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USING LIME TREATED ACID MINE WATER FOR IRRIGATION

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ABSTRACT

The disposal of acid sulphate mine water poses a universal problem. Although water quality is much improved when neutralised by lime treatment high salt loads nevertheless make release to better quality surface streams undesirable. The feasibility of using such water for irrigation was evaluated using a steady state chemical equilibrium model to predict the composition of water draining from successive soil segments under a range of leaching fractions. Large amounts of gypsum are expected to precipitate in the soil profile resulting in a greater reduction in salinity than would occur if the water contained chloride instead of sulphate. A comparatively smaller reduction in crop yields can thus be expected and a greater variety of the marginally salt sensitive crops can be grown. The precipitation of gypsum however results in an increased sodium hazard to soil physical properties. This does not appear serious when evaluated against published data on soil hydraulic conductivity as affected by sodium and electrolyte concentration. A drastic reduction in the salt load in drainage from irrigated land compared to that in the applied water is predicted. Irrigation with lime treated acid mine water does not only seem feasible but also advantageous for the protection of water resources from mineral pollution.

KEYWORDS

Neutralized acid mine water; mathematical modelling; irrigation water quality; sulphate water; crop yield reduction; environmental impact.

INTRODUCTION

Contact with water and air results in iron pyrite being oxidised to sulphuric acid and iron sulphate. As pyritic formations are found worldwide the formation of acid sulphate containing waters during mining and other rock exposure operations poses a universal problem. South African gold bearing ores always contain pyrites, as does most of the coal deposits. Acid mine waters are formed both at the surface and underground. At the surface they originate mostly from mine dumps as a result of weathering and rainfall. Acid water from this source is difficult to control or treat and constitutes a large proportion of the acid mine waters found in South Africa. The gold mine dumps on the Witwatersrand alone covers an area of about 80 km^2. The underground acid waters are on the other hand easier to control and mostly neutralised with lime before being released to public streams. For example about 34 000 m^3/d of acid underground water (enough to irrigate more than 1 000 ha) is treated by East Rand Proprietary Mines (ERPM) with a high density sludge process and released to a public stream (Van Staden, 1979). Similar processes are used to treat acid water resulting from coal mining operations in the Eastern Transvaal and northern Natal in South Africa.

Lime treated acid mine waters are virtually neutral in pH, contain virtually no ferrugenous compounds, but remain high in dissolved solids, a factor which severely limit their usefulness. Although much improved in quality compared to untreated acid mine waters they are thus still likely to degrade the water in public streams to which they are discharged. It is therefore necessary to investigate alternative means of disposing of these waters. Ideally maximum use should be made of this type of water while simultaneously minimizing its degrading effect on other water resources. The fact that the main constituents of these waters are calcium and sulphate leads to interesting possibilities of using them in irrigation agriculture.

Calcium sulphate, or gypsum, is used widely in irrigation agriculture as an ameliorant in reclaiming sodic soils. Lime treated acid mine waters could easily be used for the same purpose. Utilizing them in this way will however find only limited applicability because of the short term nature of most reclamation projects.

A more attractive but challenging alternative is to use them for irrigation. Normally waters having similar salt concentrations will be at best rated as marginally suitable for irrigation. In the case of a calcium sulphate water it can however be expected that the depressing effect which salt normally has on crop yield will be less pronounced as the limited solubility of gypsum reduces the effective soil salt concentration to which the plant is subjected.

In this paper the feasibility of using lime treated acid mine water for the irrigation of crops will be evaluated and compared with the use of water of similar salt content but with chloride as the main anion. The yield depression that can be expected by irrigating with these waters, and the impact of irrigation on the pollution of other water sources will be discussed.

MATERIALS AND METHODS

Reports containing complete analyses of lime treated acid mine waters could not be found. Consequently, their composition had to be deduced from analyses of untreated acid mine waters such as those reported by Cronce, Kardos and Ciolkosz (1980) for acid coal mine drainage in Pennsylvania and Thompson (1980) for acid coal, gold mine and mine dump waters in South Africa. These analyses suggest that after treatment calcium would be the main cation, although magnesium would commonly occur and some sodium would always be present. By nature of the origin of acid mine waters, sulphate is the major anion, but chloride is also present in lower concentrations. Thompson (1980) found coal mine waters to be less saline than those from gold mine dumps. Van Staden (1975) reported a TDS of 5 600 mg/ℓ for the lime treated acid mine water resulting from the high density sludge process at ERPM. Against this background an idealised composition of a treated acid mine water was assumed and is presented in Table 1. This composition is judged to be fairly typical and should serve to illustrate the possibility of using these waters for irrigation. The composition of a chloride water used as an example of other saline waters for comparison with treated acid mine waters is also presented in Table 1.

