The Dependence of Permanent Crop Production on Efficient Irrigation and Drainage at the Vaalharts Government Water Scheme

A. STREUTKER
[SOIL AND IRRIGATION RESEARCH INSTITUTE,
DEPARTMENT OF AGRICULTURAL TECHNICAL SERVICES,
PRIVATE BAG X79, PRETORIA]

Abstract

In order to find suitable measures for preventing or reclaiming waterlogged and saline soil conditions at Vaalharts (and also at other existing or future schemes) several aspects of the situation at Vaalharts were investigated. These comprised:

1. The origin of the developing high ground water table (the water balance of the area).
2. The control of the high ground water table by means of subsurface drains.
3. The influence of the high ground water table on crop production.
4. The salt accumulation in the soil above a high ground water table (the salt balance of the area).

The fluctuating high ground water table resulted mainly from leaking canals and dams and from over-irrigation at a rate exceeding the low natural permeability of the subsoil. With occasional rain of high intensity this has led to waterlogging and a decrease in crop production.

The high ground water table was successfully controlled by means of subsurface drains. Blockages due to organic iron and manganese hydroxide deposits in the drains and obtaining the right filter around the drain caused difficulties.

The yield of seed-cotton and wheat, with low irrigation frequency, was found to be higher on a soil with a ground water table within 1,2 m of the soil surface than on a soil with a deeper or no ground water table. Subsoil, kept moist by capillary action from the underlying ground water table, was capable of providing considerable amounts of water for crop growth.

From the salt balance it was calculated that about 1 500 kg of salt per hectare was retained in the soil annually. This potential danger was, to a certain extent, confirmed by soil analyses.

Because of soil deterioration, maintenance requirements of drains and the danger of salt accumulation, it is strongly advisable to terminate practices which add excess water to the subsoil, and use the water so conserved for lighter irrigations at shorter intervals, or for irrigating a larger area. However, in certain low-lying areas with a natural ground water table, subsurface drains can be very useful in coping with waterlogging and salt accumulation for improving temporary crop production.

To deliberately persist with an artificial high ground water table as a means of supplying soil moisture to crops is a reckless experiment which will undoubtedly lead either to the decay of the scheme or to a successful rarity in irrigated agriculture in semi-arid regions. The small chance of success will depend on a high level of management of drainage and irrigation systems.

Introduction

The Vaalharts Government Water Scheme is situated about 30 km south of Vryburg (Fig. 1) in a flat sandy area, 1100 m above sea level, in a semi-arid region, with an annual rainfall between 254 mm and 660 mm (mainly from October to May) and an annual evaporation of about 2600 mm water from a Class A-pan. Irrigation water is obtained from a weir in the Vaal River and distributed by means of a 600 km open canal system. The drainage and storm water is delivered to the Harts River through a 300 km system of open storm water drains. The scheme is divided into the West Canal area comprising about 5000 ha of irrigated land and the North Canal area of about 25 000 ha. The latter consists of blocks A to N totalling 1000 plots, each of about 25 ha, of which 24 ha are under irrigation, and which have been planted at various times to wheat, groundnuts, lucerne, cotton and maize (Fig. 2).

When first supplied with irrigation water between 1935 and 1940, the Harts River Valley had a ground water table (GWT) located at a depth of about 24 m. The first soil survey report (Van Garderen, Louw and Rosenstrauch, 1934) ascribed a very high infiltration rate to the sandy soils, and considered the calcrete layer in the sub-soil to be potentially beneficial in slowing down excessively fast drainage of soil moisture. It was not foreseen that some years later, after the commencement of irrigation, waterlogging would assume serious proportions and

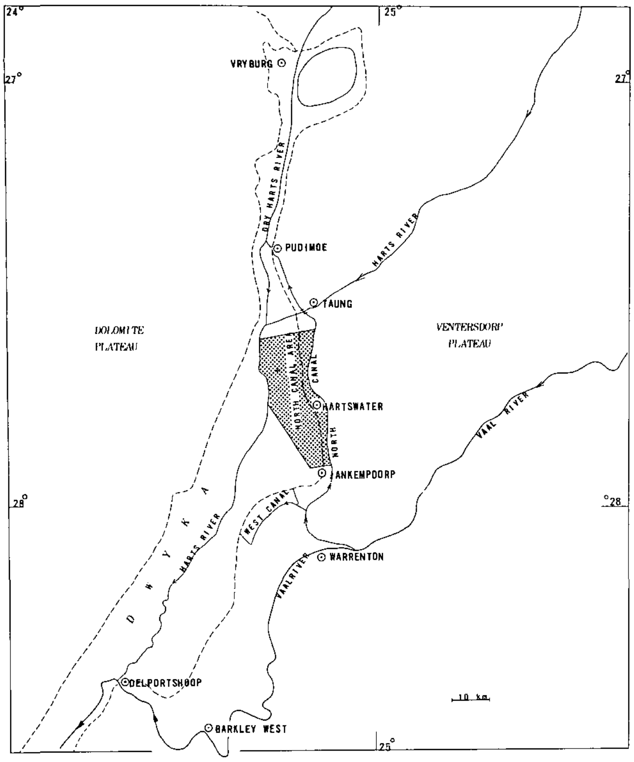


Figure 1
The North Canal area on the Dwyka formation in the Harts River Valley (Geological Survey).

eventually become the major problem at Vaalharts (Rosenstrauch, 1945), leading to crop failures in years of intensive rainfall.

Recognition of the seriousness of the waterlogging problem was followed by efforts on the part of the Departments of Agricultural Technical Services, Water Affairs, and Lands to alleviate the situation. These included a slope experiment to evaluate the efficiency of flood irrigation, the lining of earth dams, and the construction and lining of 300 km of storm water drains. Drainage plans were provided by the Division of Chemical Services (now the Soil and Irrigation Research Institute) following surveys of waterlogging and salinisation carried out on some 400 plots over the years 1942-1967 (Van Woerkom, 1967).

In spite of these efforts, Streutker (1967a) found as much as 10% of the area to be more or less waterlogged. There had been few improvements in the flood irrigation method; only 27% and 6% of the earth dams and furrows, respectively, were lined (Meyer, 1967); only 22% of the open drains recommended for the North Canal area had been constructed and these, because of fine drift sand, were not a success (Streutker, 1967b); only 45% of the plots were provided with storm water drains to serve as outlets for internal drainage. Finally many farmers actually favoured the high GWT for the cultivation of winter wheat, because only one or two irrigations would be required instead of five on a dry soil.

Against this background the problem of waterlogging on the Vaalharts Water Scheme, and particularly in the North Canal area, was investigated, the research objectives being:

(1) Origin of the high GWT.

(2) Control of the high GWT by means of subsurface drains.

(3) Influence of the high GWT on crop production.

(4) Danger of salt accumulation in the soil above a high GWT.

The greater part of this research was carried out from 1965 to 1971 (Streutker, 1971), but certain aspects were pursued in greater detail from 1971 to 1976 and is discussed as part 5.

The purpose of this article is to give an account of the most important results of the four inter-related facets of the investigation to provide an understanding of the present situation at Vaalharts, and to use it as a springboard for remedial action not only for Vaalharts, but also for other schemes where similar problems may arise. Details of the results will be published in other papers.

1. Origin of the High Ground Water Table (the Water Balance of the Area)

The investigation of the water balance of a large area (an excellent example is given by Bower, Spencer and Weeks, 1969) was applied to the North Canal area to assess the importance of various contributory factors to the high GWT. Such factors included leakage from irrigation dams, earth canals and earth furrows, over-irrigation and inadequate drainage of the subsoil formation.

Water supply to the North Canal area

The water supply to the area for the periods 1959-1966 and 1966-1969 was calculated from records of the Dept. of Water Affairs. The daily supply to the area was the sum of the daily demand by farmers and additional amounts released to compensate for distribution losses, leakage and evaporation from canals.

