Salinity guidelines for irrigation: Case studies from Water Research Commission projects along the Lower Vaal, Riet, Berg and Breede Rivers

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Abstract

A vast number of projects on salinity in irrigated agriculture were funded by the Water Research Commission (WRC) during the past 40 years. However, due to the diversity of the projects it is virtually impossible to cover all aspects thoroughly in a paper of limited length. Thus this review focuses mainly on projects along the Lower Vaal, Riet, Berg and Breede Rivers in South Africa. The results on the water quality of these rivers indicate that irrigation has led to the deterioration of water sources. There is a direct relationship between river water quality and soils irrigated. Fortunately, effective land-suitability guidelines were developed and applied during the establishment of the major irrigation schemes. This facilitated the management of soils under irrigation. The results from long-term irrigation case studies along the Lower Vaal River and Breede River show that the quality of soils can be improved. The opposite is also true where mismanagement occurred. Research on the salinity threshold of major crops (grapevines, wheat, maize, groundnuts, etc.) confirmed the empiric nature of the guidelines. It is suggested that a more dynamic approach be used for managing salinity under irrigation at farm level, i.e. the use of models. Amongst others, future research should focus on determining the spatial and temporal distribution of salt in irrigated soils.

Keywords: crop response, electrical conductivity, sodium adsorption ratio, soil type, water quality

Introduction

Irrigation contributes significantly to crop production in South Africa since the country does not have rainfall in abundance (Backeberg, 2003). The mean annual precipitation for the country as a whole is only 480 mm. It follows that sustained food production in some of the drier provinces is only possible with irrigation. For example, in the Western Cape virtually the entire fruit and wine industries are dependent on irrigation. Cropping in the Eastern and Northern Cape also relies heavily on irrigation. Salinisation of water resources in these provinces is therefore of great concern for irrigation. High levels of salinity impact negatively on soil quality and crop yield.

According to various reports published during the 1960s to 1980s, the salinity of South Africa's water resources has been deteriorating steadily, albeit slowly (Stander, 1987). This has been true especially for rivers and storage dams in the Gauteng industrial area (Stander, 1987) and in the semi-arid south-western and south-eastern parts of South Africa (Fourie, 1976). At that stage problems associated with salinity in irrigated agriculture had already been encountered in some of these areas. Some examples are the irrigation schemes of the Fish and Sundays Rivers in the Eastern Cape (Hall and Du Plessis, 1979), the Riet River in the Free State (Van der Merwe, 1965), the Berg and Breede Rivers in the Western Cape (Cass, 1986) and the Vaalharts Irrigation Scheme in the Northern Cape (Streutker et al., 1981). These earlier studies were sporadically conducted by either the Department of Agriculture or the Department of Water Affairs to solve problems experienced by irrigation farmers. However, research undertaken at the University of the Free State, Rhodes University and Stellenbosch University also contributed to our knowledge.

During the 1970s and even the 1980s elevated salinity levels were attributed to the quality of water received from the Department of Water Affairs (DWA) for distribution to users. The idea that water quality in rivers and hence storage dams could be affected by land use was not generally accepted. The department decided therefore not to monitor land salinity, but to intensify water quantity and quality measurement in rivers. This resulted in an expansion of the DWA's database, which originated in the 1960s, to one of the largest national attributes for planning and research concerning water resources. In retrospect it was a good decision by the DWA.

Fortunately, in 1971 the Water Research Commission (WRC) was founded to coordinate water research in South Africa. This resulted in research prioritisation. Cass (1986) for example, was commissioned to take stock of water-quality data suitable for modelling irrigation return flows. He concluded that insufficient long-term data sets existed, particularly on soils and crops for this purpose, with the exception of data collected by Streutker et al. (1981) for the Vaalharts area. This finding of Cass (1986), and recommendations made in reviews on the degradation of irrigated soils (Scotney and Van der Merwe, 1995) and irrigation water quality (Du Plessis, 1995), led to a substantial number of WRC projects, spanning 40 years, which dealt in one way or another with salinity management under irrigation (e.g. Cass, 1986; Nel, 1988; Greef, 1990; Moolman, 1993; Herold and Bailey, 1996; Herald, 1999; Moolman et al., 1999; Du Preez et al., 2000; De Clercq et al., 2001a; b; Ehlers et al., 2003; Ellington et al., 2004; Fey and

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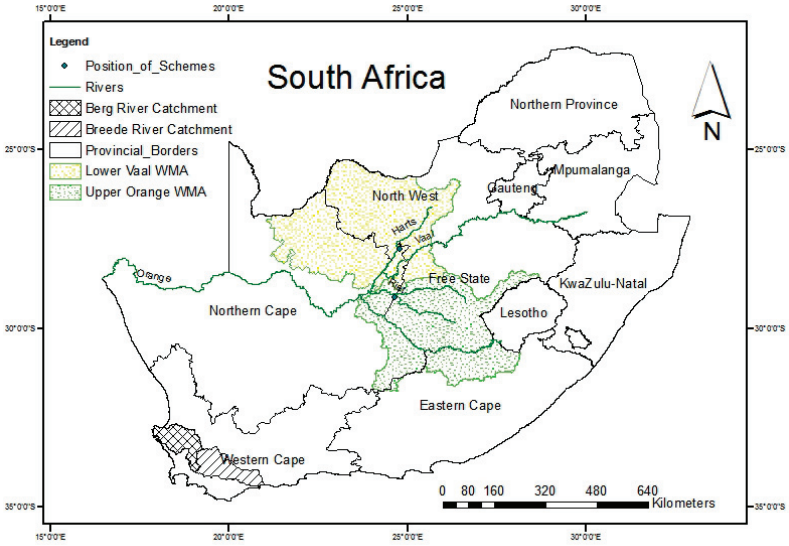

Figure 1
Location of the rivers selected for the water-quality review: The Lower Vaal River and its tributaries (Harts and Riet Rivers), Berg River and the Breede River

De Clercq, 2004; Cullis et al., 2005; Görgens and De Clercq, 2006; Viljoen et al., 2006; Ehlers et al., 2007). The projects were diverse and covered topics such as hydrology, soils, crops, economy and modelling.

