Irrigation Water Quality of Some Natal Rivers

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Abstract

The irrigation water quality of some Natal rivers is assessed in terms of water salinity and sodicity and used to estimate the expected soil water salinity and sodicity values for poorly drained soils. In this estimation, rainfall, evapotranspiration, soil drainage and certain management practices are taken into account. Four variables are then available for assessment of water quality : water salinity and sodicity and soil salinity and sodicity. Grouping the data according to crop salt tolerance and soil sodicity limitations confirmed the evaluation of water quality obtained using three independent methods for irrigation water assessment. About half of the Natal waters examined had sufficient sodium carbonate to downgrade quality and predispose the soil solution to high sodicity under specified climatic conditions, alkaline soil pH and poor internal drainage rates. A feature associated with the high sodium carbonate of some waters is a relatively low total salt concentration, which would predispose structurally unstable soils to deterioration of hydrarulic conductivity. Many of the remaining waters were sufficiently affected by mine effluents, salt-rich geological formations or saline ground water to render them an irrigation risk for the more salt sensitive crops grown on poorly drained soils. In consequence careful attention needs to be directed to selection of suitable sites and soils in the development of irrigation schemes in the Natal interior.

Introduction

Assessment of irrigation water quality is an essential and primary step in the development of any irrigation enterprise. However, little attention has generally been given to this essential prerequisite in feasibility studies of irrigation schemes in Natal. This may have contributed to the steady development of salinity and drainage problems in some areas and it seems certain that with expansion of industrial and mining activity and the ever-increasing exploitation of water resources, river water quality will play an important role in determining the viability of irrigation enterprises in the future. For this reason a survey of irrigation water quality in the interior of Natal was undertaken. This paper presents the results of this survey and uses a simple model to estimate the possible composition of soil water derived from particular irrigation waters under specified climatic, soil and management conditions.

Theory

Increasing recognition has been given to the fact that absolute standards of irrigation water quality do not exist but must be related to the other components of an irrigation system, soil, climate, plants and management factors (Rhoades and Bernstein, 1971; Rhoades, 1972; Ayers, 1977; Christiansen, Olsen and Willardson, 1977; Cass, 1980). The major difficulty at present is to quantify this relationship in a relevant yet practical way. For this reason numerous proposals for assessing water quality have appeared which base water quality evaluation on salinity [total salt concentration : Na + Ca + Mg, (me/ℓ) or specific electrical conductivity, EC_{iw}, at 25°C] and sodicity [amount of Na in relation to divalent cations, 100.Na/(Na + Ca + Mg), (%); or sodium adsorption ratio, $SAR_{iw} = Na/\sqrt{(Ca + Mg)/2}$, (mmol/ℓ)$^{1/2}$]. The most widely used scheme for assessment of water quality for irrigation is that of the United States Salinity Laboratory Staff (USSL, 1954). However, this scheme appears to have given misleading results in some cases (Ayers, 1977; Christiansen *et al*, 1977). Specifically, it fails to take account of the effects of waters with high levels of sodium carbonate (Na_2CO_3) and low salinity, on soils that are structurally unstable. This has tended to direct attention to the fact that soil and plant responses are not necessarily related to the properties of the applied irrigation water but to the properties of the soil solution. The relationship of the composition and concentration of the latter to that of irrigation water is both complex and dynamic, being dependent upon a large number of factors which may be difficult to quantify. For this reason it is difficult to define absolute standards of irrigation water quality (Rhoades, 1972; Dregne, 1974).

Evaluation of water quality should therefore include the effect of environmental factors such as climate, soil properties and management. A simple model that includes many of these factors was presented by the USSL (1954) for systems where irrigation water is applied to supplement rainfall. Using this model it is possible to predict soil salinity (EC_{sw}) from the salinity of the irrigation water (EC_{iw}) and rain water (EC_{rw}) weighted for the depth of irrigation water applied per annum (D_{iw}) and the mean annual rainfall (D_{rw}), multiplied by a concentration factor (1/LF). Bernstein (1967) modified this approach to take account of restricted soil drainage by defining LF, the leaching fraction in terms of soil drainage rate (H) and evapotranspiration rate (E), both of which determine the amount of leaching which may take place in poorly drained soils : LF = H/(E + H). Under these conditions the steady state soil salinity in poorly drained soils may be estimated from

$$EC_{sw} = \frac{D_{rw}\,EC_{rw} + D_{iw}\,EC_{iw}}{D_{rw} + D_{iw}} \cdot \frac{E + H}{H} \tag{1}$$

Since EC_{rw} is usually small, the term $D_{rw} \cdot EC_{rw}$ may be neglected and it may be assumed that because LF is of necessity small in poorly drained soils, that the sum of rainfall and irrigation water ($D_{rw} + D_{iw}$) will not exceed evapotranspiration, E, and $D_{iw} \simeq (E - D_{rw})$, and $E + H \simeq E$

$$EC_{sw} = \frac{(E - D_{rw})\,EC_{iw}}{H} \tag{2}$$

Equation (2) does not take account of salt precipitation but does represent possible extreme values for soil salinity in terms of the conditions defined. It resembles the models proposed by Dregne (1974) and Van Schilfgaarde, Bernstein, Rhoades and Rawlins (1974).

The other major factor in water quality evaluation, sodicity, may also be influenced by environmental factors as well as soil chemical reactions. Bower, Ogata and Tucker (1968) proposed an equation that accounted for an increase in the relative proportion of sodium to other cations as the soil solution was concentrated and if precipitation of divalent cations occurred as carbonate. The equation was subsequently modified by Rhoades (1968) to include dissolution of weatherable minerals in soils and is

$$SAR_{sw} = \sqrt{\frac{y^{(1 + 2 LF)}}{LF}} \; SAR_{iw} \left[1 + (pH_s - pH_c^*)\right] \quad (3)$$

where SAR is the sodium adsorption ratio $(Na/\sqrt{(Ca + Mg)2})$
y is the weathering coefficient $(0 < y \leq 1)$,
pH_s is the soil pH (usually assumed to be 8,4, the value of a non-sodic soil in equilibrium with calcium carbonate),
pH_c^* is the pH the water would adopt if in equilibrium with calcium carbonate (calculated from an expression originally applied to soil by Bower and Maasland, 1963).

