems also had iron and manganese related problems.

About 20% of the systems experienced some known flood damage during construction or operation of the system. Only one of these systems, the biggest well point system, with a design yield of 1020 l/s, did not suffer from a reduction in yield after the flood event.

Generally it was found that most of the sand abstraction systems were suitably designed from a structural and hydraulic point of view. However, the geohydrological aspects and the hydraulic flow through the sand formation were mostly neglected in the design of sand abstraction systems. Similarly not much attention were given to aspects such as operation and maintenance during the design phase.

8.1.2 Problems Experienced with Sand Abstraction Systems

Several problems experienced with sand abstraction systems were identified during the research. The following three main types of problems were identified that contributed most to the problems experienced at sand abstraction systems:

- Low yield,
- Poor quality of abstracted water and
- Flood damage to the systems.

8.1.2.1 *Low Yield*

As mentioned previously the problem of low yield was identified in about half of the systems evaluated in the research. Problems could generally be attributed to insufficient design and/or construction methods used, or a combination thereof. Typical causes of low yield are the following:

- The recharge rate of an aquifer is lower than the abstraction rate of the system, resulting in over pumping and low draw down of the aquifer;
- A reduction in the permeability of the sand formation due to the accumulation or deposition of fine silt in or on the sand bed;
- The clogging of well screens by iron or manganese precipitates or by the development and accumulation of biofilm in the screens;
- The degradation or rusting of materials used for well screens and pipes, which caused either clogging of the system and or damage to pumps;
- The clogging of certain geofabrics, which in some cases resulted in a permeability of 10 times lower than when originally installed;
- A drop in the level of the water table due to low rainfall, excessive draw down or over pumping;
- The displacement or movement of well screens during fluidisation of the riverbed when floods occur;
- A change in the river course flow within the river bed over time, thereby changing the location of the system in relation to the aquifer;
- Insufficient developing of the system after installation, resulting in accelerated clogging of the system.

8.1.2.2 *Poor Quality of Abstracted Water*

Generally the poor quality of abstracted water could be associated with the presence of high concentrations of iron and manganese in the water. This problem was noted at several of the systems visited in the field. Besides discolouring, scaling, precipitation and eventual biofouling and clogging of the system elements, it also causes corrosion of screens, pipes, valves and pumps.

At several sand abstraction systems it was found that the surface water was of a better quality than the abstracted water in terms of iron and manganese concentrations. It appears that favourable conditions are sometimes created within sand abstraction systems for the development of iron and manganese precipitation and iron bacteria. In most cases these conditions are caused by high flow velocities in the sand formation or screens and could have been be prevented through proper design and installation of the system.

8.1.2.3 *Flood Damage*

Although surprisingly resilient under flood conditions all sand abstraction systems are susceptible to flood damage during or after installation. About

23% of the systems visited have been damaged during floods. Through careful design and installation methods the possibility of flood damage to sand abstraction systems could be significantly reduced.

Typical problems that occurred during floods were damage to the infrastructure (pipes, screens, collector wells and pumps) of the system due to surface water flow and sand bed fluidisation due to subsoil water flows. Damage to the system infrastructure could generally be minimised by constructing the system elements on bedrock or anchoring them to bedrock with ties. The deeper well screens are placed within a sand bed the lesser the damage would be in the case of sand bed fluidisation.

It is essential that the design and layout of each system should be suited to the site conditions to minimise flood damage as far as possible.

8.1.3 Observations of Successful Abstraction Systems

Many sand abstraction systems in Southern Africa are successfully in operation years after installation. The following observations regarding the design, installation and operation were made at some of the successful abstraction systems visited:

- Chisumbanje
  - Very favourable site conditions prevail at the location of this system
  - Following the second dry season of operation of the system installed in 1983, it was recognised that the system needed minimal monitoring and did not require any maintenance.
  - The system of vertical well points was never backwashed.
  - An unexpected benefit of the system was a significant reduction in herbicide application requirements when the estate was irrigated using only water from the abstraction system. This was due to the exclusion of weed seeds and poor quality associated with river surface water.
- Laingsburg
  - Innovation played a major role in the success of this system. Different types of systems were installed to utilise the scarce water resources.
  - Modifications were made to the system to suit changing conditions.
  - Comprehensive testing was done prior to installation of the system. These testing included geophysical investigations, electrical soundings for cross-sectional profile of the riverbed, core samples, pump testing from caissons and piezometer tubes to monitor sub-surface flow.
- Mtwalume Umgeni Water & Umkomaas
  - The operation of this system was a key factor to its success.
  - The design including for backwashing at high pressures as problems were experienced with accumulation of fines in the river sand. The

system is normally backwashed about four or more times per week as the need arises.

- Mtwalume:
  - The success of this system could be ascribed to effective filtration through the sand. This made it possible to overload the sedimentation basin of the water treatment plant by up to 100%, with respect to through flow time.
  - A maximum limit of turbidity of 0.5 NTU is set for water quality requirements for domestic water consumption. The turbidity of the abstracted water normally varies between 1 NTU during the rainy season in summer and 0.4 NTU during low flow periods in winter.
- Opuzane & Makhosine
  - The success of these systems are mainly because of innovative designs and the extremely favourable site conditions
- Nqutu
  - This system is successful because of the suitable site and
  - because it is well designed.
- Messina
  - Good operational practices and adaptation to changes played a major role in the success of this system.
  - The low recharge rates in the alluvium are taken into account during operation of the system in order not to stress the aquifer.
  - The success of the system could further be attributed to continual upgrading and modification of the system whenever problems are experienced.
- Nottingham
  - The operation of the system and adaptation to changed conditions.
- Whuwana and Shangani
  - These systems were installed on favourable sites and the
  - demand is very low so that the system never stresses the aquifer
- Nondweni
  - This abstraction system has a deep vertical well, which contributes to the success of the system.
- Dysselsdorp
  - This system also has a deep vertical well,
  - the testing results were good and
  - good operational practices are applied.
- Mtwalume School and Pungashe
  - Very suitable site conditions and

- ➢ an innovative design was used at this system.

Other successful sand abstraction systems were also visited at Umdloti, *Melkbosstrand and Mpungamhlophe. The successful use of these systems* could be attributed to proper testing, good design and construction of the systems.

From discussions with Mr Fox, and other persons who have worked with abstraction system for a long time, it is also evident that the success of abstraction systems cannot necessarily be based on "scientific or engineering design", although good design does contribute to the success of a system. It was also evident that abstraction systems should never be considered as systems that require low maintenance and management. On a daily basis, maintenance requirements are low, but the production/yield of any system should be monitored and steps taken to alleviate any problems that may occur with system as and when they do arise.

From the literature study and the observations above it is clear that the following aspects are of critical importance for the implementation of a successful sand abstraction system:

- The location of the site – the location of the sand deposits in relation to flood levels is critical in order to minimise potential flood damage to the abstraction system and to determine the optimum layout of the system.
- The parameters of the water bearing sand formation – the thickness of the sand deposit, the grading, grain size, permeability and the specific yield are all important parameters to consider before deciding which type of abstraction system to design and implement.
- The quality of the subsurface water – sufficient testing should be carried out to determine the quality of the abstracted water, as too high treatment costs could make the abstraction system uneconomical.
- The design of the system – the system should be designed to best suit the conditions prevailing at the selected site. The individual elements such as collector wells, pipes, screens and pumps should be sized correctly to prevent over pumping, excessive draw down and high flow velocities through the system.
- The construction and installation of the system – it is very important that the construction and installation methods are suited to the site conditions and that the properties of the water bearing formation are not changed during construction of the system.
- Development of the system – it was found that the performance of a system is significantly improved if it is properly developed before being used. Several methods of development are available and the best method or combinations of methods should be employed.