The diversity of the WRC projects makes it virtually impossible to cover all aspects thoroughly in a paper of limited length. Thus this paper focuses on salinity guidelines for irrigation with respect to selected rivers, soils and crops within the summer- and winter-rainfall regions. Case studies along the Vaal, Harts and Riet Rivers were selected to represent the summer-rainfall region and those along the Berg and Breede Rivers for the winter-rainfall region. The methodologies applied in these case studies are readily available in the relevant WRC reports and are therefore not repeated, except where essential to support results that are discussed herein.

Irrigation and river water quality

This section focuses on the effect of irrigation on the quality of water along the course of selected rivers, namely the Lower Vaal River and its tributaries (Harts and Riet Rivers), Berg River and Breede River (Fig. 1). The Lower Vaal River and its tributaries are located in the summer-rainfall area, while the Berg and Breede rivers are situated in the winter-rainfall area. The Lower Vaal River and its tributaries supply water to irrigate 80 000 ha of land, viz. 58 000 ha along the Lower Vaal River, 19 500 ha along the Riet River and 2 500 ha along the Harts River. Farmers irrigate mainly field crops (maize, wheat, groundnuts, peas, oats, potatoes, etc.), pastures like lucerne and teff, and small areas of perennials (vineyards, pecans, citrus and olives) (Herold and Bailey, 1996; Ninham Shand, 2004). For the Berg River, only 6% of the land surface area is related to irrigation and explains the absence of an irrigation scheme. Thus land use is mainly allocated to dryland agriculture (mainly wheat). The Breede River Valley forms part of drainage region H (DWAF, 1986) and is an important agricultural area for the production of high-value crops under intensive irrigation. Irrigated agriculture accounts for more than 80% of the total water use in drainage region H. There is a wide and dynamic crop mix, but wine is the primary product with 65% of the area under wine-grape varieties. Other crops produced in the valley are peaches and apricots (13%), vegetables, mainly tomatoes (3%) and irrigated pastures (7%) (Moolman et al., 1999).

Since the 1950s, the Department of Water Affairs and Forestry (DWAF) collected water quality data on the major river systems in South Africa (Du Preez et al., 2000). The data were used to assess the broader impact of irrigation and other anthropogenic factors on the water quality of the selected rivers. The quality parameters were: calcium, magnesium, sodium, potassium, silicon, sulphate, chloride, fluoride, ammonium, nitrate, nitrite, phosphorus, pH, calcium carbonate (total alkalinity) and electrical conductivity (EC). Of these parameters, EC and sodium adsorption ratio (SAR, derived from Na, Ca and Mg concentrations) are discussed. The results of the long-term mean EC and SAR for the rivers have been summarised and are given in Table 1. It was not possible to estimate the 2020 impact of irrigation on the water quality of Berg and Breede Rivers.

Lower Vaal River and tributaries

The water quality of the Lower Vaal River reflects the irrigated agriculture sector, because water use by industries and municipalities is relatively low. The results in Table 1 show clearly that EC and SAR increased along the course of the rivers. For example, the Vaalharts Irrigation Scheme (Fig. 2) abstracts water from the Vaalharts weir (C2S1 class) and discharges most of the leachate and excess water into the Harts River. This management system causes the water quality of the Harts River to deteriorate from a C2S1 class (above discharge) to a C3S1 class (below discharge). The problem is that the water flows into Spitskop Dam where it is further used to irrigate mainly clay soils. Fortunately, the sodium load of the water is low and the EC is high, which means that the infiltration capacity of the soils is not seriously affected. However, users of Spitskop Dam water should be aware of this situation and the need to adopt best management practices to sustain irrigation farming in the long run. The long-term projection (2020) of Du Preez et al. (2000) indicated that the SAR will increase to just above 6, which implies that the hydraulic properties of the clay soils will be degraded. If this happens farmers might be forced to install artificial drains to leach the excess salts. Thus, the current water management option will bring about huge costs for future farming downstream of Vaalharts Irrigation Scheme. Excess water from Spitskop scheme drains back into the Vaal River near Delportshoop. The salt is then transported downstream where it blends with water from the Riet River.

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Table 1
Long-term mean electrical conductivity (EC, mS·m^{-1}) and sodium adsorption ration (SAR) for rivers associated with selected irrigation schemes (data from Du Preez et al., 2000)

River	Measuring points	Long-term mean	
		EC	SAR*
Vaal	Bloemhof Dam downstream to Vaalharts Weir	52	1.2
	From Vaalharts Weir downstream to Vaalharts confluence at Delportshoop	54	1.3
	From Delportshoop downstream to the Vaal-Orange confluence	72	1.8
	From the Vaal-Riet confluence, downstream to the Vaal-Orange confluence	74	1.9
Harts	Schweizer-Reneke, downstream to Taung	70	2.3
	From Taung, downstream to Delportshoop	115	2.4
Modder	Upstream of Krugersdrift Dam	48	1.16
	From Krugersdrift Dam downstream to the confluence of Modder/Riet	63	1.49
Riet	From Jacobsdal upstream	51	1.43
	Orange-Riet canal at Riet River scheme	21	0.39
	Downstream of the confluence of the Riet/Modder	136	3.17
Orange	Upstream of Hopetown	17	0.33
	Between Hopetown and the Vaal-Orange confluence	19	0.38
	Downstream of the Vaal-Orange confluence	23	0.53

