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Department of Primary Industries and Regional Development, Western Australia, Perth. Technical Bulletin 52.

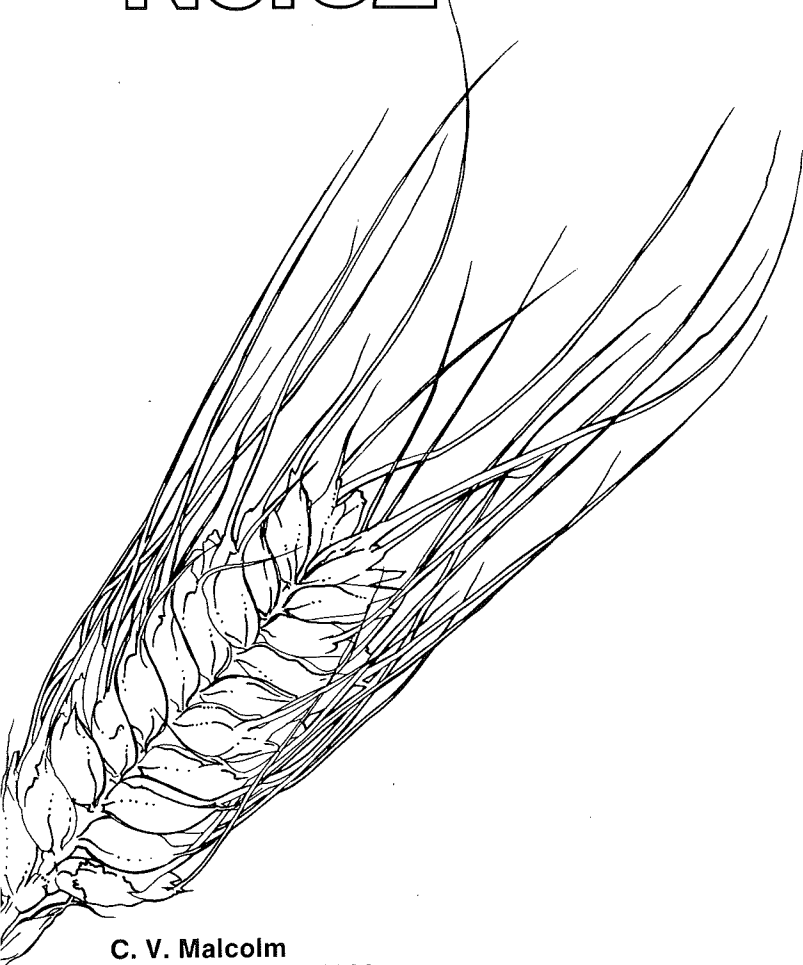
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Technical Bulletin

Wheatbelt Salinity

A review of the salt land problem
in South-Western Australia

No. 52



C. V. Malcolm
Revised Edition 1983

WHEATBELT SALINITY

A review of the salt land problem in South-Western Australia

**REVISED EDITION
1983**

By: C. V. Malcolm

Editor: D. A. W. Johnston

The first edition of this Technical Bulletin, issued in March 1982, was edited by C. H. Trotman. Such has been the demand for this publication, that the author has taken the opportunity to make revisions to the text on the occasion of its reprinting.

Technical Bulletin No. 52
November 1983
Department of Agriculture
Jarrah Road, South Perth, 6151
Western Australia

ISSN 0083-8675

Malcolm, C. V., 1933-

Wheatbelt salinity, a review of the salt land problem in South-Western Australia.

Rev. ed.

Previous ed.: Perth, W.A.: Western Australian Dept. of Agriculture, 1982.

Bibliography.

Agdex 512.

ISBN 0 7244 9500 2.

1. Soils, Salts in—Western Australia.

I. Western Australia. Dept. of Agriculture.

II. Title. (Series: Technical bulletin (Western Australia. Dept. of Agriculture); No. 52).

631.4'16

ACKNOWLEDGMENTS

The author gratefully acknowledges the helpful criticisms made by numerous extension personnel in the Department of Agriculture who used the early drafts of this publication as a training handbook. In particular the detailed comments from Drs R. A. Nulsen and W. J. Cox and Mr E. Bettenay (CSIRO) have been most helpful. The help of Mr J. A. Bessell-Browne in detailed reading and the preparation of the subject matter index is much appreciated. Helpful suggestions were also made by Mr G. H. Burvill, and the late Dr L. J. H. Teakle.

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Manuscript Revised August, 1983

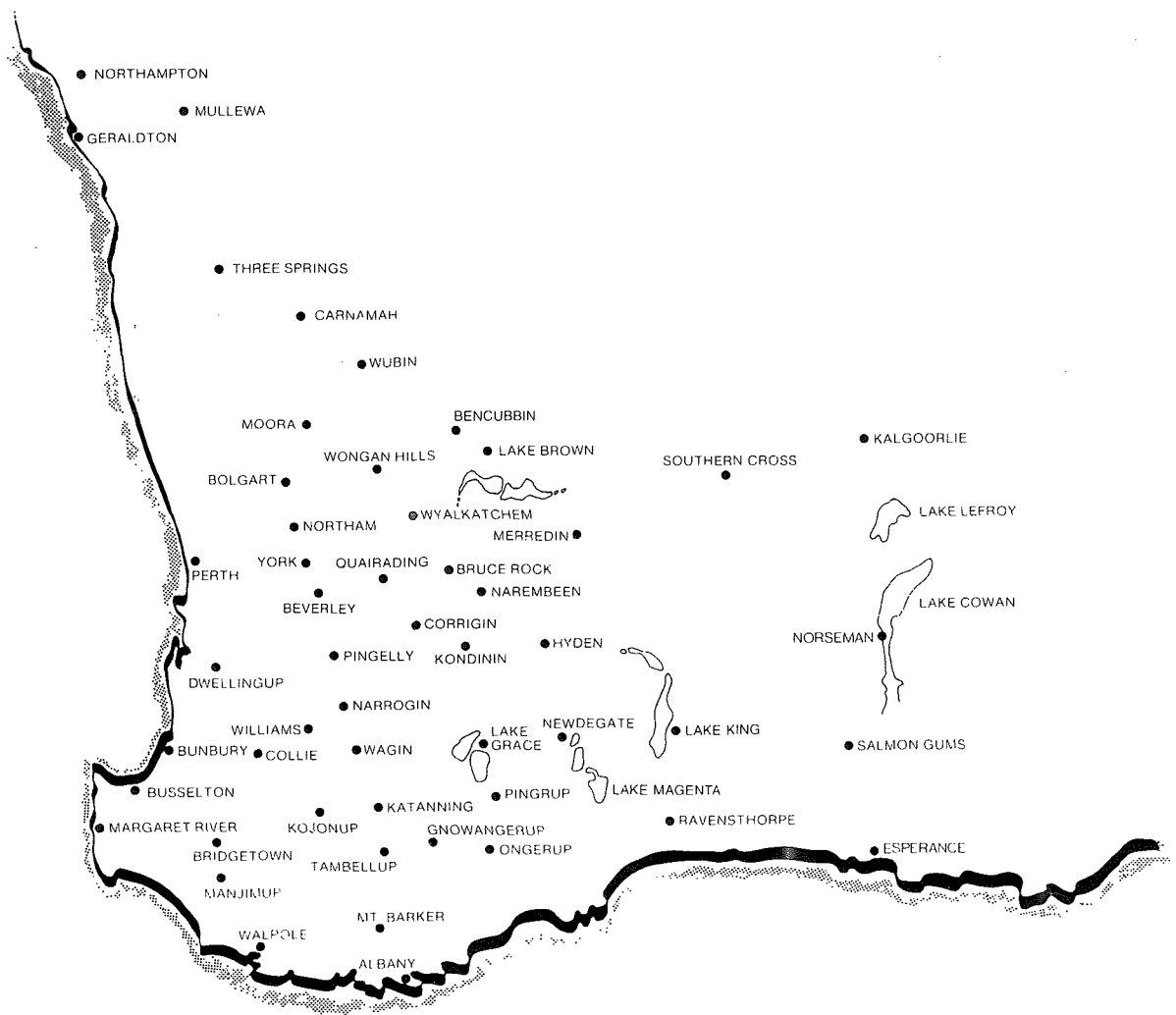
WHEATBELT SALINITY

A review of the salt land problem
in South Western Australia

by C. V. Malcolm

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South-Western Australia showing major place names mentioned in this Bulletin. See also figures 9, 10, 16

Botanical Nomenclature

In most cases species of plants are referred to in the text by their common names. However, botanical names are given where plants are first referred to, and the Glossary includes a listing of the botanical names.

Expressions for Salinity

The salt content of soils or waters may be expressed in terms of individual ions such as chloride, sodium or sulphate, as salts such as sodium chloride or as conductivity measurements which reflect the total soluble salts. In Western Australia the practice has developed over many years of analysing for chloride by titration, and expressing the result as sodium chloride (common salt). Because most literature on salt problems in Western Australia employs this expression it has been followed in this publication. Figures given for sodium chloride may be converted to chloride values by multiplying by 0.6.

INTRODUCTION

Under virgin conditions, the sub-soils of South Western Australia contain appreciable quantities of soluble salts. Since agricultural development hydrological changes have caused the salts to concentrate in the surface soil in low-lying parts of the landscape. As a result about a quarter of a million hectares of good agricultural land have become unproductive.

The salt problem has proved over the years to be intractable. Many studies on its nature and cause have been conducted, and many suggested solutions have been offered.

The aim of this bulletin is to provide a clear understanding of factors leading to the accumulation of salts in soils under natural rainfall, the effects of land use on redistribution of stored salts and possible approaches to the prevention and treatment of saltland. Although primarily concentrated on the wheatbelt, where saltland occupies the greatest area, many of the principles are applicable in higher rainfall areas. No attempt has been made to deal with the stream salinity problem of higher rainfall areas.

HISTORICAL REVIEW

Although wheat production in Western Australia started soon after colonisation (Figure 1), the area planted did not increase rapidly until the period 1900 to 1930.

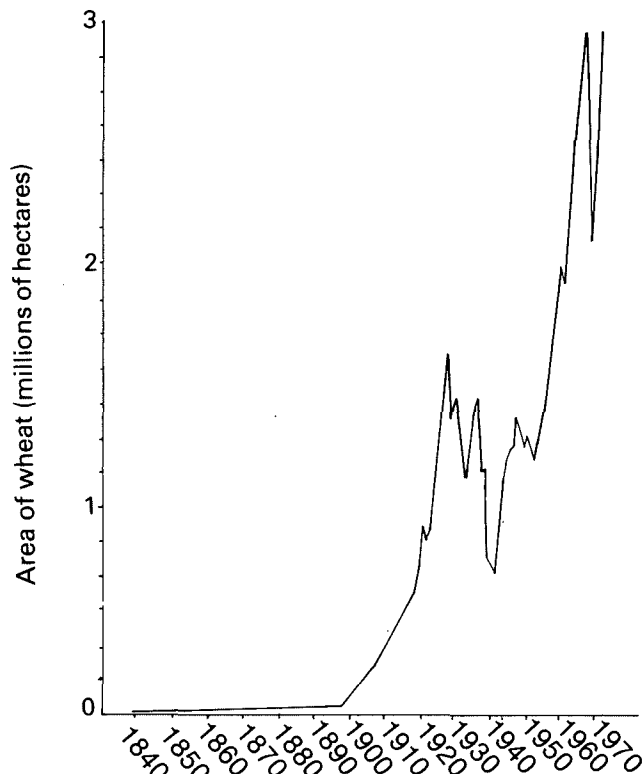


Figure 1.—Area sown to wheat in Western Australia—1840 to 1977. (W.A. Yearbook, 1975).

As the State's major areas of saltland are in the wheat growing areas (Malcolm and Stoneman 1976) the problem of saltland received little attention until about 1910, and then it was the Railways Department which was concerned with salty water supplies long before the problem of saltland became a concern of the Department of Agriculture (Wood, 1924). The first record appeared in 1907 as a reply printed in the *Journal of Agriculture* under the heading "Does clearing increase salt in ground?" The reply indicated that a farmer's query had been referred to the Government Analyst for attention and the answer indicated that it had been "pretty conclusively proved" that the removal of trees affected water supplies materially, because rainfall passing through the soil took salts with it. It was considered that to prevent salting it would be necessary to replant a very high proportion of the trees that had been removed.

In 1917 the Royal Commission on the Mallee Belt and Esperance Lands made reference to

soil salt concentrations in the Esperance region, and disclosed a sharp difference of opinion concerning what level was liable to be of serious consequence for agriculture. Overseas authorities were quoted in many cases to support both proponents and opponents of land release.

Paterson (1917) outlined in considerable detail the manner in which salts accumulated in the soil and factors influencing the level of salt which was significant for crops. He presented the results of soil analyses from the Salmon Gums area and concluded that about a third of the area was suitable for settlement, a sixth doubtful and a half had too much salt to be put to profitable use. However, the Commission, which was chaired by Mr C. E. Dempster of Esperance, strongly criticised Paterson's Report and advocated land release.

