CHAPTER 7

GENERAL DISCUSSION AND CONCLUSIONS

This research originated from the need to dispose of large volumes of $CaSO_4$-dominated water generated in the neutralization of acid mine drainage water with lime in coal mining operations in the eastern highveld of Mpumalanga, South Africa. One possible means of disposal is the use of such waters for irrigation of agricultural crops.

Previous research on the influence of $CaSO_4$-dominated waters on plant and crop growth has, however, been extremely limited. Where researched, it mainly pertained to the influence on yield, quality of crops and the influence on soil chemistry (du Plessis, 1983; Papadopoulos, 1986; MacAdam et al., 1995).

The current studies were initiated to screen crops and cultivars already cultivated in the geographical area of the coal mines, for tolerance to $CaSO_4$-dominated mine waters, as part of a South African Water Research Commission funded project. As salt tolerance is a multifaceted concept, varying with many environmental and biological factors, the use of such waters for irrigation warranted more information than simply the yield response.

The main focus of this study was to investigate **seedling growth responses to increasing concentrations of Ca, Mg and SO_4 and the influence of the precipitation of gypsum on growth** response curves. It is generally expected that the relatively low solubility and precipitation of gypsum would limit extreme increases of salinity which could be beneficial for crop growth. In order to gain some insight into the role of gypsum precipitation on growth, suspensions where $CaSO_4$ crystals were increasingly present, were included in the growth response treatments.

The seedling growth stage is generally regarded as the most sensitive of growth stages and was therefore considered to be the best developmental stage to demonstrate growth response differences.

The seedling growth of most of the crops followed an irregular three-piece or four-piece pattern in the growth curves:

In the *first* and *second* parts of the growth response curve, where the concentrations of Ca and SO_4 in the treatment solutions were below the solubility product for $CaSO_4$, seedling growth generally decreased in a linear manner above a threshold salinity, which was similar to the growth response curves expounded by Maas & Hoffman (1977). The continued linear decreases up to the saturation concentrations indicated that in this part of the growth curve salinity increases were not limited by precipitation during evapotranspiration. It is suggested that the rate of precipitation was probably too slow, due to the absence of crystallizing nuclei in the quartz sand and to the short time intervals between replenishing. Seedling growth generally reached a minimum where saturation concentrations of Ca and SO_4 were present in the original treatment solutions.

In the third part of the growth curve, where undissolved $CaSO_4$ crystals were increasingly present, seedling growth increased unexpectedly, despite further increasing conductivities of the treatment solutions. These growth curves suggest that the seedling growth was improved when crystallizing nuclei were present in the growth medium.

In the treatment with the highest concentration, where the Mg to Ca ratio in solution was ≥ 1, seedling growth finally decreased again. In practice such a situation could develop in an arid area with prolonged irrigation with a $CaSO_4$ water with relatively high Mg content, where leaching with good quality water is not possible.

When increasing SO_4 concentrations were obtained with Na_2SO_4 in a simulated mine water saturated with $CaSO_4$, seedling growth generally tended to decrease in a linear manner.

It is suggested that when the solubility product is reached, whether by evapo-transpiration or in treatments with higher concentrations, the effective osmotic potential - that is the average osmotic potential in the root growth zone over the whole growth period - is determined by the rapidity of the precipitation of gypsum. In a *soil* environment this rate of precipitation may be stimulated by the abundantly present soil nuclei which would have an eventual effect of *increasing* the effective osmotic potential and probably also the seedling growth. Drying of the soil in a field situation should thus not lead to the same rate of concentration by evapotranspiration, with a concomitantly lower osmotic potential, as in the sand culture. If the soil water is kept at field capacity by frequent irrigation, precipitation may, however, also be slower than with longer time intervals and subsequent drying of the soil. The rate of precipitation may, however, also be *inhibited* by coatings of different humic and mineral substances present in soils, for instance aluminium phosphates on nuclei in acid soils (as quoted by Van den Ende, 1991). The extent of such an influence would depend on the amount of coating.

It has furthermore been found for annual ryegrass that osmoregulation is influenced by the cation concentration in the plant tissue and therefore indirectly by that of the soil solution (Sagi et al., 1997). The decrease of the Ca content of the soil solution by rapid precipitation may therefore also diminish the osmotic adaptation and growth of ryegrass and possibly of other crop species with a similar osmoregulation metabolism.