**Derived from Na, Ca and Mg concentrations*

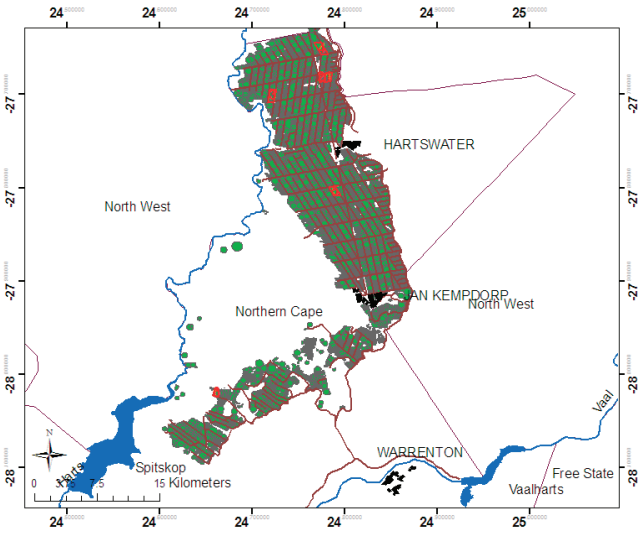

Figure 2
Layout of the Lower Vaal River with the Harts River as a tributary

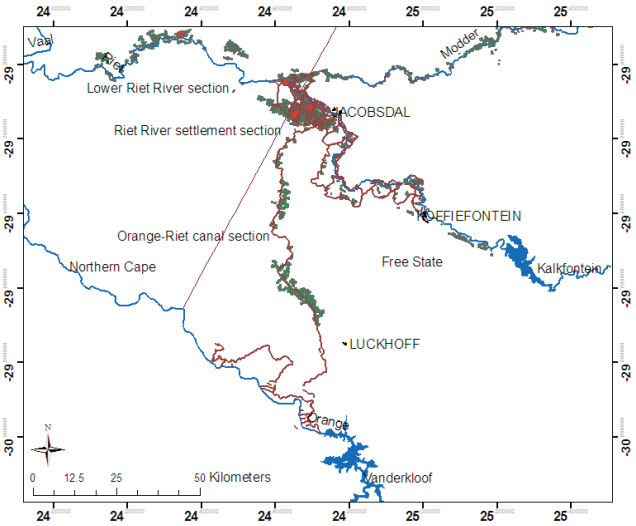

Figure 3
Layout of Orange – Riet Irrigation Scheme, showing the Riet and Modder Rivers in relation to the Orange River

Drastic measures were taken in the past to control the effluent of the irrigation sector along the Riet River (Fig. 3). Water of a high quality (C1S1) is transferred via the Orange-Riet Canal to the Jacobsdal Irrigation Settlement and the excess water as well as the drainage effluent is discharged into the Riet River. Despite this effort the water quality of the river downstream of the confluence of the Riet and Modder Rivers remained a C3S1 class. This can be ascribed to the salt load of the Modder River (C2S1), Riet River (C2S1) and the lithology of the catchment. The salts in the soils and sediments are mobilised through irrigation activities and the effluent drains to the river to be used by irrigators downstream. The 2020 prediction revealed that the EC will increase from long-term (1971-1997) average values of 136 mS·m^{-1} to 157 mS·m^{-1} and the SAR from 3.2 to 4.6. This implies that extension officers and advisors need to promote best management practices to avoid the negative impact of the salt load on soils and crops along the Riet River.

Berg and Breede Rivers

The water quality results of the rivers are presented in Table 2, and patterns along the main streams of the Berg and Breede Rivers are shown in Fig. 4 and Fig. 5, respectively. The chronic water shortage during the summer season due to the absence of rain is a major problem in these rivers. During this period water seeps from the crop fields into the tributaries, causing the water quality to deteriorate, as indicated in the results. This effect suggests that water flow in the river should be managed by the water user associations (WUAs). For example, the results indicated higher average EC values measured at the Nuy and Kogmanskloof River tributaries. During the period 1981 to 1990 the mean annual salinity rate increased for four of the principle tributaries of the Breede River between Worcester and Bonnievale. The mean annual salinity ranged from 38 mg·ℓ$^{-1}$·a^{-1} for the Kogmanskloof River to 145 mg·ℓ$^{-1}$·a^{-1} for the Poesjesnel River (Kienzle, 1990). Similar data exist for the Berg River and the natural trends of increased salinity at the time (1976 to 1990) are alarming. It is also quite evident from the Berg River data that the water quality of the main stream was affected by the tributaries, in most cases increasing the salinity of the Berg River.

Since both river systems also supply water to the fast-growing Cape Town metropolis, the lack of water during summer months is currently posing an increased problem for the farming communities of these catchments. De Villiers (2007) and

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Table 2
The long-term median and maximum electrical conductivity (*EC*) values for the Berg and Breede Rivers of the Western Cape showing only selected measuring points (De Clercq et al., 2001a)

River	Measurement point	*EC* (mS·m^{-1}) Median	*EC* (mS·m^{-1}) Maximum
Berg	Paarl	10	19
	Hermon	21	42
	Drieheuwels	24	68
	Misverstand	35	97
	Jantjiesfontein	82	481
Breede	Ceres	24	60
	Nekkies	10	32
	Nuy River	385	653
	Le Chasseur	24	62
	Kogmanskloof River	305	531
	Wolvendrift	70	320
	Drew	82	234
	Swellendam	53	171

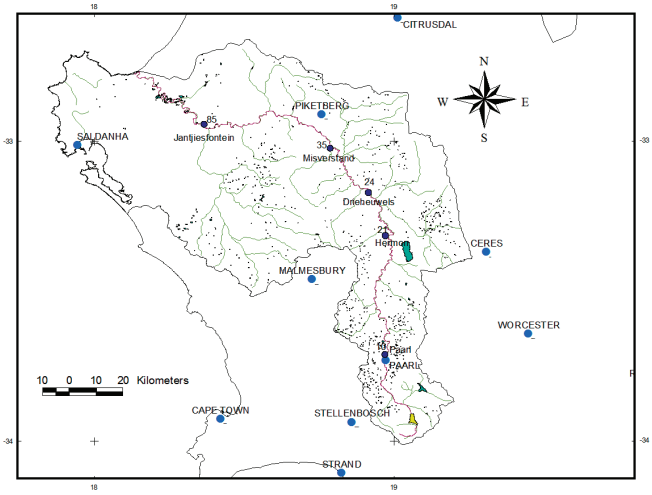

Figure 4
The Berg River catchment indicating the river system and the major dams and the electrical conductivity (EC) measurements at selected points (see Table 2)

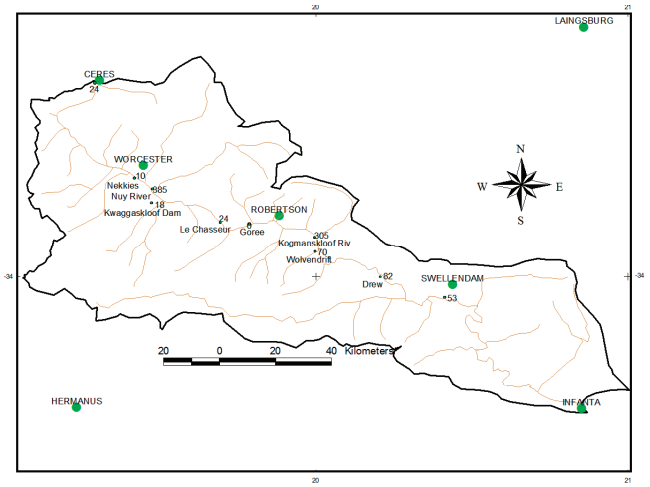

Figure 5
The Breede River catchment indicating the river system and the major dams and the electrical conductivity (EC) measurements at selected points (see Table 2)

Nieuwoudt et al. (2008) indicated that, with the addition of the new Franschhoek Dam and subsequent increase in the storage capacity of dams in the Berg River catchment, the reduction in the occurrence and effectiveness of floods to lower the salinity levels in the main stream may also be a potential cause for concern in future.