TABLE 1 Composition of an Idealised Lime Treated Acid Mine (sulphate) water and a Saline (chloride) water to be Evaluated for Irrigation Suitability

	Lime treated acid mine water	Chloride water
pH	7,4	7,4
TDS (mg/ℓ)	1932	1644
Conductivity (mS/m)	229	309
Calcium (me/ℓ)	18,0	18,0
Magnesium (me/ℓ)	7,0	7,0
Sodium (me/ℓ)	5,0	5,0
Sulphate (me/ℓ)	25,0	4,0
Chloride (me/ℓ)	5,0	25,0
Bicarbonate (me/ℓ)	-	1,0
SAR ((mmol/ℓ)^{0,5})	1,4	1,4
USDA classification*	C4S1	C4S1

* according to USSL Staff (1954)

The composition of soil water at different depths in the soil profile were calculated using a steady state chemical equilibrium model as described by Oster and Rhoades (1975). This model was translated to run on a Hewlett Packard 9825A. It calculates and updates the equilibrium composition of water when the salt content is concentrated (as happens in soil when water is taken up by plants) by considering partial carbon dioxide pressure, precipitation of calcium carbonate and sulphate and pairing of the ions normally found in irrigation water. The model was adapted to calculate changes in water composition as it moves successively through four equal segments of a soil profile. It was assumed that 0,4 of the plant water uptake occured in the top segment; 0,3 in the second; 0,2 in the third and 0,1 in the fourth. Partial carbon dioxide pressures of 1,6; 3,3; 4,6 and 5,3 kPa were assumed for the successive segments. Similar adaptions and assumptions were made by Rhoades and Merril (1975). The equilibrium composition of the soil water leaching from each soil segment was calculated for profile leaching fractions of 0,05; 0,1; 0,2; 0,3; 0,4 and 0,5.

The sodium adsorption ratio and conductivity of the leachate from each segment was calculated. The average profile conductivity of the soil saturation extract was calculated from the average for the four soil segments and by assuming that the water content at saturation will be double that at field capacity at which it is assumed all water movement take place. The salt balance for the profile was calculated from the composition of the irrigation water and that leaching from the bottom soil segment as well as the amounts of water applied by irrigation and drainage from the bottom segment.

RESULTS AND DISCUSSION

In evaluating the potential for using lime treated acid mine waters for irrigation, their limitations and advantages with respect to crop performance, sodium induced changes in soil physical properties and mineral pollution of the environment, will be discussed. This evaluation is based on the assumption that the composition of the idealised lime treated acid mine water (Table 1) is representative of such waters and that the chemical equilibrium model used gives a fair indication of the chemical reactions involved. To maintain the necessary perspective the effects of treated acid mine water will also be compared with those of a chloride water having similar ionic strength and cationic composition.

The concept of minimum leaching to achieve the double benefit of using less water for irrigation and maximizing potential precipitation of salts in the soil profile (therefore reducing the salt load and environmental pollution associated with irrigation) while still maintaining the soil salinity at such a level that crop yield is not adversely affected was thoroughly examined by van Schilfgaarde, Bernstein, Rhoades and Rawlins (1974). Minimum leaching is necessary if a significant reduction in the salt load associated with treated acid mine water is to be achieved through irrigation. The question is whether significant reductions in the salt load of water draining from an irrigated area can be maintained while still obtaining an acceptable crop yield and avoiding adverse effects on sodium related soil physical characteristics.

Soil Solution Conductivity and Crop Yield

The computed soil solution conductivity variation with depth is shown in Fig 1 for the sulphate and chloride waters using different leaching fractions.

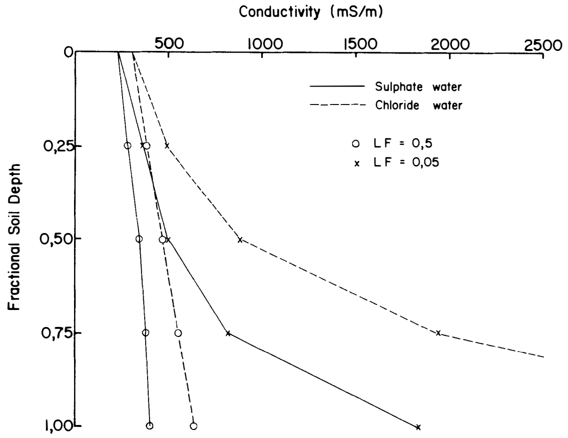

Fig 1 Soil solution conductivity (mS/m) of the sulphate and and chloride waters as predicted by the model for different leaching fractions.