The term $(pH_s - pH_c^*)$, the "saturation index" (I), indicates the tendency of carbonate to precipitate from irrigation water $(I > 0)$ or dissolve $(I < 0)$ in soil (Bower and Maasland, 1963). Precipitation of carbonates depends on the divalent, total and CO_3 plus HCO_3 ion concentrations of the irrigation water, the divalent ion status, pH and CO_2 partial pressure of the soil and the extent to which the soil solution is concentrated by evapotranspiration (Bower and Maasland, 1963). The validity of equation (3) in predicting carbonate precipitation in soils has been confirmed by Bower *et al.* (1968) and Pratt and Blair (1969). The most likely conditions for precipitation of carbonates in soil are poor drainage, a saline soil solution and high pH values. Such conditions are frequently found in soils of the more arid areas of Natal. The importance of weatherable minerals in influencing the SAR value of the soil solution has been demonstrated by Rhoades, Krueger and Reed (1968). However, for highly weathered soils the presence of large quantities of weatherable minerals is uncommon and y is unity for many Natal soils (unpublished findings by the author). Replacing LF of equation (3) with H/E and setting pH_s equal to 8,4 gives

$$SAR_{sw} = \sqrt{E/H} \; SAR_{iw} \left[1 + (8{,}4 - pH_c^*)\right] \quad (4)$$

Using equations (2) and (4) it is possible to express irrigation water quality in terms of four values EC_{iw}, EC_{sw}, SAR_{iw} and SAR_{sw} which define a rectangle and not a point on the SAR/EC diagram introduced by the USSL (1954) to characterise water quality. These values indicate the *possible maximum* and *minimum* variation of soil solution salinity and sodicity under the conditions present at the specified site. The predictive qualities of this model have been tested against several qualitative methods for irrigation water quality assessment (USSL, 1954; Christiansen *et al.*, 1977; Ayers, 1977), a computer based quantitative model (Oster and Rhoades, 1975) and field investigation of soil water salinity and sodicity at selected sites in Natal (Cass, 1980). This approach thus provides a qualitative but nevertheless realistic method for assessing water quality in relation to local climatic soil and management conditions. Wherever extensive and more refined data on the environmental factors exist, more sophisticated models (Dutt, Shaffer and Moore, 1972; Oster and Rhoades, 1975) can be used to predict soil water salinity and sodicity.

Materials and Methods

Irrigation waters selected for analysis were confined to inland sites either at the headwaters of important irrigation water sources or near important or potentially important irrigation areas in the interior of Natal. A completely comprehensive and regular sampling programme that covered all sampling sites could not be instituted, some sites being sampled only sporadically during the survey period from May 1974 to December 1976. The data presented here should be accepted with this limitation in mind. The survey does, however, constitute the first long-term attempt at assessment of irrigation water in Natal and provides a preliminary data base on which to plan both future surveys and immediate irrigation development.

Wherever possible sites were sampled during both dry and wet seasons but not during abnormally low or high flow. The analytical values presented here represent the mean of all data including published results of previous surveys by Brand *et al.* (1967b,c); Archibald *et al.* (1969) and Johnston (1976).

Methods of analysis conformed to those outlined by the USSL (1954) except for modifications that included use of 5 000 mg/ℓ $SrCl_2$ to suppress ionisation in the analysis of cation concentration by atomic absorption. Chloride was determined by a potentiometric method (Cotlove, 1966). Climatic data for each sampling site were gleaned from a variety of sources (Schultze, 1981), and wherever specific information was lacking values were interpolated from general climatic maps of Natal. This was particularly true of evapotranspiration data because of the inadequacy of meteorological stations which record climate variables suitable for estimation of this parameter. Fairly comprehensive "potential evapotranspiration" (PE) data for Natal are available (Thornthwaite, 1962) but it is generally recognised that this paramter does not provide a satisfactory estimate of actual evapotranspiration. In arid areas actual evapotranspiration may exceed PE by a factor as high as 1,9 to 2 (Chang, 1974; Ward, 1971). For this reason evapotranspiration for each sampling site was estimated as E = 2 PE. Data for class A pan evaporation available for some sites compared favourably with this calculated E value. (Louw and Kruger, 1968).

The variable in equations (2) and (4) which is most arbitrary, however, is H, the drainage rate of the soil. Measured values of H for Natal soils are not available and it was necessary to assume a value of 0,1 m/annum to represent the mean drainage rate of a poorly drained soil at moisture potential values in excess of −10 J/kg. The validity of this estimate is supported by much of the published information on hydraulic conductivity, for example Van Schilfgaarde *et al.* (1974). Use of this value makes subsequent assessment of water quality true for extreme conditions of soil drainage only.

Results

Sampling site descriptions, analytical data and climatic information are presented in Table 1 for nine catchment regions

TABLE 1(a)
CHEMICAL CHARACTERISTICS OF SELECTED RIVERS IN SOUTHERN NATAL

M(n) = mean value (number of observations); SD = standard deviation; other symbols defined in the text

	Ca	Mg	Na	Total	EC_{iw}	SAR_{iw}	pH	pH_c^*	HCO_3	Cl	SO_4	Irrigation water quality ratings (See note below)	D_{rw}	E	EC_{sw}	SAR_{sw}
	Measured water composition and concentration: Salinity					Sodicity	Reaction			Anions			Site climatic data		Calculated soil solution concentration	
	mmol/ℓ				mS/m	(mmol/ℓ)$^{1/2}$	—	—		mmol/ℓ			mm/annum		mS/m	(mmol/ℓ)$^{1/2}$
SITE 1: MZIMVUBU RIVER: Cedarville (30° 20' S; 29° 06' E)																
M(3)	0,40	0,35	0,26	1,02	9,00	0,40	7,05	8,72	0,71	0,04	0,74	C1-S1	691	1 478	75	1,08
SD	0,16	0,14	0,15	0,45	2,95	0,16	0,38	0,32	0,32			1-1-1-1				
												O-SP				
SITE 2: MZIMHLAVA RIVER: Kokstad (30° 33' S; 29° 25' E)																
M(3)	0,45	0,42	0,25	1,13	28,80	0,39	7,23	8,65	0,70	0,06	0,18	C1-S1	691	1 478	242	1,16
SD	0,02	0,03	0,05	0,03	15,09	0,08	0,14	0,13	0,21			1-1-1-1				
												O-P				
SITE 3: MKOMAZI RIVER: Pietermaritzburg Ixopo Road Bridge (30° 01' S; 30° 11' E)																
M(2)	0,43	0,45	0,56	1,44	16,80	0,84	7,26	8,40	1,33	0,30	0,06	C1-S1	916	1 752	155	3,6
SD	0,09	0,01	0,01	0,08	1,56	0,05	0,22	0,16	0,59	0,04		1-1-1-2				
												O-SP				
SITE 4: MLAZI RIVER: Pietermaritzburg-Kingburgh Road Bridge (29° 49' S; 30° 32' E)																
M(11)	0,53	0,73	0,97	2,25	24,70	1,18	7,69	8,32	1,31	0,47	0,08	C1-S1	916	1 752	218	5,5
SD	0,19	0,32	0,53	1,02	13,17	0,40	0,21	0,30	0,67	0,18	0,04	1-2-1-2				
												O-P				
SITE 5: STERKSPRUIT RIVER: Cliffdale Market Gardens (29° 48' S: 30° 41' E)																
M(4)	0,56	0,62	1,78	2,96	29,18	2,51	7,26	8,51	0,87	0,96	0,77	C2-S1	1 145	2 050	277	10,4
SD	0,15	0,37	1,73	1,55	4,24	2,75	0,13	0,26	0,24	0,17	0,32	1-2-1-2				
												O-P				
SITE 6: MPUSHINI RIVER: Ukulinga Research Station, Pietermaritzburg (29° 42' S: 30° 28' E)																
M(11)	1,35	1,30	2,37	5,03	57,18	2,14	7,59	7,82	2,43			C2-S1	601	1 752	695	14,5
SD	0,68	0,51	0,68	1,28	15,74	0,66	0,25	0,35	1,42			2-2-1-4				
												O-P				
SITE 7: MVOTI RIVER: Pietermaritzburg-Greytown Road Bridge (29° 09' S; 30° 38' E)																
M(3)	0,26	0,29	0,22	0,78	8,10	0,45	7,07	8,94	0,63	0,11	0,06	C1-S1	916	1 752	71	0,9
SD	0,09	0,17	0,66	0,28	2,36	0,15	0,21	0,49	0,34	0,08	0,09	1-1-1-1				
												O-P				