Sutton (1927) described the results of applying stable manure and sheep manure to saltland on a property at York, but the first article of any consequence concerning saltland was by Teakle (1929) who reviewed overseas and local work on soil salinity and discussed causes of the problem in Western Australia. He described three ways in which salts could be distributed in the landscape after its deposition, which he believed was from rainfall—

- Sufficient rainfall and suitable topography enabled salts to be drained from creeks and thence to the ocean.
- In dry areas, salts were only leached to a certain depth where they accumulated.
- Where the drainage was reasonable, creeks became salty and saline springs and seepage patches developed following clearing.

Overseas reclamation measures were suited only to very valuable land and he suggested that drainage or the application of stable and sheep manure were suited only for small patches.

In an appendix to Teakle's article, C. A. Gardner described plants usually found on salt prone soils and suggested that saltbush could be planted on saline areas.

Thus by 1929 it had been recognised that—

- The salt problem was at least partly due to cyclic salt, that is salt brought in with the rainfall.
- Salt problems were more prevalent in areas where rainfall was low.
- Occurrence of salt was influenced by topography and soil type.

- Removal of the natural vegetation was the basic cause of salt encroachment.
- Possible treatment measures included drainage, surface mulches, the use of salt tolerant plants, and soil management to maintain a surface cover of growing plants. It had also been observed that one approach to preventing salt encroachment was to replant the hills with trees.

Teakle proposed three general categories of saltland; seepage areas and waterlogged valleys, and dry land areas in which seepage and waterlogging played no part. In 1931, Prescott further refined the list of causes of the salt problem when he concluded that soils in which salt occurred naturally in appreciable amounts were found primarily in those areas receiving less than 5 mm of rain per wet day as an annual average.

The 1930s and 1940s were periods of intense soil survey activity in the agricultural areas. The prediction of Paterson in 1917, concerning the likelihood of salt problems developing in the Salmon Gums area, proved to be substantially true, and the resulting problems with saltland led to extensive soil surveys in the Salmon Gums area. Other surveys were done in the Lake Brown area, the Lakes District, the East Pingrup-Lake Magenta area, and the 3 500 Farms Scheme area to the south east of Southern Cross (Teakle and Burvill, 1938; Teakle, 1939; Teakle *et al.*, 1940; Burvill, 1945 and Burvill, 1947). Details of the soil survey in the Salmon Gums district remain to be published (Burvill, private communication). Teakle (1953) in a later survey in the Many Peaks district reported that under natural conditions soils in somewhat higher rainfall areas also stored salt in their profiles. The surveys led to a much more detailed understanding of the extent and nature of the salt problem in Western Australian soils.

The period of soil survey activity corresponded with a time of increasing incidence of soil salinity on farm land. Teakle and Burvill (1938) reported that in the Carnamah, Wubin and Moulyinning areas saltland developed 10 to 20 years after agricultural development and there were numerous references to farmers reporting increasing flow of streams, increasing seepage and shallower groundwater. This period was approximately 10 to 20 years after the main early increase in cropped area (Figure 1).

Concern for the salt problem in the late 1940s led to the appointment of a CSIRO officer to report on the salt problem (Pennefather, 1950).

He reported that the most important occurrence of salting in the Western Australian wheatbelt was associated with the growing waterlogging of relatively flat valleys which contained much of the best wheat lands and considered that a further 280 000 to 400 000 hectares was threatened. As insufficient data were available on which to base advice on the effective control of waterlogging, he recommended that investigations into the nature of the problem and methods of treatment should be undertaken.

The investigations were to also provide a better understanding of other aspects of salting, such as hillside seepages and the increasing incidence of saline surface and underground waters. Aspects to be studied were—

- The development of saltland and its present extent.
- The soils and geology in relation to saltland.
- The nature and extent of waterlogging in valleys.
- Water and salt movement under—
 - (a) natural vegetation
 - (b) agriculture
- Preventative or remedial measures such as:
 - (a) salt tolerant plants
 - (b) dewatering plants
 - (c) afforestation and control of clearing
 - (d) subsoiling
 - (e) surface drainage
 - (f) sub-surface drainage, perhaps including pumping
 - (g) natural reclamation and water spreading which would have to be accompanied by a lowering of the watertable.

A Senior Soil Research Officer was appointed to the Western Australian Department of Agriculture in 1953 with the prime responsibility of investigating the salt problem.

Many of the early results were reported by Smith (1962) who showed that highly saline groundwater existed at shallow depths beneath salt-affected wheatbelt valleys. Piezometric studies indicated that the water was under pressure and tending to flow to the soil surface, and that the groundwater extended, but at a greater depth, beneath the non-saline land on the valley sides. Soil surface treatments such as cultivation and application of a sand mulch were shown to reduce the concentration of salt at the soil surface, but attempts to reclaim saline areas by means of normal cultivation methods and normal plants, such as cereals and annual (Wimmera) ryegrass, indicated that these

methods were only likely to be suitable for mildly affected areas having perhaps 20 per cent of their area as scattered bare saline patches. On more severely affected areas special salt tolerant forage plants needed to be sown and a programme of research to identify suitable plants and develop methods for their establishment and management was embarked upon. This programme is still continuing.

In the late 1950s and early 1960s, work by the CSIRO Division of Soils (Bettenay, 1961; Bettenay *et al.*, 1962; and Mulcahy and Hingston, 1961) provided detailed information on wheatbelt soils in areas not covered by earlier soil surveys. These studies provided explanations for saltland occurrences in particular situations. They drew attention to the effect of clearing of the valley floors, and of intake areas around

granite rocks in the development of water tables in wheatbelt valleys. Mulcahy and Hingston (1961), indicated the topographical and pedological situations where seepages were likely to occur and mapped the sandy outwash areas which appeared to be associated with salinity in some broad valley situations.

Conacher (1975) drew attention to shallow seepage flow which he believed to be more important in the development of saltland than deeper and/or confined groundwater.

In recent years quantification of the salt balance of the landscape has been emphasized (e.g. Peck and Hurle, 1973) but in general this work has been concentrated in areas receiving more than 400 mm annual rainfall. This Technical Bulletin deals with drier areas.

THE CAUSE AND NATURE OF THE SALT PROBLEM

Attempts to prevent salting or to design treatments for restoring the productivity of saltland must be based on a clear understanding of the problem. Knowledge of the factors involved then enables each problem to be tackled according to its particular characteristics.

Salt in rainfall

Rainfall appears to have been first suspected as a source of soil salinity in Western Australia by Wood (1924). He suggested that the salt came airborne, either in rain, powder form or dew, mainly during the summer. A special committee of the Royal Society of Western

Australia then obtained data on the salinity of rainfall at various centres during 1926, Table 1 (Wood and Wilsmore 1928). Since that time a great deal of information has become available concerning the role of rainfall in the development of salinity problems.

The salts found in rainfall come in part from the bursting of bubbles on the ocean. As extremely fine droplets of sea water are formed and evaporate, they leave minute particles of salts which are easily transported into the upper atmosphere by wind, (Mason 1962). Some atmospheric salts also come from aeolian dust (Hutton and Leslie 1958) and when falling to the soil surface are referred to as 'dry fall'.

TABLE 1.—Summary of information published by the Royal Society of Western Australia concerning the salinity of rainfall at various centres and the estimated precipitation of salt per hectare during 1926.

Station	Number of days recorded	Total rainfall on the days recorded mm	Total rainfall for year (1926) mm	Salinity of rain water NaCl* mg L ⁻¹	Estimated precipitation of salt per hectare per annum† kg
A. Coastal:					
Perth	100	1 050	1 250	27.7	341.4
Geraldton.....	15	139	412	47.3	195.4
Esperance.....	9	226	849	31.1	290.7
Condon.....	6	152	318	13.5	42.7
B. Inland:					
Coolgardie.....	5	78	202	19.8	40.5
Cue	15	115	263	15.8	41.5
Mundiwindi.....	12	132	188	5.8	10.9
Wiluna	6	59	168	6.6	11.1
Rawlinna	3	29	93	10.4	9.7

* NaCl calculated from chloride ion determined by titration with standard silver nitrate.

† For the purpose of this calculation it was assumed that the total rainfall for the year had the same average composition as that portion actually analysed.

The amount of salt in rainfall is a function of the amount of rainfall and its salt concentration. The salinity of rainwater ranged from 27.7 mg L⁻¹ NaCl at Perth to 13.5 mg L⁻¹ at Condon for coastal sampling sites. A difference in rainfall at these sites resulted in an overall deposition of salt of 240 and 43 kg ha⁻¹ per annum respectively. Inland areas received as little as 10 kg ha⁻¹.

Teakle (1937) reported data for NaCl in rainfall at Merredin and Salmon Gums Research Station between 1933 and 1936. The annual average deposition of salt was about 30 kg ha⁻¹ at Salmon Gums and 18 kg ha⁻¹ at Merredin.

It was calculated that if all the salt deposited was accumulated in the soil it would take more than 200 years at Merredin and about 120 years at Salmon Gums to raise the salt concentration of 0.3 m depth of soil by 0.1 per cent salt (g NaCl per 100 g soil) (c.f. Table 3). No attempt was made to separate dry fall from rainfall in Teakle's study but the highest salt accessions occurred during the wettest months.

Rainfall composition

Hingston (1958), and Hingston and Gailitis (1976), studied the composition of rainfall in Western Australia. They noted that samples of rainfall from Perth tended to be high in calcium and presumed this to be due to contributions from sources such as industry or coastal dunes. At Kojonup and Pingelly the level of calcium was sufficiently high relative to sodium to indicate a terrestrial, as distinct from marine, contribution to salt in the rainfall. The rainfall from Dwellingup approached most nearly to the Na:Ca ratio in seawater (approximately 22). Teakle (1929) recognised that near salt lakes dry accessions of salts were of considerable importance.

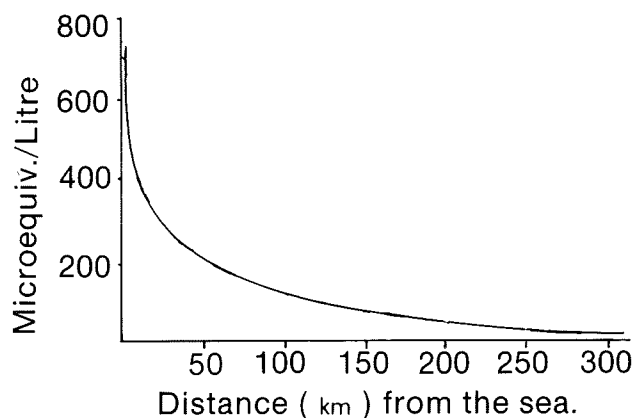


Figure 2.—Variation in chloride concentration in Western Australia with distance from the sea. (Hingston 1958).

Teakle (1937), observed that in coastal areas the NaCl content of the rainfall was of the order of 15 to 50 mg L⁻¹, compared with 20 to 40 mg L⁻¹ in inland areas.

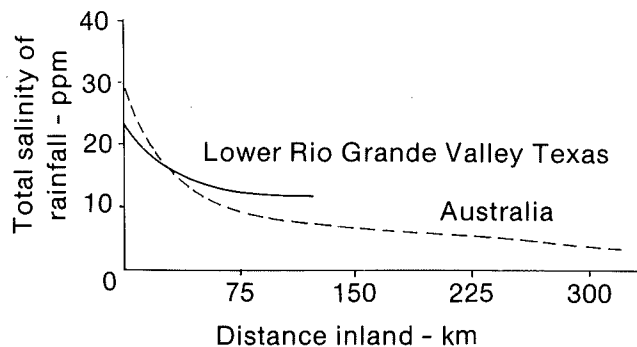


Figure 3.—Comparison of Australian rainfall salinity data (Hutton and Leslie, 1958) with data from the Lower Rio Grande Valley of Texas. (Fanning and Lyles, 1964).

Hingston (1958), showed the variation in chloride concentration of rainfall with distance from the sea (Figure 2). A comparison of Australian and overseas data was provided by Fanning and Lyles (1964), who compared Hutton and Lesley's (1958), data with their own for the lower Rio Grande Valley of Texas (Figure 3). In both cases it was found that the influence of the coast is decreased after about 60 km. Their calculations indicated that the salt content of rainfall decreases linearly with the logarithm of distance inland.

Rainfall characteristics

Prescott (1931), drew attention to the relationship in Australia between rain per wet day and the existence of appreciable amounts of salt in soil. Burvill (1939), also drew attention to the fact that in areas of low available rain per wet day there were few well defined water courses, a factor which would also contribute to the development of saline soils. However, on Prescott's map (Figure 4) the area of the south east of Western Australia enclosed by the area receiving less than 5 mm of rain per wet day excludes some of the shires worst affected by soil salinity (Malcolm and Stoneman, 1976) in the northern agricultural areas.

The importance of the seasonal balance between rainfall and evaporation in determining the movement of salts vertically in the soil is discussed by Yaalon (1963). He suggests that during dry years salt may be accumulated within the root zone and that in occasional wet years deeper percolation occurs and washes saline water into the groundwater system.