The daily quantities were accumulated and are presented in Table 1 (as totals for the winter season) and Table 2 (as totals for the summer season). For winter and summer together, the average annual gross water supply totalled 173 × 10^6 m^3 for the period 1959–1966 and 170 × 10^6 m^3 for 1966–1969. The average annual nett water supply defined as the gross water supply minus the amount of wasted irrigation water, was 142 × 10^6 m^3 and 160 × 10^6 m^3, i.e. 82% and 94% respectively of the average annual gross supply for the corresponding periods. Wasted irrigation water was estimated by first calculating the total discharge of water (wasted irrigation water plus subsoil drainage) from the North Canal area on the basis of the difference in streamflow in the Harts River between Taung and Espagsdrif (Fig. 2), and then subtracting the subsoil drainage component. The latter was calculated by noting the difference in streamflow of the river between the same stations at the end of an irrigation off-period of 7 to 14 days, on condition that no recent rain had been recorded on the scheme, the surrounding area or the hinterland of the Harts River and the Dry Harts River.

The average annual water supply (142 × 10^6 m^3 for the period 1959–1966 and 160 × 10^6 m^3 for the period 1966–1969), while slightly less than the quota of 161,5 ×10^6 m^3 (1,87 cumec-hours per hectare per year) is however unlikely to have been received in full at the farm sluices. Undoubtedly an unmeasured quantity of water must have been lost from the concrete lined canals through seams and cracks. Evaporation will have accounted for further, though minor, losses from the canals.

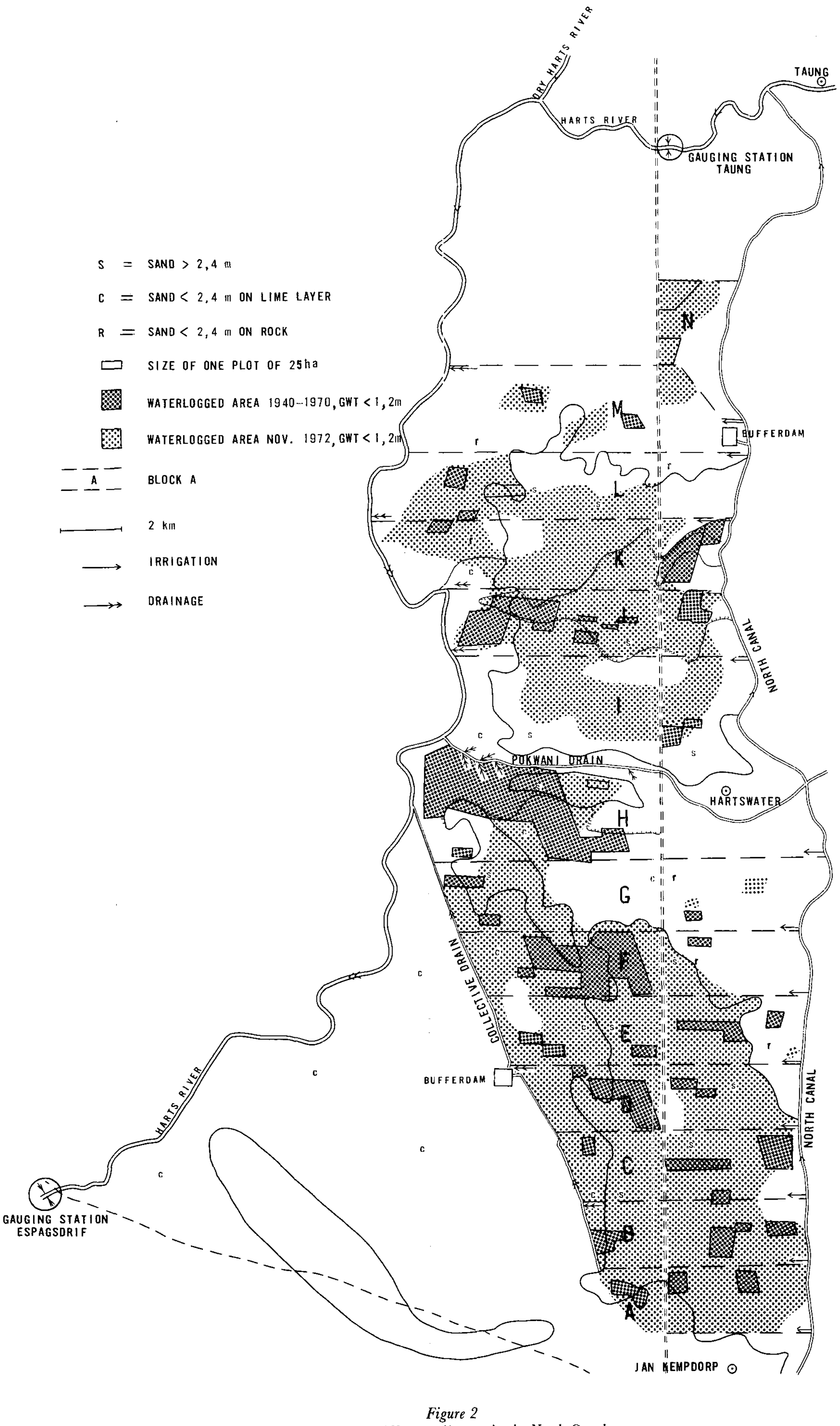


Figure 2
Waterlogging and different soil types in the North Canal area.

TABLE 1

SUPPLY OF IRRIGATION WATER (× 10⁶ m³)AND RAINFALL (mm) ***DURING THE WINTER SEASON*** **(1 MAY – 1 NOVEMBER) TO WHEAT ON 50% OF THE NORTH CANAL AREA, or 12 000 ha.**

Year	Gross water supply		Irr. wasted water & drain water	Drain water	Irr. wasted water	Nett. water supply to farm sluices	Rain
	Demand	Additional					
1959	88,4	12,8	29,0	5,2	23,8	77,4	57
1960	79,9	11,0	28,0	5,7	22,3	68,6	47
1961	78,3	12,9	28,0	5,2	22,8	68,4	74
1962	88,0	13,2	21,8	5,2	16,6	84,6	6
1963	79,2	9,5	24,9	5,2	19,7	69,0	57
1964	71,0	8,5	16,1	4,7	11,4	68,1	74
1965	84,1	10,1	21,3	4,7	16,6	77,6	13
Average '59–'66	**81,3**	**11,1**	—	—	**19,0**	**73,4**	—
1966	60,5	7,3	10,9	4,7	6,2	61,5	8
1967	72,5	8,6	10,9	4,7	6,2	74,9	112
1968	84,0	10,0	10,9	4,1	6,8	87,2	72
1969	59,0	7,1	8,8	4,1	4,7	61,4	157
Average '66–'69	**69,0**	**8,3**	—	—	**6,0**	**71,3**	—

TABLE 2

SUPPLY OF IRRIGATION WATER (× 10⁶ m³) AND RAINFALL (mm) ***DURING THE SUMMER SEASON*** **(1 NOVEMBER – 1 MAY) ON 75% OF THE NORTH CANAL AREA, OR 18 000 HA[1]**

Year	Gross water supply		Irr. wasted water & drain water	Drain water	Irr. wasted water	Nett water supply to farm sluices	Rain
	Demand	Additional					
'59/'60	57,0	7,9	20,7	5,2	15,6	49,4	406
'60/'61	57,6	13,3	19,2	5,7	13,5	57,5	401
'61/'62	75,3	11,3	19,2	5,2	14,0	72,6	357
'62/'63	43,9	5,3	17,6	5,2	12,4	36,7	528
'63/'64	86,1	10,4	17,6	5,2	12,4	84,1	265
'64/'65	99,6	11,9	14,5	4,7	9,8	101,7	185
'65/'66	77,1	9,2	11,9	4,7	7,3	79,1	271
Average '59 – '66	**70,9**	**9,9**	—	—	**12,1**	**68,7**	—
'66/'67	27,7[2]	3,3	10,4	3,6	6,7	24,3	473
'67/'68	88,5	10,6	8,8	3,6	5,2[3]	93,9	205
'68/'69	72,9	8,7	7,8	3,6	4,1	77,5	240
'69/'70	88,1	10,5	7,8	3,1	4,7[3]	94,0	93
Average '67 – '70	**83,1**	**9,9**	—	—	**4,6**	**88,4**	—

1. Because of 25% annual double cropping of 24 000 ha;
2. Because of a decrease of the water quota not many summer crops were planted in Oct. '66; this figure is omitted from the average;
3. Irrigation wasted water was partly collected by new large buffer dams.