Note: Uppermost rating USSL (1954), middle rating Christiansen *et al.* (1977) in the order EC_{iw} - Na % - SAR - Na_2CO_3 (me/ℓ), lower rating Ayers (1977) in the order: salinity problem permeability problem

TABLE 1(b)
CHEMICAL CHARACTERISTICS OF SELECTED RIVERS IN THE MOOI RIVER AND BUSHMANS RIVER CATCHMENTS

M(n) = mean value (number of observations); SD = standard deviation; other symbols defined in the text

	Ca	Mg	Na	Total	EC_{iw}	SAR_{iw}	pH	pH_c^*	HCO_3	Cl	SO_4	Irrigation water quality ratings (See note below)	D_{rw}	E	EC_{sw}	SAR_{sw}
	Measured water composition and concentration: Salinity					Sodicity	Reaction			Anions			Site climatic data		Calculated soil solution concentration	
	mmol/ℓ				mS/m	(mmol/ℓ)$^{1/2}$	—	—		mmol/ℓ			mm/annum		mS/m	(mmol/ℓ)$^{1/2}$
SITE 8: LITTLE BUSHMANS RIVER, Estcourt (29° 01' S; 29° 48' E)																
M(9)	0,50	0,40	0,46	1,38	14,74	0,68	7,04	8,56	0,91	0,08	0,40	C1-S1	733	1 466	115	2,3
SD	0,16	0,17	0,16	0,44	4,34	0,16	0,30	0,22	0,23	0,04	0,29	1-1-1-1				
												O-SP				
SITE 9: BUSHMANS RIVER, Wagondrift Dam, Estcourt (29° 53' S, 29° 53' E)																
M(12)	0,30	0,20	0,12	0,62	6,47	0,23	6,90	8,97	0,52	0,03	0,18	C1-S1	733	1 466	50	0,6
SD	0,06	0,03	0,07	0,13	0,83	0,11	0,27	0,15	0,14		0,02	1-1-1-1				
												O-SP				
SITE 10: MNYAMVUBU RIVER, Craigie Burn Dam (29° 09' S, 30° 16' E)																
M(11)	0,25	0,27	0,20	0,73	8,48	0,40	6,96	9,01	0,55	0,14	0,08	C1-S1	1 000	2 000	89	0,7
SD	0,14	0,17	0,09	0,38	3,81	0,09	0,32	0,34	0,33	0,11	0,03	1-1-1-1				
												O-SP				
SITE 11: MOOI RIVER, Muden Irrigation Scheme, Greytown (28° 58' S, 30° 23' E)																
M(2)	0,42	0,33	0,28	1,03	10,80	0,43	7,48	8,62	0,97	0,14	0,10	C1-S1	669	1 338	77	1,3
SD	0,22	0,16	0,23	0,60	4,81	0,28	0,60	0,47	0,59	0,10	0,03	1-1-1-1				
												O-SP				
SITE 12: MOOI RIVER, Keats Drift, Greytown-Dundee Road (28° 50' S, 30° 31' E)																
M(5)	0,70	0,71	0,57	1,98	20,00	0,66	7,57	8,12	1,71	0,20	0,19	C1-S1	669	1 338	143	3,4
SD	0,13	0,22	0,33	0,59	4,96	0,34	0,51	0,24	0,64	0,09	0,23	1-1-1-2				
												O-P				

Note: Uppermost rating USSL (1954), middle rating Christiansen *et al.* (1977) in the order EC_{iw} - Na % - SAR - Na_2CO_3 (me/ℓ); lower rating Ayers (1977) in the order: salinity problem permeability problem

TABLE 1(c)
CHEMICAL CHARACTERISTICS OF SELECTED RIVERS IN UPPER TUGELA RIVER CATCHMENT
M(n) = mean value (number of observations); SD = standard deviation; other symbols defined in the text

	Measured water composition and concentration: Salinity					Sodicity	Reaction		Anions			Irrigation water quality	Site climatic data		Calculated soil solution concentration	
	Ca	Mg	Na	Total	EC_{iw}	SAR_{iw}	pH	pH_c^*	HCO_3	Cl	SO_4	ratings (See note below)	D_{rw}	E	EC_{sw}	SAR_{sw}
	mmol/ℓ				mS/m	(mmol/ℓ)$^{1/2}$	—	—	mmol/ℓ				mm/annum		mS/m	(mmol/ℓ)$^{1/2}$
SITE 13: LITTLE TUGELA RIVER, Winterton-Bergville Road Bridge (28° 48' S, 29° 32' E)																
M(12)	0,43	0,27	0,18	0,89	9,03	0,30	7,27	8,68	0,81	0,03	0,06	C1 S1	950	1 400	43	0,8
SD	0,13	0,11	0,08	0,29	3,16	0,12	0,31	0,24	0,24	0,02	0,06	1-1-1-1				
												O-SP				
SITE 14: TUGELA RIVER, Spioenkop Dam, Winterton (28° 40' S, 29° 33' E)																
M(12)	0,30	0,21	0,12	0,65	6,65	0,24	7,05	8,96	0,52	0,03	0,39	C1 S1	850	1 400	39	0,4
SD	0,04	0,04	0,04	0,09	0,80	0,07	0,32	0,14	0,12	0,02	0,29	1-1-1-1				
												O-SP				
SITE 15: BLOUKRANS RIVER, Estcourt-Colenso Road Bridge (28° 53' S, 29° 48' E)																
M(8)	1,37	1,49	1,02	3,89	35,70	0,77	7,92	7,70	2,73	1,30	0,50	C2 S1	850	1 500	247	5,2
SD	0,73	0,76	1,01	2,46	18,61	0,56	0,24	0,35	1,11	1,35	0,22	1-1 1-3				
												O-P				
SITE 16: NGANE RIVER, Chelmsford Dam, Newcastle (27° 53' S, 29° 58' E)																
M(10)	0,44	0,34	0,45	1,25	13,61	0,72	7,14	8,74	0,66	0,14	0,69	C1-S1	924	1 682	109	2,0
SD	0,17	0,08	0,14	0,30	2,62	0,19	0,48	0,18	0,19	0,11	0,33	1-1 1-1				
												O-SP				
SITE 17: INKUNZI RIVER, Ladysmith-Newcastle Road Bridge (28° 15' S, 29° 58' E)																
M(8)	0,52	0,81	0,28	1,63	15,41	0,35	7,50	8,26	1,25	0,09	0,17	C1-S1	734	1 796	172	1,7
SD	0,15	0,21	0,08	0,42	3,47	0,06	0,19	0,20	0,34			1-1 1-1				
												O-SP				
SITE 18: SUNDAYS RIVER, Ladysmith-Newcastle Road Bridge (28° 21' S, 29° 58' E)																
M(10)	0,65	0,56	0,41	1,63	13,14	0,47	7,55	8,41	1,09	0,03	0,20	C1-S1	734	1 796	147	2,0
SD	0,59	0,21	0,51	1,21	4,80	0,38	0,37	0,32	0,52	0,02	0,19	1-1-1-1				
												O-SP				
SITE 19: TUGELA RIVER, Tugela Ferry Greytown-Dundee Road (28° 45' S, 30° 27' E)																
M(4)	0,71	0,66	0,60	1,98	20,00	0,71	7,43	8,15	1,58	0,31	0,31	C1-S1	650	2 000	283	4,1
SD	0,16	0,12	0,45	0,63	2,00	0,51	0,30	0,18	0,542	0,21	0,13	1-1-1-2				
												O-P				
SITE 20: MINOR TRIBUTARY OF TUGELA RIVER, Tugela Ferry, Greytown-Dundee Road (28° 45' S, 30° 27' E)																
M(1)	2,08	4,48	5,53	12,10	144,7	3,05	8,21	7,06	5,45	5,64	1,75	C3-S1	650	2 000	2 051	32,8
SD												3-2-2-6				
												P-SP				
SITE 21: TUGELA RIVER, Nqutu-Kranskop Road, Greytown (28° 47' S, 30° 55' E)																
M(1)	0,83	0,76	0,58	2,18	21,8	0,65	7,15	8,11	1,47	0,15	0,33	C1-S1	700	2 000	298	3,8
SD												1-1-1-2				
												O-P				

