Corrosion in potable water systems : The Johannesburg experience

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Abstract

The corrosion effects of a polyelectrolyte flocculated water containing sulphate and chloride, and the role of *Desulfovibrio desulfuricans* in promoting pipe wall penetration in the aging Johannesburg potable water reticulation system, are described. Costs and criteria for upgrading the system with cement mortar or high density polyethylene (HDPE) liners and plastic piping are given. A pilot leak detection survey has demonstrated the need for continuing investigation in this field.

Historical

Johannesburg owes its origin to the discovery of gold in 1886, not far from the present centre of the city. It was a site remote from any reasonably-sized river and early water supplies had, of necessity, to be drawn from shallow wells and springs, and sold to inhabitants from water carts at 2,5 to 5,0 c for a small bucket, the price depending on the distance it had to be transported (Knight and Leonie, 1986).

State concessions were granted to three different private companies, namely the Johannesburg Waterworks Estate and Exploration Company, the Vierfontein Syndicate and the Braamfontein Company. These undertakings, however, were unable to supply sufficient water of good quality. After various commissions had investigated and reported on the problem, the Rand Water Board (RWB) was brought into being by legislation on 8 May 1903, and expropriated the rights of the existing water supply companies (RWB, 1978). The Johannesburg Town Council took over certain reservoirs in the municipal area, as well as a reticulation system consisting of 435 km of mains. The town expanded rapidly and some of the steel water mains which had been laid in the 1920s, are believed to have survived until the 1980s.

Water treatment systems

The life of any water reticulation system is dependent on the aggressiveness of the ground in which the pipes are laid, and on the quality of the water flowing within the system. It is therefore expedient to trace the history of the water treatment systems used over the last half century.

Johannesburg receives its water from the Rand Water Board which supplies an area of 16 815 km^2, in which some 6 500 000 people, about 25% of South Africa's total population, reside. It obtains its supplies from two main sources, the Vaal Dam and the Vaal River Barrage. The former source is of relatively low salt content but of a fairly high turbidity, whilst the latter is a highly mineralised source containing recycled sewage effluent and high sulphate waters from the gold mining industry.

Hydrated lime coagulation

The Rand Water Board has used hydrated lime to achieve coagulation and flocculation at pH values of 10,5 to 11,0 since 1932, and in 1959, it introduced activated sodium silicate as an aid to flocculation (Van der Merwe, 1988). After sedimentation and pH correction to 8,7 the water was sand-filtered and chlorinated, and after about 6 h in the pumping mains, was again disinfected using monochloramine (James, 1985).

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Polyelectrolyte coagulation

In the mid-1970s, laboratory tests carried out by the RWB demonstrated that cationic organic polymers were likely to be economic and effective for the coagulation of water stored in the Vaal Dam. The polymer used was of medium to high molecular mass (75 000), and was a polyamine-type based on a polyquaternary resin. It was found to be most effective for the coagulation of low electrolytic raw water ($<$40 mS/m at 20°C), high in turbidity ($>$20 NTU), and containing low concentrations of organic material (5 mg/ℓ). Although coagulation was found to be effective at turbidities above 120 NTU, polyelectrolyte addition was more costly than lime coagulation (James, 1985).

In January 1975 the Rand Water Board commissioned a 600 Mℓ/d plant using this coagulant, and during the initial 4-month commissioning period, water was intermittently produced without any pH correction and was undersaturated in terms of calcium carbonate. This was later corrected by the addition of lime, but in spite of this, the Board started to receive complaints of red water after a period of 18 months (Van der Merwe, 1988).

Problems with polyelectrolyte-treated waters

Rand Water Board experience

For extended periods during the 8-year trial with polyelectrolytes, a large percentage of sewage effluent and mine pumpage was present in the water being treated. There was also insufficient energy available for coagulation and these factors collectively necessitated an overdose of polyelectrolyte to achieve the desired results. Associated with this condition was the high concentration of dissolved organic material which hindered the coagulation/flocculation process. Flotation was also sometimes experienced when a specific type of clay from the Suikerbosrand River was introduced into the raw water supply. Organic matter was not effectively removed and resulted in high doses of chlorine (3 to 4 mg/ℓ) to achieve disinfection. Further problems arose from the passage of residual polyelectrolyte onto, and through, the sand filters. Lower filter run-

