Groundwater dynamics influenced by irrigation and associated problems of river salination; Breede River, Western Cape Province, R.S.A.

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ABSTRACT A research program was launched 1987 in the Breede River valley, in order to estimate the contribution of saline groundwater to the salination of the main river. Groundwater observation holes, drainage ditches, and the major tributaries are included in this program. Groundwater under non-irrigated land is very saline and EC-values up to 8000 mS/m were measured. Its variations are negligible, and water levels remain constant more than 15 m below the surface. Groundwater under irrigated land is shallow and corresponds immediately to the irrigation cycles. Its relief always shows a gradient towards the Breede River and partly flows in buried former flood channels towards the river. The investigated drains indicate that salts are temporarily stored in the unsaturated zone during the irrigation season and later are flushed out by the winter rainfall. The tributaries show an EC-distribution and salt output dynamics similar to those of the drains. During the irrigation season their salinity increases continuously by inflow from point sources and seepage of saline groundwater. In a first approach, the groundwater contribution to the discharge of the tributaries was estimated by using the measured EC and assuming different irrigation efficiencies. The simulation proved, that groundwater discharge is of dominant importance to the discharge of each tributary, if irrigation efficiencies vary between 70 and 80%.

INTRODUCTION

The Breede River catchment is one of the most important agricultural production areas in the Mediterranean, semiarid Western Cape Province. Irrigation began in the 18th century, and at the present time, more than 50,000 ha are under irrigation. Due to irrigation the groundwater level in the sandy alluvial deposits partly increased up into the root zone. Capillary rise of saline groundwater generated saline and saline-alkali soils (Reeve & Fireman, 1967), causing considerable leaching problems (Moolman et al., 1983).

Together with the irrigation water, salts are transported to the fields. A surplus of water, called leaching requirement, has to be applied in order to leach these salts out of the root zone. The leaching requirement describes the smallest portion of the irrigation water, which must pass through the root zone, transporting all of the imported salts down to the groundwater (Hoffmann, 1983). Consequently the total irrigation must exceed the maximum crop evapotranspiration by the required leaching volume. The optimal adjustment of the leaching requirements determines the efficiency of each irrigation technique. It is obvious, that the
leaching return flow must always have a higher salt content than the applied irrigation water, even if there is no dissolution of fertilizers (Schepers et al., 1983) and weathered soil salts (Rhoades et al., 1974). It consequently increases the TDS (Total Dissolved Salts) of the underlying groundwater (Bouwer et al., 1983; Bouwer, 1987; Surez & van Genuchten, 1981) causing its salination. By mean of artificial drainage it must be kept below the capillary fringe (Bouwer, 1974). Saline groundwater and percolating saline irrigation return flow, collected in the drainage system, flows to the nearest stream (Silvester & Seabloom, 1963; Wilcox, 1962). This inflow deteriorates the quality of the supply water and gives problems to downstream irrigation users. An optimal irrigation efficiency is required in order to reduce the leaching requirement to a minimum, thereby reducing the salt input to the rivers (Rhoades, 1974; Rhoades et al., 1974; Branson et al., 1975).

BREED RIVER VALLEY

The Breede River drains a catchment of about 12600 sqkm in size. The valley is located in the central part of the Cape Fold Belt, formed by the lower paleozoic sediments of the Cape Supergroup. The general strike of this fold system is WNW-ENE. The three main relief units are shown in Fig. 1. Together with their associated geological formations they can be described as follows:

Fig. 1 Breede River catchment and its three main relief units.

(a) The high mountain ranges north and south of the river are composed of quartzites and sandstones of the Table Mountain Group, which are resistant to weathering and therefore form the bordering mountain chains with heights up to 1800 m.
(b) South of the Breede River sandstones and shales of the Bokkeveld and Witteberg Group (Devon) are bordering the southern
mountain chain. They vary in height between 300 and 800 m. A narrow strip of metamorphic shales (Precambrian) also borders the northern chain, but is too small to be presented at this scale.

(c) The valley itself has a gentle hill relief of permian glaciocene sediments of the Dwyka Group (tillites, sandstones, mudstones), the Ecca Group (sandstones, shales, mudstones), and of cretacious clayey Enon-conglomerate. The latter was subject to an intensive peneplain forming process during the tertiary. The valley always was a trap for sediments brought in by the different tributaries. Flowing from the northern and southern mountain chains, they accumulated large alluvial fans of boulders and sand, before they could reach the Breede River. The latter flows in a broad alluvial channel filled with coarse boulders covered by about 3 m of fine sand. Due to heavy winds the sand is blown in some areas to high dunes.

The annual rainfall distribution is typical Mediterranean with the rainfall season in the winter half year between May and October. The areal rainfall distribution is very closely associated with the three relief units (Fig. 1) and can be described as follows:

(a) The northwest of the catchment upstream of Brandvlei Dam receives the highest rainfall, varying between 800 and 2500 mm. The maximum falls in the northwestern mountain chain.

(b) Downstream of Brandvlei Dam the rainfall in the southern mountain range decreases, but is still slightly higher than in the northern chain.