For practical agronomic application it was also important to establish **whether cultivars** of crops likely to be utilized in this area, **differed in their tolerance** to this type of water.

Cultivar differences on a $CaSO_4$-dominated water were investigated in water culture in a glasshouse, where the seedling growth of several cultivars of each crop species was compared on actual $CaSO_4$-dominated mine waters from the Kleinkopje mine. There were significant cultivar differences in the seedling growth of maize, sorghum, pearl millet, dry bean, wheat and lucerne with the $CaSO_4$ water. Soybean cultivars did not differ in their response to this water. The subtropical cereal crops exhibited more cultivar differences with the high sulphate water than did the subtropical legumes and the annual temperate cereals.

These cultivar differences found in the seedling growth stage may not necessarily be as prominent in the mature stages. When considering irrigation with these mine waters, it should nevertheless be taken into consideration that the yield of especially the cereals can be influenced by the effect of salinity on the primordial development of spikelets in the seedling growth stage (Francois & Maas, 1994).

It must be emphasized that the crops and cultivars used in these trials were selected for their tolerance under irrigation or drought conditions, and were therefore probably genetically developed for salinity. Other cultivars not suitable for irrigation may be more sensitive to $CaSO_4$-dominated water, especially if the tolerance of a specific crop is mainly related to the osmotic potential effect of salinity.

It can therefore be said that although the seedling growth of some cultivars, especially of the subtropical cereals, was decreased by a saturated $CaSO_4$ water, the seedling growth of several high yielding cultivars was tolerant enough to be successfully utilised for irrigation with these waters.

Tolerance to NaCl-dominated water has been found to differ during *ontological development*. The findings with seedling growth may therefore not be applicable to further growth stages. This would depend on the property/ies of this type of water that are responsible for limiting growth of specific crops/cultivars in the respective growth stages. **Possible differences in the tolerance of the germination, seedling and vegetative growth stages** with actual $CaSO_4$-dominated mine waters were therefore investigated.

- The relative *germination percentages* of most cultivars of both the subtropical and temperate annual crops were not influenced by the $CaSO_4$-dominated mine waters used. This is in agreement with observations that germination percentages of most crops are generally not affected at osmotic potentials below *ca* 700 mS m^{-1} for NaCl salinity (Francois and Maas, 1994). There were exceptions where germination percentages of some cultivars of sorghum, pearl millet and soybean were slightly suppressed with sulphate salinity. Germination should, however, not be a problem if these crops are irrigated with these waters. Where it was suppressed, it ranged from 5 to 12 %, which could be compensated for by sowing more densely.

- The relative *seedling growth* on both the actual 'worst case' and the simulated $CaSO_4$ mine waters showed that the *subtropical cereal* crops exhibited greater sensitivity with the high sulphate water than the subtropical legumes or the annual temperate crop species. The soybean cultivars were not significantly affected while most of the dry bean cultivars showed significant *increases*. The seedling growth of the annual temperate crops did not generally show significant sensitivity.The seedling growth of rye, oats, ryegrass and barley cultivars was not significantly decreased on the actual mine water, but with simulated $CaSO_4$ mine water in the growth response curves, the seedling growth of wheat, rye and oats was significantly decreased, although at higher salinities than were present in the actual mine water. The concentrations where growth started to decrease (the threshold) were lower with the subtropical cereals than those of the temperates. The relative seedling growth of wheat was more tolerant to the sulphate water when N was partly supplied as NH_4 in the ratio of NO_3 to NH_4 of 2:1 rather than 4:1. All the selected lucerne cultivars were significantly sensitive to the sulphate mine water in the seedling growth stage.

The tolerance to the $CaSO_4$-dominated mine water was generally greater than with the NaCl-dominated mine water where the seedling growth of the majority of cultivars, with the exception of oats and cowpea, was significantly and severely suppressed.

The data suggest that crops and cultivars which are generally sensitive to the decreased osmotic potential of salinity such as maize, sorghum and pearl millet - and lucerne in the seedling stage - are more sensitive to this $CaSO_4$water in the seedling growth stage than crops where tolerance is mainly connected to ionic effects of Na and Cl.