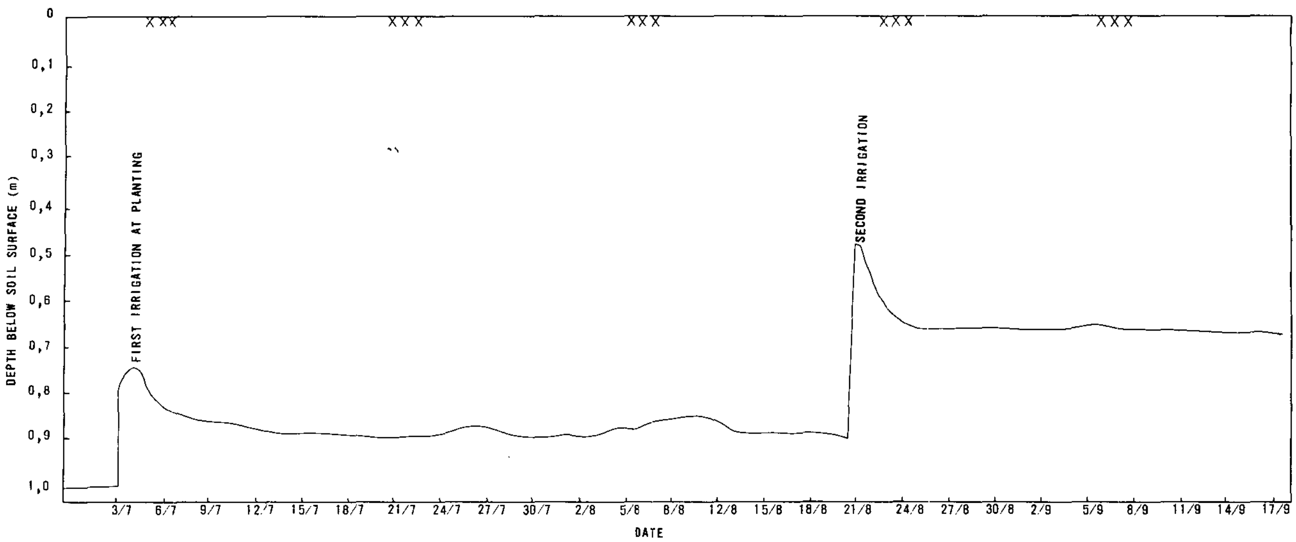


Figure 3
Recorded fluctuations of the GWT during and after two irrigations in 1973 on plot 5J9.

Water losses on the plots

Water losses on the plots, which potentially contribute to a high GWT, consist of leakages from earth dams and canals, and over-irrigation.

Leakages from earth dams were measured by noting the overnight change of the water level in a dam (Department of Water Affairs) or calculated from the loss of irrigation hours when water was used *via* a dam, instead of directly from a farm sluice. Leakages from earth furrows were measured by means of two Parshall flumes some 100 m from each other. Possible over-irrigation when using flood and sprinkler irrigation methods was looked into several times during one year by obtaining the advance and recession curves in irrigation beds, by measuring differences between soil moisture before and after irrigation and by noting changes indicated by a GWT recorder.

Leakage measurements yielded an average of 16% from earth dams and 20% from earth furrows. Over-irrigation was decidedly pronounced when flood irrigation on wheat, groundnuts and lucerne was practised (Fig. 3). No less than 60 to 80 mm per unit area would commonly be applied per flood irrigation even though the actual requirement corresponding to GWT depths of 1,2 m, 1,8 m and 2,5 m was only 30, 40 and 50 mm, respectively. An average of about 40% of the nett water used in the irrigation beds drained directly through the root zone into the subsoil. Total losses on the farms thus amounted to 60% of the nett supply at the farm sluices. This represented an annual average of 85×10^6 m^3 during 1959–1966 and 96×10^6 m^3 during 1966–1969.

Effect of subsoil formation on the water balance

To help explain the effect of water losses on the GWT, the natural drainage of the subsoil formations was investigated by the Geological Survey of the Department of Mines. The downward and lateral movement of the large volume of water resulting from farm losses was greatly impeded by unweathered bedrock of Dwyka shale and tillite at an average depth of 15 m and by an irregular calcrete layer at a depth of 0–5 m overlying the bedrock (Fig. 4 and Fig. 5). This layer, consisting of impermeable rock as well as permeable soft, spongy material, reduced the effective depth of the ground water reservoir to between 0 and 5 m (Temperley, 1967).

The loss of water on farms (85×10^6 m^3 and 96×10^6m^3 per annum) must be compared with quantities of subsoil drainage (Tables 1 and 2) reaching the Harts River (10×10^6 m^3 and 8×10^6 m^3 per annum) for the corresponding periods 1959–1966 and 1966–1969, respectively, to appreciate the effect of the subsoil formations on the water balance. The greater part of the water losses started contributing to the rising GWT immediately after the start of irrigation in 1940. In November 1972 67% of the area had a GWT higher than 1,2 m (Meyer, 1973).

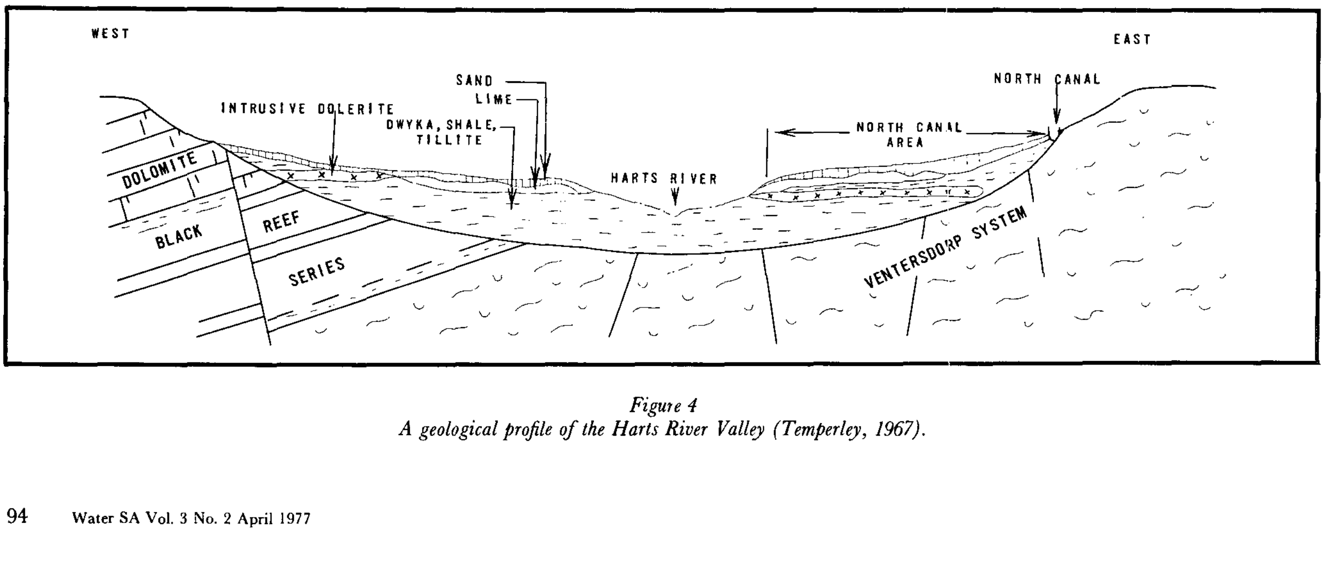


Figure 4
A geological profile of the Harts River Valley (Temperley, 1967).

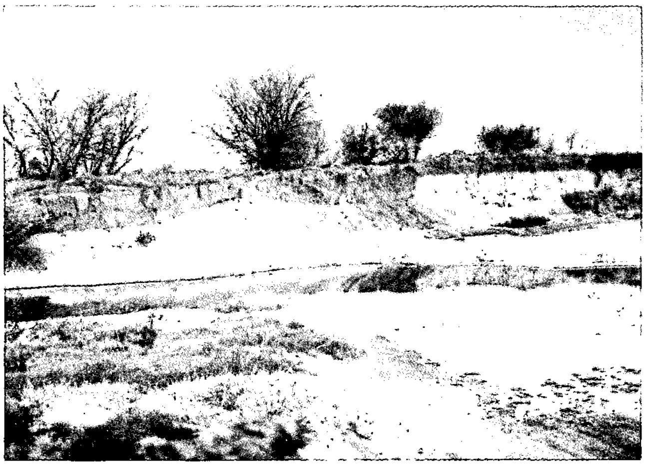


Figure 5
Undulating lime layer, here at a depth of 0,75-1,00 m below the soil surface.