The marked reduction in soil solution conductivity for the sulphate water relative to the chloride water for all leaching fractions is the result of precipitation of gypsum from the gypsum-saturated sulphate water as the soil solution becomes increasingly concentrated due to water uptake by plants. The difference between the two waters is more pronounced at low leaching fractions. The higher conductivity of the chloride water at the soil surface (irrigation water conductivity) is the result of the higher specific conductivity of chloride relative to sulphate at the same ionic concentration.

In relating crop yield depression to soil salinity the average saturation extract conductivity of the soil profile has traditionally been used. The most recent list of soil salinity-crop yield relationships published by Maas and Hoffman (1977) contains information on the origin and limitations of these relationships.

The relationships were mostly obtained under irrigation with high leaching fractions which resulted in almost uniform soil salinity profiles whereas markedly different soil salinity profiles are formed under low leaching fractions. This limits the use of the published relationships. In a study comparing various indices for calculating the "average" soil salinity to which plants respond Ingvalson, Rhoades and Page (1976) found that time integrated in situ salinity parameters correlated best with yield. Parameters describing the mean profile saturation extract salinity correlated almost as well and definitely better than parameters weighted according to relative water uptake from different parts of the soil. For this reason the average saturation extract conductivity of the different soil profile segments were used in this study to calculate expected crop yield.

Bearing in mind that the salinity-yield relationships of Maas and Hoffman (1977) use conductivity of the saturation extract as a soil salinity parameter and the salinity profile computed according to the model is for the in situ soil solution, the conductivities were halved to approximate saturation extract conductivities. This is based on the reasonable assumption that water retention by the soil at saturation is approximately double that at field capacity and also that significant amounts of precipitated salt will not dissolve upon dilution to the saturated water content. The latter assumption is reasonable for the chloride water, but for the sulphate water it can be expected that some of the precipitated gypsum will dissolve upon dilution. However to consider the dissolution of precipitated gypsum would for the present purpose give a biased impression of the in situ salinity to which a plant will be subjected and to which it will respond with a yield reduction.

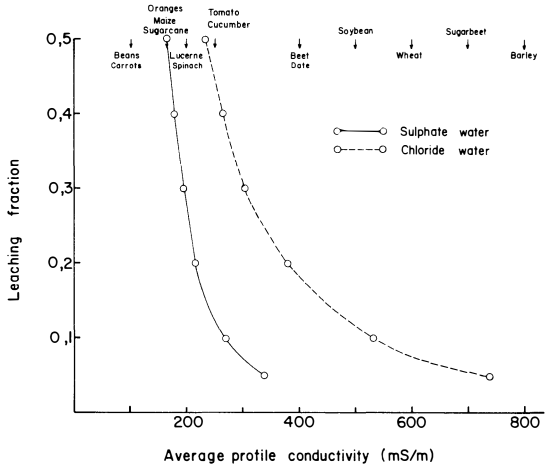

Fig 2 Profile average saturation extract conductivities (mS/m) for the sulphate and chloride waters at different leaching fractions with an indication of threshold conductivities for various crops.

Figure 2 shows that although both the sulphate and chloride waters have similar salinities and would be classed as C4 waters according to the USSL Staff (1954), using them for irrigation will result in widely different effects on plant growth. While it is for example possible to grow grapes, maize and lucerne using the sulphate water without suffering a yield reduction, it is not possible with the chloride water. The moderating effect gypsum precipitation has on the average profile conductivity is demonstrated by the facts that even at the unrealistically high leaching fraction of 0,5 the average conductivity of the chloride water is still 1,4 times that of the sulphate water, and that the same conductivity achieved with the chloride water at a leaching fraction of 0,5 is achieved at a leaching fraction of about 0,1 with the sulphate water.

It is further apparent that the average profile conductivity of the sulphate water increases less with decreasing leaching fraction (it doubles from leaching fraction 0,5 to 0,05) than that of the chloride water (which triples). This is also borne out by a more gradual decrease in relative crop yields for the sulphate water in Fig 3.