The known mechanisms by which salinity generally affects the salt tolerance of specific crops, may therefore be an indication of how the seedling growth of the respective crops will respond to this type of water. As salt tolerance is mostly poligenic, the tolerance to $CaSO_4$ water of the crop species which are subject to ionic effects, would also depend on the degree to which the decreased osmotic potential of salinity contributes to sensitivity (Shannon, 1997).

- A comparison of the tolerance in the *seedling* versus the **vegetative growth stages** for $CaSO_4$-dominated waters at similar osmotic potentials revealed that tolerance in the vegetative growth stage could be much *greater*, *less* or *similar* in a specific crop cultivar :

  - The vegetative growth of sunflower cv. SNK 43, rye cv. SSR 1, lucerne cv. PAN 4860 and the yield of dry bean cv. PAN 122 was increased on this water, with the tolerance being *much greater than in that of the seedling growth stage*.

    It is suggested that the vegetative growth may be more tolerant than seedling growth in crops where sensitivity in the vegetative stage is generally correlated to ion imbalances - such as Na/Ca (rye) and Na/K ratios (dry bean) - accumulation effects of Na and/or Cl (lucerne), and/or osmotic adaptation (sunflower).

    Stimulation of the relative growth may also be due to a nutrient effect of for instance Ca and S in legumes or to the improvement of osmotic adaptation caused by the high Ca and Mg content as seemed to be the case with annual ryegrass (Sagi et al., 1997).

  - The tolerance of maize cv. SNK 2340 and cowpea cv. Dr Saunders *was less in the vegetative growth stage than in the seedling stage.*

  - The tolerance of sorghum cv. PAN 888, pearl millet cv. SA Standard, soybean cv. Ibis, wheat cv. Inia, oats cv. Overberg, triticale cv. Cloc 1 and annual ryegrass cv. Midmar did *not differ markedly in these two growth stages*. Whether this would be the case at higher concentrations remains unanswered, but it would probably depend on the degree of sensitivity to osmotic potential of the specific crop cultivar in the vegetative growth stage. In the case of ryegrass, tolerance can be expected to increase with increasing concentrations as osmoregulation is indirectly related to the cation content of the growth medium (Sagi et al., 1997).

It is suggested that vegetative growth may be affected more than seedling growth in crops where a reduction of growth appears to be caused by a reduced leaf area which is primarily due to an osmotic potential effect, as is the case with maize (Cramer, 1994). With cowpea, the SO_4 water also resulted in a significantly reduced leaf area and may therefore have had an effect similar to that of maize on the vegetative growth.

In the case of sorghum and pearl millet, where osmotic potential is nevertheless an accepted growth reducing mechanism in the vegetative stage, the leaf area was not affected; vegetative growth may therefore tend to be influenced in a similar way to the seedling growth.

It is therefore clear that tolerance to a $CaSO_4$-dominated water may be influenced by the growth stage during which crops are irrigated.

These observations, together with the above conclusions on growth suppressing mechanisms in the seedling growth stage, explain why the presence of high concentrations of Na, Cl, Mg and other possibly toxic ions in $CaSO_4$ waters should also be taken into account when evaluating such waters for irrigation in the seedling growth stage.

It is concluded that the tolerance to a $CaSO_4$-dominated water depends mainly on the sensitivity of a crop or cultivar to external osmotic potential and on the chemical composition of specific irrigation waters. The severity of suppression would furthermore depend on the rapidity of $CaSO_4$ precipitation, which influences the effective osmotic potential; the rate of precipitation may in turn be influenced by soil properties, the rate of evapo-transpiration and the time interval between irrigations. It is suggested that a knowledge of the major tolerance/sensitivity mechanisms generally operative in a specific crop species and in the different growth stages, would be helpful in indicating tolerance to this type of water.

Probably the most pressing question on $CaSO_4$ salinity for future use is **which property/ies of such a water are the major growth suppressing (or stimulating) properties of $CaSO_4$-dominated waters?** There are two possibilities that warrant consideration, namely *osmotic potential* and negative or positive *nutrient effects*.