Water losses on farms could therefore be regarded as potentially re-usable once they have raised the GWT to such an extent that the topsoil can be kept moist through capillary water movement. A high GWT delays the need for irrigation, and reduces the total number of irrigations required to produce a crop, and for this reason has come to be favoured by many Vaalharts farmers. An equilibrium situation is reached whereby the difference between farm water losses to the GWT and drainage to the Harts River is balanced by plant water usage from the GWT. The annual usage in this way, as calculated from measurements of capillary moisture movement (on experimental fields and lysimeters) and from the fluctuations of the GWT between seasons, was 74×10^6 m^3 and 78×10^6 m^3 for the periods 1959–1966 and 1966–1969 respectively. These figures proved that the gains and losses of the water balance were in equilibrium.

The equilibrium level fluctuated normally from winter to summer, when the average GWT was at 1,0 m and 1,5 m below the soil surface, respectively (Fig. 6). Use of ground water by plants was greatest during spring and early summer when the highest evaporative demand existed. Abnormal deviations from the equilibrium occurred during rains of high intensity and frequency when, under low evaporative demand, the GWT for some days reached equilibrium at a level as high as 0,3 m or 0,6 m below the soil surface. The soil became waterlogged and the crops gradually died because of the very slow natural drainage of the subsoil. This happened in 1943, 1950, 1956, 1963, 1967, 1975 and 1976, and each time after the investigation of the situation, the lining of dams and furrows, and improvement of the irrigation method were recommended. Although some improvements were made, it was not until the last two years when extensive salt accumulation became visible at the soil surface, that farmers realised the danger of a high GWT and started to install subsurface drains at a depth of 1,5 m. It was (and is) hoped on the one hand to leach the salts out of the soil profile and on the other hand to control the GWT at a high "convenient" level by means of these drains. Research on experimental drainage systems at Vaalharts over the last decade throws some light on the potential success of these measures.

2. Control of the High Ground Water Table by means of Subsurface Drains

Because of lack of experience with subsurface drains at Vaalharts and because of the high fine sand fraction of the soil, which tend to block the drain pipes and filters around the pipes very easily (Rosenstrauch, 1945; Sisson, 1965), it was decided in 1965 to investigate the possibilities of artificial drainage by means of internal pilot subsurface drainage systems on several plots. This was possible because water from the internal subsurface drains could be discharged into the external open storm water drains (on or outside plot boundaries) and find its way to the Harts River.

This system of external open storm water canals was built primarily to cope with surface runoff, either due to irrigation or rain. Small holes in the concrete slabs were provided to drain the ground water in order to decrease the water pressure behind the slabs. The efficiency of the holes was unfortunately very low because of blockages by iron deposits and calcium carbonate.

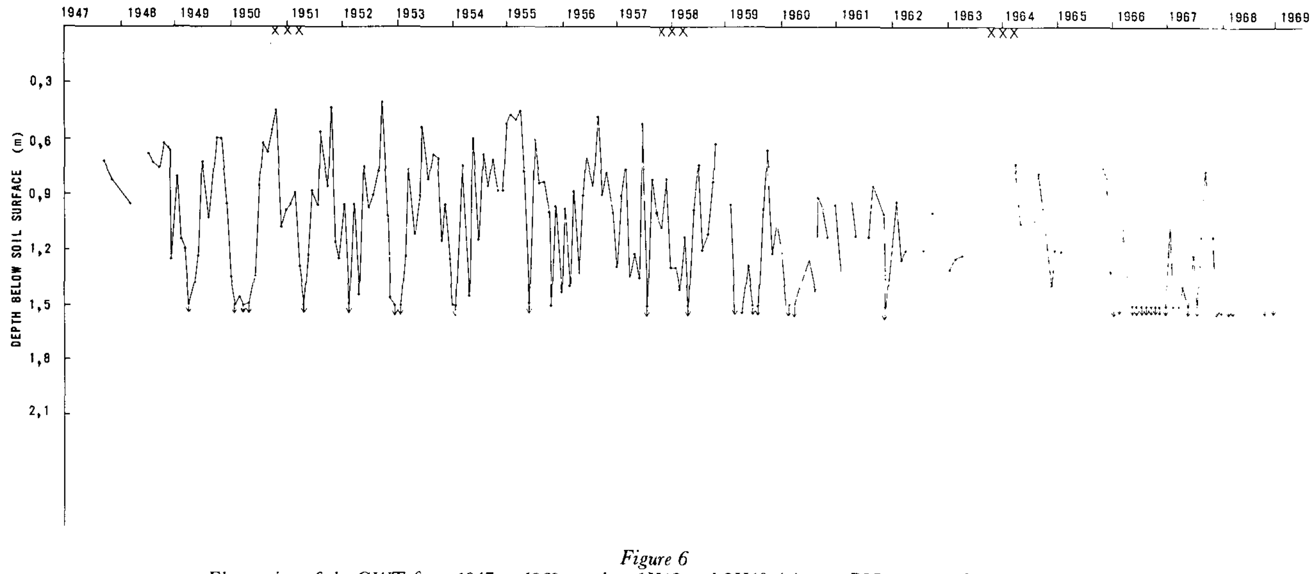


Figure 6
Fluctuation of the GWT from 1947 to 1969 on plots 1H13 and 2H13 (pipe 11 P2E, Dept. of Water Affairs).

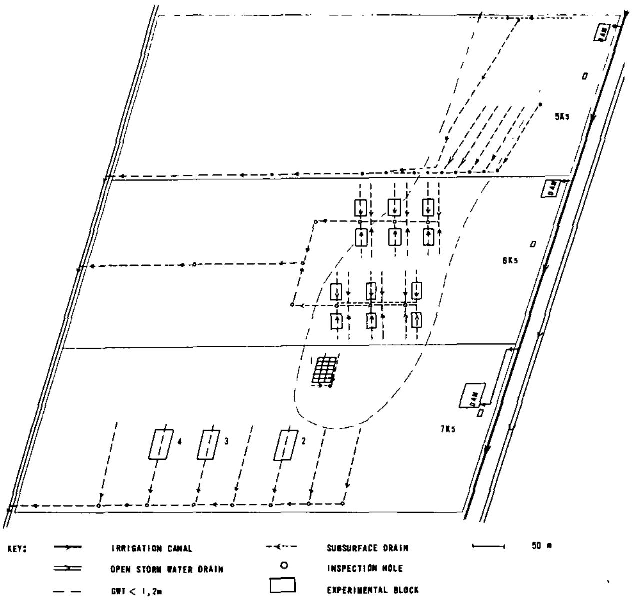


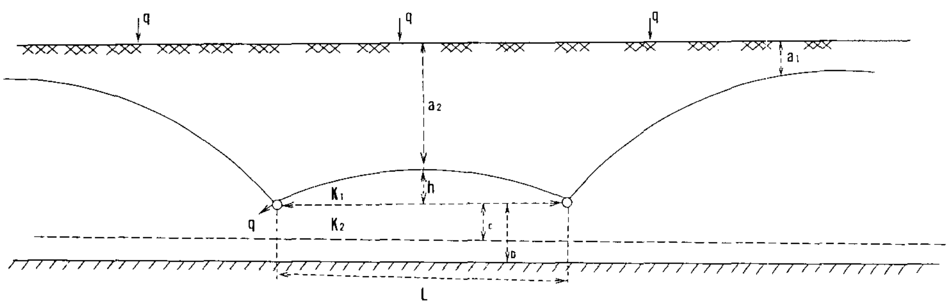
Figure 7
Experimental subsurface drainage systems on plots 5K5, 6K5 and 7K5.

Planning, design and construction of pilot drainage systems

A soil survey on plots 5K5, 6K5, 7K5 (Fig. 7) produced a soil map, a GWT-map, the depth to the calcrete layer and the hydraulic conductivity (K) of the saturated soil. With this information and a choice of a certain rate of drain discharge, and different allowable heights of the GWT above the drains, the distances between parallel lateral drains were calculated. Use was made of the 1940 Hooghoudt drainage formula (Fig. 8), (Van Woerkom and Streutker, 1971). Two types of drainage pipe (viz. baked tile and perforated PVC pipe) and three types of filter material (viz. fibre-glass film, fibre-glass sheet and river gravel-sand) were chosen. Three pilot drainage systems were constructed (Fig. 9).