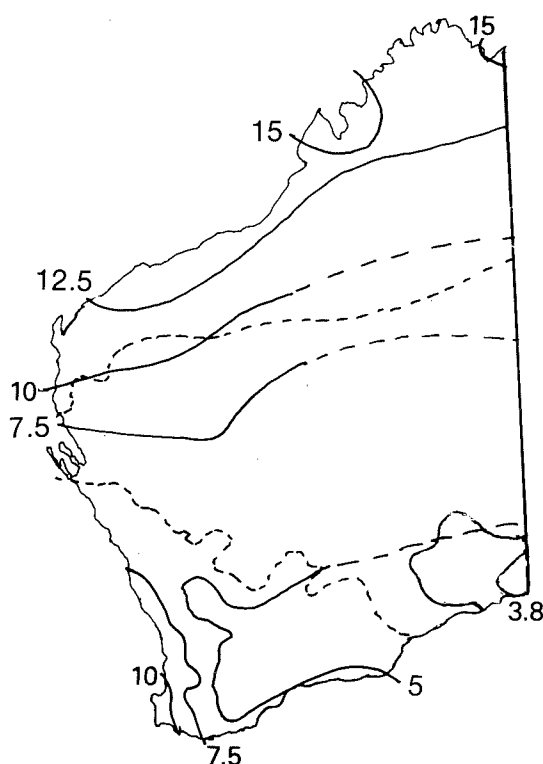


Figure 4.—Map of Western Australia showing the isologs of equal rainfall (mm) per wet day. The critical area from the salt accession and low leaching point of view lies within the limit of 5 mm rain per wet day (Compare with Figure 9). (Prescott, 1931).

Burvill (1950), observed that rapid worsening of saltland appeared to occur one to two years after wet years such as 1945 and 1946. This could be related to increased groundwater pressure or to flooding and subsequent death of plant surface cover in the valleys.

The accumulation in soil of salt from rainfall

Based on the amount of salt falling in rainfall in Western Australia Teakle (1937), concluded that there was no need to postulate that the salt in Western Australian soils and waters had its origin in the Miocene sea which existed 40 million years ago. He calculated that for Salmon Gums it would take only 37 000 years to raise the soil to its present 0.6 per cent salt to a depth of 15 m and only 35 000 years to raise the soil at Merredin to 0.35 per cent salt from rainfall alone. (The growth of plants such as wheat is affected at levels approaching 0.2 per cent NaCl.) Although this calculation made no allowance for possible loss of salt by deep drainage or recycling of salts locally through dust, the time since the retreat of the Miocene sea was many times these time periods, making cyclic accumulation an adequate explanation for the present levels of soil salt.

A similar conclusion was reached by Dimmock *et al.* (1974), for the Bakers Hill area where, at the current accession rate of salts, 17 000 years was needed to accumulate the measured salt storages if no loss occurred from the system, an assumption which may not be valid.

Soils, topography and hydrology

Once salt arrives on the landscape, either in rainfall or in dry fallout, its movement determines whether sufficient accumulates in certain sections of the landscape to cause damage to plants. Prescott (1931), listed the major factors affecting soil salinity as the amount and character of rainfall, the soil texture and local topography. The factors which determine where, how much and how quickly salt moves are soils, topography and hydrology.

Soil factors influencing salt accumulation

For the Lakes District soil survey (Teakle, Southern and Stokes, 1940), and the 3 500 farms area soil survey (Teakle, 1939), it was reported that heavier soils were the saltier, there being a good correlation between heaviness—or clayiness—of soil and salinity. In these cases the higher levels of salts were believed to be carried by the reduced percolation of water and salt through the fine textured soils into the groundwater.

Localised differences in salinity due to textural differences are reported for salt spots in the lower Rio Grande Valley in Texas (Lyles and Allen, 1966). The salt spots occur in relatively flat areas but are themselves higher in elevation and clay content than the surrounding soil. Because water runs off the salt spots,

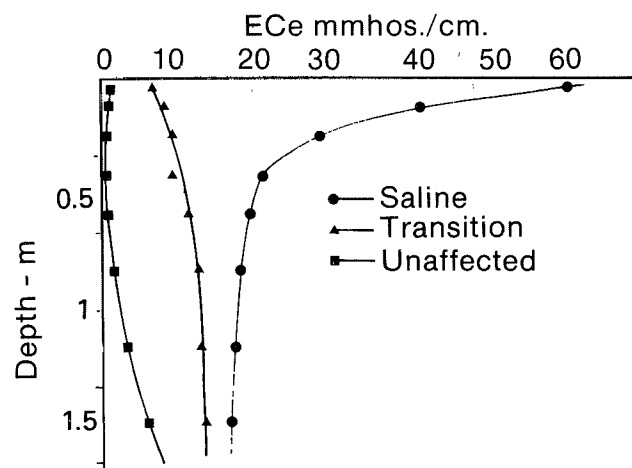


Figure 5.—Average salinity level in relation to depth for soils of three salinity categories. (Carter & Wiegand, 1965).

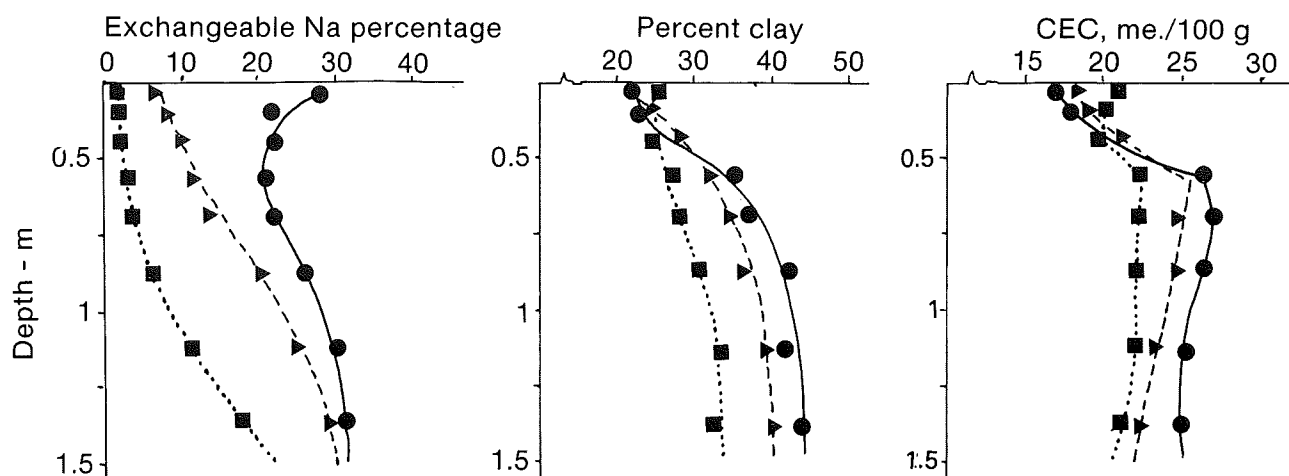


Figure 6.—Average exchangeable Na, clay and cation-exchange capacities in relation to depth for soils of three salinity categories. (Carter & Wiegand, 1965).

leaching is decreased there but increased in nearby depressions. Capillary rise from the regional water table then leads to greater salt accumulation on the rises. Data for the levels of salinity and clay in these soils are reported by Carter and Wiegand (1965), (Figures 5 and 6).

The possibility that similar differences may account for the variability in salinity over short distances in Western Australian soils has not been investigated.

On a broader scale, extensive soil surveys of low rainfall areas in Western Australia showed lower salinity in sandy-surfaced as distinct from fine textured soils (Teakle, 1939; Teakle *et al.*, 1940; Burvill, 1945).

However, Teakle (1938), has also indicated that in the 375 to 625 mm rainfall zone red-brown earths of sandy to loamy texture over clayey subsoil with decomposing rock at depth have accumulated salt in the clayey subsoil. This may be from a few centimetres to many metres deep.

Mulcahy (1960), reported on the salt content of soils between York and Quairading which he said represent an appreciable part of the inner agricultural area (rainfall 350 to 450 mm approximately). Soils of the lateritic and sandy uplands are generally acidic and low in salt, seldom rising above 0.01 per cent NaCl in any horizon; an exception being the Quailing erosional surface which can have 0.05 per cent NaCl in the surface and higher salinity at depth (see Table 8). Balkuling soils formed on the erosion products of the pallid and transitional zones of the old laterite, tend to become calcareous and high in soluble salts towards the drier eastern end of the study area. Soils of the York surface, with country rock as parent

material, tend to be somewhat more saline than soils on the lateritic surface and in spillways, while the finer textured soils of the Avon surface, which occur in the extensive valley floor, rise to over 0.18 per cent chloride within 0.6 m of the surface. The salt contents of the landscape surfaces are therefore related to the soil texture and profile characteristics, the rainfall and the topography.

Laboratory data on soils of the Merredin area are reported by Hingston and Bettenay (1961), and Bettenay *et al.* (1964), and follow the general pattern of soils in other areas by having higher amounts of salt stored in finer textured soils. They calculated that soils of the Belka Valley contained about 112×10^6 tonnes of salt, or 650 t ha^{-1} (this figure is minimum as sampling was not always to bedrock). The salt was not evenly distributed and, for example, sand—and gravel—plain soils comprised 47.8 per cent of the area but held 32 per cent of the total salts. Valley sides comprised 28.5 per cent of the area and contained only 4 per cent of the salt compared with valley floor soils covering 23.7 per cent of the total area but containing 65 per cent of the valley's total salt in their subsoils.

It may be concluded that although salt is mainly associated with finely textured soils, there are, in the lower horizons of some coarser textured soils, appreciable amounts of salt likely to be mobilised following clearing. These amounts are important in the development of salinity problems.

Parent material

In some areas of the world soils have formed from highly saline sedimentary rocks and as a result contain high salt. The original igneous parent material in Western Australia contained

TABLE 2.—Total soluble salts in soils in the Darling Range, Western Australia, in relation to annual rainfall.
(Mean \pm SD with range below)

Rainfall zone	No. of bores	Depth to rock (m)	Salt content (g/100g)	Salt storage* (x 10 ⁵ kg ha)
High (1 000 mm p.a.)	10	20.6 \pm 7.2 10.1 - 29.0	0.04 \pm 0.03 0.01 - 0.10	1.7 \pm 1.4 0.2 - 5.1
Medium (800-1 000 mm p.a.)	4	21.6 \pm 11.3 7.1 - 33.6	0.13 \pm 0.15 0.03 - 0.19	2.9 \pm 1.7 1.1 - 4.5
Low (800 mm p.a.)	29+	20.6 \pm 9.9 5.4 - 42.1	0.22 \pm 0.10 0.05 - 0.49	8.1 \pm 5.3 0.5 - 19.2
Bakers Hill area (590 mm p.a.)	19	22.5 \pm 10.5 7.1 - 42.1	0.25 \pm 0.10 0.10 - 0.49	9.5 \pm 5.4 2.3 - 19.2

* Assuming average bulk density of 1 700 kg/m³ for profile. (After Dimmock *et al.* 1974).

+ Includes six bores from Bakers Hill

little chloride but there has been sufficient chloride imported with the rainfall to account for that present in the landscape. Wind action in the region of salt lakes has been shown by Bettenay (1961), to have led to the formation of sheets of highly saline soil material comprising aggregates of clay, silt and sand blown from the lake beds. These saline and fine textured soils are not readily leached and cause problems in the growth of normal agricultural crops.

The pallid zone materials in the laterite profile have been shown to store appreciable quantities of salt in the landscape. They comprise, in many cases, a considerable depth of medium to fine textured soil material and have therefore been a major soil water storage and rooting medium. Dimmock, Bettenay and Mulcahy (1974), examined the salt content of lateritic profiles in the Darling Range (Table 2). In areas receiving 590 to 800 mm annual rainfall subsoils of pallid zone materials were found to contain up to 0.5 per cent total soluble salts. By contrast, where pallid zones were absent, as in the Avon Valley near York, salt

storage was low and soil salinity following clearing was of little consequence. Following dissection these saline zones may be exposed on pediments as soil parent materials (Stephens 1946).

Characteristics of saline soil.

Chemical and physical properties.

As salt was recognised early as a factor which could be responsible for limiting agricultural development, most Western Australian soil surveys conducted in agricultural areas have provided data concerning the salt content of soils. Other data, such as the mechanical composition of the soil profile and details of the exchangeable cations, are frequently provided.

Burvill (1947), provided a table summarising the results of several soil surveys (Table 3). The data indicate clearly that in the Lakes District and Salmon Gums District, a high proportion of the total area of non-sandplain soils was highly saline before development. Under virgin conditions, soils in these areas tended to be fine in texture and poorly leached.

TABLE 3.—Soil salinity in certain districts of Western Australia (After Burvill 1947).