Note: Uppermost rating USSL (1954), middle rating Christiansen *et al.* (1977) in the order EC_{iw} - Na % - SAR - Na_2CO_3 (me/ℓ); lower rating Ayers (1977) in the order: salinity problem - permeability problem

TABLE 1(d)
CHEMICAL CHARACTERISTICS OF SELECTED RIVERS IN THE BUFFALO RIVER CATCHMENT
M(n) = mean value (number of observations); SD = standard deviation; other symbols defined in the text

	Measured water composition and concentration: Salinity					Sodicity	Reaction		Anions			Irrigation water quality	Site climatic data		Calculated soil solution concentration	
	Ca	Mg	Na	Total	EC_{iw}	SAR_{iw}	pH	pH_c^*	HCO_3	Cl	SO_4	ratings (See note below)	D_{rw}	E	EC_{sw}	SAR_{sw}
	mmol/ℓ				mS/m	(mmol/ℓ)$^{1/2}$	—	—	mmol/ℓ				mm/annum		mS/m	(mmol/ℓ)$^{1/2}$
SITE 22: MZINYASHANA RIVER, Alletta, Dundee (28° 05' S, 30° 15' E)																
M(2)	1,81	2,24	5,38	9,44	98,55	3,67	8,26	7,32	4,84	0,20	4,91	C3-S1	800	1 614	855	31,6
SD	0,42	1,33	3,02	4,77	34,29	1,34	0,06	0,20	0,57	0,08	3,68	2-2-[illegible]-6				
												P-SP				
SITE 23: MZINYASHANA RIVER, Vryheid-Dundee Road Bridge (28° 08' S, 30° 20' E)																
M(2)	2,25	2,14	2,17	6,56	66,90	1,45	7,28	7,62	2,05	0,43	3,63	C2-S1	800	1 614	580	10,7
SD	0,26	0,88	0,64	1,78	13,01	0,24	0,04	0,03	0,30	0,21	2,48	2-1-[illegible]-4				
												O-P				
SITE 24: BUFFALO RIVER, Dundee-Nqutu Road Bridge (28° 15' S, 30° 31' E)																
M(4)	0,76	0,66	0,50	1,94	20,6	0,59	7,31	8,23	1,27	0,12	0,45	C1-S1	800	1 614	179	2,9
SD	0,17	0,15	0,23	0,49	5,83	0,27	0,30	0,18	0,44	0,06	0,33	1-1-1-1				
												O-P				

Note: Uppermost rating USSL (1954), middle rating Christiansen *et al.* (1977) in the order EC_{iw} Na % - SAR - Na_2CO_3 (me/ℓ); lower rating Ayers (1977) in the order: salinity problem permeability problem

TABLE 1(e)

CHEMICAL CHRACTERISTICS OF SELECTED RIVERS IN THE WASBANK RIVER CATCHMENT

M(n) = mean value (number of observations); SD = standard deviation; other symbols defined in the text

	Measured water composition and concentration											Irrigation water quality	Site climatic data		Calculated soil solution concentration	
	Salinity					Sodicity	Reaction			Anions						
	Ca	Mg	Na	Total	EC_{iw}	SAR_{iw}	pH	pH^*_c	HCO_3	Cl	SO_4	ratings (See note below)	D_{rw}	E	EC_{sw}	SAR_{sw}
	mmol/ℓ				mS/m	(mmol/ℓ)$^{1/2}$	—	—	mmol/ℓ				mm/annum		mS/m	(mmol/ℓ)$^{1/2}$
SITE 25: WASBANK RIVER, Upstream of Burnside Colliery, Dundee (28° 11' S, 30° 05' E)																
M(5)	0,31	0,40	0,27	1,00	11,56	0,47	7,16	8,69	0,79	0,07	0,07	C1-S1				
SD	0,15	0,10	0,02	0,24	1,64	0,11	0,49	0,21	0,16	0,03	0,11	1-1-1-1 O-SP	800	1 614	100	1,4
SITE 26: WASBANK RIVER, Dundee-Wasbank Road Bridge (28° 18' S, 30° 09' E)																
M(9)	2,06	1,96	5,59	9,63	98,58	3,98	7,93	7,48	3,45	0,38	5,33	C3-S1				
SD	0,90	0,64	1,67	2,71	26,35	0,90	0,28	0,14	0,72	0,11	2,02	2-2-2-5 P-SP	750	1 700	992	32,4
SITE 27: TOLENI RIVER, Helpmekaar-Wasbank Road Bridge (28° 23' S, 30° 15' E)																
M(2)	0,91	0,95	1,42	3,29	30,85	1,43	7,40	7,99	1,92			C2-S1				
SD	0,35	0,06	0,91	1,31	20,15	0,78	0,14	0,30	0,98			1-2-1-3 O-P	750	1 700	310	8,5

Note: Uppermost rating USSL (1954), middle rating Christiansen *et al.* (1977) in the order EC_{iw} Na % - SAR -Na_2CO_3 (me/ℓ); lower rating Ayers (1977) in the order: salinity problem permeability problem

TABLE 1(f)

CHEMICAL CHARACTERISTICS OF SELECTED RIVERS IN THE BLACK MFOLOZI RIVER CATCHMENT

M(n) = mean value (number of observations); SD = standard deviation; other symbols defined in the text