When evaluating the various investigations in this study, it was noticed that it was mostly the same crops that were sensitive to $CaSO_4$-dominated waters. These crops were maize and sorghum in both the seedling and vegetative stage and lucerne in the seedling growth stage. The common characteristic shared by these crops is that the property of NaCl-salinity that mainly suppresses their growth has been found to be the lower osmotic potential of the external saline growth medium.Other crops such as soybean, wheat, triticale and rye, where ionic effects such as accumulation or nutrient imbalances by Na and/or Cl were the main growth suppressing properties of salinity, were generally more tolerant to the $CaSO_4$ waters.

Salt tolerance of plants may, however, be poligenic with, for instance, both osmotic potential and ionic properties affecting growth in saline conditions (Shannon, 1997). It is therefore possible that osmotic potential effects can also contribute to the salt tolerance, even though ionic effects have been found to be the major suppressing property for a specific crop. As Na and Cl were virtually absent in the $CaSO_4$ waters used it is suggested that the degree of suppression on thése crops could be an indication of the sensitivity to osmotic potential effects.

Another possibility is that *interactions* of the high Ca and SO_4 with other nutrients may have affected growth. The current research was mainly designed to investigate growth responses. Some indications could, however, be elicited from firstly comparing seedling growth responses with increasing concentrations of $CaSO_4$, Na_2SO_4 and NaCl respectively at similar osmotic potentials of the applied treatment solutions, and secondly from the nutrient analyses of the top growth.

Generally $CaSO_4$ treatments decreased seedling growth *less* than NaCl or Na_2SO_4 at similar osmotic potentials of the treatment solutions. Because the actual effective osmotic potentials in the root zones were influenced by evapo-transpiration and the precipitation of $CaSO_4$, a comparison with the in situ osmotic potentials of the root growth zones was, however, not possible. No conclusive deductions on Ca and SO_4 interactions with other nutrients in the seedling stage could therefore be drawn from these comparisons. Nutrient analyses of the top growth of the maize seedlings did not, however, reveal any antagonistic cationic or anionic effects in the seedling growth stage. On the other hand severe chlorosis did develop in wheat seedlings with the $CaSO_4$ water when less NH_4 was applied (Ströhmenger et al., 1999).

In the vegetative growth stage nutrient analyses of the top growth showed that the high concentrations and uptake of Ca and SO_4 with the lime-treated acid mine drainage water did not generally affect the uptake of other nutrients. There were however, two exceptions:

The N concentration in maize top growth was decreased significantly. The significant decreases in stem growth of maize and sorghum may be related to either less growth due to an osmotic potential effect, or the high concentrations of Ca and SO_4 could have influenced growth via nutrient effects. A white marginal chlorosis on a few of the younger mature leaves of soybean could also have been an indication of Mo deficiency (Bennett, 1993), although differential plant analyses were not carried out to confirm this.

The second exception was decreases of Mg concentrations in the temperate crops, and increases in the summer crops, which were not reflected in visual symptoms of the top growth.

This water may also be *nutritionally beneficial* to crops. It may benefit crops such as legumes that have a high Ca and S requirement. The exceptionally good yield of dry bean and lucerne with this water illustrates the possibility of such an effect. In ryegrass the increased Ca and Mg content probably stimulated the metabolic process of osmoregulation (Sagi et al., 1997).

Excessive rainfall in the area of these coal mines has also been known to result in S deficiencies in crops in subsequent seasons which could be alleviated when irrigating with this water.

It is concluded that the tolerance to a $CaSO_4$-dominated water where the concentrations of Na, Cl or other possibly toxic ions are negligible, is mainly related to the degree in which growth of a specific crop cultivar is affected by the external osmotic potential in the different growth stages. Possible nutrient interactions, especially between SO_4 and N nutrition should, however, be investigated in greater depth.

When considering the tolerance of a crop species or cultivar for irrigation with a $CaSO_4$-dominated water it is important that the following should be taken into account :

Climate - if leaching with adequate rainfall or good quality water is not possible it must be kept in mind that leaching with this type of water is ineffective in controlling the electrical conductivity derived from the $CaSO_4$; the latter can lead to salinity with a higher conductivity than that of the irrigation water (Papadopoulos, 1984).These mines are, however, situated in a summer rainfall area, which should prevent a serious salt build-up. In an arid climate - besides salt build-up - the precipitation of gypsum from waters with appreciable amounts of Mg may also lead to ratios of Mg to Ca that could be detrimental to growth.