District	Average annual rainfall (mm)	Area of normal agricultural soils*			Total area (ha)
		Low salinity (%)	Medium salinity (%)	High salinity (%)	
Lake Brown	280-330	72	14	14	118,741
Cleary	280	66	25	9	3 816
Lakes District	300-380	54	4	42	66 741
Salmon Gums	300-400	52	12	36	220 422

Some cleared land is included but scrub plain soils, low-lying lakey soil types, rocks, lakes, etc., are excluded from these areas.

Burvill (pers. com.) confirms that these criteria are the ones applied to define the categories in Table 5. The criteria are described in Teakle, Southern & Stokes (1940).

Salinity criteria used in the surveys are shown below.

Low salinity	0-30 cm	< 0.10% NaCl
	30-60 cm	< 0.25% NaCl
Medium salinity	0-30 cm	0.10-0.15% NaCl
	30-60 cm	0.25-0.30% NaCl
High salinity	0-30 cm	> 0.15% NaCl
	30-60 cm	> 0.30% NaCl

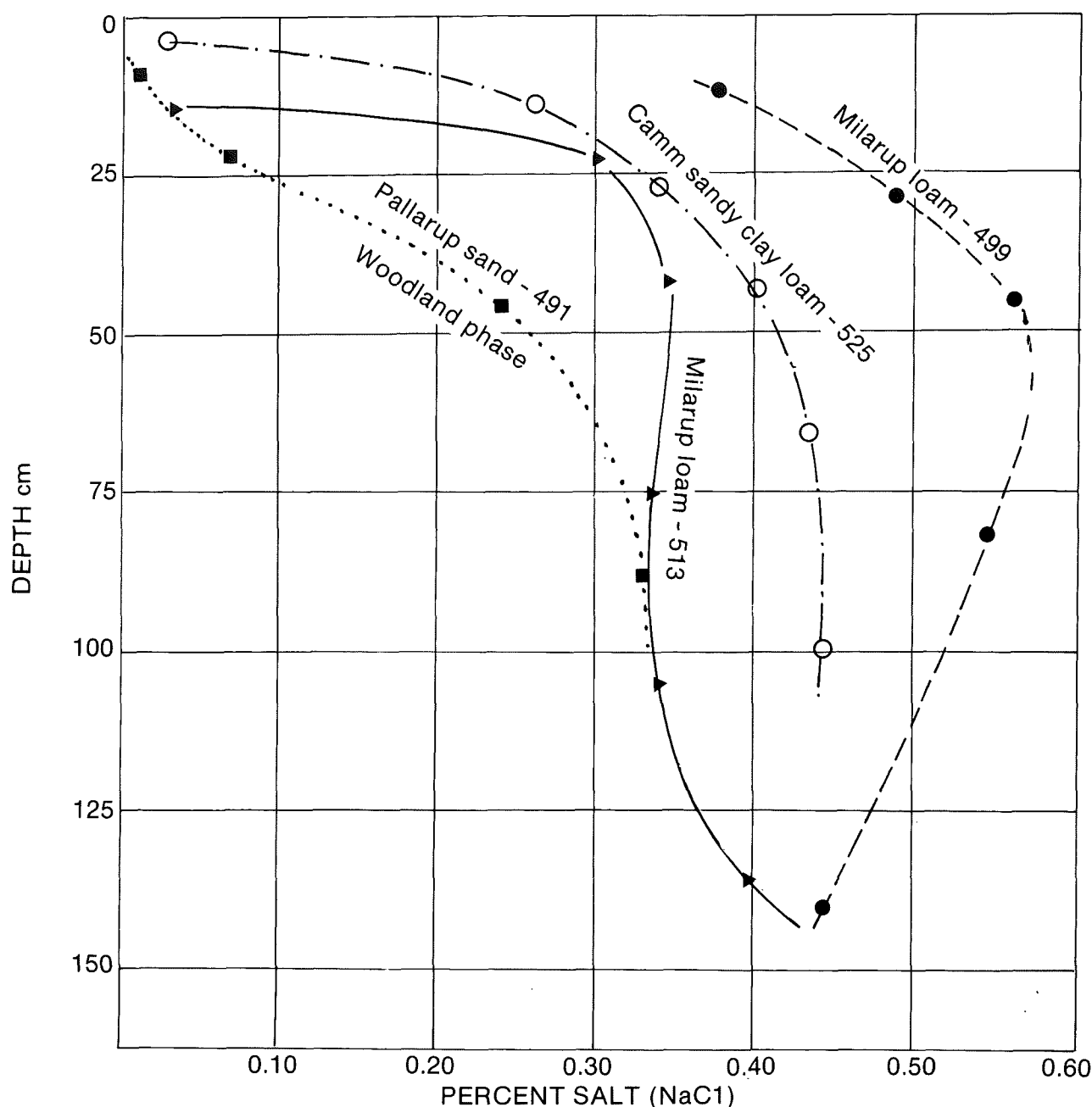


Figure 7.—Changes in salt concentration with depth in the case of representative virgin soil profiles. (Teakle, Southern & Stokes, 1940).

Salt levels in four profiles are compared in Figure 7 (Teakle et al., 1940). All profiles contained over 0.3 per cent salt in the subsoil. Sampling emphasized the woodland soils which were believed to be the most suitable for cropping. Prescott (1931), reported data obtained by Teakle on 650 soil samples from areas of sclerophyll woodland between Southern Cross and Salmon Gums (Table 4).

In this survey only about 12 per cent of the soils contained less than 0.1 per cent NaCl in the top 0.6 m and less than a third of the soils contained less than 0.2 per cent NaCl. It was

apparent from these data that large quantities of salts may be stored under virgin woodland conditions and the potential for the development of the salt problem following agricultural clearing could be very considerable.

Apart from soluble salts, saline soils may also contain high levels of exchangeable sodium and magnesium. The effect of high levels of exchangeable sodium, and to a lesser extent magnesium, in the absence of high levels of soluble salt, is to cause the soil to disperse readily when wetted. High levels of salt in the soil solution tend to keep the soil in a flocculated

TABLE 4.—Total content of NaCl in top 60 cm for 650 soil samples from between Southern Cross and Salmon Gums, Western Australia (Teakle)* (After Prescott 1931).

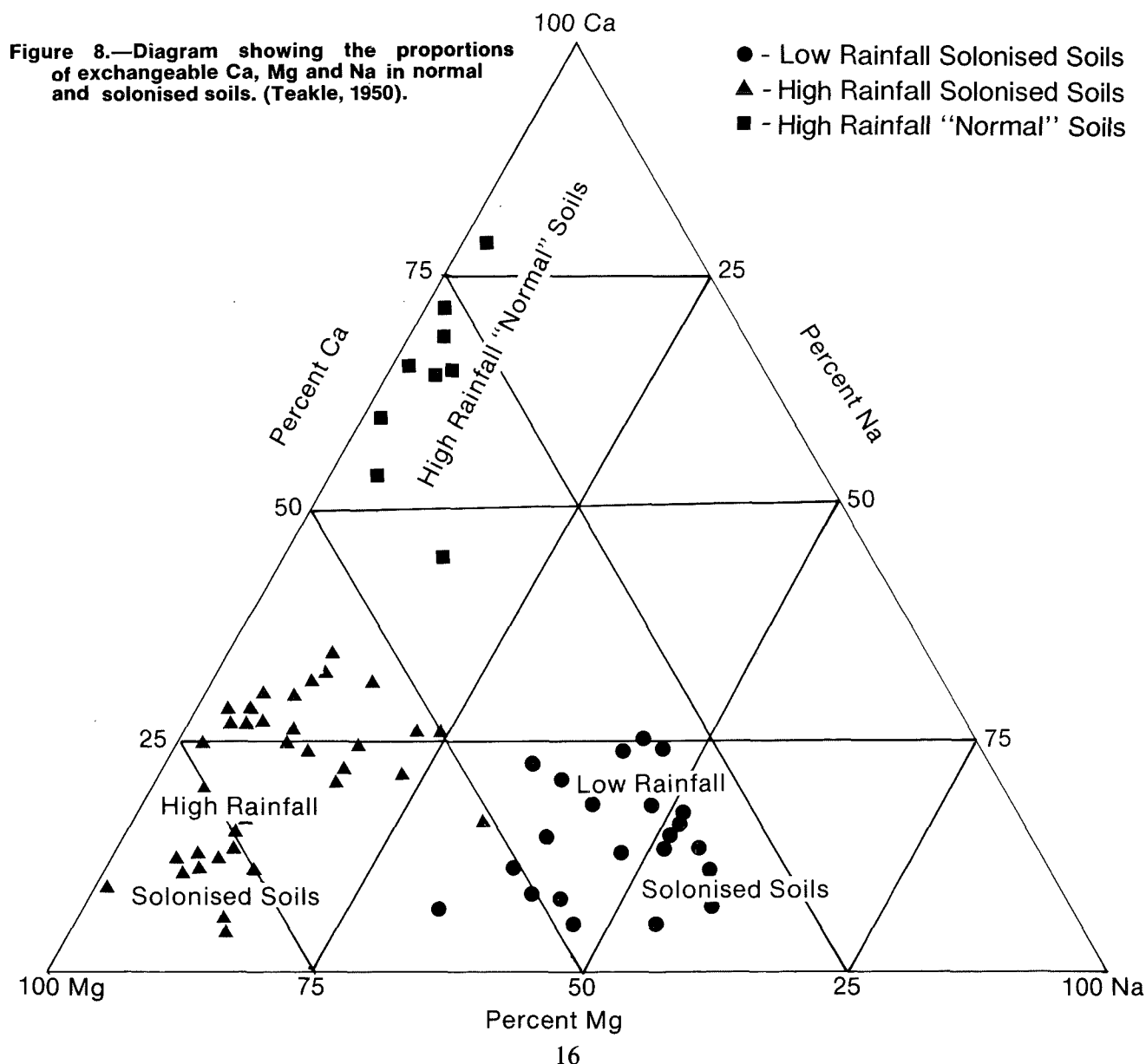
Salt content of soil to 0.6 m as percentage NaCl										
0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
to	to	to	to	to	to	to	to	to	to	to
0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1
Number of samples	83	120	117	100	66	45	25	11	8	2

*Data reported to Western Australian Government. Chloride determined by titration and expressed as NaCl.

condition but when salt affected soils are leached they usually disperse and water infiltration and movement are reduced.

Where excess salts have played an important part in the development of soil the resulting soils are referred to as solonised. They normally contain an excess of salts or a large proportion

of sodium, magnesium or both on the exchange complex of the clay. Such soils have certain structural and morphological features such as a surface of sand overlying a domed fine textured subsoil. Teakle (1950), examined the influence of salt in the development of Western Australian soils and Figure 8 shows the relationship he found between calcium,



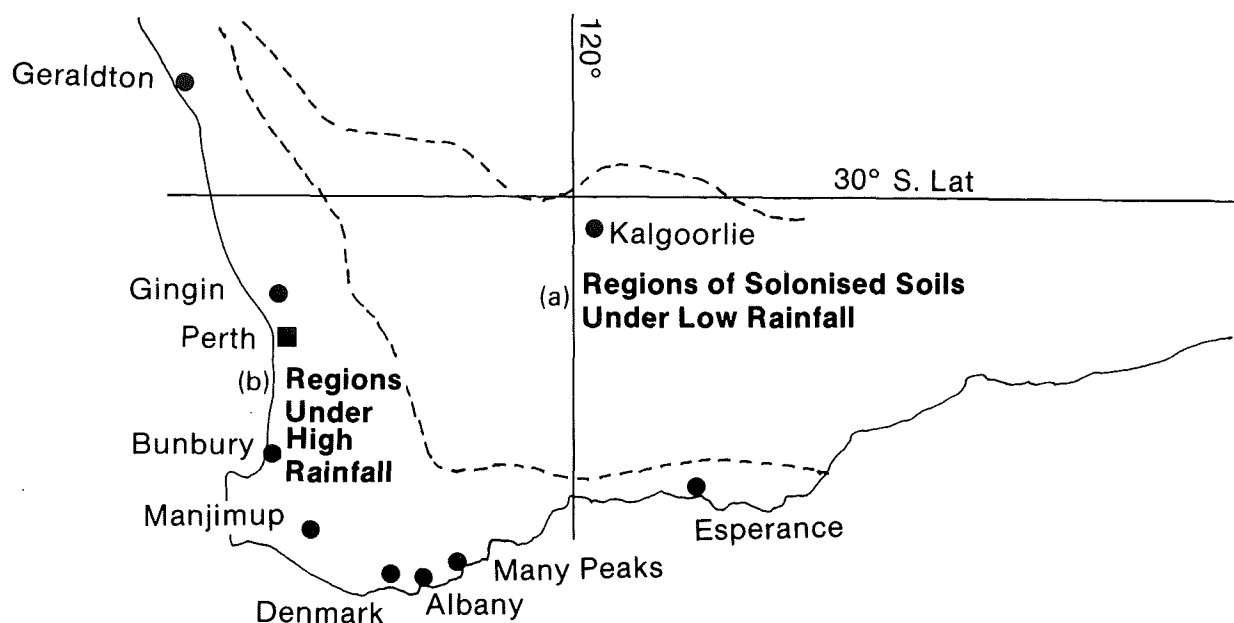


Figure 9.—The southern portion of Western Australia showing (a) the Location of regions of solonised soils under low rainfall (b), the high rainfall localities of Many Peaks, Denmark, Manjimup and Gingin from which soils were obtained. (Teakle, 1950).

magnesium and sodium on the exchange complex of normal and solonised soils in high and low rainfall areas. It will be seen that solonised soils in high rainfall areas normally contain high levels of exchangeable magnesium and low levels of exchangeable calcium and sodium. Solonised soils in low rainfall areas are commonly low in exchangeable calcium but moderately high in both exchangeable sodium and exchangeable magnesium.