	Measured water composition and concentration											Irrigation water quality	Site climatic data		Calculated soil solution concentration	
	Salinity					Sodicity	Reaction			Anions						
	Ca	Mg	Na	Total	EC_{iw}	SAR_{iw}	pH	pH^*_c	HCO_3	Cl	SO_4	ratings (See note below)	D_{rw}	E	EC_{sw}	SAR_{sw}
	mmol/ℓ				mS/m	(mmol/ℓ)$^{1/2}$	—	—	mmol/ℓ				mm/annum		mS/m	(mmol/ℓ)$^{1/2}$
SITE 28: BLACK MFOLOZI RIVER, Rensburg, Vryheid District (27° 51' S, 31° 08' E)																
M(7)	4,02	1,87	2,34	8,24	85,7	2,62	5,34	9,19	0,14	0,11	6,10	C3-S1				
SD	2,02	0,97	1,15	4,11	38,6	2,41	1,19	0,85	0,18	0,08	1,82	2-1-1-1 P-O	895	1 660	695	2,3
SITE 29: BLACK MFOLOZI RIVER, Mademoisselle, Vryheid (27° 53' S, 31° 11 e) (Below confluence with Mgobhozi River)																
M(7)	1,57	0,87	1,08	3,53	42,4	0,97	6,44	9,10	0,22	0,12	3,57	C2-S1				
SD	0,88	0,11	0,39	1,30	15,1	0,18	0,92	0,56	0,26	0,03	2,18	1-1-1-1 O-P	850	1 650	360	1,2
SITE 30: MGOBHOZI RIVER, Mademoisselle, Vryheid (27° 52' S, 31° 12' E) (Tributary of Black Mfolozi)																
M(4)	0,27	0,21	0,33	0,83	9,85	0,66	6,83	9,22	0,31	0,11	0,37	C1-S1				
SD	0,06	0,07	0,11	0,23	1,22	0,14	0,39	0,16	0,06	0,02	0,11	1-1-1-1 O-SP	850	1 650	84	0,5
SITE 31: BLACK MFOLOZI RIVER, Mademoisselle, Vryheid (27° 53' S, 31° 11' E) (Below confluence with Hlungwe River)																
M(1)	0,74	0,52	0,59	1,87	20,6	0,75	6,80	8,85	0,32	0,08	1,20	C1-S1				
SD												1-1-1-1 O-P	850	1 650	175	1,7
SITE 32: BLACK MFOLOZI RIVER, Swart Mfolozi Clinic, Vryheid (27° 56' S, 31° 13' E)																
M(1)	1,25	0,78	1,02	3,07	36,4	1,01	7,35	8,61	0,38	0,12	2,53	C2-S1				
SD												1-1-1-1 O-P	800	1 700	347	3,4
SITE 33: BLACK MFOLOZI RIVER (27° 57' S, 31° 14' E)																
M(4)	0,60	0,55	0,53	1,70	18,5	0,71	7,31	8,55	0,79	0,16	0,68	C1-S1				
SD	0,09	0,27	0,08	0,26	2,02	0,06	0,78	0,31	0,43	0,07	0,52	1-1-1-1 O-SP	800	1 700	176	2,6

Note: Uppermost rating USSL (1954), middle rating Christiansen *et al.* (1977) in the order EC_{iw} - Na % - SAR -Na_2CO_3 (me/ℓ); lower rating Ayers (1977) in the order: salinity problem permeability problem

TABLE 1(g)

CHEMICAL CHARACTERISTICS OF SELECTED RIVERS IN THE MKUZI RIVER CATCHMENT

M(n) = mean value (number of observations); SD = standard deviation; other symbols defined in the text

	Measured water composition and concentration											Irrigation water quality	Site climatic data		Calculated soil solution concentration	
	Salinity					Sodicity	Reaction			Anions						
	Ca	Mg	Na	Total	EC_{iw}	SAR_{iw}	pH	pH_c^*	HCO_3	Cl	SO_4	ratings See note below)	D_{rw}	E	EC_{sw}	SAR_{sw}
	mmol/ℓ				mS/m	(mmol/ℓ)$^{1/2}$	—	—		mmol/ℓ			mm annum		mS/m	(mmol ℓ)$^{1/2}$
SITE 34: NKONGOLWANA RIVER, Uitzicht, Vryheid (27° 42' S. 31° 06' E) (Tributary of Mkuzi River)																
M(6)	0,83	0,88	0,37	2.09	27,7	0,40	4.91	9,99	0,0	0,14	1,94	C1-S1 -1-1-1 O-P	895	1 660	225	0,00
SD	0,06	0,09	0,08	0,09	1,93	0,09	0,88	0,36		0,02	0,49					
SITE 35: NKONGOLWANA RIVER, Skutari; Vryheid (27° 52' S. 31° 08' E)																
M(10)	4,66	3,18	2,50	10,42	108,4	1,25	4,60	9,88	0,00	0,26	12,34	C3-S1 -1-1-1 P-O	895	1 660	879	0,0
SD	1,28	0,68	0,70	2,49	21,7	0,24	0,69	0,38		0,07	2,67					
SITE 36: MKUZI RIVER, Ontevrede, Vryheid (27° 41' S. 31° 13' E) (Above confluence with Nkongolwana River)																
M(10)	1,33	1,16	1,08	3,54	3,75	0,98	7,35	8,16	1,27	0,30	1,90	C2-S1 -1-1-3 O-SP	895	1 660	304	5,1
SD	0,29	0,35	0,57	0,87	7,10	0,57	0,62	0,48	0,81	0,11	0,84					
SITE 37: MKUZI RIVER, Ontevrede, Vryheid (27° 42' S. 31° 12' E) (Below confluence with Nkongolwana River)																
M(12)	3,86	2,58	2,03	8,48	88,1	1,12	6,06	8,82	0,21	0,29	8,59	C3-S1 -1-1-1 P-O	895	1 660	714	2,7
SD	1,29	0,84	0,72	2,64	23,8	0,27	1,33	0,75	0,23	0,08	3,81					
SITE 38: MKUZI RIVER, Mkuzi Falls Irrigation Scheme, Magut (27° 39' S. 31° 43' E)																
M(14)	1,00	1,06	1,27	3,34	34,7	1,17	7,44	8,20	1,30	0,73	0,89	C2-S1 1-1-1-3 O-P	600	2 000	510	6,4
SD	0,37	0,57	1,23	2,02	20,0	0,77	0,53	0,39	1,17	0,90	0,61					
SITE 39: MKUZI RIVER, Mkuzi-Gollel Road Bridge (27° 37' S. 32° 02' E) (Data from Johnston, 1976)																
M(26)	3,58	6,08	10,30	19,96	191,4	4,12	7,80	7,02	4,50	12,47		C3-S1 -2-2-6 I-SP	600	2 050	2 911	45,0
SD																

Note: Uppermost rating USSL (1954), middle rating Christiansen *et al.* (1977) in the order EC_{iw} - Na % - SAR - Na CO_3 (me/ℓ); lower rating Ayers (1977) in the order salinity problem permeability problem

TABLE 1(h)

CHEMICAL CHARACTERISTICS OF SELECTED RIVERS IN THE PONGOLA RIVER CATCHMENT

M(n) = mean value (number of observations); SD = standard deviation; other symbols defined in the text