The *composition of the water* - as the tolerance to this type of water was found to be closely related to the salt tolerance/sensitivity mechanisms operative in specific crops, the presence of high concentrations of Na and Cl may affect crops where tolerance is related to ionic effects. As mentioned above, a too high Mg content may also influence growth negatively.

Soil types to be irrigated can influence the usefulness of this water. It is a well known practice to improve sodic soils with the application of gypsum. Precipitation or absorption of Ca could, however, influence growth via an increase in the fraction of Na in the soil solution and therefore also the soil solution sodium adsorption ratio (SAR), and the permeability of the soil. In an evaluation of a lime-treated acid mine drainage water du Plessis (1983), however, concluded that no serious Na related soil physical problems were expected with this type of water. On a calcareous soil the precipitation of $CaCO_3$ and the formation of $MgSO_4$ ion pairs can enhance gypsum solubility and SO_4 accumulation in the soil solution (MacAdam et al., 1997).

The major **conclusion** of the current research is therefore that the *sensitivity* to $CaSO_4$-dominated water is mainly related to osmotic potential effects, whereas *tolerance* is found in crops that are generally sensitive to ionic effects and in crops that possess the ability of osmotic adaptation.

It is furthermore suggested that the effective osmotic potential of the soil solution (i.e. the average osmotic potential throughout the whole growth period) is determined by the rapidity of the precipitation of gypsum which in turn can be influenced by growth rate (evapotranspiration), temporal, environmental and soil factors. A decrease of Ca in the soil solution by rapid precipitation may also suppress the growth of crop species such as annual ryegrass where the cation content of the soil solution may indirectly influence organic syntheses related to osmoregulation.

In summary it can be said that the major growth suppressing property of a $CaSO_4$-dominated water is the decreased osmotic potential. Nutrient effects were less prominent, but there were indications of a possible effect on N nutrition and Mg uptake.

These conclusions have the practical advantage of facilitating the choice of suitable crops and cultivars for irrigation with $CaSO_4$-dominated water, which may be very different from those hitherto recommended for NaCl-dominated waters. They also give some insight into environmental conditions where the use of this water would be advantageous or harmful to crop growth and soil properties in the long-term. These conclusions may also be useful in crop growth models which incorporate a $CaSO_4$-dominated type of salinity.

The following areas of future research into the tolerance of agronomic crops and pastures to

$CaSO_4$-dominated water are recommended:

- The dynamics of gypsum precipitation during evapo-transpiration in different soil types and its influence on the effective osmotic potential.

- The influence of high Ca and SO_4 content on N nutrition and other nutrient interactions at concentrations encountered in saturated gypsum waters, together with the fertilization needed to ensure balanced nutrition with this type of water.

- The effect on the tolerance in the reproductive stage, yield and especially on the quality of fodder and grains for animal and human consumption.

- The tolerance should be further tested under practical field conditions on the different soil types found in the agricultural areas within reach of these waters. Careful monitoring of plant growth, soil conditions - both chemical and plant nutritional - and drainage water would be required.

- The long term effect of a saturated $CaSO_4$ water on the physical, exchange and soil solution properties of the local soil types and its influence on crop growth.

- Other aspects relating to gypsiferous water, such as wetland dynamics, other possible usages as for instance for hydroponic culture or the cultivation of plant species used for purposes other than human or animal nutrition, could also be followed up.

It is clear that a large spectrum of agronomic and pasture species have the growth potential with gypsiferous water to make irrigation with this type of water viable. With this knowledge of plant tolerance and the necessary irrigation and fertilization management, $CaSO_4$-dominated water could play an important role in at least augmenting irrigation water, of which both the supply and quality are steadily decreasing in the Mpumalanga region of the Republic of South Africa. Whether this can be done in an environmentally acceptable manner is currently being further investigated in a comprehensive multifaceted project co-sponsored by the Environmental Services of the AMCOAL mining group and the South African Water Research Commission.

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