On plot 7K5 and 5K5 the drain laterals were all of different materials, with a different filter. They were installed at depths of 1,2 m, 1,8 m and 2,4 m with a distance between two drains of 50 m, 60 m and 80 m respectively. The diameter of all the laterals was 50 mm. The main drain was of perforated pitch fibre material of a diameter of 100 mm. On plot 6K5 the short laterals of the system consisted only of PVC pipes with a gravel-sand filter at depths of 1,2 m and 1,8 m, spaced 20 m apart. The diameter of the laterals was 70 mm and of the unperforated pitch fibre main drain 150 mm. Inspection holes were constructed to measure the drain discharge of the laterals, and GWT-observation pipes were installed to measure the depth of the GWT on and between drains.

Figure 9
Construction of a subsurface drain.



KEY: $$L^2 = \frac{8 K_2 d h}{q} + \frac{4 K_1 h^2}{q}$$

a_1 AND a_2 — DEWATERED DEPTH (m)
h — DISTANCE OF GWT ABOVE DRAIN LEVEL (m)
D — DISTANCE OF IMPERMEABLE LAYER BELOW DRAIN LEVEL (m)
d — DISTANCE OF EQUIVALENT IMPERMEABLE LAYER' A FUNCTION OF D (m)
L — DISTANCE BETWEEN TWO DRAINS (m)
K_1 AND K_2 — HYDRAULIC CONDUCTIVITY OF THE SOIL ABOVE AND BELOW DRAIN LEVEL RESP. (m/day)
q — REPLENISHMENT OF WATER TO THE SURFACE AND DRAIN DISCHARGE PER UNIT AREA (m/day)

Figure 8
Change in the depth of the GWT by means of two drains, in relation to several factors.

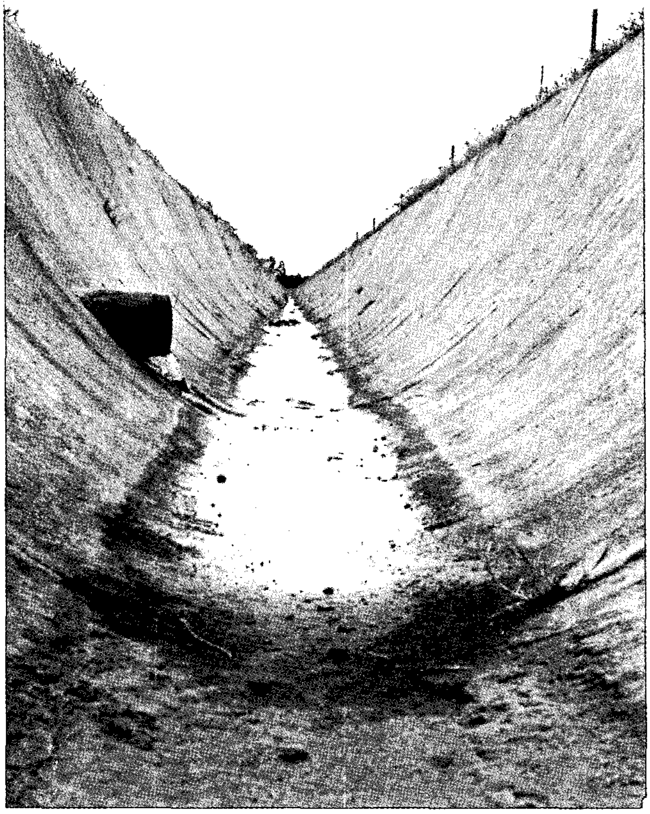


Figure 10
Discharge of ground-water by means of the main subsurface drain of plot 6K5 into a stormwater drain.

Long-term performance of drainage systems

Immediately after the construction of the subsurface drains the high GWT dropped. During the five years of the research project it was possible to control the highest GWT after rain or irrigation at a level of about 0,2 m to 0,3 m above the drains. The corresponding discharge of a drain of 100 m length was 0,6 m^3/h. Fig. 10 shows the discharge from the main drain into the storm water canal.

In order to achieve and maintain a good drain discharge, the following requirements must be satisfied: Long perforated pipes are necessary; good filter of a mixture of gravel and sand must be provided and not just an envelope; careful construction of the drain is essential; and very regular maintenance of the drains is required.

During construction, precautions were taken not to puddle the watersaturated subsoil in such a way that an impermeable layer was formed around the drain. Maintenance of the drains proved to be necessary because of the accumulation of organic iron and manganese hydroxide deposits in the filter and inside the drains. Clogging by iron deposits and the associated problems are well-known (Ford and Spencer, 1962). Plant roots also caused blockages, even at a depth of 2,1 m. Cleaning the drains easily by means of a long flexible iron rod and water was only possible when the roots were young and the deposits fresh, when the pipe diameter was not smaller than 70 mm, and when there was free access to the drain end by means of an inspection hole or open storm water canal. Maintenance of the filter around the drain proved to be very difficult or impossible. The choice of the correct filter is therefore very important. When for some years after completion of the project no maintenance was carried out, the two drainage systems with the 50 mm pipe diameter became largely blocked. The drainage system with the 70 mm diameter pipe is, after 9 years, still operating satisfactorily.

It may be concluded that the level of a high GWT can be controlled or regulated by an artificial drainage system, but not without difficulty. The choice of the depth of the drain below the soil surface will depend on the influence of the depth of the GWT on crop production.

3. Influence of a High Ground Water Table on Crop Production

A high GWT has a definite influence on the soil and plant roots directly above it. This influence can be advantageous through the supply of soil moisture, or disadvantageous through a deficiency of oxygen, a low temperature or an accumulation of salts. These are well-known facts and are described for cotton by, among others, Namken, Wiegand and Brown (1969) and for wheat by Wesseling and Van Wijk (1957). In the Vaalharts studies, the combined influence of the above mentioned factors on the production of cotton and wheat was investigated.

During the winter and summer seasons of 1968–1970 cotton and wheat were grown on experimental blocks and on lysimeters with the GWT at different depths and with different amounts of irrigation water (Fig. 11 and Fig. 12). These two crops were chosen because they predominate at Vaalharts. The minimum depth (highest level) of the GWT on the experimental blocks was controlled at various levels between 1,1 m and

Figure 11
Cotton on soil with a ground water table of 1,4 m below the surface.

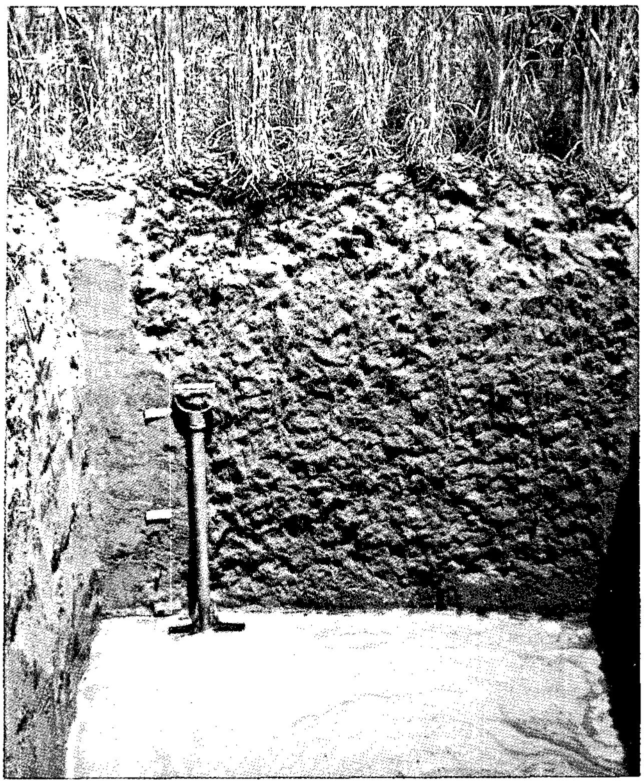


Figure 12
On land with a ground water table of 1,2 m the production of wheat with one irrigation was the same as with four irrigations on a land with a GWT at 2,5 m. Note the dry 0 – 300 mm soil layer.

2,5 m by means of one or two subsurface drains. In one case it was necessary to control the maximum depth (deepest level) of the GWT by means of sub-irrigation through the drain. Each experimental block consisted of several small units of 6 m × 6 m, which were used for replicated treatments comprising different combinations of amount of irrigation and amount of fertilizer. Lysimeters, consisting of six square concrete tanks and thirty-two concrete cylinders closed at the bottom, were constructed on two experimental units and filled with the original soil. The GWT in the two groups of lysimeters was kept constant at 1,1 m or 1,7 m by refilling water through a pipe. The surrounding experimental units had roughly corresponding GWT depths.