- The operation and maintenance of the system – it was found that successful abstraction systems are generally operated within the design parameters and that potential problems could be detected at an early stage with regular monitoring. Corrective measures and maintenance as required would generally ensure successful performance of the system.

8.1.4 Observations of Problematic Abstraction Systems

The following observations regarding the design, installation and operation were made at some of the problematic abstraction systems visited:

- At Havercroft Mine the system performed poorly despite comprehensive testing that was done to a depth of 3m. The screens were installed underneath a clay layer, which resulted in fines being drawn into the system.
- All the pumps at Havercroft Mine were installed below the top of the wedge wire screen sections. If the system is operated incorrectly and the water level in the caissons is allowed to drop to the level of the pumps (when the pumps would cut out), then sections of the screens would be exposed to air. This would cause aeration of the sand around the screens, which would probably induce the development of biological fouling and/or the precipitation of iron and manganese out of solution through oxidation.
- At Umdloti the pumping station has station tipped over, probably because of poor founding conditions at the site.
- At Mtwalume, Umgeni the pumping station was flooded. The level of the sill was raised and sand bags were packed in strategic positions to remedy the problem.
- The movement of the river course in the riverbed also caused problems at Umdloti, Apel and Mtwalume. The river no longer flowed over the screens or close to the abstraction system. Sand bags were used to divert the river back to its original position.
- A problem with high concentrations of iron was noted at Mtubatuba, Fairview, Hibberdene and Illovo. The problem was aggravated because of the intermittent use of the systems and because the screens were not located directly in the riverbed, but in flood plains adjacent to the riverbed. Reeds and/or other vegetal growth also covered the systems, resulting in possibly a higher rate of biofouling and subsequently low yield.
- Problems with low oxidation (low redox potential) were experienced at Dysselsdorp. This was probably due to low vegetation in the area surrounding the abstraction system. A low redox potential could be an indication of several risks, including precipitates of iron and manganese and difficulty in reducing the water's concentration of these metals in soluble form. It could also indicate microbiologically mediated dissolution of manganese and ferrihydrite involving organic matter (bacteria), which could cause clogging of well screens and the subsequent poor performance of abstraction systems.

A problem rating was assigned to all systems visited (Table 9) in order to rate the typical problems experienced at each system in terms of low yield, biofouling, clogging of sand and iron and manganese concentrations. This rating does not necessarily give an indication of the success or failure of a system, because in many instances the problems are contained through good operational and management practices.

Once problems start developing in a system, they will rapidly become worse and are then extremely difficult to remedy if not dealt with as soon as possible. It is essential that lessons be learned from experience with these systems, and that the users of the systems be open to adaptation of the systems if required.

8.2 CORRELATION OF SYSTEM PARAMETERS WITH SYSTEM PERFORMANCE AND PROBLEMS EXPERIENCED

8.2.1 Water Quality

Several water quality parameters were measured at the sand abstraction systems visited to determine whether there is a relationship between the water quality and the problems being experienced at the system. The results of a regression analysis performed on the data are shown in *Appendix L.2* of the report.

Generally it was found that the water quality parameters measured were not very good indicators of problems that could be expected at a sand abstraction system. However, it was found that the nitrate concentration in the surface water is a good indicator of the total bacteria counts in the system water and would therefore be a good indicator of biofouling problems. The relationship shown in Figure A.70 in *Appendix L* could be used to estimate the total bacteria counts in the system.

Similarly the turbidity is also a good indicator to estimate the total iron concentration, which could be an indication of potential problems related to iron and manganese precipitation or the presence of iron bacteria. The equations shown in Figures A.85 and A.86 could be used to estimate the total iron concentration in the abstracted water.

Selected graphs in *Appendix O.1* (Figures A.176 to A.199) show the correlation between water quality parameters and system performance in terms of problem rating. These findings are summarised in terms of risk (low, moderate and high) in Table A.62 of *Appendix O.1* of this report. These results could be of great value when determining the potential risk of the occurrence of a certain type of problem in a system.

8.2.2 Microbiological Aspects

Several methods and techniques, such as DAPI, SEM, light microscopy, etc were used to carry out bacterial counts on samples obtained from various sand abstraction systems. It was generally found that there is a moderate risk of bacterial biofouling in most of the systems evaluated, with a high risk of bacterial biofouling occurrence in a few of the systems.

With regards to the samples drawn from the Nqutu System, it was found that bacteria was the main agent in the sample and that the black substance from the walls of the collector well was a result of bacterial fouling. The sulphate reducing bacteria (SRB) count was too low to have played any role in the biofouling that occurred in this system.

With regards to the Ulundi System, the following conclusions could be drawn from the testing of the samples:

- The slime in the system was produced by bacteria and/or algae.
- After an initial decrease in bacterial numbers, the number of bacteria in the system started to increase, indicating that biofouling is occurring in the system. This is supported by the presence of the slime matrix and the algae in the system.
- The high number of planktonic bacteria in the system together with the high number of bacteria on the slides from the Pederson device is also an indication of bacterial biofouling.
- The biofilm possibly formed because of the presence of algae among the sand particles, which provided a growth surface for the bacteria.
- It could not be determined whether bacteria or algae are the main causative agent of the slime production, and subsequently the formation of the biofilm.
- However, it is clear that SRB does not form part of the biofouling problem.

No conclusions could be made on the part that iron bacteria plays in the biofouling in these systems. Although SRB normally has a major effect on biofouling, it was found in this study that the number of SRB in the samples was too low to cause the biofouling. It is, however, clear that the risk of biofouling increases significantly when algae and/or high counts of bacteria are present in the system.

8.2.3 Sand Properties

Several sand properties were measured and compared with the problem rating at each sand abstraction site visited. The results for each system, including a photograph showing the composition of the sand, are included in *Appendix M.6* of the report. The relationship between system performance and various sand properties are summarised in *Appendix O.2* of the report. The findings and conclusions for the relevant sand properties are discussed in more detail in the following paragraphs.

8.2.3.1 *Grading Analysis*

The results of all grading analyses conducted on sand samples from the systems visited are shown in *Appendix M.6* whereas the results of grading analyses done by others are included in *Appendix J*. Selected grading analyses graphs related to system performance are shown in *Appendix M.5* of the report.

From these results it is clear that generally problems of low permeability and subsequently low yield and clogging of sand could be expected if more than 50% of the sand is smaller than 0.60 mm and the D_{80}/D_{20} relationship is less than 5.0. Another good indicator of potential problems related to low permeability, low yield and possible clogging is when $D_{10} \leq 0.20$ i.e. at least 10% of the sand is smaller than 0.20 mm.

No acceptable correlation could be determined between the grading analysis and other system problems such as biofouling and iron or manganese related problems.

8.2.3.2 *Permeability*

The correlation analysis conducted to determine the relationship between sand parameters and permeability was conducted on two sets of data, one using full grading analysis, and one using the partial grading analysis. Better correlations were obtained using the partial grading analysis, which indicate that the larger fractions of the sand have minimal impact on the permeability of the sand.

From the results in the scale model it was found that the permeability at the surface of the sand bed tended to decrease rapidly after abstraction of water was started. However, there was always an improvement in permeability after backwashing was done.