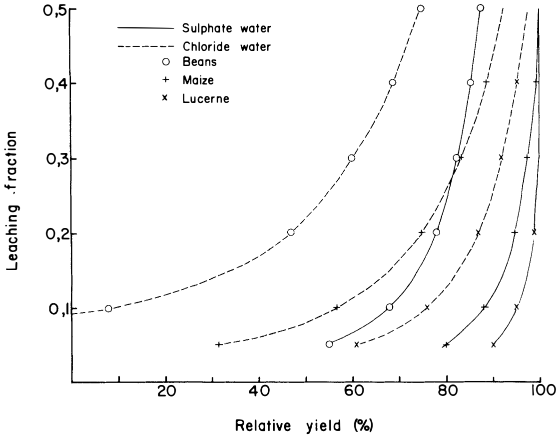

Fig 3 Expected relative yields of beans, maize and lucerne irrigated with sulphate and chloride waters under different leaching fractions (from the relationships of Maas and Hoffman, 1977)

The most significant information in Fig 3 is however that relatively high yields can be achieved for widely-grown crops such as maize and lucerne under low leaching fractions with the sulphate water (representing lime treated acid mine water) and that even salt sensitive beans may be grown at high leaching fractions. This makes the use of these waters attractive from both the crop type and crop yield points of view. Their use should prove economically feasible in the absence of other limiting or prohibiting factors.

Effect of Sodium on Soil Physical Properties

Sodium adsorption ratios (SAR) calculated by excluding ions bound as ion pairs (Fig 4) were considered to give a better indication of the effective sodium hazard than those obtained by including ion pairs. This procedure gave rise to slightly higher SAR's that otherwise. It is apparent in Fig 4 that higher SAR's can be expected under irrigation with sulphate water compared to chloride water. This is to be expected on account of the precipitation of gypsum in the soil leaving a relatively calcium depleted soil solution. The question is whether these increased SAR's will have any significant effect on the potential usefulness of this water for irrigation. The problems associated with sodium under irrigation are primarily linked to its effect on soil physical properties in general and hydraulic conductivity in particular rather that to its potential toxic effects on specific crops. A number of researchers have studied and reported on attempts to quantify the effect of sodium and salt concentration on soil hydraulic conductivity and associated structural stability. The SAR-conductivity values obtained with the model under different leaching fractions for the two waters are indicated in Fig 5 and compared with the SAR-conductivity stability relationship

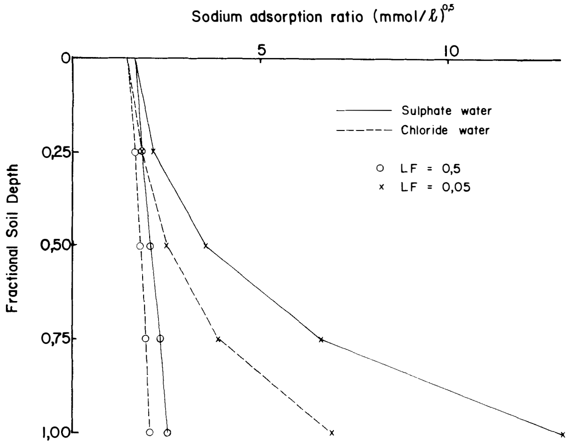

Fig 4 Modelled soil solution sodium adsorption ratio (SAR, (mmol/ℓ)^{0,5}) of the sulphate and chloride waters for different leaching fractions.

found by Quirk and Schofield (1955) and a selection of similar relationships reported for South African soils (van der Merwe and Burger, 1972) (alluvial soils); du Plessis and Hutson, 1975 (recent surface deposit); Johnston, 1978 (vertic soil); Moolman and Weber, 1979 (fine sandy soil)).

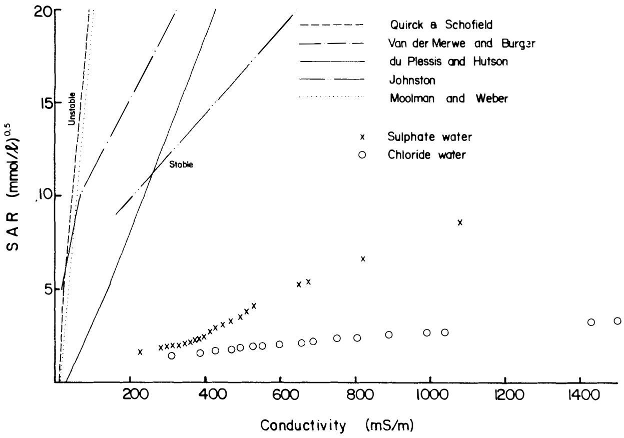

Fig 5 Comparison between the soil solution SAR-conductivity combinations for the sulphate and chloride waters and published soil stability relationships.