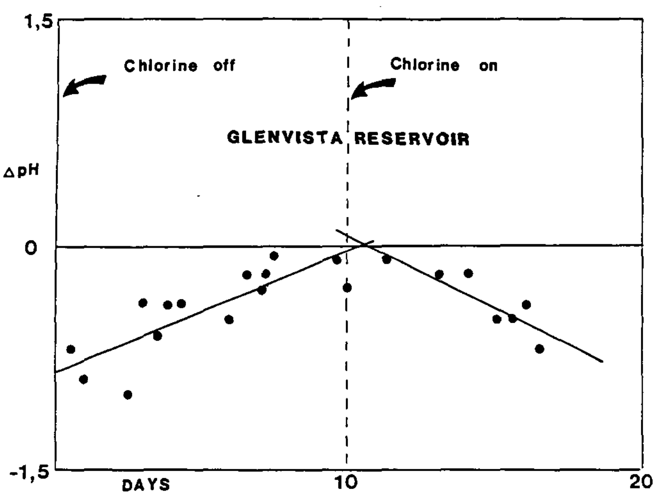
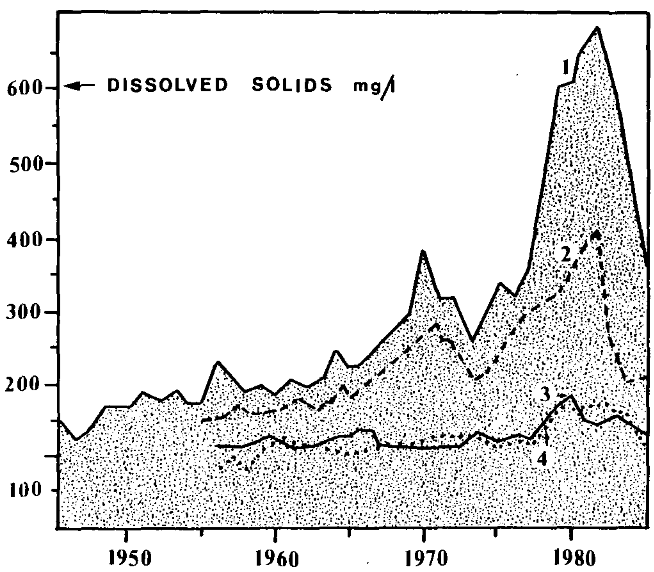


Figure 1
Acidification of potable water due to chlorine gas addition



WATER FROM :
1 RWB-Vereeniging Works
2 Johannesburg System
3 RWB - Zuikerbosch Works
4 Vaal Dam

Figure 2
Salinisation of various waters

ning times were experienced and post-precipitation occurred in the distribution mains. Under high total dissolved solids (TDS) conditions, polyelectrolyte-treated water stability was marginally improved by increasing the pH by the addition of calcium hydroxide, but the presence of high chloride and sulphate concentrations mitigated against stability (James, 1985).

The Johannesburg experience

The use of polyelectrolytes in the treatment process used by the Rand Water Board did not appear to have any immediate detrimental effect on the water quality supplied to Johannesburg. Towards the end of 1976 an increasing number of complaints were being received regarding 'dirty water'. These complaints continued during subsequent years and were most prevalent during the summer months. This observations has been explained by Van der Merwe (1988), on the basis that calcium carbonate is 33% more soluble at 10°C than at 30°C. Most complaints were received from the north-western, and some southern suburbs, and subsequent investigations showed they were receiving largely polyelectrolyte-treated water. Initially, the problem was alleviated by frequent flushing of implicated mains and installing replaceable filters on the lead lines to houses which were particularly badly affected.

As time progressed, the nature of the suspended solids formed in the reticulation system changed from a mixture containing predominantly iron and calcium salts, to one containing largely iron. Complaints from the public became more vociferous. Iron-containing salts were very effectively removed in domestic spin-driers, with associated threats from affected householders to sue the municipality for the replacement of allegedly discoloured clothing. Difficulties were also experienced with blockages in the pretreatment units of kidney dialysis machines.

From the above sequence of events it was hypothesised that excess polyelectrolyte had slowly dissolved and loosened the existing protective calcium carbonate scale until unprotected steel was exposed to the reticulated water. The presence of higher than usual concentrations of organic matter led to high bacterial resuscitation rates in the distribution pipework, in spite of the 3 to 4 mg/ℓ chlorine added by the RWB (James, 1985).