In samples from some of the more problematic systems, it was also noted that the surface permeability continued to decrease throughout the testing sequences. This could be attributed to a build up of clay on the surface of the specific sample and or the occurrence of stratification or the formation of clay lenses in the sand, which subsequently resulted in low permeability.

The permeability of the surface sand, as well as the body of the sand formation has a direct correlation with problems of low yield. Generally, whenever the permeability of a specific sand is less than 2.0 mm per second and the FM is less than 3.0 respectively, problems of low yield and clogging of sand could be expected. There is no clear correlation between the permeability of sand and any problems related to biofouling and the presence of iron and manganese in the abstracted water.

8.2.3.3 Specific Gravity

There was little variation in the specific gravities of the various size fractions of the sand samples. In some instances the fines fraction had a higher specific gravity than the coarser fractions, but there was no particular trend or relationship between system performance and specific gravity.

8.2.3.4 Bulk Density

No direct correlation could be found between the in-situ bulk density and any of the system problems such as low yield, clogging of sand, biofouling and iron or manganese related problems. However, for in-situ bulk densities higher than 1650 kg/m^3 there is a marked drop in the permeability and void ratio of sands.

Problems with low permeability and low yield could be expected for sands where the in-situ bulk density is much higher than 1650 kg/m^3, and a corresponding void ratio of less than 40%.

8.2.3.5 Particle Shape

The visual observations of the general appearance and particle shape of the sand samples were defined in Table A.28 of Appendix M.6 of this report. Observations of particle shapes are given in Appendix M.6 together with photographs of the respective sand, the permeability and in-situ bulk density of the sand, and the problem ratings for the systems installed in the sand. This information is useful as a field guide for examining sands during investigations for proposed abstraction systems and could be used as an initial indicator of the potential performance of an abstraction system installed in the sand being examined.

Generally sand particles that are more rounded, not flaky and with high clay content are the most likely to present performance problems such as low yield and clogging in sand abstraction systems.

8.2.4 Geological Factors

It is important to note that the Grootfontein system, as well as other systems on the Olifants River where problems were experienced with iron and manganese precipitation is just downstream of the confluence of the Lepalane River with the Olifants River. Specifically, the Grootfontein system was situated approximately 30 km downstream of the confluence of these rivers. The Lepalane River crosses the Merensky Ridge, which is a high ore-bearing geological formation. High concentrations of manganese and iron are brought into the Grootfontein River by the Lepalane River, causing the problems of iron and manganese precipitation in abstraction systems sited downstream of the confluence of these rivers. This clearly indicates the impact of catchment geology on abstraction system performance.

Several parameters of catchment geology were measured to determine the relationship between these parameters and system performance. The results of the analysis are shown in *Appendix O.3* of this report.

Figure A.244 in *Appendix O.3* indicates a reasonable correlation between yield and the size of the Drakensberg and Lebombo Group in the catchment upstream of the abstraction point. If the size of this geological Group is larger than 13% of the catchment some problems could be expected with low yield and the clogging of the sand, whereas problems of biofouling and excessive iron and manganese concentrations could be expected if the size is larger than 17% of the catchment area.

The relative size of the Basement Complex in Transvaal, Swaziland, Namibia and Rhodesia in the catchment area is another good indicator of biofouling and iron and manganese related problems (Figure A.230 & A.231). Generally, the smaller this Complex the lesser is the risk of biofouling and iron and manganese related problems. Figure A.239 also indicates that there is a reasonable correlation between Acid and Intermediate Intrusives in the catchment area and potential biofouling problems. The smaller the size of these intrusives the lesser the risk of biofouling becomes.

8.2.5 Geographical Factors

The geographical parameters as listed in Table A.66 in *Appendix O.4* were also analysed in order to determine whether there are any relationships between these parameters and system performance.

Generally good correlations were found between potential biofouling and the following parameters:

- The presence of sugar cane in the catchment area (Figure A.253) – the more sugar cane in the catchment upstream of the system, the more likely problems of biofouling would occur,
- MAP of the catchment (Figure A.258) – the higher the MAP, the higher the risk of biofouling becomes and
- The size of cultivated land (land use) 50 km upstream in the catchment area (Figure A.261) – the larger the size of the land the higher the risk of biofouling becomes.

The following geographical parameters were found to have a reasonable correlation with iron and manganese related problems in systems:

- Tropical bush & savannah (Bushveld), (Figure A.243) – the smaller the area of tropical bush, the higher the risk of problems occurring. This is similar to the graph shown in Figure A.262.

- MAR of the catchment (Figure A.259) – more problems could be expected the higher the MAR in the catchment upstream of the system.

It appears that geographical parameters could be used in some instances to predict problems related to biofouling and the presence of iron and manganese. It is, however, not a good indicator of potential low yield and/or the clogging of sand abstraction systems.

8.2.6 River Morphology

As discussed in the previous chapter, the river morphology could not be considered as a good indicator of potential problems that might impair system performance.

8.3 EFFECTIVENESS AND USEFULNESS OF TESTING AND SAMPLING TECHNIQUES

8.3.1 Water Sampling and Testing

Due to the remote location of the majority of the sites, it was not possible to deliver the samples to the laboratories within 24 hours of sampling as is generally preferable. Every effort was therefore made to preserve samples by refrigerating them or putting them on ice as soon as possible after they were taken. Where possible, samples were sealed in cooler bags with ice packs and couriered to the laboratories.

Despite these measures, difficulties were experienced in keeping samples at a constant temperature and it was considered possible that samples may have undergone changes in the time between sampling and analysis. To solve this problem it was decided that water quality analyses should be conducted as soon as possible after sampling. Portable equipment for water quality analysis was purchased and an additional water sample was taken for "on-site" analysis and testing. This procedure was very effective and provided more accurate results of the on-site water quality.

A second problem that became evident after completing the initial site visits was that of a probable change in the oxidation state of the iron and/or manganese in the water samples taken from the abstraction systems. It was therefore also decided that it would be of value to preserve a sample for iron and manganese analysis in the laboratory. This was done where specific investigations were being conducted into aspects of iron and/or manganese precipitation, and was applied with good effect.

At all sites, two sets of water samples (grab samples) were taken; one set from the surface water and another set from the water abstracted through the sand abstraction system, prior to any treatment. Four samples were taken for each sample set, which included:

- one 500 mℓ sample (unpreserved) for water quality analysis "on-site",

- one 500 m/ sample (unpreserved) for water quality analysis in the laboratory,
- one 250 m/ sample, (preserved, nitric acid) for water quality analysis in the laboratory, and
- one 30 m/ sample (unpreserved) for microbiological analysis.

Several testing equipment were evaluated for on-site water quality testing. Based on efficiency, cost effectiveness and ease of use, the following testing equipment was used very effectively for on-site water quality testing:

- The *HACH DR/850 colorimeter*, which could be used to test for more than 50 parameters. In this study it was used for testing Turbidity, Nitrate, Sulphate, Ferrous Iron and Total Iron.
- The *HANNA DiSTWP 3 conductivity meter*, which was used for testing the Redox Potential of the water.
- The *HANNA HI8314 pH / mV / °C meter*, which was used for testing the pH and Conductivity of the water.

The standard methods, as described by the manufacturers of the instruments were used for testing samples. Samples of high turbidity should be filtered prior to testing for Iron, Sulphate and Nitrate.

8.3.2 Sand Sampling and Testing

At each site, where conditions permitted, general sand samples were taken for grading analysis, density tests and laboratory permeability tests.