Figure 9 shows the regions of solonised soils under low rainfall in the south west of this State and a comparison of this map with Figure 4 indicates that solonised soils occur in approximately the area receiving less than 5mm of rain per wet day on the average. Maps such as this tend to give the impression that salt affected soils are extremely widespread and of very great extent but Bettenay, Blackmore and Hingston (1962), reported that in the area covered by their survey in the Belka Valley only 2.2 per cent of the valley could be classified as saline soils because the huge quantities of salt in the landscape were in the subsoils not the surface.

Soil salinity classes

A major debate as to what level of salinity was significant in soils developed at the Royal Commission on the Mallee Belt and Esperance Lands in 1917. For the soil survey of the Lakes District, Teakle *et al.* (1940), used low, medium and high salinity categories to indicate the degree of salinity in various areas (Table 5).

The break-up of the soils of each of the major types into salinity categories does not include soils bearing heath vegetation or the areas of salt lakes as these were not included in the survey.

TABLE 5.— Salinity levels in wheatbelt soils before clearing. (Data from Teakle, Southern and Stokes 1940).

Vegetation type*	Degree of salinity		
	low	Medium	High
Salmon Gum woodland.....	70**	2	28
Morrel woodland.....	32	0	68
Gimlet and Merrit thickets.....	51	—	49
Mallee scrub.....	69	11	20

* See Glossary for botanical names.

** Percentages of the total surveyed area in the respective salinity classes. Limits for the salinity classes are shown in Table 3.

The most salt-affected of the soil types was that developed beneath Morrel woodland, for which 68 per cent of the area of the soil type was judged to be of high salinity. This may be compared with 49 per cent for Gimlet and Merrit thickets, 28 per cent for Salmon Gum woodland and 20 per cent for Mallee scrub. These classifications do not take account of the different behaviour of these soils with respect to salt movement after development. High salt levels in the Salmon Gums area were believed by Teakle (1939), to be responsible for wheat yields being only 56 per cent of the State average from 1922-1930. In an on-the-spot investigation Teakle found that the poorest

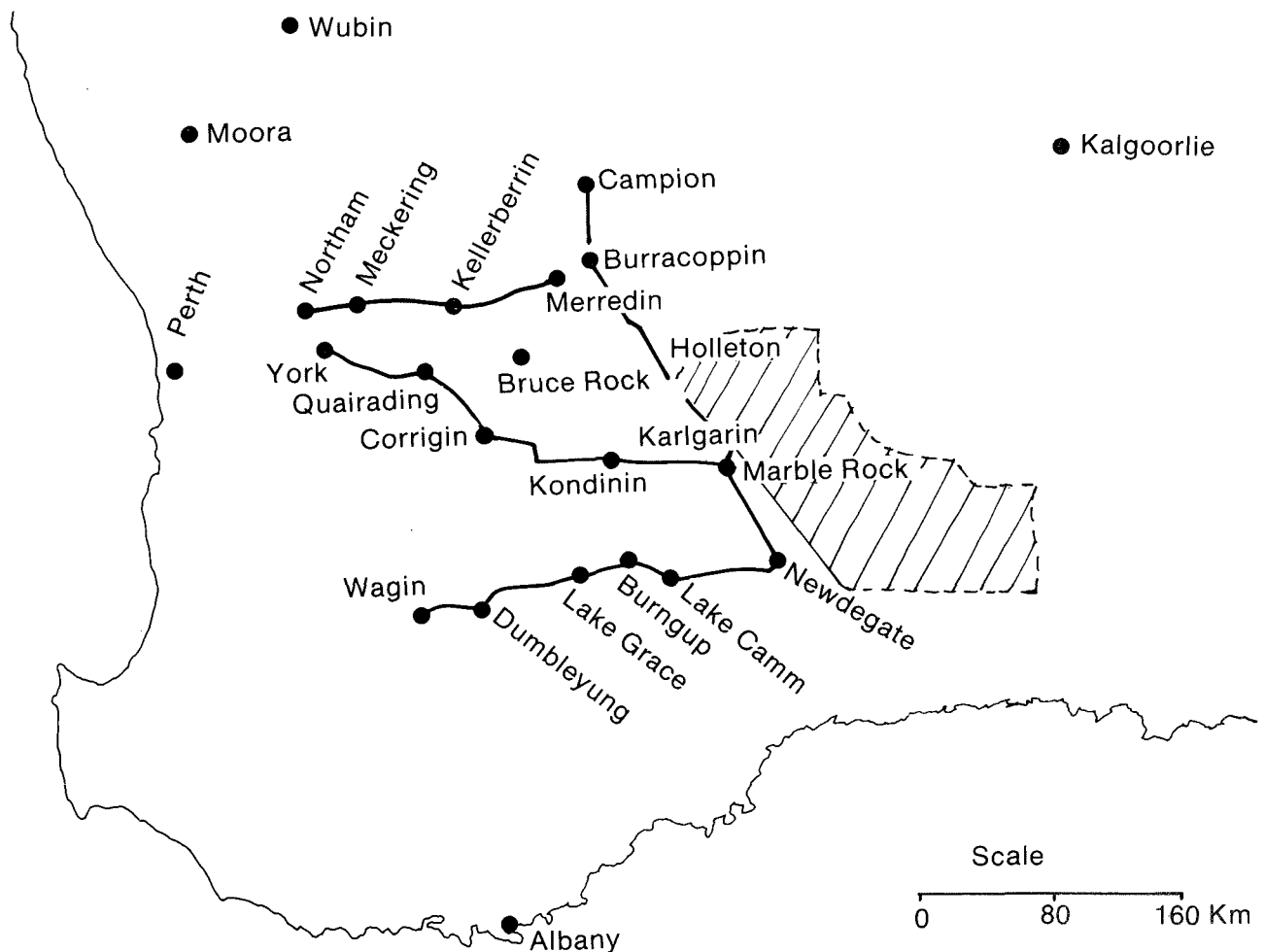


Figure 10.—South-west of Western Australia showing the location of the portion of the 3500 Farm Scheme investigated and traverses made to ascertain the conditions in the settled parts of the wheatbelt. (Teakle, 1939).

yields were in most cases on fine textured soils which still contained the high levels of salt present in the virgin state.

In attempting to interpret the results of the 3500 Farms Scheme soil survey, Teakle sampled woodland soils along several transects in the agricultural areas (Figure 10). Results of the samplings are shown in Figure 11. The sites sampled on the transects were on soils carrying Salmon Gum, Morrel and Gimlet vegetation, using virgin sites wherever possible. It was concluded that vegetation was not a good indicator of salinity, except in the case of Boree (*Melaleuca* sp.) and *Cratystylis* species. On woodland soils the second 0.3m of the subsoil varied considerably in salt content.

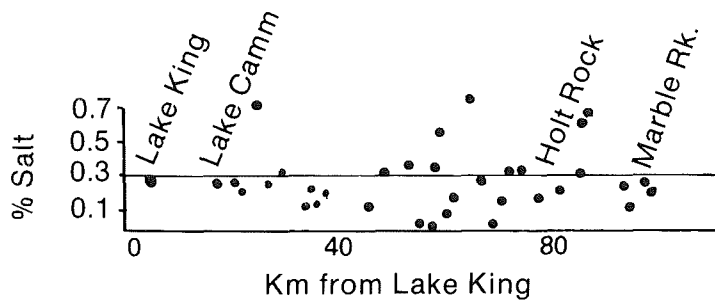
The influence of topography on soil salinity.

In the Salmon Gums district (Paterson, 1917 and Burvill, 1939) and in the wheatbelt (Burvill, 1950) where there is an absence of well defined water courses, salt problems develop on flats

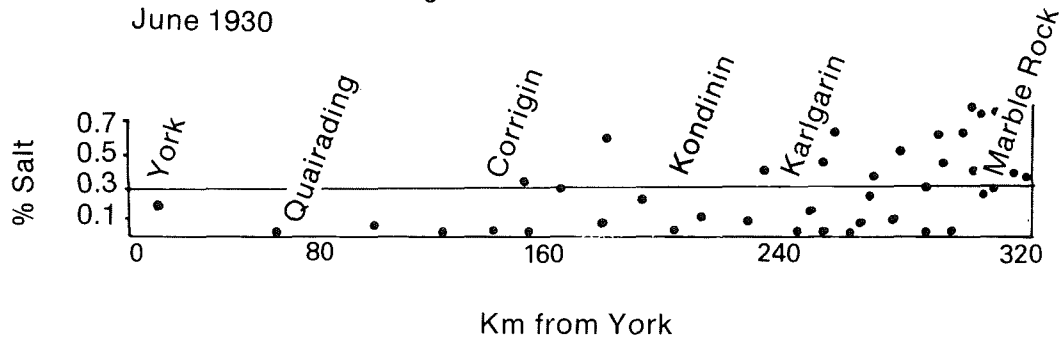
along the drainage lines. Overseas, salt problems under dry land conditions in the Lower Rio Grande Valley in Texas, in Saskatchewan and Alberta, Canada and North Dakota in the United States of America occur in flat to gently undulating soils (Greenlee *et al.*, 1968; Lüken, 1962; and Benz *et al.* 1976).

Soil surveys of the Lakes District and the Many Peaks district provide some of the earliest attempts at classifying soils and relating them to topography in Western Australia (Teakle *et al.*, 1940 and Teakle, 1953). Saline soils mainly occurred in the lowest parts of the topography.

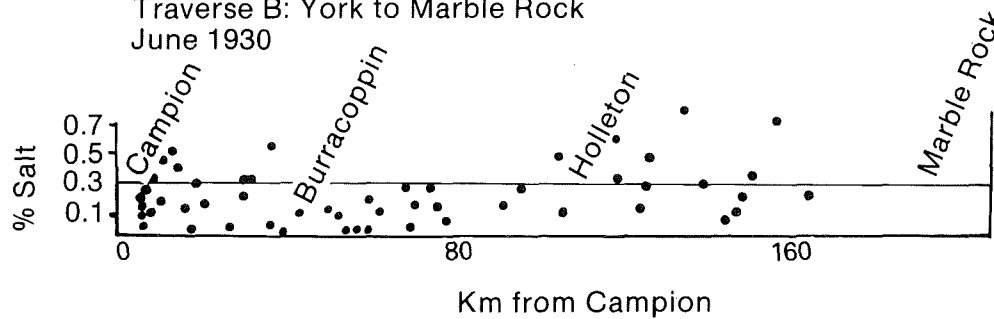
More recently, studies by CSIRO in the central wheatbelt have provided a clarification of the relationships of the soils to climate and topography. In his original studies Mulcahy (1950), studied the topographic relationships of laterite near York, and a detailed study of landscape evolution by Mulcahy and Hingston (1961), concerned the development and



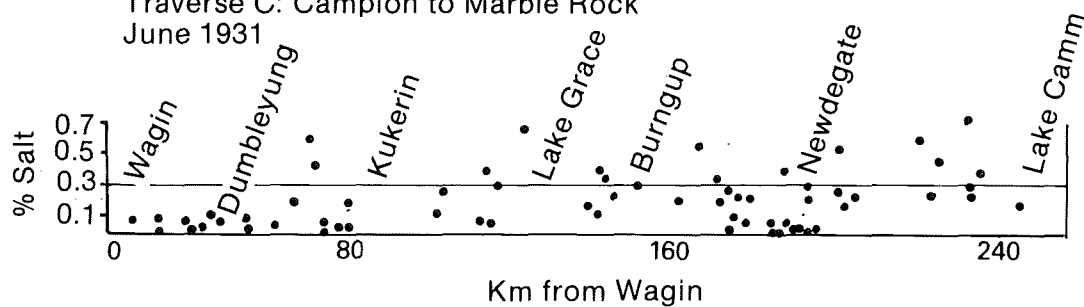
Traverse A: Lake King to Marble Rock
June 1930



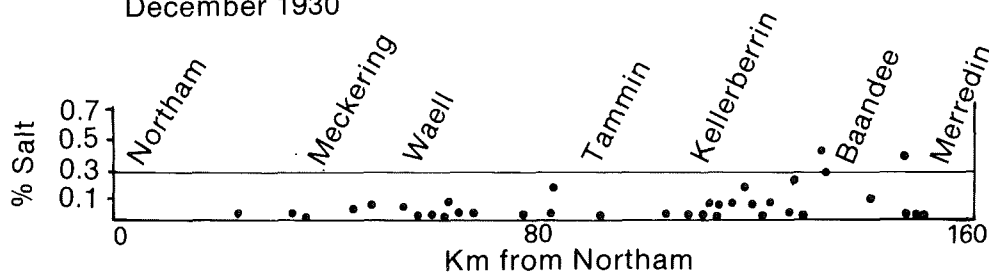
Traverse B: York to Marble Rock
June 1930



Traverse C: Campion to Marble Rock
June 1931



Traverse D: Wagin to Lake Camm
December 1930



Traverse E: Northam to Merredin
December 1931

*Distances are km by road

Figure 11.—Scatter diagram showing the concentration of salt (Sodium chloride) in the subsoil (between 0.3 and 0.6 m) of woodland soils along five traverses representing settled parts of the wheatbelt. (Teakle, 1939a).

distribution of soils in the York-Quairading area. This study was expanded by Mulcahy (1967), in his study of landscapes, laterite and soils in south-western Australia when he divided the whole of the south-west into different zones of drainage effectiveness. Finally, Bettenay and Mulcahy (1972), combined to report on the valley types in the south-west drainage division.