Irrigation and soil quality

Guidelines for evaluating irrigated soils

Evaluation of the suitability of soils for irrigation is the key element in sustaining long-term quality of irrigated soils. This was the view of many soil scientists who surveyed soils of major irrigation schemes in South Africa; Sundays River, the Great Fish River and Hartbeespoort Dam (1912-1930), followed by Vaalharts, Pongola, Riet River and Lower Orange River (1930-1940). The surveyors were very strict in their application of soil suitability guidelines for irrigation. As they gained experienced they also improved these guidelines (Verster and Stofberg, 1974; MacVicar, 1976; Irrigation Planning Staff, 1980; Hensley and Laker, 1980; Bester and Liengme, 1989). The latest guidelines include 2 terrain properties (topography and the need for drainage), 4 soil physical properties (effective depth, texture, structure and coarse fragments) and 2 soil chemical properties (Schoeman, 1987). The norms for the 2 chemical properties (EC_e and SAR) were established by United States Salinity Laboratory Staff (1969). Soils are classified as either saline (EC_e > 400 mS·m^{-1}, SAR < 15 and pH < 8.5); sodic (EC_e < 400 mS·m^{-1}, SAR > 15 and pH > 8.5) or sodic-saline (EC_e > 400 mS·m^{-1}, SAR >15 and pH >8.5). Schoeman (1987) developed a 5-class land-suitability guide (classes ranging from Class I to Class V), incorporating 6 soil properties to derive the potential hazard of irrigation to the soil, crop and environment. For example, a Class I soil poses no hazard to the sustainable management of the soil, crop and environment and is regarded as highly suitable for irrigation. A Class V soil, on the other hand, is unsuitable for irrigation because of the potential hazard to the soil, crop and environment. Thus management inputs intensify from Class I to Class IV with Class V is perceived as non-irrigable.

National perspective on quality of irrigated soils

Management of irrigated land is of utmost importance at national, local and farm level. For national purposes, Backeberg et al. (1996) estimated the area under irrigation for the provinces of South Africa (Table 3). The land was further divided into suitability classes: Class I is 'highly suitable', Class II 'suitable' and Class III 'risky'. These results indicate that 48% of the total irrigated area is regarded as 'highly suitable', 39% as 'suitable' and 13% as 'risky'. The irrigated land areas in Gauteng, Mpumalanga and North West are of a high quality, while Eastern Cape, KwaZulu-Natal, and Limpopo have significant portions of irrigated land in the risky class. The Western Cape has the largest area under irrigation, but a large portion (52 637 ha; 4% of the irrigated area of South Africa) falls in the 'risky' class (Class III). Thus, from these results a conclusion can be made that the soil quality of the irrigated land seems satisfactory. This can be attributed to

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Table 3
Distribution of land (ha and percentage of total irrigated land) under irrigation in the different provinces of South Africa in relation to land suitability classes (data from Backeberg et al., 1996)

Provinces	Class I		Class II		Class III		Total	
	ha	%	ha	%	ha	%	ha	%
Eastern Cape	34 568	3	94 993	7	25 367	2	154 928	12
Free State	39 104	3	41 131	3	18 745	1	98 980	8
Gauteng	16 925	1	6 895	1	2 864	0	26 684	2
KwaZulu-Natal	66 627	5	71 762	6	31 855	2	170 244	13
Mpumalanga	129 225	10	25 426	2	2 769	0	157 420	12
Northern Cape	80 965	6	71 356	6	9 553	1	161 874	13
Limpopo	61 752	5	46 898	4	26 496	2	135 146	10
North West	83 660	6	16 306	1	3 352	0	103 318	8
Western Cape	100 861	8	12 8038	10	52 637	4	281 536	22
Total	613 687	48	502 805	39	173 638	13	1 290 130	100

Table 4
General description of soil-sampling sites and their properties along the Vaal River (Du Preez et al., 2000)

Site	Profile	Soil form	Irrigation type	Years	Water table depth (mm)	EC_e*	SAR**	Salt content ($kg \cdot ha^{-1} \cdot m^{-1}$)	Difference from reference profile
Vaalharts	Virgin sand	Hutton	None		np***	18	0.6	423	
	Irrigated sand	Bainsvlei	Flood	53	1 600	90	1.3	2 002	+1 579
	Virgin clay	Valsrivier	None		np	76	5	5 420	
	Irrigated clay	Valsrivier	Flood	53	np	128	2.7	4 379	−1 041
Wildeklawer	Virgin sand	Hutton	None		np	40	0.7	1 469	
	Irrigated sand	Bainsvlei	Centre pivot	53	np	137	2.2	4 545	+3 076
Spitskop	Virgin clay	Arcadia	None		np	63	2.3	2 578	
	Irrigated clay	Arcadia	Flood	53	np	464	7.3	22 864	+20 286
Jackson	Virgin sand	Bloemdal	None		1 300	153	7.5	4 617	
	Irrigated sand	Bloemdal	Centre pivot	45	1 100	60	2.3	1 868	−2 749
	Irrigated clay	Sepane	Flood	45	1 200	1 224	19	84 750	

**Electrical conductivity measured in a saturated paste*
***Sodium adsorption ratio, derived from Na, Ca and Mg concentrations*
****np: not present*

the strong criteria of soil selection enforced by Department of Agriculture. However, soil quality can change rapidly under irrigation as will be seen in the next section.