During initial site visits the taking of representative sand samples proved to be problematic due to reasons of access and the method of sampling used. Due to these problems alternative sampling methods that would not require too expensive equipment and that would allow for sampling from as a great a depth as possible were sought. It should also allow for the analysis of the sand properties at different depths in the sand bed and be easily manageable by only two people.

Two samplers, a hand auger and a tube sampler, developed by Mr R. Fourie of Geotechnical Services, Pretoria, were found to work particularly well in these conditions. The samplers were relatively cheap and easy to make up, and were *extremely manageable and effective. Details of these samplers are included in* <u>*Appendix C.1*</u> of this report.

In certain conditions, such as where the riverbed material was extremely coarse, with high pebble content, or where the river flow was too deep, these samplers could not be used. In these instances samples were excavated from the surface of the riverbed.

A useful device, called the "directional" permeability test unit, was also used to measure the in-situ permeability of sand. This device could be used to measure the in-situ permeability of sand in a horisontal or vertical direction and is described in more detail in Appendix C.2 of the report. A disadvantage of this sampler is that samples could only be taken from exposed surfaces.

The bulk density of sand was measured by using one or more of the following devices or methods:

- Troxler – this instrument is useful in measuring the in-situ density of sands very quickly. However, it has certain limitations in that it is a very expensive device, it has radioactive parts which could be a health risk if not operated correctly, it should be calibrated regularly for different types of sand and it could not be used in saturated or submerged conditions.
- Volumetric measurement of excavated hole – this method is very simple to use by measuring the volume of the excavated hole by means of water replacement as described in Appendix C.3 of the report. Unfortunately it did not provide reliable results of the in-situ density of sand and also could not be used in saturated and submerged conditions.
- Density ring – this method is based on the excavation of a known volume of sand as described in Appendix C.3. The density ring could be used in surface dry, saturated or submerged conditions, and in most types of sands. However, the density ring cannot easily be used in pebbly or extremely coarse materials. Disadvantages of this method include the fact that one is limited to taking samples from exposed surfaces.
- Dynamic Cone Penetrometer (DCP) – this instrument was used to determine the relative density of the sand by counting the number of blows required to drive the penetrometer a fixed distance into the sand.

8.4 DATA AND TESTING REQUIRED FOR THE APPLICATION OF SAND ABSTRACTION SYSTEMS

For successful sand abstraction systems it is essential that appropriate investigations be conducted prior to the design and installation of such a system. These investigations should, however, be at a level appropriate for the size, sophistication and cost of the type of abstraction system to be installed. For example, minimal investigations should be conducted where small hand pump type systems are installed.

The required level of assurance of water supply should also be considered when planning investigations. Where a failure in the water supply will have serious consequences, the investigations should be comprehensive, even for small systems. It must, however, be noted that comprehensive investigations and good design procedures are no guarantee that a system will work efficiently. This has been demonstrated both at the Ulundi system (system 34) and at the Havercroft Mine system (system 37).

Existing data and information should be gathered and evaluated as far as possible before deciding on what testing is required at a specific site. For example, an extensive knowledge base about the Limpopo River in the area of Messina has been built up over a period of approximately 55 years. Very little testing, except for verification purposes, would therefore be required prior to the design and installation of new abstraction systems in this region.

The following data and information are normally readily available in well documented areas and could be very useful when selecting sites for new abstraction systems:

- The location of the riverbed of the original river course in relation to the present river course. Generally the sand depth above the riverbed of the original river course is deeper than in other parts of the river.
- Changes in the width of the original river course over time - at Beitbridge, for example, the old river course was approximately 45 m wide, whereas the existing riverbed is approximately 330 m wide.
- The depth of the seasonal water table in the sand bed. At Beitbridge the river is usually surface dry from about April to October. During this period the depth of the water table usually varies between 1.6 m and 3.0 m below surface level.
- Typical characteristics of the sand, such as the following should also be readily available in well documented regions:
  - ➢ The type of sand and the percentage fines in the sand.
  - ➢ The transmissivity and storage coefficient of the sand, which could be estimated from profiles and cross-sections of the aquifer.
  - ➢ The permeability of the sand, which could differ depending on the depth of the sand in the riverbed.
- The extent of the alluvial aquifer upstream of the system in order to determine the effective storage volume and zone of influence of the system.
- Relevant hydrogeological information such as MAP, MAR and general geology of the catchment area upstream of the system.

In riverbeds where the above data are known and available, the only tests that should be required to determine the feasibility of a new abstraction system are tests to determine the depth and profile of the sand bed by using one or more of the following methods:

- Depth probes by using steel rods in a grid pattern to determine the thickness and profile of the sand bed.
- Vertical electrical and resistivity soundings.
- Drilling and sampling of test holes.
- Digging, inspection and sampling of test pits.

Typical tests required for the design and installation of different types of systems are discussed in detail in section 6.2.4 of this report and include the following:

- Grading analysis of the sand.
- Bulk density of the sand
- Permeability of the sand, either through laboratory analysis or through theoretical calculations based on particle size distribution of the sand. From this the transmissivity of the aquifer could also be determined.
- Storativity and recharge of the water-bearing formation through theoretical calculations or through pumping tests such as step tests, at variable discharge rates, and/or constant discharge tests at the same rate as the abstraction rate. These tests should be carried out over extended periods in order to verify the sustainable potential yield of an aquifer.

It is good practice to install new systems in areas where it is known that the alluvial aquifer is contiguous with the alluvium of the riverbed. In these cases full geohydrological investigations should be conducted, including the drilling of test holes to determine the properties of the water-bearing formation and the execution of pumping tests to determine the recharge and storage properties of the aquifer.

Samples of the surface and sub-surface water should also be taken and tested for the following parameters, which might have a significant impact on the performance and operational and maintenance cost of the system:

- Nitrate concentration, which is also an indicator of the total bacteria counts and subsequent biofouling of the system.
- Turbidity, which is a good indicator of the total iron concentration in the water.
- The pH of the water, which is a reasonably good indicator of the total bacteria counts when the pH is in the range of 7 to 9.

It should be noted that the testing of these parameters should be carried out within 48 hours of the sample being taken. Where this is not possible the *HACH DR/850 colorimeter* or similar device could be used to do the testing on site.

8.5 DESIGN PROCEDURES AND CONSIDERATIONS RELATING TO DESIGN

8.5.1 Siting of a Sand Abstraction System

Several factors have an impact on the siting of an abstraction system. The parameters that should be taken into consideration are the following:

8.5.1.1 Aspects of Water Demand

Generally the first guideline for siting a sand abstraction system is the area where the water is required, the volume that is required and for what purpose the water will be used. The installation of an abstraction system too far from the place where it is required, or in an aquifer with insufficient yield or of poor quality water could make it unfeasible. It is therefore important that these three parameters are taken into consideration during the initial identification of potential sites.

8.5.1.2 River Morphology

The nature of the river morphology upstream and downstream of a proposed abstraction site is a very important when deciding where the system should be located and what system would be most suitable at that location.

Generally infiltration galleries should be placed along straight sections of the river where the river has a steady non-turbulent flow, whereas caisson types and well point systems should ideally be placed on the outside of a horseshoe bend, on the downstream section of the bend, in a meandering river.

It is very important that sand abstraction systems should be installed in such positions that the impacts resulting from high floods, such as bed fluidisation and damage to the structure of the system, would be minimised.

8.5.1.3 Geological and Geographical Aspects

Before deciding on a site for a sand abstraction system one should study the geological and geographical conditions of the catchment area upstream of the system.