Readings of several mercury manometer tensiometers at different depths in the soil were used for timing of irrigation, to determine the depth of downward movement of irrigation water and to calculate the upward capillary moisture movement from the GWT. For the latter calculation the unsaturated hydraulic conductivity was calculated from soil moisture and tensiometer data. Crop yield and total water consumption of ground water, irrigation water and rain were determined.

The influence of the depth of the GWT on the production of cotton and wheat is shown in Fig. 13. A cotton production of 5500 kg/ha lint and seed was measured on a soil with a 1,2 m GWT, in comparison with 4500 kg/ha and 3000 kg/ha on soils with a 1,7 m GWT and 2,4 m GWT respectively. These figures were obtained with five irrigations and with precision tillage. With five irrigations the total water consumption of the crop on the 1,2 m GWT was about 850 mm per unit area, of which 300 mm was provided by the GWT. The total water consumption of the crop on the 2,5 m GWT, and from five irrigations, was about 530 mm, of which only about 20 mm came from the GWT. When ten irrigations (850 mm) were applied, the contribution from the 1,2 m GWT was only 100 mm.

The production of wheat on a 1,1 m GWT after the application of two and four irrigations was about 4000 kg/ha and 4800 kg/ha respectively, in comparison with 3000 kg/ha and 4000 kg/ha with a 1,7 m GWT. The total water consumption of the crop was about 450 mm of which 240 mm was provided from the 1,1 m GWT and 190 mm from the 1,7 m GWT. This was the case for both four and seven irrigations.

These results and those from the waterbalance of Section 1 confirmed that a major part of the water lost through leakages and over-irrigation was used by the plants, but only when the

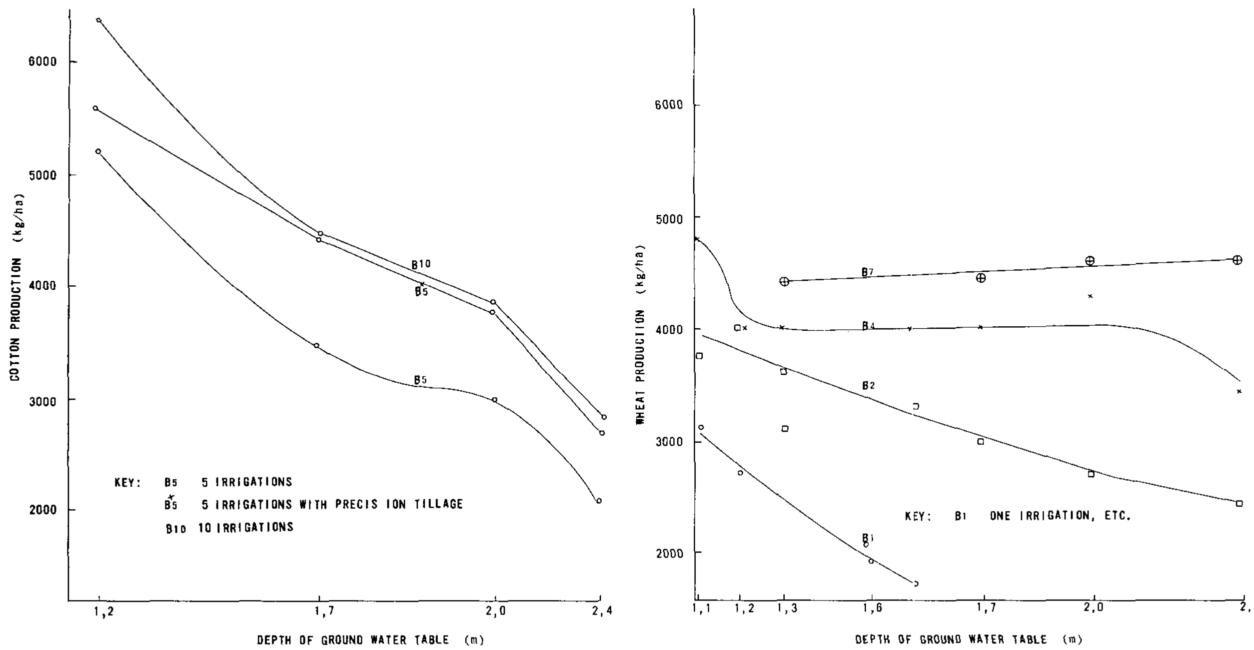


Figure 13
The influence of the depth of the GWT on the production of cotton (Cape Acala) and wheat (Zambesie) for 1971.

GWT was as high as 1,1–1,2 m and only when fewer irrigations were applied. On blocks with a GWT lower than 1,7 m the contribution of water from the GWT was not much or even nil, especially in summer. Soils with a GWT higher than 1,2 m were prone to over-irrigation, because very little water per irrigation was needed to replenish the 0–300 mm soil layer only (Fig. 12). When over-irrigation occurred the quality of the wheat grain decreased from class A to class B. Also, where for years the GWT had fluctuated between 0,3 m and 1,2 m, soils became so strongly reduced (oxygen deficient) that any potentially beneficial effect of increased soil moisture availability on yield was totally counteracted.

A sustained good crop production on a soil with a high GWT is thus only possible when the depth of the GWT is controlled and large fluctuations after heavy rains can be eliminated by means of subsurface drains. The depth of the drains should be 1,2–1,8 m below the soil surface depending on the distance between parallel drains.

4. Salt Accumulation in the Soil above a High Ground Water Table

The general danger of salt accumulation above a high GWT is described, among others, by Talsma (1963). The salt accumulation for the whole North Canal area was investigated by means of the salt balance, a very good example of which is given by Bower *et al* (1969).

The salt balance is the balance between gains and losses of salts. "If the mass of the salt input exceeds the mass of salt output, the salt balance is regarded as adverse, because this trend is in the direction of the accumulation of salt in the area and such a trend is undesirable" (Schofield, 1940). The mass of salt is the product of the volume of water (V) and the salt concentration (C) of the water. On the gains side there is the salt in the irrigation water (Vi.Ci), the salt in the capillary moisture from the GWT (V_{cm}. C_{cm}), the fertilizer salt (S_f) and the salt from weathered soil minerals (S_o). On the loss side is the salt in the drainage water (V_d' .C_d'), the salt removed by the parts of the crop that are harvested (S_{pl}) and the precipitation of inactive salt in the soil (S_p), (Fig. 14).

When S_f, S_o, S_p and S_{pl} cancel out or when they are unimportant to the amount of salt in the irrigation and drainage water, and when $V_d.C_d = V_d'.C_d' - V_{cm}. C_{cm}$, then the salt balance (SB) is:

$$SB = V_d. C_d - V_i. C_i$$

When there is no salt accumulation SB = 0, then:

$V_d. C_d = V_i . C_i$ (salt balance in equilibrium)

and

$\frac{V_d}{V_i} = \frac{C_i}{C_d}$ (leaching requirement satisfied)

The salt balance is an index of salt accumulation, whereas the leaching requirement concept makes possible the control of the salt level. To satisfy the leaching requirement demands that a certain ratio between the volume of drainage water and the volume of irrigation water, equal to the ratio of the salt concentration of the irrigation and that of the drainage water, be

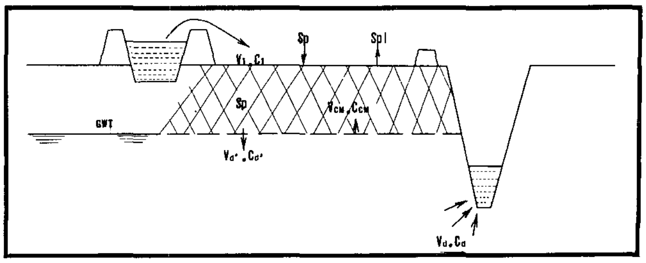


Figure 14
Salt balance. Recharge and discharge of salts. For explanation of symbols see text.

maintained. In South Africa this ratio was proposed as a requirement for permanent irrigation by Klintworth (1952) and in the USA by the Salinity Laboratory, Riverside (1954). The leaching requirement should however be based on the maximum allowable salt concentration in the soil moisture at field capacity (C_{fc}) and not on that in the drainage water (C_d). Different relations between C_d and C_{fc} were used by Boumans (1963) and Bouwer (1969).