To prevent further regrowth in the Johannesburg system, an additional dose of chlorine gas was added to the inlet supply of all municipal reservoirs, based on an anticipated turnover rate. Addition to the discharge pipe from the reservoir or feeding at flow related rates was not possible, and reliance was placed on the balancing effect exerted by the reservoir to prevent chlorine levels rising to a degree at which complaints could be expected.

This procedure, whilst controlling one problem, created another in that the pH of stored water showed a tendency to decrease (Fig. 1), and to increase the corrosion potential of water (Rimmer, 1984). This was rectified in selected reservoirs when necessary, by the manual addition of soda ash to the inlet of the reservoir. In instances where two reservoirs operated in series, it was often necessary to cease chlorination of the second reservoir periodically.

The Rand Water Board were continually informed of the problems being experienced in Johannesburg (and elsewhere), and by December 1983, had made the necessary arrangements to abandon polyelectrolyte coagulation in favour of the lime/alum/activated silica process (Van der Merwe, 1988).

Reference to Fig. 2 will show that over the past 40 years, the State-controlled sources available to the RWB have slowly increased in their degree of salinisation. This is largely attributable to large volumes of purified sewage effluents and neutralised acidic waters from the gold mining industry entering the Vaal Barrage, which is one of the major reservoirs available to the RWB. The increase in TDS has been particularly severe during the last decade when the country experienced its worst drought on record.

The problem of salinisation first became apparent in 1949 when it was decided to make no further extensions to the Vereeniging intake works of the RWB, but to build the Zuikerbosch intake works upstream of the confluence of the Klip and Suikerbosrand tributaries with the Vaal River. Further deterioration prompted the Institute of Water Pollution Control (IWPC 1969/70) to organise a symposium to draw attention to this situation. In 1974 the Water Research Commission (WRC) established a committee to study the problem, initiate research and develop mathematical models. These models were completed by the end of 1980, and were used for determining storage states and water quality in the dams in the Vaal River system, under various hydrological conditions and management strategies.

A desk study by the Department of Water Affairs (DWA) on the cost to the community of increasing TDS concentrations in the water supply, was completed in 1981. Provisional findings were that costs of between R70 million and R139 million per annum would have to be borne by users, if the TDS concentrations were allowed to rise from 300 mg/ℓ to 500 and 800 mg/ℓ respectively (DWA, 1986a).

In 1982, the RWB approved a scheme to provide the infrastructure whereby it would be possible to blend the highly salinised water in the Barrage, which constitutes about 25% of the Board's raw water supply, with the less saline water from the Vaal Dam on a controlled basis, to produce an acceptable quality of better than 350 mg/ℓ TDS for 95% of the time (James, 1985). Using the hydro-salinity model, the DWA has shown that the blending option aimed at maintaining an average salinity of 250 mg/ℓ without exceeding 300 mg/ℓ is relatively inexpensive providing a benefit/cost ratio of about 25 : 1, with very little additional water being necessary (DWA, 1986b).

Corrosion in the Johannesburg system

The increasing salinity of water described above was not without effect on the steel pipe reticulation system. In 1978 there were sporadic complaints regarding dirty water, and in 1982/83, reports on burst mains increased dramatically to about 500 per week. Despite the secondment of additional staff from other municipal departments, a backlog of repair work built up and the media became highly critical of the municipality's apparent inability to prevent large visible water losses in times of severe drought.

Reference to Fig. 3 will show that there appears to be a close relationship between the sulphate content of the reticulated water and the number of repairs to mains.

Established practice to induce a measure of internal pipeline protection, is to saturate water at the treatment plant with calcium carbonate at an artificially depressed pH, which is then subsequently raised and the water becomes supersaturated with respect to calcium carbonate. This precipitates over a period of time on the pipe walls to provide a protective layer. This technique has been practised by the RWB, except for a period of about 8 years when some of the raw water supplies were flocculated with polyelectrolytes.

A number of indexes have been developed for predicting whether a water has either scale-forming or scale-dissolving properties, including *inter alia* the Langelier (1936) Saturation Index, Ryznar (1944) Stability Index, Momentary Excess (Dye, 1952) and the Driving Force Index (McCauley, 1960).