The SAR-conductivity combinations for a specific water fall on the same line with only minor variations induced by precipitation of gypsum and lime and the varying carbon dioxide partial pressure in different soil segments. As expected appreciable variability exists among the reported SAR-conductivity soil stability relationships. It is however obvious that the SAR-conductivity combinations of the sulphate water always fall safely on the stable side of these curves indicating that no serious problems associated with sodium related physical degradation of soil structure should be experienced under irrigation with the sulphate water, although it has a greater problem potential than the chloride water.

Salt Balance and Environmental Impact

The theoretical salt balance of an irrigation area under equilibrium conditions of irrigation with the same water and leaching fraction can be calculated from the known irrigation water volume (V_i) and salt content (C_i) as well as the known drainage volume (V_d) and modelled drainage salt content (C_d). The results of such a calculation for the sulphate and chloride waters are given in Table 2.

TABLE 2 Salt Applied in Irrigation Water (C_iV_i), Salt Leached by Drainage (C_dV_d), the Amount Precipitated in the Soil (store) and the Difference in Salts Leached under Irrigation with Sulphate and Chloride Waters in t/ha annually, for Various Leaching Fractions (LF).

	Sulphate water			Chloride water			Difference in salts leached
LF	C_iV_i	C_dV_d	Store	V_iC_i	C_dV_d	Store	
0,05	20,3	8,4	11,9	17,6	15,1	2,5	9,4
0,1	21,5	9,9	11,9	18,6	17,2	1,4	10,2
0,2	24,2	13,6	10,6	20,9	20,9	-	10,6
0,3	27,6	19,5	9,1	23,9	23,9	-	9,1
0,4	32,2	25,0	7,2	27,9	27,9	-	7,2
0,5	38,7	34,0	4,7	33,5	33,5	-	4,7

It is clear that decreasing amounts of salt are stored in the soil profile with increasing leaching fractions. The only salt that is stored (precipitated) from the chloride water is lime at the two lowest leaching fractions. Much more salt (gypsum) is stored in the soil under irrigation with sulphate water compared to chloride water. In this way some of the salt in the irrigation water is effectively removed from the system thereby reducing the salt load in the drainage water and also contamination of other water sources. At the lower leaching fractions more salt is actually stored in the soil than is contained in the drainage water. A somewhat distorted impression may however be created by this presentation of data. Different volumes of water were applied to achieve the different leaching fractions. When a reduction in mineral pollution of water is the aim, the same volume of water will however have to be used irrespective of the leaching fraction. An example of a salt balance calculation where the same volume of water is applied under various leaching fractions is given in Table 3.

Almost five times as much salt will be stored under a leaching fraction of 0,05 compared to 0,5. The salt load in the drainage water will however not be reduced to the same extent, although a more than 50% reduction will be achieved. The distinct advantage of a substantial reduction of the salt load associated with lime treated acid mine waters will thus be obtained by adopting irrigation management practices which give as low a leaching fraction as possible. It must however be borne in mind that the water draining from the irrigated area will be highly mineralised. Should it be allowed to mix with only a small volume of good quality water it may degrade that water to such an extent as to render it unsuitable for its

TABLE 3 Difference in Area Irrigated and Amount of Salts Leached (tons per annum) from Soil Under Different Leaching Fractions when the Same Volume of Water (2×10^4 m^3 p.a.) is applied to all.

LF	Irrigat. mm p.a.	A_i ha	C_i mg/ℓ	C_d mg/ℓ	Ai V_i C_i t p.a.	Ai V_d C_d t p.a.	Salt stored t p.a.
0,05	1 053	1,9	1 932	15 824	38,6	15,9	22,7
0,1	1 111	1,8	1 932	8 938	38,6	17,9	20,7
0,2	1 250	1,6	1 932	5 460	38,6	21,8	16,8
0,3	1 429	1,4	1 932	4 310	38,6	25,9	12,7
0,4	1 667	1,2	1 932	3 742	38,6	30,0	8,6
0,5	2 000	1,0	1 932	3 403	38,6	34,0	4,6

intended use. The greatest benefit to the improvement of other water resources can be expected when the relatively low volume of highly mineralised drainage is intercepted and disposed of in another way.