Typical parameters such as the presence and size of certain rock formations, the type of land use, the MAR and MAP of the catchment are good indicators of potential biofouling, high iron and manganese concentrations and clogging of the filter sand. Other parameters, which could also impact on the performance of a system, are obstructions, such as weirs and bridges, and industrial and agricultural activities in the immediate vicinity of the proposed site. Most of these parameters could be obtained from regional geological and topographical maps and should be evaluated in terms of the relevant graphs summarised in *Appendix Q* of this report.

8.5.2 Design of Sand Abstraction Systems

8.5.2.1 Estimation of Yield

A sand abstraction system could be considered successful if it could supply water of appropriate quality at the required rate over the design lifetime of the system. For any good design the required abstraction rate should be in balance with the estimated yield from the aquifer. The yield from an aquifer is dependent on its recharge capability, which is determined by the flow conditions in the river and/or its interconnection with other aquifers.

The yield of a sand abstraction system is dependent on the hydraulic head above the point of abstraction and the permeability of the sand bed through which the water flows. Under natural conditions, the quantity of groundwater flowing through the alluvium under non-pumping conditions at the position of the abstraction point could be calculated by using Darcy's Law. The permeability, and consequently the potential yield from a water bearing formation, could be estimated by using either equation 6 or 7, which were developed for parameters obtained from a simple grading analysis and the site density of the relevant sand bed (see section 7.1.1). Other relationships shown in graphical and tabular format in Appendix M.4 could also be used as possible alternatives.

Various software packages, such as AQUAWIN, are available which could be used for modelling the behaviour of groundwater in an aquifer under pumped conditions. These models are normally difficult to set up and are not of much use if not calibrated correctly.

8.5.2.2 *Design Norms*

Typical design criteria that should be considered for the design of sand abstraction systems are the following:

- The infiltration rate from surface flow into the sand should be limited to about 0.4 mm/s in order to minimise the rate at which fine particles could penetrate and block the voids in the surface layer of the sand. During periods of high flow, when the water is more, turbid, an even lower infiltration rate would be desirable.
- The hydraulic gradient should be kept between 0.45 (fine sands) and 1.00 (coarse sands) to ensure laminar flow and the application of Darcy's equation for flow through the sand bed. The hydraulic gradient is at a maximum where the water enters the abstraction point. It is essential that the hydraulic gradient be controlled at this point in order to maintain laminar flow in the system.
- Where well screens are used the flow velocity through the screen slots should not exceed 0.03 m/s. This is necessary in order to keep the hydraulic gradient in the sand surrounding the screen within the limits required for laminar flow, and to minimise the infiltration of fines into the well screens, as well as to minimise head losses through the screen.
- Where abstraction pipes are used the flow velocity in the pipes should be kept between 0.9 m/s and 0.3 m/s in order to minimise head loss and the deposition of fine material in the pipes respectively. The head loss in a pipe should not exceed 0.30 m.
- The size of the slot openings in the abstraction pipes or screens should be such that 95% to 100% of the surrounding sand is retained outside the pipe or screen.
- Provision should be made in the design for the development of the sand surrounding the abstraction pipes or well screens. This is normally done through the pulse jetting of water into the screens, thereby removing the

finer particles from the sand around the screens and leaving the coarser fraction of the sand around the screen.

- Instead of developing the well, the installation of a filter pack around the abstraction pipe or screen could also be considered.
- Horisontal well screens, if used, should be installed as deep as possible in the sand bed, or anchored to the riverbed, in order to minimise the impacts of sand bed fluidisation under flood conditions. It is estimated that bed fluidisation could occur up to depths of about 2.50 m.

8.5.2.3 Design Calculations

As a guideline typical design equations for the calculation of head losses and flows through the sand bed and collector pipes are shown in <u>*Appendix R*</u> of this report. If necessary, similar equations should be developed for different assumptions and layouts other than that shown in the appendix.

Where conditions are different, revised flow nets should be compiled to determine the relevant flow and equipotential lines for different layouts and configuration of the abstraction system.

Care should be taken that assumptions made in the design phase are still valid under different operating conditions of the system.

Standard hydraulic calculations should be used when sizing the different elements (pipes, screens, valves, pumps, etc.) of the water abstraction system in terms of flow velocity, head loss and flow capacity. The well screens should be sized in accordance with the required abstraction rate, which would determine the open area required and the maximum screen velocity for specific slot widths.

8.5.2.4 Practical Design Considerations

During the research the following practical design considerations for sand abstraction systems were noted:

- A factor of safety of at least 25% should be added to allow for possible clogging or encrustation of well screens.
- The use of geofabric as a filter material should be avoided where possible due to problems of clogging and reduced yield being experienced.
- Where possible corrosion resistant materials should be used to minimise maintenance and potential reduction in yield.
- Allowance should be made for backwashing facilities in the design of an abstraction system. As such non-return valves should not be used, and vacuum tanks should rather be installed.
- Systems should be designed to facilitate easy access to critical elements for the operation and maintenance of these systems.

- Well screens should be installed deep enough to allow for expected draw down of the water.
- Where possible, one should stay away from sand beds that contain clay lenses, as it could cause reduced yield of the system. In some cases these clay lenses could be successfully removed.
- The design of the system should be re-assessed whenever new developments or structures such as weirs or bridges are built in the near vicinity.
- Provision should be made for ventilation to prevent air locks in the system.
- Well points should be designed to operate individually instead of in banks. This would reduce power consumption and optimise abstraction rates if problems occur with some of the well points.
- Allowance should be made for the priming of well point pumps. Here again vacuum tanks could be installed.
- Centrifugal pumps are more efficient than submersible pumps and mono pumps. At well point systems centrifugal pumps should ideally be backed up by submersible pumps.
- Abstraction systems should not be positioned perpendicular to the river flow due to higher risk of flood damage.
- Well points should be attached to a buried manifold with a flexible hose or couplings to provide flexibility of movement to minimise damage during flood events.

8.6 CONSTRUCTION METHODS

It was found that construction methods vary for different types of sand abstraction systems and are also dependent on the site conditions, available technology and the cost of implementing such methods.

Typical construction methods for various types of sand abstraction systems are discussed in detail in sections 3.1.4 and 6.2.6 of this report and are not repeated in this section. However, it is very important to take note of the following issues when constructing sand abstraction systems:

8.6.1 "Traditional" Sand Abstraction Wells

- The walls of these wells should be excavated at a flatter slope to prevent stability and safety problems during rainy periods.
- The protective thorn fences around these wells should be anchored or replaced with conventional fencing to prevent the trapping of silt and finer sediments during river flows, thereby making it difficult for people to find optimum well sites in the river the following season.

8.6.2 Infiltration Galleries

- It should be noted that the primary application for an infiltration gallery is in shallow aquifers and natural barriers such as impermeable rock formations could greatly enhance well efficiency.
- In most cases the hydraulic head would be low due to limitations on the depth at which a trench laid gallery could be placed. In such cases it is imperative to position galleries in materials of high hydraulic conductivity, such as alluvial deposits.
- Collection sumps should be constructed using the open-end caisson sinking method where reinforced concrete rings are sunk into the river bed by excavating the sand on the inside until the desired depth is reached.

8.6.3 Infiltration Wells

- For easy access and to minimise potential flood damage to pumps and other expensive equipment the collection sump of an infiltration well should be built on the riverbank and then connected to the well.