Results of the 1972 study have been summarised in Table 6. Data for the valley types known as Belka, Baandee, Merredin, Mortlock and Avon are those of greatest interest for saltland and Table 6 shows considerable differences between the various valley types in terms of grade, relief, drainage definition and factors such as presence or absence of saline groundwater.

Slope

Gradient down the main valleys named in Table 6 ranges from 1:1500 to 1:250. In general, valleys with the steepest grades are either not known to possess extensive groundwater, or have saline groundwater present but usually at a sufficient depth not to cause surface salting. On the other hand, valleys of lowest grade, Belka and Baandee, have saline groundwater, the former having developed saline areas since clearing and the latter containing extensive natural salt lake systems.

The author has observed in the Western Australian wheatbelt that saline areas tend to be associated, not only with the floors of broad flat low grade valleys, but also with changes in slope, whether these occur along the course of the valley or at the junction between the valley sides and floors. Groeneweg (1959), observed in the Mirool irrigation area of New South Wales that saline soils tended to develop at the

lower slopes of local sandhills and a similar observation was made by Ballantyne (1963), who observed that in south-eastern Saskatchewan saline areas occurred at and below a reduction in slope. The salt levels in the soil, in association with this phenomenon, are clearly illustrated in Figure 12.

Slope, in the instances discussed so far, affects salt accumulation in the soil by its effect on groundwater flow. An alternative situation is reported by Lükken (1962), who found that water entry was reduced on slopes with consequent reduction in salt leaching. The water which ran off provided greater leaching at lower levels in the landscape, although the effectiveness of leaching in this manner depended on the elevation of the groundwater and the permeability of the soil.

In their study of lateritic profiles in the Darling Range in Western Australia, Dimmock *et al.* (1974), found that the amount of salt stored in the profile was not markedly different for different positions in the landscape and increased as rainfall decreased for all slope positions. In this case a lack of slope effect resulted because there was a comparable depth of soil suitable for salt storage at each of the sites studied and at each slope position. By contrast, in the Belka Valley, Bettenay *et al.* (1964), showed that soils of the valley sides contained far less salt than valley floors because there was a shallower depth of soil on the slopes and it contained less salt per unit volume.

Dissection

There are two reasons for the degree of dissection of the landscape being important in the development of saline soils. Firstly, the degree of dissection determines to a

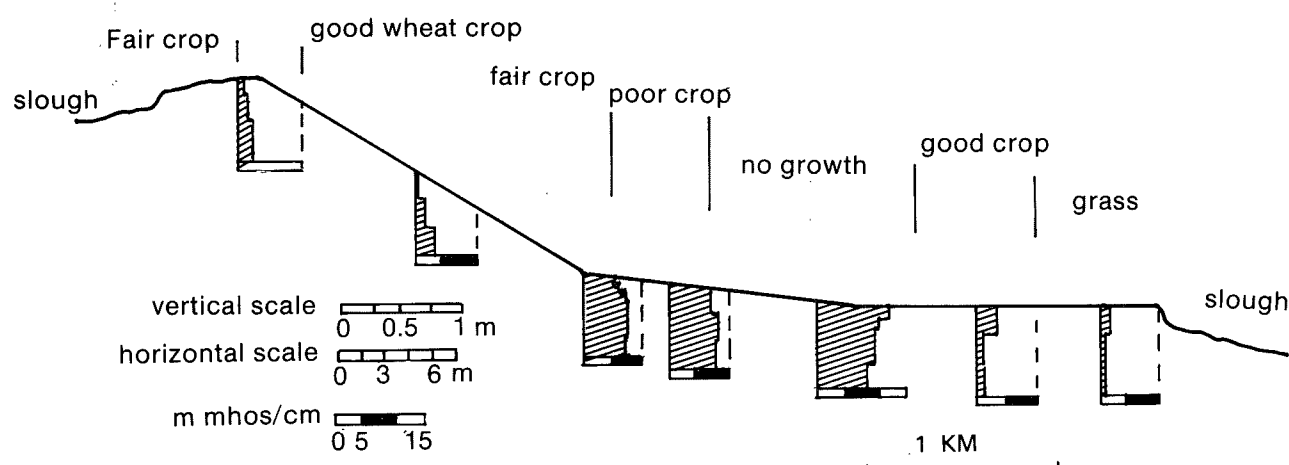


Figure 12.—Crop response, amount and position of salts (mmhos/cm, and hachures) and topographic position of profiles. (Ballantyne, 1963).

TABLE 6.—Characteristics of wheatbelt valley types in the Great Plateau and Rejuvenated Zone. (Extracted from Bettenay and Mulcahy, 1972)

Valley type	Grade	Relief	Width	Drainage definition	Lakes, etc.	Groundwater	Pallid zones	Alluvium	Valley floor	Tributary, trunk, etc.
Mature valleys of Great Plateau										
1. BAADEE	1:1500	60m	10-19km	Channels rare, rivers usually dry, water in sheets	Extensive salt lakes dunes, parna	Highly saline common < 6 m	30m+ under valleys	Saline loams etc. Modified by wind and lakes	Broad valleys with some drainage channels and lakes	Major saline trunks
2. BELKA	1:700 trips (inc to divide) to 1:1500 main	30-60m	6km	Ill-defined often braided, water in sheets	—	Saline, common, often < 6 m	30m+ under valleys	1-3m, sandy close to depositing streams, finer on broad flats	Flat, slight rises near depositing streams. Salt areas develop after clearing	Inland trunk and major tribs
3. MERREDIN	1:250 upper ends to 1:500 near trunks	30-60m	Floors to 3km	Ill-defined seasonal streams in lowest parts but also water in sheets	—	Saline where present but usually at depth	30m+ under valley	2m poorly sorted colluvium, often coarse sandy wash over finer soil in upper ends	Flat or concave Surface soils not salty	Tribes of Belka and Baandee
Mature valleys of Rejuvenated Zone										
1. MORTLOCK	1:650	30-45m	Floors to 5km	Well defined	—	Groundwaters present in pallid zones salt pools in streams	Present	4 to 5m of waterlaid terraces, lateritised	Flat, often saline	Tribes and trunks down-stream of Meckering line
2. AVON	1:250	45-75m		Well defined	—	Not known to be present extensively	Not a great depth of weathering	Truncated Morlock below alluv.	Flat, largely non-saline	Trunks down-stream of Morlock

TABLE 7.—Salinity data for type profiles in the Many Peaks Soil Survey (Teakle, 1953). The depths at which levels of NaCl above 0.01% were encountered are shown

Soil series	Parent material	Truncation	Dissection	Texture*	Depth (m)	NaCl%
Waychinicup	Laterite	Moderate	Minor	Loamy sand	84-198 (C)*	0.13-0.19
Moulyup	Sandstone	Appreciable	Minor	Loamy sand	84-122 (C)	0.01-0.05
Yilberup	Colluvium	Appreciable	Depressions	Sand	nil (C)	Trace
King Creek	Laterite	Minor	Minor	Loam	38-99 (C)	0.06-0.16
				Sandy loam	160-305 (C)	0.01-0.17
Carinyah	Colluvium	Major	Broad valley	Sandy loam	30-76 (C)	0.01-0.09
Tarnup	Laterite (?)	—	—	Loamy sand	25-142 (C)	0.11-0.15
					nil (C)	Trace
Corimup	Dunes	—	—	Sand	nil (S)	Trace
Many Peaks	Limestone	—	Deeply	Clay	30-71 (C & lime-stone)	0.01
Peak	Limestone	—	Shallow	Loam	36-117	0.02-0.17
Boulongup	Alluvium	Major	Depressions	Clay	56-198	0.19-0.46
Pleasant View	Thin clay over sandstone	Moderate	—	Loamy sand	Nil (C)	Trace

Texture refers to the surface horizon, by which the soil type is named. In most cases the subsoil is finer than the surface and the texture of the subsoil is indicated in brackets after the depth i.e. C = clay, S = sand.

considerable degree the opportunity for salts to drain out of the landscape and into the river system. Secondly, the degree of dissection directly affects the parent materials from which the soils are formed.

In a Many Peaks soil survey the highest soils in the landscape were formed, in general, on materials from the old laterite profile still *in situ* (Table 7) (Teakle, 1953). Where the laterite has been removed by erosion, the sandstone is exposed and provides a parent material for soil formation. The lowest parts of the landscape comprise soils formed on materials transported from higher levels. Accumulations of salt are found in the profiles of soils at all levels in the landscape but the sandy soils are low in salt. The clay depression has a salty soil but dissected shallow clay is not saline. Of the loamy sands the dissected Tarnup series is low in salt and the highest levels are in the Waychinicup series with minor dissection and only moderate truncation.

The importance of truncation and dissection, from the points of view of parent material and the possibility for drainage of the landscape in south-western Australia, are clearly illustrated in the studies of Bettenay and Mulcahy, (1972), (Table 6). Throughout the area the highest landscapes are usually the remnants of the old plateau, comprising coarse textured soils with sandy and gravelly surfaces overlying finer textured subsoils often of great depth. When the plateau is dissected, successive layers of the old laterite profile are truncated; consequently soils may be formed either on the remnants of the old laterite profile, or on the products of erosion which form pediments downslope of the

erosional surfaces (Stephens, 1946). In some cases the transported material lies on top of old eroded surfaces. All of the major river systems tap ancient drainage lines with salt lake chains in their upper reaches. Downstream of the salt lake chains, the valleys are successively more sharply incised and steeper and are stages in the rejuvenation of drainage of the uplifted old plateau.

The situation is further complicated by the possibility that there has been more than one cycle of lateritisation. Valleys of transported material within the old plateau may have had younger laterites formed *in situ*. These may now be eroding or may be buried beneath the products of present erosional cycles. The topographical relationships of the various soils which result from this process of landscape modification are reported in several publications (Mulcahy, 1959, 1960 and 1967; Mulcahy and Hingston, 1961; Bettenay and Hingston, 1964; and Bettenay and Mulcahy, 1972).

The inter-relationships which develop between the various soil surfaces and layers in the landscape, during dissection and truncation of the old plateau and erosion of the country rock, may be partly responsible for the development of saline areas. The relationships between the surfaces named by Hingston and Mulcahy, (1961), (Table 8) are illustrated in Figure 13. It is a common observation that seepages develop at the base of the spillway formations but owing to the low salt content of the sandy spillway soil the seepages are normally fresh. However, if conditions are such that concentration by evaporation is possible, or