(c) The luv-lee effect is obvious northeast of both mountain ranges, where the foothill zones in front of them receive between 400 and 800 mm of rain.

(d) The main irrigation area in the center of the valley has a semiarid character and receives only between 200 and 400 mm of rain.

Fig. 2 shows the mean annual distribution of rainfall and A-pan evaporation in Robertson (near point 19, Fig. 1) for the time period of 1966 to 1986. The total mean annual rainfall is less than 280 mm with a 42 mm maximum in August and a 12 mm minimum in

Fig. 2 Mean monthly rainfall and A-pan evaporation from 1966 to 1986 at Robertson in the center of the Breede River valley.
December. However, this climate is also characterized by a high variability in the annual rainfall. The annual sums varied from 1954 till 1987 between 155 mm in 1960 and 485 mm in 1962. During the irrigation season between October and March rainfall adds up to only 97 mm and is negligible. The mean annual A-pan evaporation is 1785 mm and always higher than the monthly rainfall. The maximum occurs in January with an A-pan evaporation of 260 mm.

PROBLEM AND OBJECTIVES

Irrigation in the Breede River valley is concentrated in the middle part between Brandvlei Dam and point 5 in Fig. 1. The semiarid climate and the Mediterranean annual rainfall distribution force irrigation agriculture to a management of water storage in winter and water consumption in summer between October and March. The water is stored in Brandvlei Dam during the winter and is distributed during the summer to various irrigation schemes, either via canals connected or to the dam, or, by releasing water directly into the Breede River for downstream irrigation users. Unfortunately the Breede River also receives saline irrigation return flow from the connected irrigation schemes, which deteriorates the supply water quality considerably. Therefore additional blending releases from Brandvlei Dam are necessary, in order to guarantee a suitable water quality at the end of the system (point 5, Fig. 1). Due to this operational strategy the capacity of Brandvlei Dam is not used efficiently as most of the blending water is lost for irrigation. The salination of the supply water recently became a serious problem between the two weirs 17 and 5 in Fig. 1. At this river stretch four saline tributaries join the Breede River, causing a stepwise deterioration of the supply water quality as shown in Fig. 3. For the evaluation and simulation of the salination dynamics in the Breede River an improved understanding of the groundwater contribution to the river flow is required. For the future management of the system it is necessary to achieve better irrigation efficiencies and less saline return flow. According to these research needs the following objectives were identified:

(a) Determine the hydrological dynamics of the groundwater under irrigated and non irrigated land.
(b) Calculate the salinity dynamics of the irrigation return flow in different artificial drains.
(c) Identification of the hydrological and salination dynamics of the tributaries of the Breede River.

The study is concentrating on the Robertson Irrigation Scheme in the center of the valley, which is representative of the area below Brandvlei Dam. Several deep and shallow bore holes were drilled and the level measurements provide information about the hydrosalinity dynamics of the groundwater in the sandy alluvial sediments and the underlying bedrock. Irrigation return flow was measured in all the major drains of the scheme. They collect the percolating leachate from the irrigated fields and also partly drain the shallow groundwater. Four tributaries were included in the study which contribute most of the salt load to the Breede River. They collect saline return flow from the artificial drainage system as well as seepage of saline groundwater from the bedrock and the sandy alluvial aquifer.
RESULTS

Although the project is still on-going, initial results of each of the three research objectives can be presented. Groundwater in the deep boreholes under non-irrigated land was always deeper than 15 m below the surface and showed negligible changes, also during the winter rainfall season. The EC varied between the different boreholes, but was always higher than 1500 mS/m, reaching a maximum of more than 8000 mS/m. Under irrigated land the groundwater level was never below 3 m under the surface, and the quality varied between 250 and 600 mS/m. On the floodplain of the river the groundwater in the bedrock seemed to be under artesian pressure, which could be the reason for a continuous seepage through fractures into the Breede River (Reynders et al., 1985) and the overlying alluvial aquifer.

In the alluvial deposits of the Breede River and its tributaries the dynamics of the shallow groundwater clearly reflect the irrigation cycles. This is shown in Fig. 4 by the time series of screen no. 20 in a sprinkler irrigated alfalfa field. The shallow groundwater level shows a periodical variation corresponding to the irrigation cycles. Other shallow boreholes in the alluvium exhibit a similar behavior. The amplitude of the fluctuation depends on the amount of water applied by the various irrigation techniques, the crop pattern, and the soil texture. These factors determine the irrigation efficiency of the different fields. Coarse textured soils show a smaller amplitude than more loamy soils. The shallow groundwater under non irrigated areas has no fluctuations and remains constant between 3 and 3.5 m deep, decreasing slightly during the summer season.
A cross section through the sandy alluvial deposits in the flood plain of the Breede River is shown in Fig. 5. The groundwater relief follows the relief of the underlying boulder, and the flow gradient of the groundwater is always directed to the Breede River. However, former flood channels in the boulder relief, today covered with soil after being levelled for agriculture, are acting as hidden drainage channels, through which the saline irrigation return flow reaches the main river channel. EC of the shallow groundwater under irrigated land varied between 250 and 600 mS/m and increased under non-irrigation land to EC-levels between 1000 and 2000 mS/m.