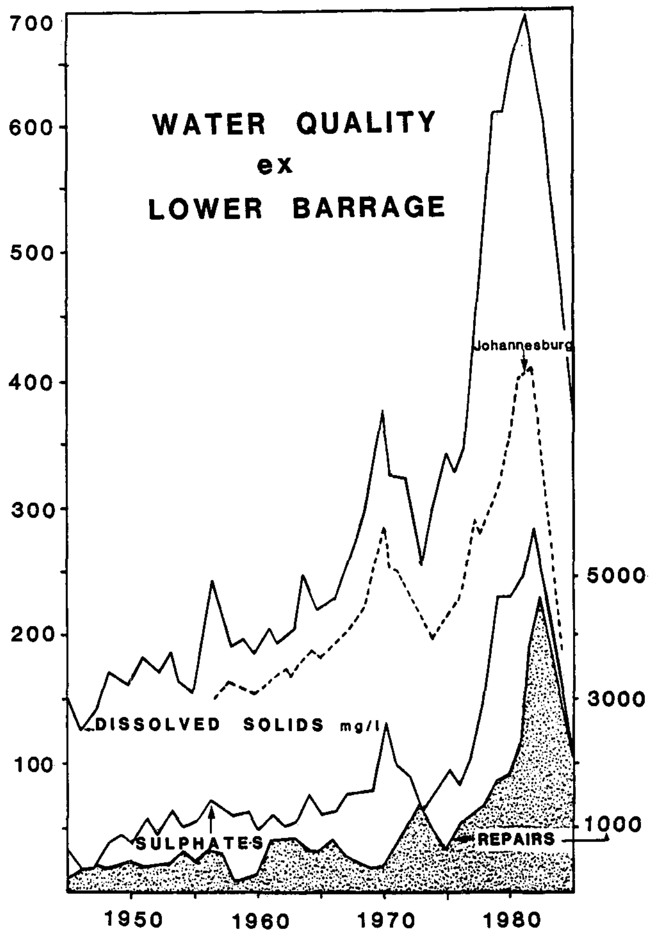


Figure 3
Water quality in relation to repairs to water mains

However, none of these indexes relate to the potential mass concentration of scale which can precipitate (or dissolve) from the water, the so-called precipitation potential.

Common practice in water treatment is to treat a water chemically prior to distribution to possess scale-forming properties in terms of one (or more) of the indexes above, and to assume the water to be non-aggressive to cement-type materials and non-corrosive to metal pipes and fittings. Whereas generally the former assumption regarding aggression to cement materials appears acceptable, the latter regarding corrosion certainly is not. A scale-dissolving water may passivate corrosion surfaces, provided calcium and alkalinity are sufficiently high, $9 > pH > 7$ and sulphates and chlorides both low, each less than about 50 mg/ℓ (Stumm, 1960; Water Research Centre, 1981; Loewenthal *et al.*, 1986). Similarly, a so-called scale-forming water is not a guarantee that corrosion will not take place, as is confirmed by the Johannesburg experience.

In order to assess the corrosivity of water, the aggressive effects of sulphate and chloride must be taken into account. Unlike the saturation indexes, which can be theoretically derived (at least under ideal conditions), corrosion indexes are empirical, as shown below:-

Larson and Skold (1958) Corrosion Index

$$= \frac{\text{meq } [Cl^-] + [SO_4^{--}]}{\text{meq Alkalinity as } CaCO_3}$$

For aerobic waters with pH 7 to 8, a value in excess of 0,1 represents a corrosive water (Standard Methods, 1980). Reference to Fig. 4 will show that on this basis, the source water available to the RWB has a corrosion potential. This guideline has relatively little merit in South Africa because virtually all the inland waters would be corrosive in terms of this index, which is contrary to observation. In this regard, probably a more realistic approach to describing a corrosive water is that of the Water Research Centre (1981). They suggest that waters be regarded as potentially corrosive when either the chloride or sulphate concentration exceeds 50 mg/ℓ.

Two corrosion coupon probes were acquired in February 1984, and installed for a period of two months in the outlet pipes from the Glenvista and Corriemoor reservoirs. Soda ash was added to the Glenvista reservoir at the rate of about 8 mg/ℓ, but none was dosed to the Corriemoor reservoir.

After one month, both probes were covered with a brown, easily removed deposit. Severe corrosion was evident on the underlying surface after the deposit had been removed in accordance with ASTM D 2328-GST, using inhibited hydrochloric acid. The mass losses converted to average thickness losses in mm/a, were as follows (Rimmer, 1984) :

at pH 5,5 to 8,5 and at pressures up to 100 000 kPa. Their presence in the Johannesburg system has been demonstrated by their isolation from the water itself and from the tubercles. The mode by which they contribute to pipe pitting and wall penetration has been described by Osborn (1984). Kendall and Osborn (1975) have also described the role of this bacterium in the disintegration of polysulphide reservoir sealants. It should be noted that once residence inside a tubercle has been established, proliferation to the critical minimum level of 200 to 500 cells, described by Von Holy (1987) as necessary to act as effective cathodic depolarisers, becomes possible. Even high levels of chlorine in the water passing over the tubercles is unlikely to cause the death of these bacteria.