The contributions of different factors to the rising salt concentration were calculated from measurements and estimates of water and fertilizer applications and water analyses over the years. Some figures are summarized in Table 3. With 40 924 t of salt in the irrigation water, (V_i is 142,1 × 10^6 m^3 and C_i is 45 mS/m or 288 mg/ℓ), 8184 t from fertilizers, 7322 t of salt in the drainage water (V_d is 10,4 × 10^6 m^3 and C_d is 110 mS/m or 704 mg/ℓ) and 6480 t of salt removed by the plants, an accumulation of 35 306 t of salt per year was calculated for the whole North Canal area. That amounted to 1471 kg/ha per year (1959–1966). The salt balance was negative, and would be more so had the figures of 22 248 t of salt in fertilizer (from 1970 onwards) been used.

The measured leaching ratio (V_d/V_i) was 10/142,1 = 0,07 (1959–1966) and 8/159,7 = 0,05 (1966–1969) (see Section 1)*. However when the 16% leakage from dams and 20% leakage from furrows were omitted from V_i then the ratio became 0,11 and 0,08 respectively. That means that 11% and 8% of the irrigation water was used for leaching and drainage. When these measured leaching ratios are compared with the calculated leaching requirements for the area of 0,15 (Boumans, 1963) and 0,09 (Bouwer, 1969), it is evident that the leaching ratio for the period 1959–1966 was about right, but the one of 0,08 for the period 1966–1969 was too low. To prevent salt accumulation the leaching requirement of 0,09–0,15 can be satisfied by either increasing the volume of drainage water or by decreasing the volume of irrigation water.

The potential danger of salt accumulation as pointed out by the salt balance was confirmed by analysis of soil samples taken in 1970 at four positions very close to the four master-pit positions of the 1932 soil survey. The salt content of the 0–300 mm soil layer had decreased in comparison with that of 1932, but the salt content of the 300–1200 mm layer had increased. A salt accumulation of 135 kg/ha per year was measured.

This is considerably less than calculated from the salt balance. The salt accumulation measured in the soil samples is however only valid for a specific day in 1970 compared to a specific day in 1932, when the samples were taken.

***Rain does not effect V_iC_i and is therefore omitted.**

TABLE 3

CHEMICAL ANALYSES OF WATER FROM DIFFERENT SOURCES AT VAALHARTS

Water Source	Date	Remarks	pH	Eℓ. Cond. mS/m	Na^+	K^+	Ca^{++}	Mg^{++} me/ℓ	HCO_3^-	$Cℓ^-$	$SO_4^=$
Vaal River	2.12.1964		8,0	36,0	1,1	—	1,8	1,4	2,0	0,8	1,7
Vaal River	17.7.1970		7,1	60,0	1,5	0,2	1,3	1,6	2,9	0,6	1,1
North Canal	Aug. 1945		7,5	41,8	0,9	—	1,4	2,4	2,6	0,3	0,8
North Canal	Oct. 1949		8,1	46,1	1,0	—	1,4	1,2	2,7	0,3	0,5
North Canal	1958 – 1959		—	29,0	0,8	0,1	1,3	0,9	2,0	0,4	0,8
North Canal	13.8.1970		7,8	48,0	1,2	0,1	1,4	1,5	2,2	1,0	1,5
High GWT 6B4	1945		7,0	77,3	3,2	—	1,6	2,6	3,3	1,1	3,0
(in sandy soil) 6B4	1970		7,0	84,5	3,4	0,1	2,3	2,6	2,2	2,6	3,9
5G15	1945		6,9	34,3	1,0	—	1,2	1,7	2,1	0,7	1,0
5G15	1970		7,5	96,0	3,0	—	1,7	3,4	3,0	1,6	3,8
6K5	1969	Average of 2 samples	—	20,0	7,0	0,2	6,6*	—	5,9	2,3	5,5
High GWT 6K5	1969	Average of 4 samples	—	350,0	17,4	0,5	21,4*	—	9,2	20,3	10,3
(on calcrete) 2K4	1970	Average of 4 samples	—	180,0	6,2	0,3	13,0*	—	16,2	2,0	1,6
Open ground 5K5	1958 – 1959		7,8	152,0	6,3	0,4	4,0	4,7	7,3	5,0	3,2
drains 1J13	1958 – 1959		7,7	370,0	10,1	0,5	12,1	12,3	4,4	26,5	5,0
Concrete lined drains	July – Aug. 1970	Average of 14 drains	8,0	113,0	4,0	0,1	2,8	4,2	5,0	1,5	4,6
Harts River at Taung	2.6.1969	Stormwater 158 ℓ/s	8,3	24,0	0,7	0,1	1,8*	—	2,0	0,5	0,0
	30.6.1969	Normal flow 48 ℓ/s	—	92,0	3,6	0,1	5,8*	—	6,2	1,1	2,2
	25.7.1969	Normal flow 82 ℓ/s	—	100,0	4,4	0,1	5,8*	—	5,8	1,5	2,8
	25.8.1969	Normal flow 79 ℓ/s	8,0	102,0	5,4	0,1	6,2*	—	6,0	2,2	3,5
	2.9.1969	Normal flow 62 ℓ/s	8,2	112,0	5,6	0,1	6,3*	—	6,3	2,3	3,7
Harts River at	2.6.1969	Normal flow 849 ℓ/s	—	61,0	2,4	0,1	3,6*	—	2,2	2,1	1,6
Espagsdrif	30.6.1969	Storm water 1188 ℓ/s	—	98,0	4,1	0,1	5,6*	—	3,2	3,2	3,1
	28.7.1969	Normal flow 906 ℓ/s	—	119,0	5,4	0,2	6,3*	—	3,2	4,7	3,5
	25.8.1969	Irr. off-period 232 ℓ/s	9,5	112,0	5,6	0,1	4,6*	—	2,4	4,0	4,1
	22.9.1969	Normal flow 453 ℓ/s	8,1	125,0	6,1	0,1	6,0*	—	3,9	4,6	4,6

*$Ca^{++} + Mg^{++}$

The recent increase in saline patches in the North Canal area however confirms the findings of the salt balance, stresses the danger of a high GWT, and emphasizes also the need for remedial action.

5. Recent Improvements and Investigations on Vaalharts

Since the conclusion of the above intensive study from 1965 to 1971 there have been improvements to irrigation canals, irrigation systems, external and internal drains and leaching of salts.

Leakage from irrigation canals has decreased because of regular maintenance and because of the elimination of thousands of trees on the banks of the canals, the shallow roots of which cracked the concrete lining. However, the natural drainage provided by the transpiration of these trees was lost at the same time. Two large buffer dams were constructed to collect irrigation distribution losses and have decreased the irrigation water waste.

On each of about 560 plots the concrete lining of the dam, one main furrow and some lateral furrows had decreased the leakage of irrigation water. On portions of about 400 plots the combination of length, width and slope of the irrigation beds, together with the flow rate of the water, were improved to decrease over-irrigation. Correct manipulation of flow rate and the application time makes it possible to obtain a high irrigation efficiency (Badenhorst, 1973). In practice, however, this is difficult to achieve and only possible on a dry soil, without a high GWT (Streutker, 1974). Some sprinkler irrigation systems have been used, but abandoned. The reasons are complex and no clear cut answer is possible as to why sprinkler systems are not in favour. Whereas with sprinkler irrigation it was possible to irrigate 15–20 ha every ten days with 70 mm water in summer, it was only possible to irrigate 12 ha in a similar period using a very good flood system (Streutker, 1974).

Figure 15
Salt accumulation on the soil surface at Vaalharts.

Despite technical refinements and improvements much however depends on the motivation of the farmer to improve his irrigation practice. On plots with a high GWT there has generally been no reason to reduce over-irrigation and save irrigation water, because the average annual available water quota per plot of 161 × $10^3 m^3$ has not yet been used in full (Table 4). On the other hand, the farmers on dry plots, and on plots with extra non-scheduled land under irrigation, find the water quota inadequate and sometimes have to buy extra water.