The EC of the irrigation return flow in the major drains varies considerably. Drains with a higher percentage of groundwater flow have also a higher EC than those with less groundwater contribution and more irrigation return flow. The EC of the first type of drains varies between 600 and 1200 mS/m, and the EC of the latter between 200 and 300 mS/m. A typical EC time series of one of the drains is shown in Fig. 6. The salinity of the outflowing irrigation return flow only changes a little. However, the winter rainfall season causes a slight decrease of the EC during July and August.

The monthly salt load shows completely different dynamics. It is computed by using a linear calibration function for the conversion of the measured EC into the salt concentration (TDS), which is then referred to the flow in the drain. The salt output to the Breede River shows a distinguishable monthly distribution. The minimum is in February during the main irrigation season, the maximum is in
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August during the highest winter rainfall. These dynamics indicate that a considerable amount of salt applied with the irrigation water is temporarily stored in the unsaturated zone during the irrigation season. The salt is later leached out of the soil during the winter rainfall and is transported to the Breede River.

Although all of the major drains were included in the study, the computed total salt output to the Breede River only accounts for a small portion of the salt input to the Robertson Irrigation Scheme. As only a small area of the scheme is artificially drained, it must be concluded that the majority of the salt input is leached down the root zone and reaches the Breede River as groundwater discharge.

All of the major tributaries between the weirs 17 and 5 (Fig. 1) are included in the study. Between these two weirs several saline tributaries marked as points 18, 19, and 11 in Fig. 1 are contributing to the stepwise salination of the Breede River (Fig. 3). Weirs are installed in each tributary, and flow as well as EC are measured continuously. During the irrigation season their discharge consists only of irrigation return flow from drains and groundwater seepage from irrigated fields. Therefore their salinity ranges between 400 and 700 mS/m, corresponding to 2.5 and 4.5 g/l TDS respectively. During the winter rainfall season surface runoff also contributes to the discharge. All tributaries show similar EC-distributions as those observed in the drain (Fig. 6). The EC during the winter discharge also remains high, ranging between 200 and 500 mS/m, and shows diluting effects during August and September.

In Fig. 7 a longitudinal EC-section is shown for the Vink River (point 19, Fig. 1), measured from its source to the confluence with the Breede River. At its origin the Vink River collects irrigation return flow and shallow groundwater, which seeps in from the adjacent sandy alluvial river banks. It therefore starts with an EC of 250 mS/m. At the following river stretch irrigation changes from drip to flooding and the contributing return flow also contains irrigation reject water from the surface of the flooded fields. Consequently the inflow from drainage ditch DD21 (Fig. 7) has an EC of only 175 mS/m and is diluting the Vink River. At the record bridge the geology changes from the less saline, sandy Witteberg Group to the more saline and shaly Bokkeveld Group.
Groundwater in the Bokkeveld Group is saline with EC-values of about 800 mS/m as measured in boreholes in the Vink River valley. Consequently the drainage pipe DPlr delivers high saline return flow and groundwater (650 mS/m) to the river. Downstream of this point source up to the confluence with the Breede River the salinity of the Vink discharge does not change, indicating, that the inflow from the different sources has an unchanged salinity. At the mouth of the Vink River, saline drainage water with an EC of about 400 mS/m is discharged to the Breede River. Similar longitudinal EC-distributions were observed in all of the other tributaries.

![Fig. 7 Longitudinal EC-profile of the Vink River from its source to the confluence with the Breede River in November 1986.](image)

The groundwater contribution to the tributaries can be estimated by using the measured EC at the confluence with the Breede River together with several assumed irrigation efficiencies. This approach conditionally implies that the salinity of the return flow is only determined by leachate from the fields, i.e. the irrigation efficiency. In this case the leaching requirement is only carrying the salts applied with the irrigation water to the fields. Making this assumption all salt dissolution from fertilizers and from the soil weathering is considered to be negligible. As fertilizing in the Breede River valley is limited to only periodical gypsum applications, this rather simple approach can be regarded as realistic. The measured supply water quality of about 40 mS/m was used for the simulations. Setting the irrigation efficiency to 90%, the EC of the resulting return flow would be high enough to explain the measured salinity of the tributaries. If the irrigation efficiencies are set to more realistic values between 80 and 70%, all tributaries would have a much lower salinity than observed. This discrepancy indicates that there must be an important additional saline groundwater contribution deteriorating the less saline irrigation return flow.

CONCLUSIONS

Primarily results of the groundwater research program in the Breede River valley indicate the importance of the groundwater contribution to the salination process in the Breede River and its tributaries. As irrigation management is not reaching the optimal leaching requirements, the underlying saline groundwater is rising
into the root zone and flows directly to the Breede River and the tributaries, or seeps into the drainage system. By using a simple salt balance method and assuming different irrigation efficiencies, the groundwater contribution to the tributaries can be estimated. Setting the irrigation efficiency realistically between 70 and 80%, every tributary shows a dominant influence by saline groundwater seepage. Future work in this research program will therefore concentrate on a more detailed groundwater observation and the evaluation of water and salt balances for the different tributaries.

REFERENCES