Soil quality along the Vaal River

The WRC report of Du Preez et al. (2000) provided insight into soil-quality changes caused by long-term irrigation. Du Preez et al. (2000) sampled virgin and irrigated soil profiles along the Vaal River. The profiles were sampled at Vaalharts, Spitskop, Wildeklawer, Zandbult and Jackson during March 1998 to a depth which was limited by either a hard layer (dry sandy loam and clay soils), a water table (some irrigated soils) or a maximum depth of 2 000 mm. Each profile was described *in situ* according to the format of Turner (1991) and classified according to the Soil Classification Working Group (1991).

Du Preez et al. (2000) used the following materials and methods: Every profile was marked in depth intervals of 200 mm and then sampled. Additional soil samples were also collected at the same depth intervals with either a Thompson or Edelman soil auger about 5 m away in all 4 wind directions from a profile pit. This was to check whether the salt content of a pit was representative of the site. The soil samples were dried at about 40°C, crushed to pass through a 2 mm sieve, thoroughly mixed and stored in glass bottles until analysed using standard methods (The Non-Affiliated Soil Analysis Work Committee, 1990). The analyses included particle-size distribution (organic matter and carbonates were not removed, but the Calgon aliquot was increased from 10 mℓ to 50 mℓ and a hydrometer was used), electrical resistance and water content of a saturation paste, electrical conductivity (EC_e) and cation (Ca, Mg and Na) content of the saturation paste extract. The concentrations of the cations were determined by atomic absorption spectrometry. SAR was estimated from the concentration of Na, Ca and Mg in the saturation paste extract.

The results of the soils sampled along the Vaal River are summarised in Table 4. In total 6 soil forms were identified: Hutton, Bloemdal, Bainsvlei, Valsrivier, Sepane and Arcadia forms (Soil Classification Working Group, 1991). None of the virgin soils were saline, sodic or sodic-saline.

Sandy soils, although highly suitable for centre-pivot irrigation systems, demand careful management. For example, the Hutton (fine sandy *Quartzipsamments*; Soil Survey Staff, 1999) form was sampled in Vaalharts and Wildeklawer. The soils were described as deep, fine sandy, dominantly red, freely drained, eutrophic and with parent material that originated from aeolian deposits. Such soils are highly suitable for centre-pivot irrigation (Class I) and to a lesser extent (Class

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II to Class III) for flood irrigation due to the high infiltrability and low water retention. These soils were extensively used under flood irrigation in the Vaalharts Irrigation Scheme, but they soon became waterlogged due to the impermeability of the underlying clay or lime in large areas of the scheme (Gombar and Erasmus, 1976). The other sandy soils, Bloemdal and the Bainsvlei soils sampled at Vaalharts, Wildeklawer and Jackson, offer similar managerial problems as the Hutton soils. Managers were forced to install artificial drainage systems to reclaim these soils in the Vaalharts and also in the Orange-Riet irrigation schemes. Since the occurrence of waterlogging in the late 1970s, centre-pivot irrigation has progressively replaced flood irrigation (Reinders et al., 2010) because water application can be controlled more accurately (Le Roux et al., 2007).

Swelling clay soils differ in their response to flood irrigation. This is evident when the salt content, EC_e and SAR of the irrigated Valsrivier (Vertic Paleargid) at Vaalharts and the Arcadia (Haplotorrets) of Spitskop are compared with their virgin profiles. The salt content of the irrigated Valsrivier was about 1 $t \cdot ha^{-1} \cdot m^{-1}$ lower than the corresponding virgin profile, while that of the Arcadia was about 20 $t \cdot ha^{-1} \cdot m^{-1}$ higher than the virgin profile. Le Roux et al. (2007) ascribed this to the morphological features of these soils. The Valsrivier has a fine sandy clay loam texture in the topsoil that gradually changes to fine sandy clay in the subsoil (200 mm - 600 mm) and deep subsoil (600 mm - 1 600 mm). The colour of the soil also changes from a dark brown in the topsoil to a very dark reddish brown in the subsoil and a dull reddish brown in the deep subsoil. Lime was present in the subsoil and in the deep subsoil, which probably helps to maintain the hydraulic conductivity in the strong, coarse angular blocky structure of the profile. In contrast, the Arcadia has a clayey texture throughout the profile. These clays have extreme swelling properties, which affect the hydraulic conductivity of the soil, depending on the EC_e and the SAR. The SAR increased from 2.3 to 7.3 and with that, fortunately, also the EC_e. This probably helped to maintain some hydraulic conductivity in the profile as shown by the long-term salt loss due to leaching as estimated by Van Rensburg et al. (2008). In conclusion, these 2 soil examples confirm the importance of matching soil qualities with irrigation methods. The soil quality of the Valsrivier improved after 5 years of irrigation and is rightfully treated as a Class III soil. The soil quality of the Arcadia deteriorates over time and should not be recommended for irrigation (Class V). The last comment is also applicable to the Sepane (Vertic Haplargids) soil at Jacksons where irrigation induced an SAR of 19 and an EC_e of 1 224 $mS \cdot m^{-1}$, way beyond any acceptable norm.

Soil quality in the Berg River valley

Another example of how irrigation has improved the soil quality is omnipresent in the Berg River valley. Görgens and De Clercq (2006) reported that irrigation of saline soils with Berg River water (EC_i ranging between 25 $mS \cdot m^{-1}$ and 75 $mS \cdot m^{-1}$) significantly reduced the EC_e and SAR of soils (Fig. 6). The results demonstrate that after 4 years of irrigation since 1996 (1996 indicates the oldest site with longest irrigation history), the salt in the soil approached equilibrium with the salt in the irrigation water. This was especially true for stony soils. A highly significant correlation was found between the stone content and the SAR of soils. This suggested that patches of high stone content in the soil constitute preferential flow paths resulting in zones with higher leaching and therefore a lower SAR (Moolman et al., 1993). Since the soils of the Berg River

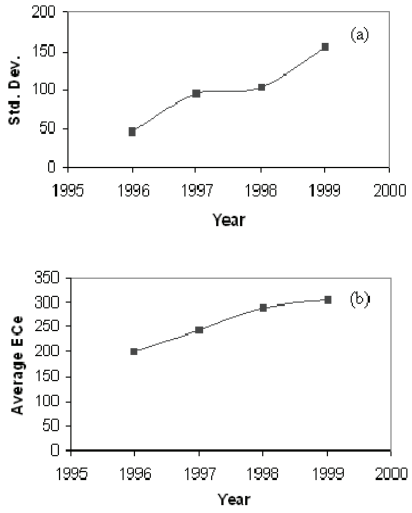

Figure 6
The change in the standard deviation (a) and average (b) soil electrical conductivity (EC_e) since the inception of irrigation in a block of vineyards. Year refers to the time irrigation commenced in a particular block and sampling was done in all of the blocks during the year 2000.