8.6.4 Collector Wells

- The excavations around the caisson should not be backfilled, as problems would be experienced when trying to sink the caisson deeper.
- After placing aggregate at the base of the sunken caisson it should be covered with a sieve or mesh with suitably sized openings to prevent movement of the aggregate and disturbance of the filter material.
- After installation of the screens, each radial should be individually developed to remove the fines from the formation in the area adjacent to the screen. This normally results in a higher yield and efficiency of the well.
- The caisson should be extended to a level above the design flood level before it is fitted with a pumping house and the required controls. Unconsolidated sand should first be excavated to the level of the water table before placing the first sections of a caisson.
- Cofferdams should be provided to prevent flooding of the works during construction. Besides damage to the works and loss of production, the performance of the system could also be impaired.

8.6.5 Well Point Systems

- It is important that once the screens are in position they should be developed using surge plungers to remove the fines from the formation in the area surrounding the well thereby improving the permeability of the surrounding soil.
- Submersible pumps should be installed above the screens in such a position as to ensure an even suction over the full length of the screen.
- Where possible the manifold system should be buried in the riverbed to minimise possible damage during floods.

- The optimum location for a well point is in a shallow alluvial aquifer where the water levels remain close to surface throughout the year.
- A well point system should ideally be installed towards the end of the dry season when the river water is at its lowest level.
- The river sand should first be removed to the top of the water-bearing layer before a manifold is installed on the water yielding sand. Slotted pipes should then be driven at an angle into the water-bearing layer and then connected to the manifold. To complete the installation the manifold should then be connected to a suction pump on the riverbank.

8.6.6 Screened Tube Wells

- Drilling, driving and/or jetting methods should be used to install the tube wells.
- It is important that the well be developed on completion of the installation in order to establish a zone of high permeability in the formation around the screen.
- The bottom of the tube well should be sealed off by pouring cement through an inner pipe to form a 300 mm thick plug at the bottom of the tube.
- A concrete collar should be provided around the part of the tube extending above the average water level.

8.6.7 Sand Storage Dams

- For a sand storage dam to be successful it is essential that it be constructed in controlled incremental stages so that the velocities of flow through the basin are sufficiently high to transport most of the fine sediments over the dam crest.
- The objective should be to promote the deposition of coarse-grained sand deposits in the dam, which will improve both the efficiency of absorption and the yield of the sand storage dam.
- It is essential that each new stage should be constructed only after the previous stage has effectively silted up.

8.7 OPERATION AND MAINTENANCE OF SAND ABSTRACTION SYSTEMS

In general it was found that the operation and maintenance of sand abstraction systems in Southern Africa has not received the level of attention that it should and that much of the success or failure of such systems are related to operation and maintenance issues. Although the successful systems were not problem free, it was found that proper operation and maintenance procedures were in place at these systems and that problems were detected and remedied at an early stage, thus preventing more serious and costly problems.

Once a sand abstraction system is in operation it should be monitored closely for any signs of deterioration as the early detection of potential problems could potentially save a lot of unnecessary costs and also ensure sustainable yield from the aquifer.

Typically, the following parameters should be monitored at water abstraction systems in order to quickly identify performance problems:

- Water turbidity – relative increases in turbidity could be an indication of deteriorating filter performance.
- Water quality – a sudden deterioration in water quality could be an indication of a new source of pollution into the aquifer. The pollution could either be from chemical (iron content) or bacterial (coliform) sources.
- Water quantity – changes in pumping rates could be an indication of a drop in the water table, insufficient recharge to the aquifer, clogged screens or filter sand or a loss of pump efficiency.

Some typical remedial measures that could be implemented once a problem is identified are the following:

- Clogging of the filter – this is generally caused by the deposition and infiltration of fine silts during low flow conditions in the river. Possible remedial actions are the back-washing or high pressure jetting of the filter medium.
- Clogging of screens – this is normally caused by fine particles plugging the slots of the screen due to high entrance velocities or insufficient filter around the screen. Surge plungers, jetting or compressed air may be used to clear the screens.
- Biofouling of screens – this is generally caused by high levels of iron and manganese in the presence of bacterial slimes. Chlorination, removing and cleaning the screens with peroxide, mechanical agitation and pumping are some of the methods that could be used to break up, dissolve and remove biofouling.
- Incrustation of screens – this is caused by the precipitation of inorganic ions such as iron, manganese, calcium and magnesium. The use of acids and mechanical agitation are some of the methods that could be used to remove incrustation.
- Accumulation of silt in pipes – this problem could be caused by too high inlet velocities, too large slot sizes or an insufficient gravel filter. Flushing, surging or brushing methods could be used to suspend the fines whereafter it is pumped or drained from the well.
- Corrosion of screens – this is generally caused by aggressive water. The damaged elements should be removed and replace with screens or pipes manufactured from corrosion resistant materials.

It should be borne in mind that no single remedial method works for all types of wells and that a combination of different treatment methods could be used in some problematic situations.

Furthermore, the operation and maintenance of sand abstraction systems should, as far as possible, be taken into consideration during the design phase of such a system and not after it has been installed. For larger abstraction systems operators should be properly trained in the monitoring and operation and maintenance of such systems.

8.8 GROUNDWATER MANAGEMENT

Where appropriate, a formal groundwater management programme should be developed and implemented, especially at large abstraction systems. The objectives of a formal groundwater management programme would be:

- To prevent an aquifer from being over-pumped. Over-pumping could result in the long-term depletion of groundwater throughout the aquifer, which could result in changes to the alluvium characteristics (through settlement etc.) and the introduction of oxidation, with its related problems, in the alluvium and the abstraction system.
- To optimise the individual abstraction rates from different parts of a system e.g. individual vertical caissons or well points. If individual pumping rates are too high, then localised depletion of the groundwater could occur, which would result in a higher pumping head and subsequently an increase in energy consumption for the operation of the system. Problems of potential cavitation in the pumps could also occur if the water level is drawn down to the pump intake levels and a combination of water and air is pumped.
- To prevent poor quality groundwater from entering the aquifer. If abstraction rates are too high, poor quality water could be drawn into the aquifer from adjacent sources.
- To monitor and maintain the ecological integrity of the aquifer and the surrounding environment.

In order to effectively manage alluvial aquifers in riverbeds, the following measurements and equipment would be required:

- Flow meters should be installed at all the abstraction points or for each abstraction network. The total quantities of water abstracted from each system should be recorded on a weekly basis.
- Water level monitoring tubes should be installed at each abstraction point to record the water levels in the aquifer. A 25 mm diameter PVC pipe installed vertically at the abstraction point could be used for this purpose. The water levels inside the pipe should then be measured by using a dip meter.
- The water levels should be monitored and recorded on a weekly basis for the first 12 months of operation, whereafter it could be measured on a monthly basis. It should be indicated on the records whether the levels were recorded while the pump was switched on or off. Levels should be recorded

at least four hours after the pump was switched on or off, to allow the water level to stabilise.

- Groundwater quality should be monitored on a monthly basis for the first year of operation and thereafter on a six monthly basis.
- Data collected over the period of a year should be submitted to a qualified geohydrologist for analysis and evaluation.

In terms of the new Water Services Act, the activities listed above are mandatory, and it is the responsibility of the local Water Authority to carry out the required monitoring.

8.9 DISCUSSION OF HYPOTHESES POSED

The hypotheses posed in Table 12, section 2.3 of this report are discussed critically in the following paragraphs, based on the findings and conclusions of this study.

8.9.1 Hypothesis 1: Biologically Induced Fouling

1.1a - Clogging of the screens by biologically induced fouling is a major cause of the reduced flow in the Ulundi sand abstraction system.