The provision of storm water drains as outlet points and the installation of more subsurface drains were stepped up in 1975. About R500 000 has already been spent on subsurface drains on portions of about 140 plots. The drainage system used consists of three or four subsurface drains per plot, of length 600 m and depth 1,5 m, and spaced approximately 100 m apart. Crushed stone was used as a filter. A number of such drainage systems are being monitored in respect of drain discharge, GWT between drains, blockages, maintenance of drains and filter performance. After the heavy rains in February 1976, several drainage systems produced a drain discharge of about 3 mm/day per unit area. In those cases the GWT was approximately 0,7 m below the surface, compared to a depth of 0,3 m in the undrained soils of the neighbouring plots. This is a reasonable drainage performance. Unfortunately some 400 plots are as yet not provided with an outlet point to an external drain.

In recent years Geological Survey has found that by pumping the ground water from deep boreholes drilled at strategic points which delivered between 8 and 65 m^3/h, the GWT can be lowered over a distance of 50 to 500 m from the borehole. The effect depended on the thickness of the sandy soil layer of 0,5–8 m, the thickness of the subsoil water carrier (D) of 5 to 26 m and the hydraulic conductivity (K) of 2,4 to 13,4 m/day. Pump drainage is therefore technically possible at several points at Vaalharts (Gombar and Erasmus, 1976). The above K- and D-figures are however inadequate to justify economical pump drainage (Peterson, 1965).

Another "disadvantage" of pump drainage was the loss of the high GWT for high crop production because of the deep drawdown of the cone-shaped GWT. In connection with the hydrological study of Gombar and Erasmus (1976), it is recommended that the possible supply of water from the eastern hinterland through the subsoil to the Vaalharts ground water reservoir should receive more attention in future.

Pumping from a vertical slotted steel cylinder (sump) of a diameter of about 2,5 m and a depth of 6 m, as deep as the calcrete subsoil, decreased the GWT over a distance of approximately 10 m from the cylinder. This was not a good drainage method, because of the clogging of the slots by the fine sand (Van der Merwe, 1973).

A significant improvement to the situation at Vaalharts, resulting from the recent installation of subsurface drains, will be the leaching of salts out of the soil profile. During 1975 there was white salt accumulation on the soil surface of 288 ha on 87 plots. This is 13% of the inspected area (Fourie, 1976). Electrical conductivity data presented in Fig. 16 show the extent to which leaching was possible on plot 7K5. A further general improvement of the situation at Vaalharts may result from a new approach to the salt balance (Van Schilfgaarde et al, 1974), which results in a lower drainage water requirement, with a higher permissible salt content. However, this will only be achieved by means of very good uniformity of water application, very good irrigation scheduling and very good control of the GWT. In other words, intensive irrigation and drainage management.

Although useful, the salt balance does not indicate the distribution of the salt in the area. This is only possible, on a small-

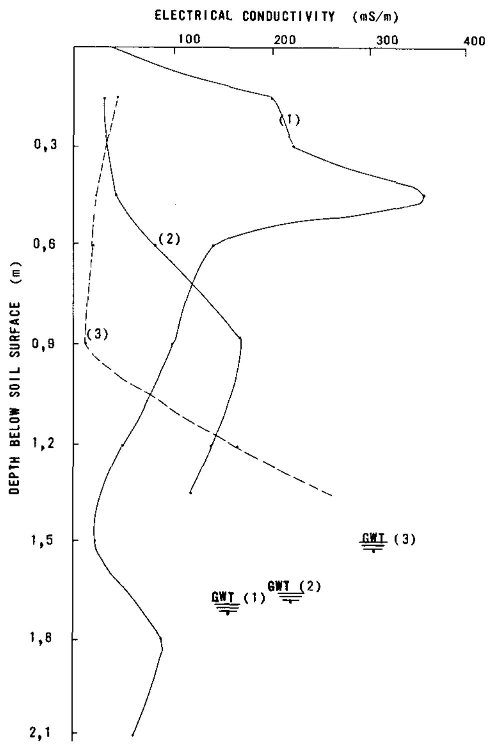


Figure 16
Leaching of salts from the Vaalharts sandy soil (experimental block no. 1, plot 7K5). (1) June 1966; (2) Febr. 1967; (3) Sept. 1967.

TABLE 4

AVERAGE IRRIGATION WATER USAGE PER PLOT (IN 1000 m³) FOR WINTER (1 MAY – 1 NOVEMBER) AND SUMMER (1 NOVEMBER – 1 MAY) DURING 1969–1973 FOR THREE GROUPS OF PLOTS: 1. PLOTS A4–C5; 2. PLOTS AX–CX; 3. PLOTS 6AY, 6Q1, 1DX2

Year	1. Plots (25 ha) with a GWT (<1,2 m) and flood irrigation[1]			2. Plots (25 ha) with no GWT (>2m) and flood irrigation			3. Plots (75 ha) with no GWT (>2m) and sprinkler irrigation[2]		
	Winter	Summer	Year	Winter	Summer	Year	Winter	Summer	Year
1969/70	36	111	147	46	116	162	48	135	183
1970/71	46	96	142	62	113	175	81	106	187
1971/72	46	79	125	65	87	152	49	89	138
1972/73	39	105	144	59	116	175	62	129	191
Average	**42**	**98**	**140**	**58**	**108**	**166**	**60**	**115**	**175**

1. The area of the plots in group No. 1 is really 19 ha, and 25 ha for the plots in group No. 2. The figures under group No. 1 in this table are converted and valid for 25 ha. There are 36 plots in group No. 1 and 30 plots in group No. 2.
2. The water quota for the plots in group No. 3 is for 25 ha, and the same as for the plots in group No. 2.

er scale, by means of monthly analysis of soil samples from 40–100 fixed observation points in the area. In future it might be possible to use satellite imagery for monitoring waterlogging and salinity.

Lastly, many of the Vaalharts problems arise because of the texture of the sandy soil. (Van der Merwe, 1970; Streutker, 1971 and Bennie, 1972). This soil (Cs + Ms, Fs, Si, Cl is 23, 67, 2 and 8% resp.) is a class 3 irrigable soil (according to the USDA classification system), because of the low water holding capacity, low fertility, high bulk density and limited depth (Maletic, 1967). For 24% of the area the depth of the soil is less than 1,2 m, and for another 15% of the area between 1,2 m and 1,8 m (Meyer, 1973). The high fine sand fraction and the low clay fraction of the soil give a small pore volume of 35% of which 70% is between 0,004–0,086 mm diameter, and consequently produce a high soil strength which have retarded root development and decreased cotton production (Streutker, 1971). The only means of dealing with the problem was by precision tillage e.g. for cotton (Stockton, Carter and Paxman, 1964) and (Fig. 13), by establishing pioneer grasses and by keeping the soil wet. Soil conditioners are uneconomical. On future irrigation schemes along the Orange River and the Vaal River with the same soil type, the problem may be somewhat alleviated by an eventual change in soil texture, when the silt and clay particles contained in the irrigation water of the Orange River will be mixed with the soil.

Conclusion

1. It is better to prevent waterlogging and salinisation of irrigated soils, than to attempt to cure the soil with doubtful success.

2. Prevention of salt accumulation in soils of future schemes is only possible by means of continuously monitoring the salt and water balance (leaching requirement), possible with the aid of satellite photography, by which the application of just sufficiently more water over and above the normal irrigation requirement can be permitted. This is however only possible when the natural subsurface drainage can cope with the extra water necessary for the leaching of the salts.

   When the natural drainage is inadequate and a ground water table (GWT) develops, the rising GWT must be detected at an early stage and immediately controlled at a level of about 2 m by means of artificial drains.

   To deliberately persist with an artificially *high* GWT as a means of supplying soil moisture to crops is a reckless experiment which will undoubtedly lead either to the failure of the scheme or, if successful, to a rarity in irrigated agriculture in semi-arid regions. The small chance of success of permanent crop production will depend on a high level of management of drainage and irrigation systems.

3. To improve waterlogging and salinisation of soils at Vaalharts it is recommended to curb over-irrigation and to prevent, as far as possible, leakage of the irrigation water (and thus reduce underground water storage), and to use the saved water for either irrigating more frequently with smaller amounts, or irrigating a larger area.

   The high GWT will remain in some areas, because of permanent deterioration of the natural drainage ability of the subsoil and because of some unavoidable leakage from distribution systems, resulting in accumulation of that water in low-lying areas. In such areas it is possible to control the level of the GWT, but it will require a continuously high level of management to control salt accumulation and to maintain permanent crop production.