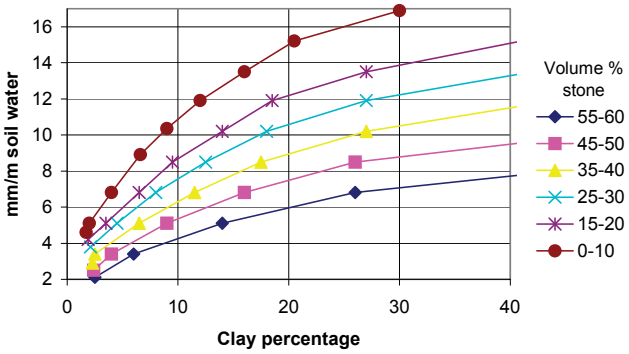

Figure 7
Relationship between clay percentage, soil-water content and volume percentage stone (De Clercq, 2009)

catchment are mostly stony, this phenomenon generally affects irrigation scheduling. Thus, in order to control drainage, relationships were established between clay percentage, soil-water content and percentage of volume the stone would occupy (Fig. 7). The ratios are generally used to determine water storage of especially stony soils, which governs the timing and amount of water application.

The capacity of soils to retain salts was indicated in a saline-water irrigation experiment carried out in the Breede River catchment by Moolman et al. (1999) and De Clercq et al. (2001a). A Trawal soil (varying between a soil family 1100 and 1200, Soil Classification Working Group, 1991) was irrigated with 6 qualities of irrigation water (30 $mS \cdot m^{-1}$, 75 $mS \cdot m^{-1}$, 150 $mS \cdot m^{-1}$, 250 $mS \cdot m^{-1}$, 230 $mS \cdot m^{-1}$ and 500 $mS \cdot m^{-1}$) over a period of 8 years. They found that the soil had a threshold salinity level of about 550 $mS \cdot m^{-1}$ (the threshold level refers to the maximum amount of salt that the soil could retain under the applied conditions) and that the soil irrigated with water with an EC of 150 $mS \cdot m^{-1}$ and higher, easily reached the threshold value and stayed there for the duration of the irrigation season. This was done using a 10% over-irrigation with each irrigation event and

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all extra salt in the system was leached. This response therefore indicated that different soil types had specific salinity threshold values and when irrigated agriculture is planned for a region, the specific salinity threshold values, which can also relate to the cation exchange capacity of the soils, need to be kept in mind.

It was traditionally believed that dryland salinity in the predominantly semi-arid Berg River basin originates from the weathering of sedimentary rocks that had formed under the ocean. However, De Clercq et al. (2010) indicated that the regolith in this semi-arid coastal region contains an abundance of stored salts of marine origin, which accumulated meteorically over a very long period. During this period, either the climate was drier than at present and/or a vegetation cover prevailed. This resulted in less water being discharged from catchments than what presently occurs under the prevailing land use (mainly winter wheat), because of increased water extraction and/or reduced surface runoff. In the present context, it seems increasingly likely that regolith salinity in the Berg River basin is primarily climate-driven and that the role of finer grained Malmesbury shales is not mineralogical, but rather one of hydrological mediation. De Clercq et al. (2010) also indicated therefore that the occurrence of rainfall in the catchment could be correlated with occurrence of salinity and that a negative relationship exists between the 2 parameters (Fig. 8).

It was indicated for the Berg River catchment that the contribution of dryland salts to the water quality of the Berg River was much more significant than that of irrigation return flow. This can also be indicated by the relative percentages of land use in the Berg River catchment (Table 5).

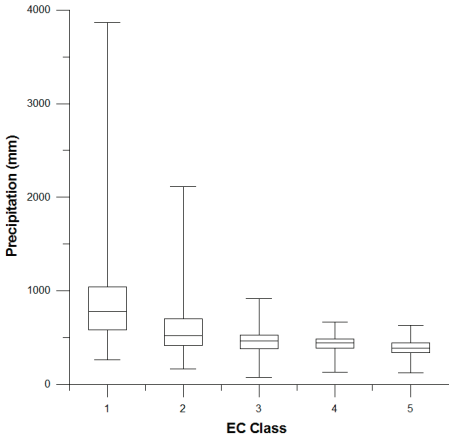

Figure 8
Comparison of precipitation in mm and electrical conductivity (EC) in groundwater (Class 1 = 0 to 70 mS·m^{-1}; Class 2 = 70 to 150 mS·m^{-1}; Class 3 = 150 to 300 mS·m^{-1}; Class 4 = 300 to 500 mS·m^{-1}; and Class 5 = 500 to 1 000 mS·m^{1})

Irrigation and soil water quality, and crop response

Crops are injured by both the quality of irrigation water and quality of the soil water. The mechanism and type of injury induced by the 2 water sources are different, and the degree of the injury also varies amongst crops. Thus, the effect of the 2 sources on crops will be discussed separately.

- ***Firstly, the quality of the irrigation water*:** Irrigation water that contains high concentrations of salt can damage the crop when the foliage is directly wetted with overhead irrigation. The severity of the damage depends on the leaf characteristics and rate of salt absorption by the foliage (Maas, 1986). These properties differ widely amongst crops. For example, leaves of deciduous fruit trees (apricots, plums, etc.) absorb Na and Cl readily and are severely damaged. Citrus leaves absorb these ions at a slower rate, but still fast enough to cause damage. Avocado and strawberry leaves absorb salt so slowly that foliar injury is negligible. Maas (1986) grouped crops according to their relative sensitivity for salt absorption (Table 6), which is a handy guideline. However, Rhoades and Loveday (1990) stated that the degree of the foliar injury can also be influenced by managerial factors, such as the concentration of the salts in the irrigation water, the frequency of irrigation and the time of irrigation. The higher the concentration of the salt in the irrigation water, the higher the absorption of salt by the leaves. Similarly, a higher irrigation frequency will result in a higher salt concentration in the leaves. The time of irrigation is important because the risk of foliar injury increases as the potential evaporation increases. This is because the rate of absorption increases rapidly as the solution evaporates from the leaf and the salt is concentrated. Once the