Uncertain. Investigations into this matter were inconclusive. It was found that many other factors, such as algae and high concentrations of iron and manganese, also have a significant impact on reduced flow.

1.1b - Biologically induced fouling results in clogging and reduced yield of sand abstraction systems.

Uncertain. The correlation between the clogging of sand and bacterial counts is very low (correlation factor of 0.02). However, biologically induced fouling could be a catalyst for other parameters causing clogging of the sand.

1.2 - Biologically induced fouling in the Ulundi system is caused by iron reducing/oxidising bacteria.

True. From the literature review it was found that iron and manganese bacteria not only produce accumulations of slimy material (biofouling) but that they also precipitate dissolved iron and manganese. This process, together with oxide and hydroxide depositions, is generally the cause of well screen clogging and failure. This correlate with the statements of Smith (1997) and the findings of the Northern Territory Government of Australia (2002) that iron bacteria is generally the catalyst for iron and manganese precipitation in abstraction wells.

1.3a - The shape of the slots of the screens used in the Ulundi system is such that the screens are more prone to biofouling.

Uncertain. This hypothesis could not be verified due to inaccessibility to the Ulundi system.

1.3b – Certain screen types are more prone to biologically induced fouling.

False. Although certain screen types are more prone to clogging and reduction in permeability, no evidence could be found that the screen type is the cause of biofouling.

1.4 – Although the conditions at the Ulundi system may be extremely suitable for the development of biofouling it is postulated that the problem was initiated and exacerbated by events that occurred during the early life of the system.

Uncertain. During flooding of the system in the construction phase fines were deposited on the sand bed, which caused clogging, reduced permeability of the sand bed and reduced performance of the system. However, no evidence could be found that the flood initiated the development of biofouling.

1.4a - The development of biofilm in the Ulundi system was initiated as a result of the flooding of the system prior to completion of construction, when a large amount of fine sand and rubbish was washed into the system. It is postulated that during this event, the system was seeded. In addition the presence of fine sand particles in the system facilitated the development of a biofilm.

Uncertain. The hypothesis is based on an unproven premise. It also could not be verified due to a lack of comparative information on the relevant system parameters before the flood event.

1.4b - Following completion of the system the river water was diverted away from the system. This allowed for the development of a biofilm in the system.

Uncertain. This hypothesis could not be verified due to the presence of other system parameters, such as algae and iron and manganese bacteria, which also contribute to the development of biofouling.

1.5 – Although bacterial growth can be expected in all sand abstraction systems, the extent to which this growth occurs and the associated risk of clogging by biofouling will vary depending on system conditions.

True. Findings from the research indicate that biofouling generally occurs under favourable biochemical and physical conditions, which include the presence of organic and inorganic matter, algae, bacteria, oxygen, the correct temperature, the flow rate, the layout, position and elements of a system etc.

1.6 – The level of risk of clogging of a system by biofouling is influenced by, and can therefore be indicated by the surface water quality.

True. It was found that certain surface water quality parameters such as nitrate concentration and pH are good indicators of potential risk of biofouling.

1.7 – The level of risk of clogging of a system by biofouling is to some extent influenced by, and can therefore be indicated by upstream land use.

True. It was found that the size of cultivated land and sugar cane land are good indicators of potential risk of biofouling.

1.8 – The level of risk of clogging of a system by biofouling is to some extent influenced by, and can therefore be indicated by upstream geology.

True. It was found that the presence of certain geological formations such as the Drakensberg and Lebombo Group and Acid and Intermediate Intrusives in the catchment upstream of the abstraction point are good indicators of potential risk of biofouling.

1.9 – Systems where flow is mainly subsurface will be less prone to problems of clogging by biofouling.

False. Of all the systems with performance problems only two were found where the flow was mainly subsurface (26 & 28). At both of these systems problems were experienced with biofouling. It could probably be attributed to the presence of reeds, bushes and other vegetal growth on the sand bed from which the water is abstracted.

8.9.2 Hypothesis 2: Sand Properties

2.1a - The nature of the sand at the Ulundi sand abstraction system changed following installation of the sand abstraction system, with an accumulation of fines in the system, particularly at depth. This is contributing to the problem of low yield of this system.

True. The findings of the research do indicate the presence of fines in the sand bed, which has a significant impact on the permeability of the sand and subsequent low yield of the system.

2.1b - The installation and operation of sand abstraction systems will alter the nature of the surrounding sand beds.

True. The findings of the research indicate significant changes in the permeability of the sand bed at various abstraction rates and periods of discharge, including the occurrence of stratification of layers in the sand.

2.2a - The accumulation of fines in the Ulundi sand is partly due to the presence of the weir immediately downstream of the system.

True. The findings of the research indicate that fines could be deposited during low flows and be drawn into the sand bed thereby reducing the permeability of the sand and the performance of the system.

2.2b - *In certain types of sands, if there is a weir downstream of a sand abstraction system then fines will accumulate in the sand.*

True. The findings of the research indicate that fines could be deposited during low flows and be drawn into the sand bed thereby reducing the permeability of the sand and the performance of the system.

2.3a - *The accumulation of fines at depth in the sand at Ulundi is partly due to the nature of the sand itself, with the finer particles having a higher specific density than the coarser particles. This in turn would be due to the geology of the source rock.*

False. No significant correlation could be established between the specific density of particles and the accumulation of particles at depth and subsequently reduced performance of a system.

2.3b - *In certain types of sands the fine particles have a higher density than the coarser particles. In such sands the fine particles can accumulate at depth in the sand.*

Uncertain. This postulation could not be verified due to a lack of information and testing data.

2.3c - *In certain geological conditions, it can be expected that fines will accumulate at depth in the sand riverbeds.*

Uncertain. This postulation could not be verified due to a lack of information and testing data.

2.4 - *Sand permeability as measured in the laboratory is not necessarily a true representation of the in situ permeability, as the bulk in-situ density of the sand is not necessarily taken into account.*

True. Laboratory testing has shown significant changes in permeability for minor adjustments in the compaction of test samples.

2.5 - *The theoretical empirical formulae that are commonly used to estimate sand permeability based on the sand grading do not account for sands with a very fine fraction, even when this fraction constitutes a very small percentage of the sand.*

True. Laboratory testing has shown that higher correlation factors are obtained when the finer fraction of sand is taken into account when estimating the permeability of sand.

2.6 - *Depending on the particle shape, the permeability of sand is markedly affected by the presence of a very fine fraction.*

True. Laboratory testing and the literature review have shown that the particle shape has a significant impact on the porosity and permeability of a sand.

2.7 - *The permeability of the sand is affected by the upstream geology, river morphology and land use. In turn these factors can be used as indicators of potential success of sand abstraction systems.*

True. Reasonably good correlations were obtained between system performance, which is related to the permeability of the sand, and parameters such as upstream geology, river morphology and land use.

8.9.3 Hypothesis 3: Iron and/or Manganese Precipitation

3.1 - *Clogging by iron and/or manganese precipitation sometimes causes problems of reduced yield.*

True. The literature review and laboratory testing have validated this postulation.

3.2 - *Risk of clogging by iron and/or manganese precipitation can be indicated by surface water quality.*

False. It was found that surface water quality is generally not a good indicator of iron and/or manganese related problems.

3.3 - *Risk of clogging by iron and/or manganese precipitation can be indicated by immediate and upstream geology.*

True. Good correlation factors were obtained to support this postulation.