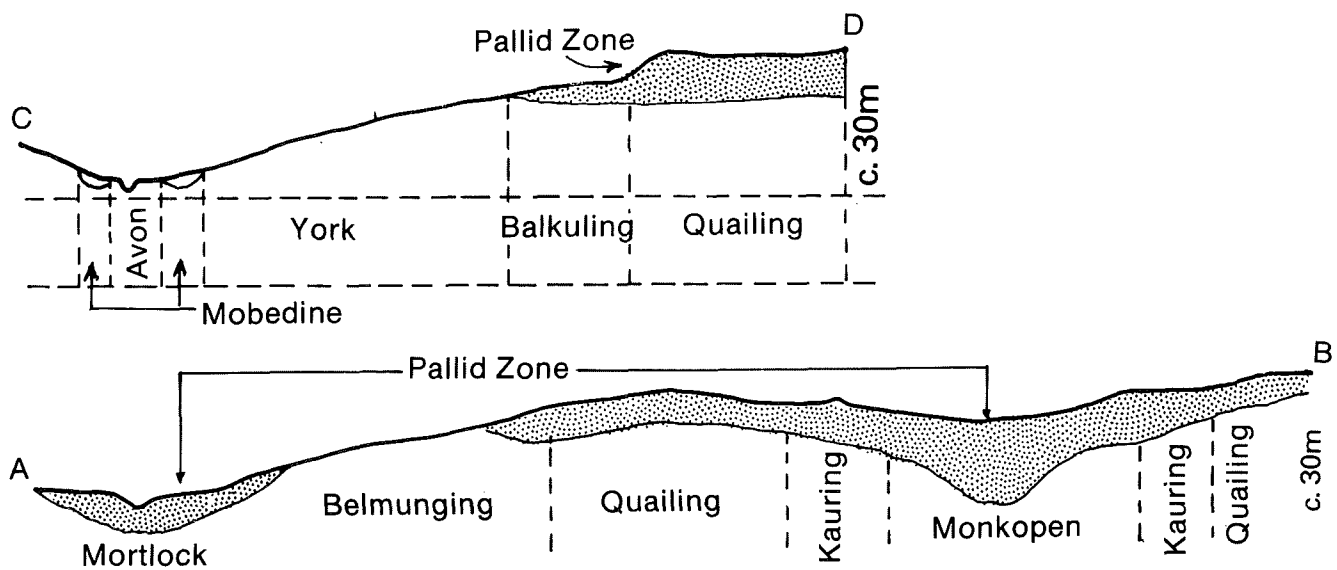
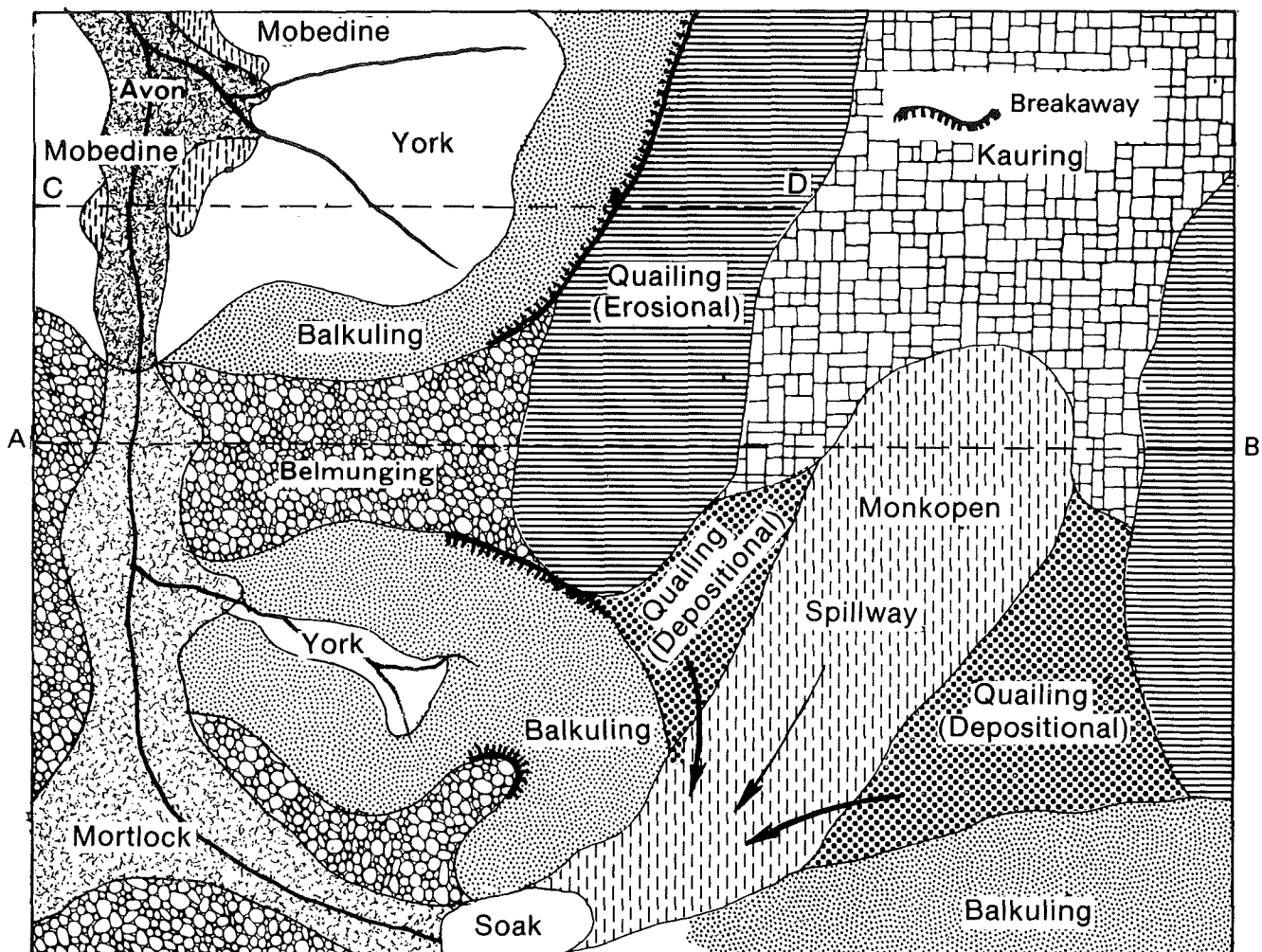


Figure 13.—Detailed distribution of the landscape surfaces in the York-Quairading area. (Mulcahy, 1959).

TABLE 8.—Salt contents of some type profiles in the York-Quairading area. (After Hingston and Mulcahy, 1961).

Name	Landscape surface Description	Salinity range (NaCl %)	Depth range sampled** (m)
Quailing (erosional)	Sandy surface, texture increasing with depth gravel from 0.20 m	0.03-0.04	0-1
Quailing (erosional)	Sandy clay loam transitional and pallid zone	0.38-1.7	2.7-7
Quailing (depositional)	Deep sandy spillway deposit	trace*	0-2
Monkopen	Sandy spillway gravel at 1.4 m	trace-0.03	0.2-5.2
Belmunging	Dissected laterite, sand over gravelly sandy loam	trace	0-1
Mortlock	Alluvium	trace	0-1.8
Balkuling (calcareous)	Gritty clay soil formed on transitional zone material	trace-0.11	0-1
Balkuling (low level)	Gritty sand overlying clay formed on transitional zone material	trace-0.22	0.1-1.3
York	Clay soil formed on epidiorite	0.01-0.02	0-0.8
York	Loam surface overlying clay with grit and rock formed on gneiss and basic rock	0.26-0.40 ⁺	0.1-1.3
Avon	Alluvium, sandy loam over clay loam. some gravel	0.05-0.28	0-2.2

* Trace = less than 0.01% NaCl.

** The deeper subsoils of some surfaces, e.g. Balkuling, are highly saline.

+ This seems to be an unusual soil perhaps affected by secondary salinity since other York soils are reported to have salinities of 0.003 to 0.03% NaCl, (Bettenay personal communication).

if on its way to the soakage the water is able to dissolve appreciable amounts of salt from the materials through which it passes, saline seepage areas will develop.

Mulcahy (1959), indicates that the sandy deposits may be 15 or more metres deep and that there is evidence of more than one layer of deposition separated by bands of ferruginous concretions.

Mulcahy and Hingston (1961), report that soils of the Balkuling surface are not highly saline but tend to be higher in salt the further east they occur. In places subsoils of Balkuling (or Booraan) soils which are derived from pallid zones are naturally saline, having 0.5 per cent total salts (Hingston and Bettenay, 1961). The subsoils beneath the Balkuling surfaces in Table 8 would be expected to be highly saline

(Bettenay, private communication) and Balkuling soils are frequently saline in the vicinity of intermittent brackish springs. These form seepages around the base of the breakaways and may outcrop at the junction between the transitional zone and the country rock at the downslope limit of pediments, that is, at the junction between the Balkuling and York surfaces.

The same authors draw attention to the contrast between the tributaries of the Avon and Mortlock Rivers in the area of their survey. The tributaries of the Avon are relatively short and their valleys sharply cut, while those of the Mortlock are long, with a gentle fall and sluggish flow. The latter are thus often filled with sandy detritus and more liable to salt accumulations.

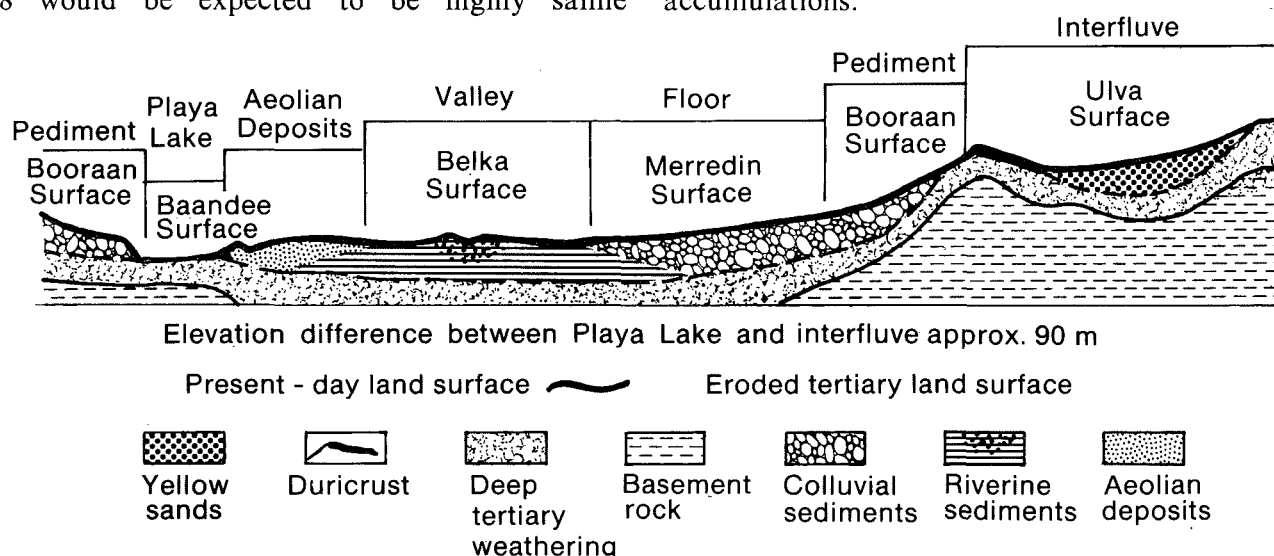
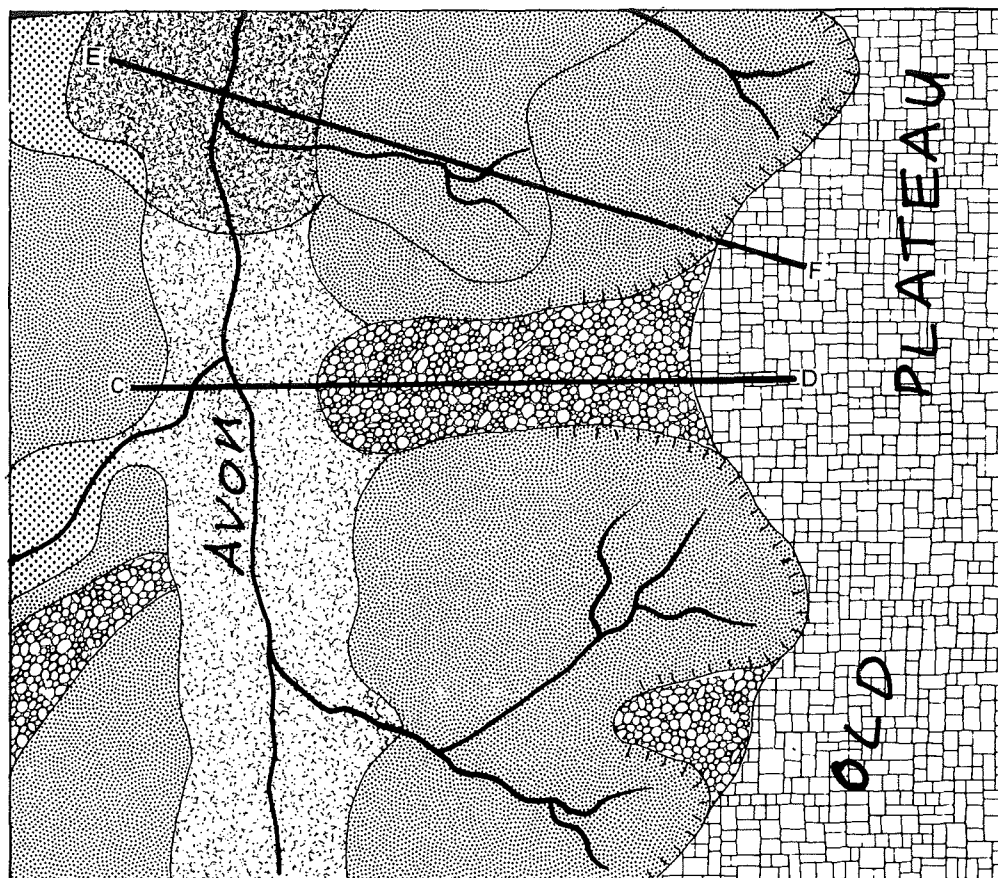


Figure 14.—Modification of the laterised tertiary landscapes in the Belka Valley in S.W. Australia. (Bettenay & Hingston, 1964).