Table 5
Area of land use for various crops of the Swartland region (De Clercq et al., 2001a)

Dryland crops	Area (ha)	Irrigated crops	Area (ha)	Vegetable crops	Area (ha)
Wheat	267 600	Fruit	4 260	Potatoes	2 234
Oats	30 590	Vegetables	7 290	Onions	240
Legume pastures	43 860	Grapes	16 600	Tomatoes	70
Other pastures	66 100	Pastures	3 690	Peas	900
Other crops	73 920	Other crops	460	Sweet melon	160
Fallow land	211 330			Other cucurbits	485
				Brassicas	720
				Carrots	220
				Green beans	140
				Sweet potatoes	110
				Beetroot	105
				Other	1 900
Total	693 400		32 300		7 284
Percentage	94		5		1

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Table 6
Guidelines to manage the effect of irrigation water quality on crop (Maas, 1986)[a]; relative susceptibility of crops to foliar injury from saline sprinkling waters

Na or Cl concentrations (mol·m^{-3}) causing foliar injury[b]			
<5	5 - 10	10 - 20	>20
Almond	Grape	Alfalfa	Cauliflower
Apricot	Pepper	Barley	Cotton
Citrus	Potato	Corn	Sugar-beet
Plum	Tomato	Cucumber	Sunflower
		Safflower	
		Sesame	
		Sorghum	

[a] *Susceptibility based on direct accumulation through the leaves.*
[b] *Foliar injury is influenced by production and environmental conditions.*

salts become dry, absorption stops (Maas, 1990). Thus, it is better to irrigate during the night than during the day.

- ***Secondly, the quality of the soil water*:** Salt in the irrigation water will eventually be transferred to the soil during irrigation, changing the concentration and composition of salt in the soil water. Since only pure water evaporates at the soil and plant surfaces it implies that the salt will remain in the soil, unless leaching occurs. Thus, irrigation tends to concentrate the salt in soil water, which lowers the osmotic potential and hence the total soil water potential (matric plus osmotic) of the soil (Hillel, 1998). The corresponding decrease in the potential difference between the root xylem and surrounding soil solution results in less water being taken up under conditions of normally adequate water supply. If the transpiration falls below the daily water requirement, water stress and yield losses are inevitable (Moolman et al., 1999; Van Rensburg, 2010).

The degree of water stress and its effect on yields varies amongst crops. Thus, Maas and Hoffman (1977) established a simple equation to manage the effect of soil water quality (EC_e) on crop yield:

$$Y_r = 100 - b\,(EC_e - a) \qquad (1)$$

where:

Y_r = the percentage of the yield of the crop grown under saline conditions relative to that obtained under non-saline conditions

a = the threshold electrical conductivity (mS·m^{-1}) of the saturated soil paste at which yield decreases commence

b = the percentage yield loss per unit increase in the electrical conductivity of the soil extract in excess of the threshold value

EC_e = electrical conductivity of the soil extract (mS·m^{-1})

The salt tolerance rating of selected crops based on their threshold value (mS·m^{-1}) and slope of yield reduction (% mS·m^{-1}) is given in Table 7.

Ehlers et al. (2007) tested the thresholds for South African conditions using wheat, peas, beans and maize. Two experiments were conducted: A pot experiment in the glasshouse facility at the Bloemfontein main campus of the University of the Free State (UFS) and the other at the Field Research Facility of the Department of Soil, Crop and Climate Sciences (UFS). The second experiment used the field lysimeter facility at Kenilworth Experimental Field, about 15 km north-west of Bloemfontein (29°01'00''S, 26°08'50''E). The details on the materials and methods of these experiments are described in Ehlers et al. (2007). The results for one of the crops are presented in Fig. 9, viz. a linear response relationship between relative biomass yield and EC of the soil water. The results of the intercept (threshold EC_{sw}, mS·m^{-1}) and slope (relative yield reduction per mS·m^{-1}) represents the threshold which is calculated by means of Eq. (1). The thresholds of peas and 3 other crops are summarised in Table 7. From the results it is clear that the crop-specific thresholds and slope differ between the 2 experiments conducted by Ehlers et al. (2007). These thresholds also differ from those published by Rhoades and Loveday (1990; Table 7).

Salinity thresholds were also determined for grapevines in the Breede River. Details of the experiment were described by De Clercq et al. (2001b). The research was conducted at Robertson (33° 46'S, 19° 46'E) under conditions of intensive

Table 7
Threshold soil water salinity (EC_{sw}, mS·m^{-1}) and slope (relative yield reduction per mS·m^{-1}) according to the regression analysis of the relationship between relative biomass yield and EC_{sw} of the saline treatments (Ehlers et al., 2007)

Crop	Threshold EC_{sw} (mS·m^{-1})			Slope (relative yield reduction; % mS·m^{-1})		
	Glasshouse	Field	R and L**	Glasshouse	Field	R and L**
Wheat	331	*	860	−0.0004	−0.00011	−0.0003
Beans	202	82	100	−0.0009	−0.00086	−0.0019
Peas	*	105	-	−0.0004	−0.00096	-
Maize	*	499	170	−0.0008	−0.00073	−0.0012

* *Negative value*
** *Rhoades and Loveday (1990)*

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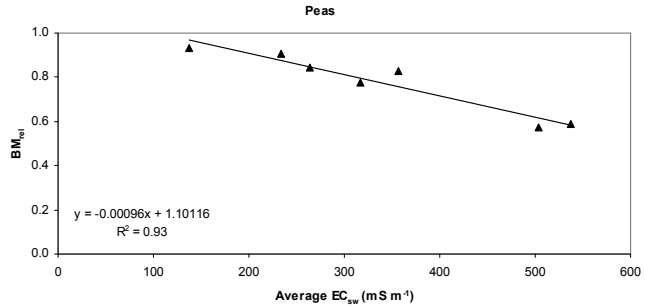

Figure 9
The relationship between the relative biomass yield (BM_{rel}) and mean seasonal soil-water salinity (EC_{sw}) for peas (Ehlers et al., 2007)