CONCLUSIONS

Neutralising acid mine water with lime results in a water rich in calcium and sulphate; mostly with a high total dissolved solid content which makes it of limited use as a water resource and a large potential source of mineral pollution of high quality water resources.

Calculations with a chemical equilibrium model indicate that irrigating with a calcium sulphate water will result in a lower soil salinity than with chloride water of otherwise similar ionic composition. This can be attributed to the precipitation of gypsum in the soil, especially at low leaching fractions. It can thus be expected that relative yields of the same crop will be higher when irrigated with a sulphate water and that a greater variety of the more salt sensitive crops would be grown successfully than when irrigated with a chloride water.

No serious sodium related soil physical problems are expected as a result of the relative increase in sodium when calcium is precipitated as gypsum. The SAR-conductivity combinations found under the different leaching fractions in the four soil segments all fall in the stable region of a number of stability relationships reported in the literature.

A significant reduction in drainage salinity is predicted for sulphate compared to chloride water. This reduction calculated as salt load is further improved under lower leaching fractions, so that the potential for contamination of other water sources is further reduced. The greatest benefit of irrigating with this water will be realised when the low volume of highly mineralized drainage which has no further value as a water source under normal circumstances, can be intercepted and disposed of where it cannot pollute high quality water resources.

Theoretically it is thus not only feasible to use lime treated acid mine water for irrigation and produce a crop without suffering soil physical problems, but also desirable in order to minimize mineral polution of water resources. It must be emphasised that a high degree of irrigation efficiency and management skills will be required for any such project, and that it is best started on a pilot scale.

REFERENCES

Cronce, R.C., L.T. Kardos, and E.J. Ciolkosz (1980). The effect of soil on the renovation of acid coal mine drainage water. J. Environ. Qual., 4, 621-626.

Du Plessis, H. M., and J. L. Hutson (1975). Feasibility of effluent disposal by means of irrigation. Symp. on recycling of Waste Water for Agric. and Indust. uses, Herzliya-on-sea, Israel, 24-26 Nov. 1975.

Ingvalson, R. D., J. D. Rhoades, and A. L. Page (1976). Correlation of alfalfa yield with various indeces of salinity. Soil Science, 122, 145-153.

Johnston, M. A (1978). Soil salinity and sodicity problems in the South African sugar industry. M.Sc. (Agric) thesis. Department of Soil Scinece and Agrometeorology, University of Natal. Nov. 1978.

Maas, E. V., and M. Hoffman (1977). Crop salt tolerance - current assesment. Journal of the Irrigation and Drainage Division, ASCE, 103, 115-134.

Moolman, J. H., and H. W. Weber (1979). Die toepassing van die grenskonsentrasiekonsep op die beoordeling van die bruikbaarheid van water vir besproeiing van brak fynsandgronde in Suid-Kaapland. Water S.A., 5, 26-38.

Oster, J. D., and J. D. Rhoades (1975). Calculated drainage water composition and salt burdens resulting from irrigation with river waters in the Western United States. J. Environ. Qual., 4, 73-79.

Quirk, J. P., and R. K. Schofield (1955). The effect of electrolyte concentration on soil permeability. Jour. Soil Science, 6, 163-178.

Rhoades, J. D., and S. D. Merrill (1975). Assesing the suitability of water for irrigation: Theoretical and empirical approaches. Proc. Expert Constultation on Prognosis of Salinity and Alkalinity, Rome, Italy, June 1975.

Thompson, J. G. (1980). Acid mine waters in South Africa and their amelioration. Water S.A., 6, 130-134.

USSL Staff (1954). Diagnosis and Improvement of Saline and Alkali Soils. U.S. Department of Agriculture Hoandbook 60, Washington, D.C.

Van der Merwe, A. J. And R. du T. Burger (1973). Relationship between hydraulic conductivity and irrigability of OFS-region soils. Paper delivered at the 5th National Soil Sci. Soc. of Southern Africa Congress. Salisbury, 14-16 February 1973.

Van Schilfgaarde, J., L. Bernstein, J. D. Rhoades, and S. L. Rawlins (1974). Irrigation management for salt control. Journal of the Irrigation and Drainage Division, ASCE, 100, 321-338.

Van Staden, C. M. (1979). How ERPM uses lime to solve unique underground water problem. Coal Gold and Base Minerals of Southern Africa, 27, 100-109.