Rejuvenation of the Johannesburg water reticulation network

During the 1982/83 period when an unprecedented number of burst pipes was being experienced, complaints were computerised to facilitate monitoring progress and to identify specific areas which needed urgent replacement of pipework. During this period of crisis management, consultants were employed to recommend more permanent solutions to the problem. Their report showed that the life expectancy for the system was 50 years, although it was known that some pipes were over 60 years old and still in good condition. If a 'steady state' pipe system was to be achieved, 2% of the pipes, or about 60km, would have to be replaced each year. To

TABLE 1
CORROSIVITY OF UNTREATED AND SODIUM CARBONATE TREATED JOHANNESBURG RESERVOIR WATERS

Coupon thickness loss mm/year	Corriemoor untreated	Glenvista 8 mg/ℓ Na_2CO_3
After 1 month	3,4	2,2
After 2 months	1,8	1,2
Fe/Ca (after 2 months)	15,6	0,82

The addition of soda ash to elevate the pH by about 0,2 units at the Glenvista reservoir, appears to have had a beneficial effect in that calcium carbonate deposition was promoted. It should be noted that by the end of the second month, both probes had been forced out of the main flow by the pressure, and the thickness loss for the second period may therefore have been suspect.

It must be stressed that corrosion indexes such as those described above, do not predict microbiological attack on the pipe surface. The presence of organic matter and sulphates provides nutrient for the growth of *Desulfovibrio desulfuricans* which find the anaerobic conditions inside corrosion tubercles ideal for proliferation. Stern (1985) has indicated that they survive comfortably

meet this emergency situation, it was recommended that for a period of 3 years, 4% of the system be replaced or reconditioned every year, followed by a reduced programme until the 'steady state' or 2% replacement was acceptable (Knight and Leonie, 1986). The guidelines adopted for replacing mains are presented in Table 2.

Cement mortar lining (5mm) of pipes was first carried out in the Saxonwold area on a limited scale in 1975 (JCEAR, 1975), but its use was discontinued the following year due to financial stringency. In 1974 a limited number of PVC mains were laid on an experimental basis, when difficulty was experienced in obtaining steel piping. About the same time, high density polyethylene

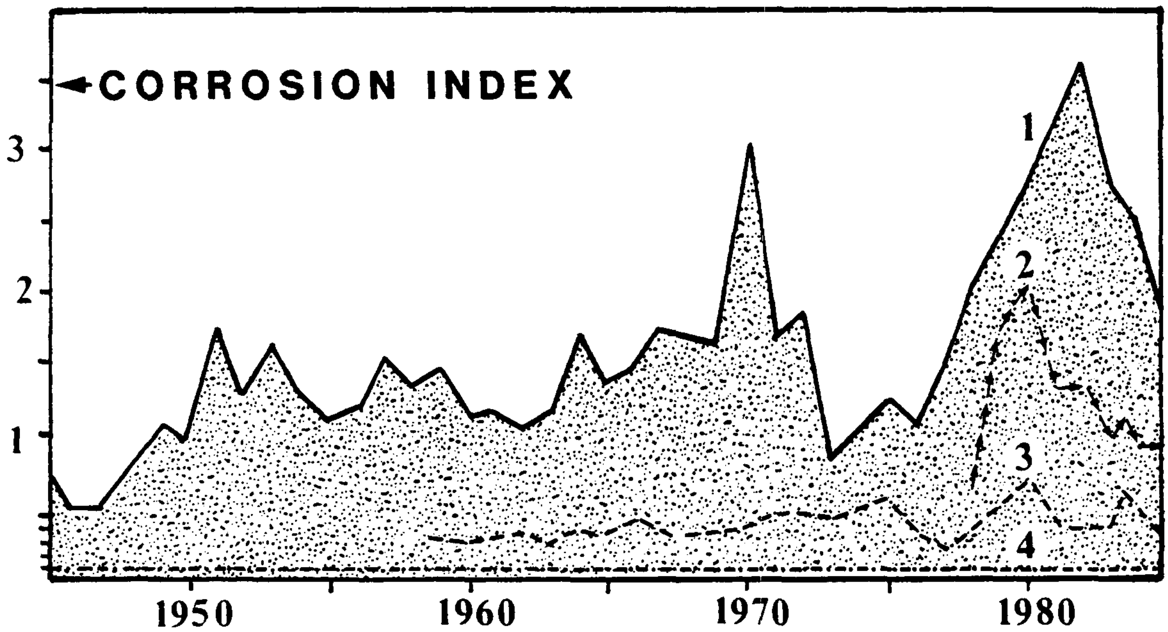
E) was introduced to replace galvanised steel house connec- Failures were encountered with plastic piping, and the in- :tion of further plastic pipes into Johannesburg was resisted a complete range was available with similar external ters to the pipes which were being replaced. In the early and e 1980s, this situation improved considerably, and again it ecided to use high density rigid uPVC pipes with Victualic joints, which were interchangeable with joints for steel pipes (Knight and Leonie, 1986).