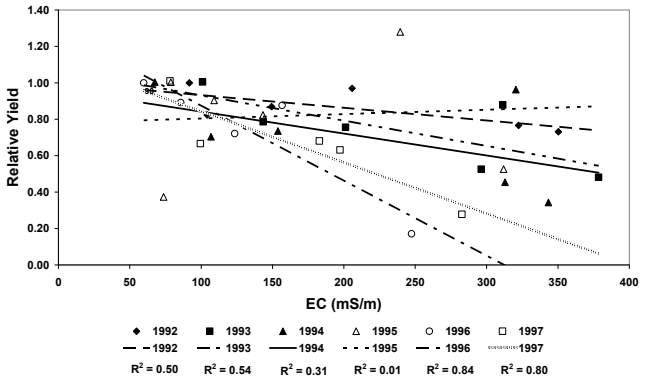

Figure 10
Relationships between relative yield and salinity (EC_e) at Robertson plotted for each year from 1992 to 1997. The data represent seasonal block means (after De Clercq et al., 2001b).

irrigation and at Stellenbosch (33^{O} 58'S, 18^{O} 50'E) where supplemental irrigation was applied. In both vineyards the soil-water and soil salinity regimes were measured continuously using a neutron probe and suction cup samplers. Vegetative and reproductive growth was monitored at selected phenological growth stages. The results showed no threshold salinity EC_e value and yield decreased progressively above EC_e of 75 mS·m^{-1} at a rate of about 3% per 10 mS m^{-1} (Fig. 10), which is 3 times higher than the decreasing rate reported by Maas and Hoffman (1977) as quoted by Ayers and Westcot (1985). A pattern seemed to have emerged, suggesting that, irrespective of whether the inhibitory effect of the saline irrigation treatments on yield is osmotic, toxic (Na and/or Cl), or both, the threshold level remains the same over a number of irrigation seasons, but the sensitivity of the crop to levels beyond the threshold increases with the number of seasons of exposure. Irrespective of the specific cultivar response function, the response pattern changed over time and the effect of the treatments was cumulative over time. This result indicated a very important management implication because it suggested that even moderately acceptable water by current standards may, in the longer term, and not necessarily because of soil deterioration, have cumulative debilitating effects leading to premature failure of the vineyard (De Clercq et al., 2001b).

Thus, the results confirmed the view of Maas (1986) that the salt-tolerance guidelines cannot provide a fully accurate, quantitative measure of crop yield losses to be expected from salinity for every situation. The actual response to salinity varies with growth conditions such as climate, irrigation management, agronomic management and crop response to saline conditions.

Based on the above results, Ehlers et al. (2007) determined the effect of water quality on the water production function of crops. The hypothesis was that the reduction in water uptake induced by osmotic potential of the soil water should correlate with the reduction in yield. The relationship as proposed by Stewart et al. (1977) was used to determine reduction of crop yields:

$$1 - \frac{Y_a}{Y_m} = b \left[1 - \left(\frac{ET_a}{ET_m}\right)\right] \qquad (2)$$

where:

Y_a = actual crop biomass yield (t·ha^{-1}) of a treatment
Y_m = biomass yield (t·ha^{-1}) of the control treatment with no water stress
ET_a = actual crop evapotranspiration (mm) of a saline treatment
ET_m = potential crop evapotranspiration (mm) of the control treatment
b = slope of the relationship between relative yield and relative evapotranspiration

Taking Y_m and ET_m as the biomass yield and evapotranspiration (ET) of the control treatments, the analysis of the results gives a linear relationship between relative evapotranspiration and relative yield as illustrated by Fig. 11 for the combined data of all of the crops. This is a clear indication that the relative decrease in growth of all the crops was directly proportional to the relative decrease in ET caused by the decreasing osmotic potential with increased salinity. Hence, this proves that, irrespective of the differences in salt tolerance of the different crops, in all cases the reduction in growth was proportionally related to the increase in plant-water stress induced by lower water uptake. From the results it is clear that the guidelines provided in the literature are rather static, while a more dynamic approach is required. This can only be achieved through models such as SWB and SWAMP (Singels et al., 2010).

Conclusion and recommendations

This review shows that remarkable progress has been made on salinity research over the past 40 years since the establishment of the WRC. The diversity and range of the WRC projects makes it virtually impossible to cover all aspects thoroughly in a paper of limited length. Thus, it was decided to narrow the focus down to salinity guidelines associated with the management of rivers, soils and crops. From the research examples used in the Lower Vaal, Riet, Berg and Breede Rivers it has been shown that the quality of the river water depends heavily on the management of the irrigated soils and crops. Fortunately, very effective soil-suitability guidelines for the selection of irrigation soils were developed and enforced by the government during the development of major irrigation schemes. However, management plays a pivotal role in sustaining the quality of the soils. Long-term irrigation case studies along the Lower Vaal River and Breede River showed that the quality of soils can be improved with irrigation. The opposite is also true where mismanagement has occurred. Research on the salinity threshold values of the major crops (grapevines, wheat, maize, groundnuts, etc.) confirmed the empiric nature of the guidelines. It was suggested that a more dynamic approach be used for managing salinity under irrigation at farm level, i.e. the use of models.

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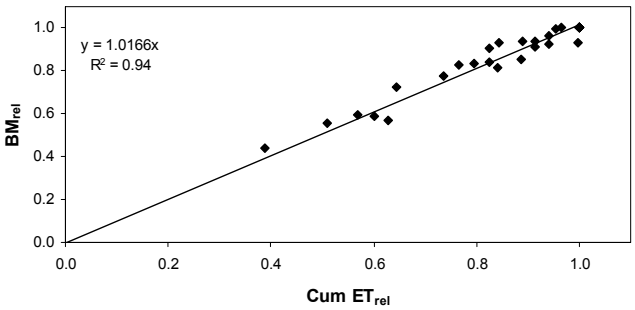

Figure 11
Relationship between the relative biomass yield (BM_{rel}) and the relative cumulative evapotranspiration (Cum ET_{rel}) for all the crops (Ehlers et al., 2007)

The following are considered to be important research and development needs:

- The effect of irrigation on the quality of soils needs to be determined for the major irrigation schemes. The last survey was done in the late 1980s.
- Survey methods for determining the spatial and temporal distribution of salt in soils should be developed and tested.
- Survey methods for determining the spatial and temporal distribution of waterlogging in irrigated fields.
- The combined effect of salinity and waterlogging on crops.
- Formulation of best salinity management practices and the application thereof on field, farm and scheme level.

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