3.4 - *Clogging by iron and/or manganese precipitation cannot necessarily be separated from clogging by bacteria, the two mechanisms acting in conjunction with each other.*

True. From the literature review it was found that iron bacteria generally acts as a catalyst for the precipitation of iron and/or manganese.

8.9.4 Hypothesis 4: Screen Selection

4.1 - *The type of screen used will affect the performance of a sand abstraction system.*

True. From the literature review and the scale model unit testing it was found that the screen type has a significant impact on the permeability of the sand bed and therefore the system performance.

8.9.5 Hypothesis 5: General

5.1 - *Geofabrics should not be used in sand abstraction systems.*

True. From the literature review and observations at the visited systems it was found that geotextiles tend to clog, resulting in reduced performance of the system.

5.2 - *The method of construction of a system may affect the performance of the system, possibly increasing the risk of biofouling of the system or alteration of sand properties.*

Uncertain. Different construction methods were used at Ulundi and Nqutu, which could have had an impact on the system performance. However, scale model testing on the same screens with sand from Ulundi and Nqutu respectively gave different results in permeability for the same flow rates, which is an indication that the sand properties could be a major cause of the different performances of the two systems.

5.3 - *Ideally, systems should not be operated at velocities less than a certain minimum velocity. If velocities are lower than some (as yet undetermined) minimum velocity, fines will not wash through the sand and system, and will accumulate in the sand surrounding the system and will therefore reduce the permeability of the sand.*

Unsure. This postulation could not be verified from the literature review or any laboratory tests done on samples from the systems visited.

5.4 - *In sands with high fines content, the development of biofouling in an abstraction system will exacerbate the accumulation of fines in sand surrounding a system. The development of biofouling in a system will result in a reduced flow through the system and surrounding sand. This, in turn, will result in an accumulation of fines in the sand, as velocities are sufficient to draw the fines towards the system, but not sufficiently high to draw the fines through the system. The permeability of the surrounding sand will therefore reduce with time, the mechanisms of clogging by biofouling and clogging of the sand acting in conjunction to reduce the yield of a system.*

True. Results from the literature review indicate that the flow through the sand bed should be limited to about 4.0 mm/s to minimise the accumulation of fines. At a constant abstraction rate the velocity in the sand would increase with the accumulation of fines (reduced flow area), resulting in further accumulation of fines and a reduction in permeability. This, together with biofouling would result in the reduction of the yield of the system.

5.5 - *The yield of systems that are not operated regularly and/or are only operated at a fraction of their design yield will generally reduce in time. There will be an increase in problems experienced with biofouling, clogging of the sand, iron and/or manganese precipitation and high iron content of the abstracted water.*

True. Results have indicated that a minimum flow of 0.3 m/s should be maintained in the abstraction pipes of a system to prevent finer particles from settling in the system. Reduced abstraction rates would therefore result in settling of finer particles, clogging of the sand and reduced performance of the system.

9 RECOMMENDATIONS

9.1 DATABASE OF SAND ABSTRACTION SYSTEMS

A large volume of information regarding the application of sand abstraction systems in Southern Africa has been gathered and evaluated during this research project. Typical design guidelines for the various types of abstraction systems visited, including a field guide based on the properties of the sand from which water is to be abstracted and a comprehensive risk profile of the potential occurrence of particular problems based on easily measured parameters are included in this report for use in the design of new abstraction systems.

It is recommended that the information on these abstraction systems be captured on a separate database, and be continuously updated as new information and data becomes available. The data could then be available for further analysis and evaluation as required.

As the bulk of the content of this report is not required for the design and implementation of new sand abstraction systems it is recommended that the technology be transferred by the development of reference manuals with guidelines for the design, construction and operation and maintenance of abstraction systems.

9.2 TECHNOLOGY TRANSFER

9.2.1 Design of Sand Abstraction Systems

It is recommended that the design manual should provide appropriate guidelines with regards to the following parameters:

- Identification of suitable sites
- Appropriate sampling and testing requirements for the sand bed and water
- Identification of potential problems and the risk of occurrence of problems at the selected sites
- Determination of the specific yield and recharge of the aquifer by making use of the developed equations for permeability in section 7.1.1 and Appendix M.4 of this report. The permeability is based on the grading analysis and site density of the relevant sand bed. The most accurate equation developed is based on the D_2, D_5, D_{10}, D_{15}, D_{20}, D_{50} and D_{80} range of sizes of a particular sand.
- Determination of the type of abstraction system most suitable to the site conditions and required water demand
- The layout and design of the following abstraction system elements, where applicable:
  - Screen type, size, percentage of open area and slot widths,
  - Diameter, length and material type of collector pipes,

- Galleries, collector wells and/or caissons, including ventilation
- Gravel packs and/or filter materials
- Manifolds, pumps, pumping house, valves, instrumentation and backwashing facilities

- Accessibility features for operation and maintenance of the systems
- Flood protection measures, where applicable

It should be noted that the design manual should be seen as a guideline for the design of sand abstraction systems in Southern Africa and that an experienced person should carry out the final design of a system in order to find the optimum design for a specific site.

9.2.2 Construction of Sand Abstraction Systems

As for the design of a sand abstraction system it is equally important that the best-suited construction methods and technology be employed during the installation of an abstraction system. It is therefore recommended that a construction manual be developed in conjunction with existing contractors to provide general "best practice" guidelines for the installation of the different types of abstraction systems. The following issues need to be included:

- Alternative methods of installation i.e. open excavations, caissons, drilling of holes, jacking, jetting etc.
- Protection of the works against flooding
- Dewatering of the works
- Restrictions and safety measures
- Suitable methods for the development of wells
- Testing of the installed system
- The use of local materials and labour
- Stakeholder involvement

It should be noted that the construction manual guidelines should not be prescriptive but should rather address typical practical issues as listed above. Contractors should have the opportunity to develop and implements their own construction methods.

9.2.3 Operation and Maintenance of Sand Abstraction Systems

The research has shown that, although most of the sand abstraction systems develop problems at some point during its lifetime, these problems could be effectively countered by the implementation of proper operational and maintenance procedures. It is therefore recommended that a reference manual be developed specifically for the operation and maintenance of abstraction systems.

The manual should provide general guidelines with regards to the following parameters:

- Typical operational procedures required for the various types of systems
- Permissible rate of water abstraction
- Minimum and maximum periods of water abstraction
- Monitoring and logging of the quantity and quality of the water abstracted
- Typical indicators of potential problems that could be expected and possible solutions to rectify the problem
- Typical maintenance procedures for the different types of systems
- Minimum skills and training requirements for the operation and maintenance of sand abstraction systems

It is further recommended that, where appropriate, formal groundwater management programmes should be developed and implemented, especially for large abstraction systems.

9.3 PILOT STUDIES

It is recommended that pilot field studies be carried out for larger water abstraction schemes, in order to verify the specific yields of aquifers and the assumptions made for the designs of such abstraction systems. The results obtained from such studies would enable designers to optimise the designs and construction of these systems before investing large capital amounts.

9.4 ONGOING RESEARCH

The findings of this research have indicated that there is a need for further research into the behaviour of sand abstraction systems under certain conditions. It is recommended that the following research be carried out in the near future:

- Research to establish the relationship between biofouling, the presence of iron and manganese concentrations in the water, clogging of the sand and screens and the performance of the abstraction system.
- Further research into the cause and nature of the specific problems that occurred at Ulundi. This research should include the impacts of different construction methods, very low flow velocities through the sand and flooding on the performance of sand abstraction systems.
- Further research to find a more practical relationship between sieve analysis, permeability of the sand bed and the specific yield of an aquifer.

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