When slip lining with HDPE was first introduced as an alternative to cement mortar lining, a by-pass supply was provided to affected householders. Subsequently, this proved to be unnecessary, as approximately 100 m of pipe could be lined within one working day, including replacement of all connections. A fur-

TABLE 2
GUIDELINES FOR PIPE REPLACEMENTS IN JOHANNESBURG

Existing pipe	Ground condition	Recommendation
Steel	Non-aggressive	Cement-mortar lining*
Steel	Aggressive ∅	Slip lined with HDPE
Galvanised	Any	HDPE (house connections only)
Asbestos (undersized)		High impact uPVC
'Old' (1974) uPVC	Non-rocky	" " "
Pipes too small	" "	" " "
Steel	Rocky	Steel : Copon lined
Over 200 mm	Any	" " "

*Subject to a 6 mm lining extending the life of the pipe by 15 to 20 years
∅ Determined by soil surveys, cathodic protection installed if required



KEY:
1 Rand Water Board water ex Vereeniging Works
2 Water supplied to Johannesburg
3 Rand Water Board water ex Zuikerbosch Works
4 Vaal Dam water

Figure 4
Larson and Skold corrosion index of various waters

ther development of slip lining was the introduction of the pipe insertion machine (PIM). This machine, believed to be the first in South Africa, was inserted into undersized asbestos mains (50 and 75 mm), and the percussion head used to shatter the pipe walls as the machine was drawn through. This had the effect of increasing the bore size and permitting a larger size (110mm) HDPE pipe to replace the old main. Initial problems with the machine, and the caving in of broken material, necessitated the provision of thin wall HDPE pipe to be drawn through at the back of the machine. This provided a sleeve through which the thicker walled HDPE pressure pipe could be drawn (Knight and Leonie, 1986).

House connections were initially remade by laying small-bore HDPE piping in trenches across roads. However, numerous complaints regarding subsidences were received, and equipment was purchased to permit the trenchless transfer of piping across roads, without disturbing the surface.

Water loss

Reference to Fig. 5 will show that there is a significant difference between the volume of water purchased and that accounted for as sales. During the year ended 30 June 1979, i.e. when corrosion of the pipework was becoming evident due to the presence of 'red water', water unaccounted for in Johannesburg and Soweto amounted to 10,6% (Dollery, 1980) or 17% in Johannesburg itself. Two major contributions to this apparent loss are 'meter-slip', which is aggravated by the presence of suspended scale from the pipes, and water seeping into the ground through corroded pipes. Both these aspects were subjected to further investigation.

Before embarking on a programme to change some 140 000 meters in Johannesburg, and in order to operate such a programme, it was necessary to computerise all the historical data relating to each meter. A water test rig capable of calibrating meters in accordance with the International Standard, BS6199, has been constructed and is currently being commissioned. When consumer leads were replaced as part of the mains renovation programme, new meters up to and including 40 mm, were installed in meter boxes with quick release couplings. These have the advantage of reducing the labour time required to change a meter to one fifth of that for a conventional coupling (Knight and Leonie, 1986).