	Measured water composition and concentration											Irrigation water quality	Site climatic data		Calculated soil solution concentration	
	Salinity					Sodicity	Reaction			Anions						
	Ca	Mg	Na	Total	EC_{iw}	SAR_{iw}	pH	pH_c^*	HCO_3	Cl	SO_4	ratings (See note below)	D_{rw}	E	EC_{sw}	SAR_{sw}
	mmol/ℓ				mS/m	(mmol/ℓ)$^{1/2}$	—	—		mmol/ℓ			mm/annum		mS/m	(mmol ℓ)$^{1/2}$
SITE 40: MQUALUSINI RIVER, (Tributary of Bivane River), Makulusini, Vryheid (27° 39' S. 31° 02' E)																
M(10)	10,34	5,47	7,22	23,05	197,9	2,57	7,45	7,62	0,93	0,17	27,15	C4-S1 3-1-1-2 P-SP	800	1 600	1 682	18,9
SD	1,35	1,23	0,91	2,59	30,76	0,31	0,39	0,34	0,68	0,05	5,48					
SITE 41: BIVANE RIVER, Piet Retief Vryheid Road Bridge (27° 32' S. 30° 42' E)																
M(1)	0,21	0,22	0,14	0,58	6,4	0,30	6,72	9,08	0,44	0,04	0,00	C1-S1 1-1-1-1 O-SP	905	1 638	50	0,4
SD																
SITE 42: PONGOLA RIVER, Piet Retief Vryheid Road Bridge (27° 18' S. 30° 54' E)																
M(3)	0,29	0,31	0,17	0,78	7,73	0,33	7,49	8,82	0,63	0,07	0,02	C1-S1 1-1-1-1 O-SP	918	1 586	55	0,8
SD	0,04	0,05	0,05	0,13	2,00	0,08	0,53	0,14	0,14	0,03	0,02					
SITE 43: PONGOLA RIVER, Makatini Research Station, Jozini (27° 26' S. 32° 09' E)																
M(21)	0,73	0,92	1,69	3,36	33,3	1,63	7,59	8,05	2,35	1,00	0,33	C2-S1 -2-1-3 O-P	570	2 000	500	10,1
SD	0,36	0,64	2,05	2,89	28,1	1,51	0,39	0,40	2,19	1,33	0,24					

Note: Uppermost rating USSL (1954), middle rating Christiansen *et al.* (1977) in the order EC_{iw} - Na % - SAR - Na_2CO_3 (me/ℓ); lower rating Ayers (1977) in the order: salinity problem permeability problem

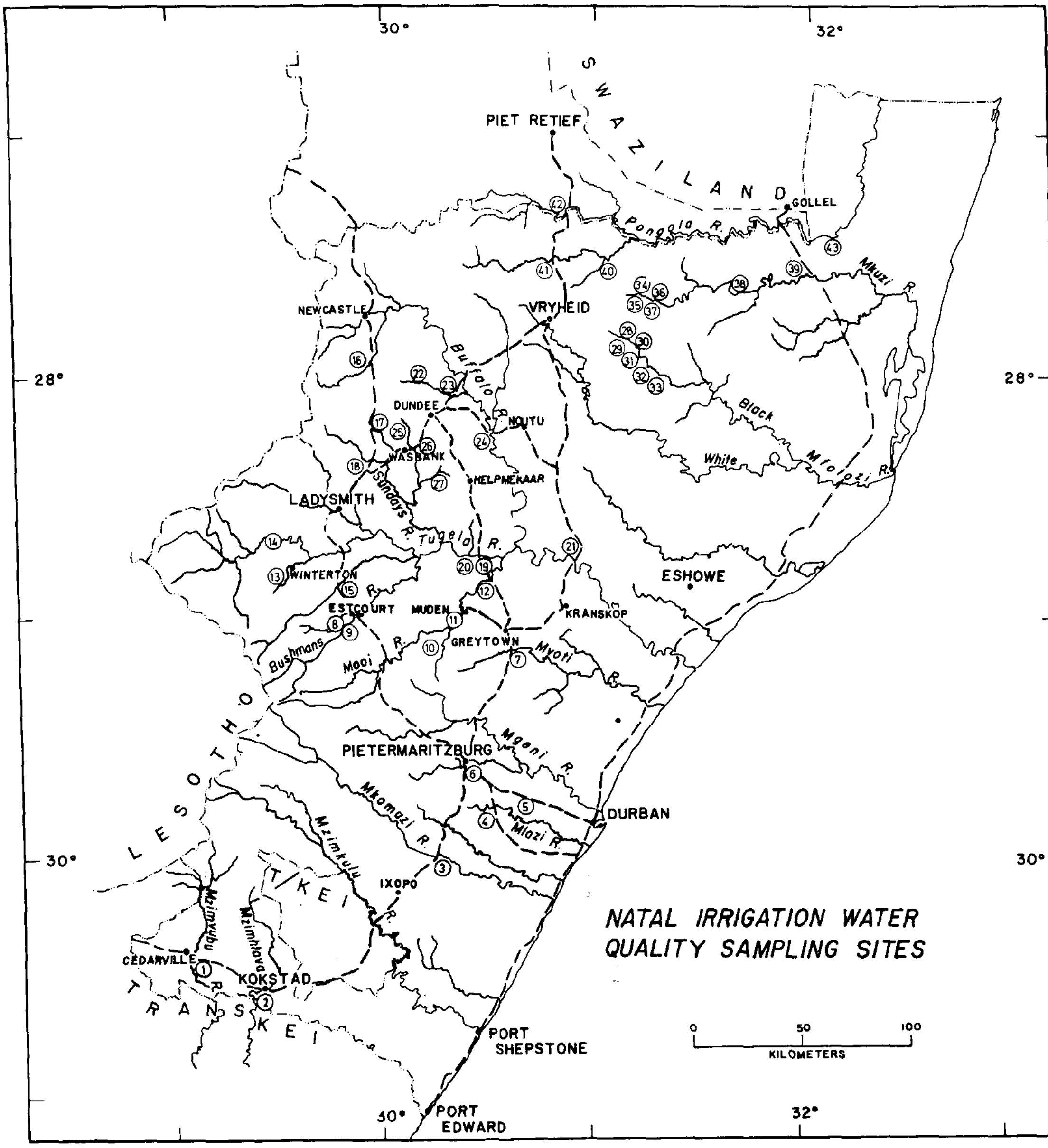

Figure 1
Sampling sites for the survey of irrigation water quality in Natal

covered by this survey. The location of the sampling points are also shown on a map of Natal (Fig. 1). The quality class of water from each site are shown in Table 1 in terms of the well-known criteria of the USSL (1954) as well as the more recent classifications of Ayers (1977) and Christiansen *et al.* (1977). Included in the table are values of soil salinity (EC_{sw}) and sodicity (SAR_{sw}) calculated from equations (2) and (4) respectively. Measured EC_{iw} and SAR_{iw} and calculated EC_{sw} and SAR_{sw} values are plotted in Fig. 2 to illustrate that four distinct groups of waters based on soil solution composition and concentration are recognisable in Natal. Salinity tolerance values (Maas and Hoffman, 1977) for common crops grown in Natal are shown on this figure.

Brand *et al.* (1967a) have shown that river water concentration may be related to the surface geology of the region traversed by the rivers in Natal. The data presented by these authors have been recalculated to conform to the units used here and are shown in Table 2 for the major geological series of Natal. Calculated soil solution values for a hypothetical soil irrigated with these waters are included in this table using climatic data from site 38.

Discussion

The standard deviations shown in Tables 1a to 1h are generally high for most analytical parameters, indicating marked variation in concentrations for river water constituents analysed during the course of this survey. Such variation should form an intrinsic part of irrigation water assessment, but for the sake of simplicity has not been considered in this general discussion.

Assessment of river water quality in terms of the criteria of the USSL (1954) indicates that the majority of inland sources of irrigation water in Natal are of the best quality ratings (C1 and S1) with a few poorer sources (C2 and C3). No site gave a poor sodicity assessment. However, in terms of the criteria of

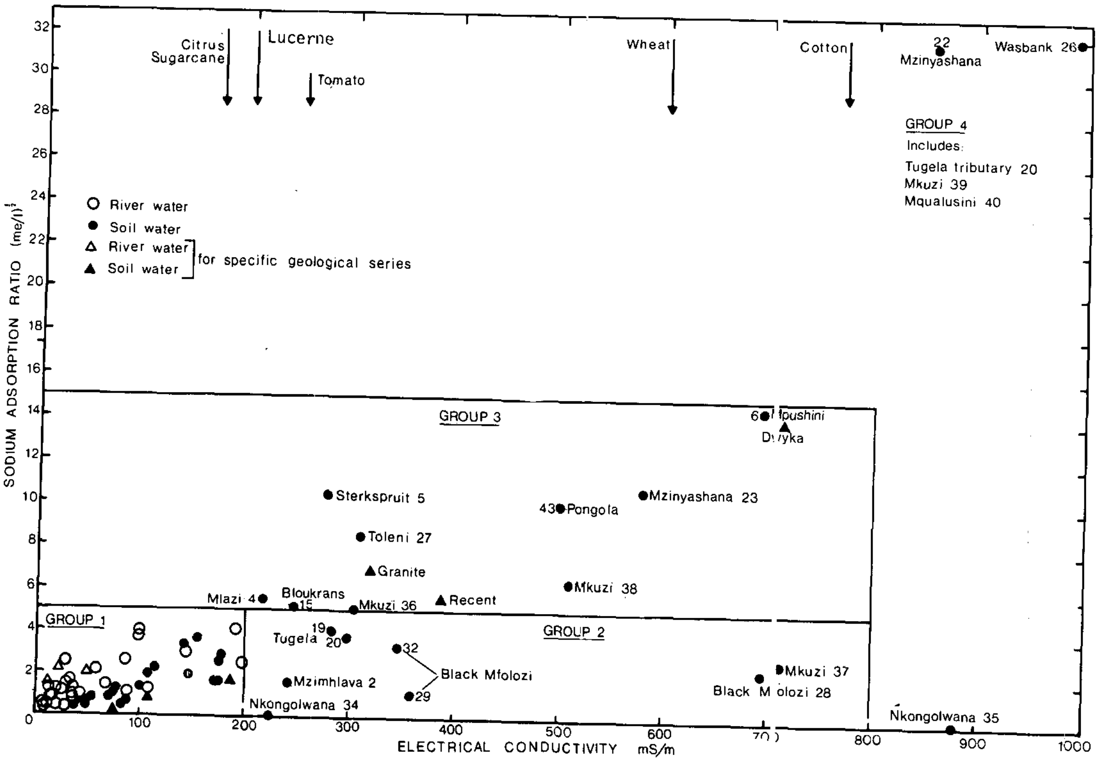

Figure 2
The electrical conductivity and sodium adsorption ratio of river water (measured) and soil water (calculated) of some Natal rivers grouped according to salt tolerance of common crop plants and sodicity limits for structurally stable soils (SAR 15) and unstable soils (SAR 5). Characteristic water composition for common geological series in Natal are also plotted. Site numbers are shown behind the names of those rivers which fall outside group 1. All soil water values represent the most extreme condition that can be expected to develop at the particular site.

TABLE 2
MEAN EXPECTED COMPOSITION AND CONCENTRATION OF SURFACE WATERS DRAINING SPECIFIC GEOLOGICAL SERIES (AFTER BRAND *ET AL.* 1967a)

Geological Series	Ca	Mg	Na	Total	EC_{iw}	SAR_{iw}	pH	pH_c^*	ALK	Cl	SO_4	Irrigation water quality class See note 1 below	EC_{sw}	SAR_{sw}
	Measured water composition and concentration: Salinity					Sodicity	Alkalinity			Anions			Calculated[2] soil solution	
	mmol/ℓ				mS/m	$(mmol/\ell)^{1/2}$	—	—		mmol/ℓ			mS/m	$(mmol/\ell)^{1/2}$
Beaufort	0,20	0,16	0,16	0,52	5,2	0,39		9,35	0,35	0,11	0,06	C1-S1 1-1-1-1 O-SP	76,4	0,1
Ecca	0,23	0,24	0,27	0,74	7,4	0,56		9,03	0,51	0,12	0,11	C1-S1 1-1-1-1 O-SP	108,8	0,9
Dwyka	1,05	1,56	2,25	4,86	48,6	1,97		7,82	2,10	2,52	0,24	C2-S1 1-2-1-4 O-SP	714,4	14,2
Table Mountain Sandstone	0,18	0,33	0,76	1,27	12,7	1,50		9,15	0,37	0,72	0,18	C1-S1 1-2-1-1 O-SP	186,7	1,7
Granite	0,41	0,56	1,20	2,17	21,7	1,70		8,51	0,88	1,09	0,20	C1-S1 1-2-1-2 O-P	319,0	6,9
Recent	1,42	0,26	0,95	2,63	26,3	1,04		8,23	1,05	1,32	0,26	C2-S1 1-1-1-2 O-P	386,6	5,6

Note 1: Uppermost rating USSL (1954), middle rating Christiansen *et al.* (1977) in the order EC_{iw} - Na % - SAR - Na_2CO_3 (m·/ℓ); lower rating Ayers (1977) in the order: salinity hazard permeability hazard.
Note 2: Based on D_{rw} and E of the Mkuzi Falls Irrigation Scheme (site No. 38).

Christiansen *et al* (1977) (Class 1: No restriction for irrigation; classes 2 to 5: increasing restriction depending on local conditions; class 6: unsuitable for irrigation), only about half the sites (58%) showed Na_2CO_3 levels that fall in class 1. In terms of the definition of the classes proposed by these authors this means that although the remainder are not regarded as unsuitable for irrigation, they should be critically examined in relation to local conditions before being recommended for use. The proportion of sites in class 1 for other quality parameters ranged from 100% for Cl, 90% for SAR, 79% for Na percentage and 77% for EC_{iw}. Three sources of irrigation water, the Mzinyashana headwaters, Wasbank River and the lower reaches of the Mkuzi River are regarded as being totally unsuitable for irrigation since one or more parameters fall in class 6.