To arrive at the optimum 'in-service' life of a particular group of meters, a random sample is removed from service and tested in accordance with the Assize Board requirements. If the sample meters meet the prescribed standards, the remaining meters are left in service for an additional year. Should the sample fail the prescribed standards, the whole group of meters is then replaced (Knight and Leonie, 1986). Further useful information can be found in a

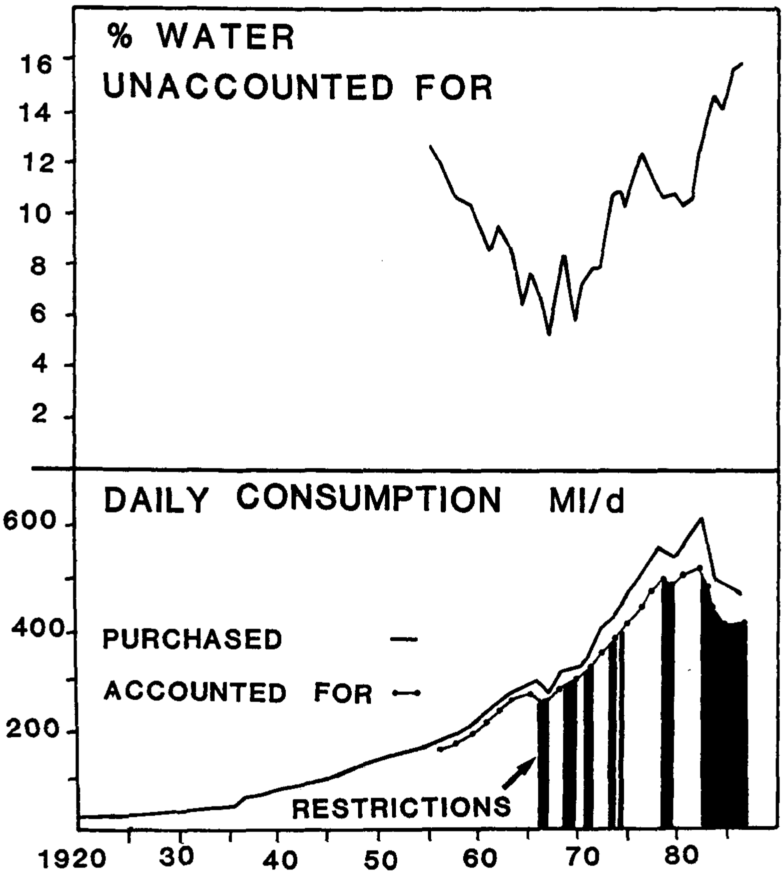


Figure 5
Average daily quantity of water purchased and accounted for in Johannesburg

bulletin prepared by the National Building Research Institute (now the Division of Building Technology) of CSIR, for the Water Research Commission (NBRI, 1986).

A pilot leak detection programme to determine truly 'hidden leaks' was embarked upon in November 1984, and involved the collaborative efforts of the Johannesburg City Council, the Water Research Commission and Castle Brass Holdings. A total of 19 test areas, including some industrial areas, were selected involving some 15 715 connections. A sophisticated leak noise correlator of German design was used to pinpoint the position of leaks. One such leak was found to be due to a complete break in a 100 mm diameter pipe which permitted water to run unseen from the surface into a stormwater drain. Test lengths were limited to about 1 km and it was usually possible to test 9 km/d.

Modern leak detection equipment obviously has a role to play in the maintenance of any water reticulation system, and it is envisaged that it will be more extensively used in Johannesburg, to minimise water wastage.

Discussion and conclusions

The Johannesburg experience is particularly noteworthy, because of the large numbers of burst mains that were experienced in a very short period of time, in many different parts of the city. The age of the pipes was undoubtedly a major contributing factor, but the quality of water flowing within the pipes also appears to have played a major role. The high concentrations of sulphates, and occasionally, the high levels of organic matter apparently originating from recycled purified sewage effluents, have provided suitable conditions for the growth of *Desulfovibrio desulfuricans,* which can proliferate in the tubercles present in the aging pipes and ultimately cause perforation. The presence of relatively high concentrations of chloride and sulphate ions in the absence of a suitable level of alkalinity, have also been conducive to providing corrosive conditions for steel pipes.

During the past decade, considerable progress has been made in determining water resource management options for the Rand Water Board supply area, with particular reference to identifying and managing sources of salinity. In the short term, considerable expenditure has been incurred to provide the engineering infrastructure required to enable the RWB to blend water derived from the Vaal River Barrage and Vaal Dam more effectively, and thereby achieving a higher and more constant standard of reticulated water quality.

The cost to Johannesburg of replacing its water reticulation pipework has been high. From 1 July 1982 to 30 June 1987, some R77,6 million has been spent. This figure excludes the densely built-up central business area, where pipes will have to be enlarged in size and installed by the open trench method. Interesting changes have also taken place in the materials of construction being used. Out of a total length of mains (50 to 1 020 mm) of 3 000 km, some 135 km are cement mortar lined steel pipes, 100 km of uPVC, 75 km of HDPE, 132 km slip lined with 90/140 mm HDPE, 400 km of asbestos cement pipes, and the remainder of mild steel. The performance of this system with a higher content of plastics will be watched with considerable interest.

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References

DYE, JF (1952) Calculations on the effect of temperature on pH, free carbon dioxide and the three forms of alkalinity. *JAWWA* **44** 356.

DOLLERY, AS (1980) The operation of tariffs and the control of losses in water reticulation systems. *IMIESA* **5** 15.

DWA (1986a) Management of the water resources of the Republic of South Africa. Published by the Department of Water Affairs, Private Bag X313, Pretoria 0001. 4.10.

DWA (1986b) Management of the water resources of the Republic of South Africa. Published by the Department of Water Affairs, Private Bag X313, Pretoria 0001. 4.12.

IWPC (1969/70) The Institute of Water Pollution Control (Southern African Branch) Symposium on dissolved solids loads in the Vaal Barrage water system. Johannesburg, November 1969; April 1970.

JAMES, LH (1985) Water quality problems encountered by the Rand Water Board in the supply of potable water involving the indirect re-use of sewage and acid mine water. *Proceedings of the Australian Water and Wastewater Association, 11th Federal Convention,*Melbourne, Australia 28 April - 3 May. 76.

JCEAR (1975) Annual Report of the Johannesburg City Engineer.

KENDALL, JE and OSBORN, DW (1975) Problems associated with the sealing of joints in water retaining structures in Johannesburg. *The Civil Engineer in South Africa* **17** 135.

KNIGHT, R and LEONIE, T (1986) Maintenance programme : Johannesburg water reticulation system. Paper presented at the South African Institution of Civil Engineers Symposium on Practical Problems With Pipelines. CSIR Conference Centre, Pretoria. 13 October 1986.

LANGELIER, WF (1936) The analytical control of anti-corrosion water treatment. *JAWWA* **28** 1500.

LARSON, TW, and SKOLD, RV (1958) Laboratory studies relating mineral quality of water to corrosion of steel and cast iron. *Corrosion* **14** 285.

LOEWENTHAL, RE, WEICHERS, HNS and MARAIS, GvR (1986) *Softening and Stabilisation of Municipal Waters.* WRC, Pretoria.

McCAULEY, RF (1980) Controlled deposition of protective calcite coatings in water mains. *JAWWA* **52** 1386.

NBRI (1986) *Water Economy Measures : Guidelines for Local Authorities.* Available from the Water Research Commission, PO Box 824, Pretoria 0001, South Africa.

OSBORN, DW (1984) Corrosion in the water reticulation system of Johannesburg. Wat. *Sew. and Effl.* **19,** Dec. 33.

RIMMER, R (1984) Personal communication. Johannesburg City Health Department Laboratories, PO Box 1477, Johannesburg 2000, South Africa.

ROSSUM, JR and MERRILL, DT (1983) An evaluation of the calcium carbonate saturation indexes. *JAWWA* **75** 95.

RWB (1978) Rand Water Board Information Brochure. Rand Water Board, PO Box 1127, Johannesburg 2000, South Africa.

RYZNAR, JW (1944) A new index for determining the amount of calcium carbonate scale formed by a water. *JAWWA* **36** 472.

STANDARD METHODS (1980) *Standard Methods for the Examination of Water and Wastewater.* Published by APHA, AWWA, WPCF. 47

STERN, DJ (1985) Microbial intervention in corrosion of metals. *IMIESA* **10** 11.

STUMM, W (1969) Investigation on the corrosive behaviour of waters. *ASCE* **86** 2657.

VAN DER MERWE, SW(1988) The effect of water quality variables on the corrosive behaviour of water coagulated with a cationic polyelectrolyte and with lime/activated silica. *Water Supply* **6** Lisbon S2. 9.

VAN HOLY, A (1987) New approaches to microbiologically induced corrosion. *Wat. Sew. and Effl.* Sept. 39.

WATER RESEARCH CENTRE (1981) A guide to solving water quality problems in distribution systems. Technical Report TR 167, Medmenham, England.