The criteria of Ayers (1977) (O = no problem; P = increasing problem; SP = severe problem) in relation to salinity and sodicity show that many of the waters are regarded as salinity problems (rating P) which correspond closely to those waters with ratings of 2 or more for EC_{iw} by the criteria of Christiansen *et al.* (1977). Furthermore, a large proportion of the waters are judged to be a permeability problem (P or SP in Tables 1a to 1h). This assessment arises as a result of either high sodicity (sites 4, 5, 6, 15, 19, 20, 21, 22, 23, 26, 27, 36, 38, 39, 40, 43), or very low salinity. This is the only evaluation scheme which takes account of the tendency of very pure water to cause deflocculation of clay in soils that are structurally unstable.

The general evaluation of irrigation water quality in Natal by the criteria of Christiansen *et al* (1977) and Ayers (1977) is that both salinity and sodicity need to be considered in development of irrigation schemes. The large number of waters which have ratings of 2 to 5 or "P" indicate that final evaluation of water quality must rely on use of local soil, climate and management data as has been embodied in the classification system proposed here (Fig. 2), for predicted soil salinity and sodicity.

The conclusions drawn from classifying the waters in terms of the criteria of Ayers (1977) and Christiansen *et al.* (1977) tend to support the criteria applied in grouping the calculated soil solution salinity and sodicity values in Fig. 2. These groups are defined in terms of the tolerance limits of common crop plants and the generally accepted limits of soil sodicity (SAR 5 and 15). Waters which fall in group 1 of Fig. 2 will tend to develop soil salinity and sodicity values below the maximum value at which lucerne, maize, citrus, and sugar cane can be produced without a yield reduction due to osmotic stress (Maas and Hoffman, 1977) and below an SAR of 5, the limit of sodicity generally accepted for soils which are structurally unstable. It is noteworthy that only 46 % of the waters examined in Natal fall within this group, i.e. only a proportion of irrigation waters may be used on soils with drainage rates of less than 0,1 m/annum under the climatic conditions specified, without danger of yield reduction or soil deterioration owing to either salt accumulation or sodicity increase.

Sites which tend to have characteristics conducive to development of high salinity in poorly drained soils, but which have relatively little Na_2CO_3 fall into group 2 (19 % of the waters analysed). These waters may be used for the production of salt tolerant crops such as wheat and cotton on all soils, but are unsuitable for production of salt sensitive crops on poorly drained soils.

Group 3 waters (21 %) have a high potential salinity and contain sufficient Na_2CO_3 (low pH_c^*) to render them an irrigation risk on soils which are structurally unstable and poorly drained, but may be suited to production of salt tolerant crops (cotton and wheat) on well drained soils. However, the low salinity of some of these waters, coupled with a high potential sodicity may introduce hydraulic conductivity deterioration in soils of unstable structure (Ayers, 1977). For this reason, the use of these waters can be recommended only with caution.

Group 4 waters (14 %) which include those previously judged unsuitable for irrigation by the criteria of Christiansen *et al* (1977) as well as the minor tributaries of the Tugela River, at Tugela Ferry, the lower reaches of the Nkongolwana and the upper reaches of the Mqualusini Rivers, are not suitable for irrigation of poorly drained soils and will probably be a hazard on well drained soils as well.

The general pattern of water quality is that the majority of the larger rivers in the interior of Natal show irrigation water quality that is good by all standards, particularly in central and southern Natal. Use of these waters on sodic or unstable soils will, however, cause permeability reductions. Some of the larger rivers in Northern Natal have rather poorer water quality (Pongola and Mkuzi Rivers) which hold severe implications for indiscriminate irrigation in these catchments. In addition, many of the smaller rivers throughout Natal show poor quality and this may have important consequences for smaller irrigation enterprises. The survey did not include irrigation water from sources close to the Natal coast, but data presented by Archibald, *et al.* (1969), and Brand *et al.* (1967b,c) indicate that steady deterioration of water quality occurs downstream for most of the Natal rivers, so that the foregoing constraints with regard to the use of some Natal waters for irrigation of poorly drained soils is probably applicable to this region as well.

Reasons for the variable pattern in water quality in Natal must be sought in the distribution of coal mines, in the nature of the surface geology and in the presence of saline groundwater in certain parts of the region.

The presence of extensive coal fields in northern Natal (Dundee, Newcastle, Utrecht and Vryheid districts) means that the headwaters of the Wasbank, Buffalo, Mfolozi, Mkuze, Pongola, Sundays and Tugela Rivers (data not presented for the latter two rivers) are considerably disturbed by effluents draining from active and abandoned mines (Brand *et al.*, 1967c). This is inferred from the abnormally high sulphate ion contents of water from sites 22, 23, 26, 28, 29, 35 and 40 compared to the expected contents shown in Table 2 for water associated with the major geological series of Natal (Kemp, 1966). Mine effluents from the Dundee area appear to be more alkaline, containing less sulphate and more carbonate (sites 22, 23 and 26). Consequently rivers in the Vryheid area tend to fall into group 2 waters while rivers in the Dundee area tend to fall into groups 3 or 4. Despite the fact that the effect of mineralisation diminishes downstream from the mining areas owing to inflow of unpolluted water from tributaries, it does not entirely disappear. This is because the acidity of mine effluents tends to be neutralised by calcium carbonate in the sediments and rocks of the river beds thereby increasing the carbonate load of the water. The best example of this phenomenon in the data presented here is to be found in the Mkuzi river catchment, sites 35, 37 and 38, where soil water salinity decreases downstream, but soil water sodicity increases. The quality of the river therefore shifts from group 2 (site 37) to group 3 (site 38), a change which must be interpreted as water quality deterioration.

The second factor affecting river water quality is surface geology. The Mpushini, Mlazi and middle reaches of the Mkuzi River traverse extensive tracts of Dwyka series, while the Sterkspruit and Pongola Rivers cross granite outcrops. Fig. 2 shows that all these rivers have chemical characteristics similar to the values predicted by Brand *et al.* (1967c). In addition the lower

Mkuzi River (site 39) appears to be influenced by an additional factor which may be the saline groundwaters found in this area (Van Wyk, 1963). These ground waters, with more than 750 mg/ℓ total solids may also have an adverse effect on the lower reaches of the Pongola, Black Mfolozi, White Mfolozi and other smaller rivers.

Conclusions

The use of a comprehensive approach to irrigation water quality assessment, involving water, soil properties, climatic and management factors may provide a different evaluation to that provided by older methods of assessment. However, more recent criteria, such as that of Ayers (1977) and Christiansen *et al.* (1977), accord well with the more comprehensive approach adopted here. The model on which evaluation is based is, nevertheless, sufficiently simple to offer wide applicability of the method.

Natal irrigation waters are variable in quality and this may be one of the causes of salinity and waterlogging problems that have developed on some irrigation schemes. Generally alkaline, poorly drained and structurally unstable soils are more adversely affected by poor quality water rather than stable, well drained, acid soils.

No simple geographical pattern in water quality is present in Natal. However, any coal mining activity, certain geological formations (Dwyka, Table Mountain Sandstone, Granite and Recent series) as well as extensive tracts of saline groundwater may have a detrimental influence on irrigation water quality.

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