Key to surfaces

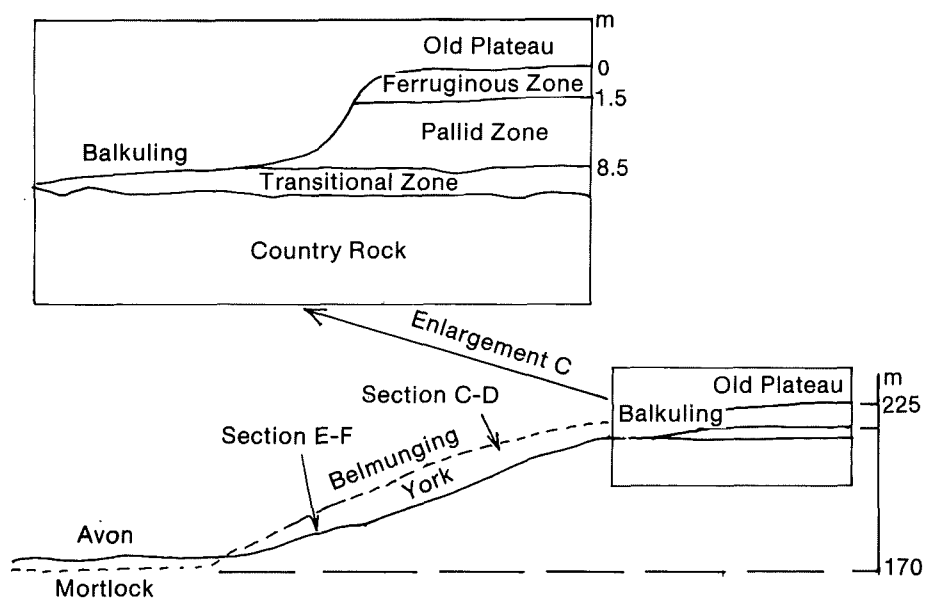


Figure 15.—Dissection of old valley, and the laterite profile and its relation to the younger surfaces in the York-Quairading area in S.W. Australia. (Mulcahy, 1960).

The eastern-most section of the soil survey work of Mulcahy and Hingston (1961), is in the vicinity of Quairading and northwards, an area considered typical of a considerable part of the wheatbelt. Attention is drawn to the occurrence of wet saline areas often associated with the end points of distributory streams on the Avon surface. The pallid zones of the Mortlock surface are present as deep highly weathered dense saline clay beneath the Avon surface north east of Quairading.

The inter-relationships of the soils and landscapes are shown in Figures 14 and 15 for the Belka and York-Quairading areas respectively. The juxtaposition of the various soil surfaces and their subsurface layers indicate many points in the landscape at which salt may have accumulated before use of the land for agriculture. There are also many ways in which water may move into and through the surfaces

and their subsoils, with resulting redistribution of the salt and its reappearance at various points lower down the landscape. The distribution of the old, mature and young drainage types referred to in Table 6 is shown in Figure 16. It can be seen that for most of the wheat growing areas the major trunk valleys are those of the old drainage systems.

The soil surveys have established the principles on which the landscape has developed and the figures give representative sections of landscape. For specific areas of saltland it is necessary to identify the surfaces and the relationships between them to understand the source of the salt problem.

Micro-topography

Crabholes (gilgais) are depressions of one to several metres diameter, and up to half a metre deep, which occur in some fine textured soils.

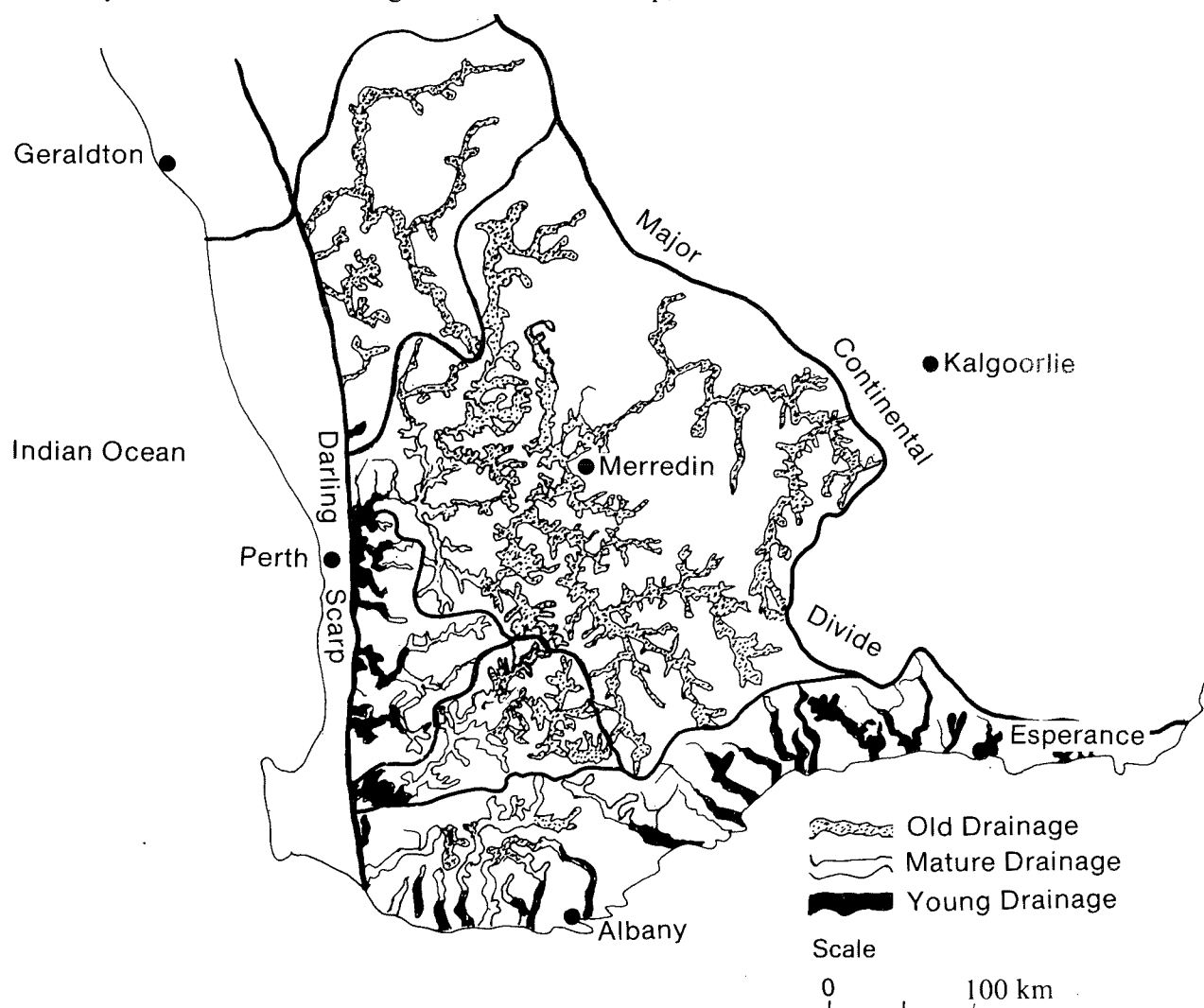


Figure 16.—The south west drainage division in Western Australia showing the extent of young, mature and old drainage. (Bettenay & Mulcahy, 1972).

Teakle and Burvill (1938), drew attention to the fact that the rims of many gilgais were salt affected and Charley and McGarity (1964), also found the rim or shelf to have much higher nitrate and chloride levels than depressions. It was postulated that when water was in the crabhole there was a capillary or 'wick' action set up whereby evaporation occurred at the rims and salts became concentrated in that position.

In studies in the United States of America, Bernstein and Fireman (1957), have indicated that micro-topography of the soil may be important in influencing salt movement and in particular salt concentrations that may occur in the surface where seeds are germinating. Studies of various bed shapes prepared for planting irrigation crops showed that seeds planted on the top of square or rounded mounds were likely to be subjected to high salt concentrations due to a wick action occurring from water in the adjacent irrigation channel. If seed was planted on the slope of a relatively flat but nevertheless sloping bed, salts tended to move from the furrow, past the seed to the tip of the bed, giving more favourable conditions for germination.

Workers in the lower Rio Grande Valley in Texas also observed differences in soil salinity associated with small rises. They found that salt spots apparently scattered at random were higher in elevation than the non-saline soils in the area (Lyles and Allen, 1965; Carter and Wiegand, 1965).

Hydrology and salinity

Some valley types in south western Australia are described in Table 6. The salt lake system in the Western Australian wheatbelt has been discussed by Bettenay (1961), and by Bettenay and Mulcahy (1972), and described as the surface expression of extensive saline groundwaters lying beneath the main trunk valleys of the Baandee type. The Belka valleys are of a slightly steeper grade and the groundwaters are marginally deeper, although salinity may develop after clearing. In the Merredin type valleys the groundwater is present and saline but usually at sufficient depth not to cause soil salinity. In the rejuvenated zone the mature valleys are steeper than those in the great plateau and have defined stream systems; saline groundwaters are present in some cases but are not as extensive as in the Great Plateau valleys.

Salinity problems are therefore related to the valley types and their grades, increasing from the steepest to the flattest valleys.

Downstream from the salt lake system the grade of valleys increases and Morrissey (1974) has pointed out that the Blackwood River has a reverse longitudinal salinity profile compared with normal river systems. Salinity of the Blackwood River decreases as it gets closer to its mouth because of fresh in-flow near the coast.

Bettenay *et al.*, (1962), studied the groundwater in the Belka Valley. The groundwater was present over much of the valley, usually confined and sub-artesian, and its salinity increased from the highest points in the landscape to the trunk (main) valley system. The main aquifer bearing the water appeared to be in the zone of decomposed rock underlying both the pallid zone material and the alluvial deposits in the valleys. Where the overlay of relatively impermeable material was sufficiently thin, and the elevation low the groundwater found its expression in saline soils and lakes. The decomposed rock layer was more permeable than the pallid zone but Bettenay (private communication) believes that both contain large volumes of water.

Localised groundwater flow systems comprise the seepage areas which occur beneath spillways of sand, around the base of breakaways and at the junction between the transitional zone and the country rock, downslope of pediment limits (Mulcahy and Hingston, 1961). Hydrological aspects of salinity problems will be discussed in detail in later sections.

Effect of land use on salinity

The earliest indications that removing native vegetation caused salinity came from the effect on railway water supplies (Bleazby, 1917). Bleazby noted that the common overseas practice of ringbarking vegetation on water supply catchments to increase water yield was followed in Western Australia by increased salinity. In other cases salinity was noted where there was agricultural development in the catchment of railway reservoirs. It became the practice to preserve the catchments of reservoirs in order to protect them from salinity.

The influence of vegetation removal on soil salinity was discussed by Paterson (1917). He claimed that forest scrub influenced salt behaviour by using water and thereby stopping salt rising, not by using salt. After land was cleared the salt was assumed to move from the

high ground to the low ground by surface and underground flow. Teakle (1928) and (1929), also discussed the importance of clearing in causing the salt problem. Roots under forest, he claimed, prevented the movement of salt to the surface by capillarity because they absorbed the moisture too rapidly. The importance of vegetation removal was thus recognised very early in the development of the salt problem.

There are many overseas reports of increased water flow in catchments following forest clearing. Reports of an effect of clearing on soil salinity are uncommon but Greenlee *et al.*, (1968), reported that removal of brush from areas in south-western Alberta was thought to have decreased evapotranspiration and thereby contributed to a rise in the saline groundwater and an increase in salinity at the soil surface.

Williamson and Bettenay (1979), studied the change in groundwater levels and run-off salinity in a catchment at Bakers Hill, Western Australia, following replacement of perennial vegetation with annual crops and pasture. The groundwater fluctuated annually but was higher each year than the year before. When the potentiometric level of groundwater approached the soil surface there was a major increase in the salinity of run-off, indicating contribution from saline groundwater.

The effect on the water and salt yield of catchments of replacing natural vegetation with annual crops and pastures has been studied in considerable detail for high rainfall areas in Western Australia (e.g. Peck and Hurle, 1973). These studies indicate similar water and salt movement is occurring to that in low rainfall areas, but at a much faster rate.

Salt movement and accumulation in soil and groundwater

It has been shown in earlier sections that there were appreciable amounts of salt present in many Western Australian soils before agricultural development. In certain areas, the salts were present at the surface in sufficient quantities to have an adverse effect on plant growth. In other cases there was sufficient salt present in soils with susceptible physical characteristics for the salts to concentrate at the surface under agricultural use. Other areas contained less salt and what was present was likely to be washed further into the ground after clearing.

An essential feature of salinity problems is that sufficient salt accumulates in the surface or root zone layers of soil to reduce or inhibit the growth of normal crops and pasture plants. Consideration therefore must be given to the way in which salts move and accumulate in the soil and groundwater.

Yaalon (1963), described the types of moisture regimes governing the accumulation of salts in soils (Figure 17). Under his first set of conditions, which he called 'normal percolative', rainfall exceeds evaporation for most of the year, the subsoil is permeable, the water table low and salts do not accumulate in the soil but are leached through the profile and into the drainage system.

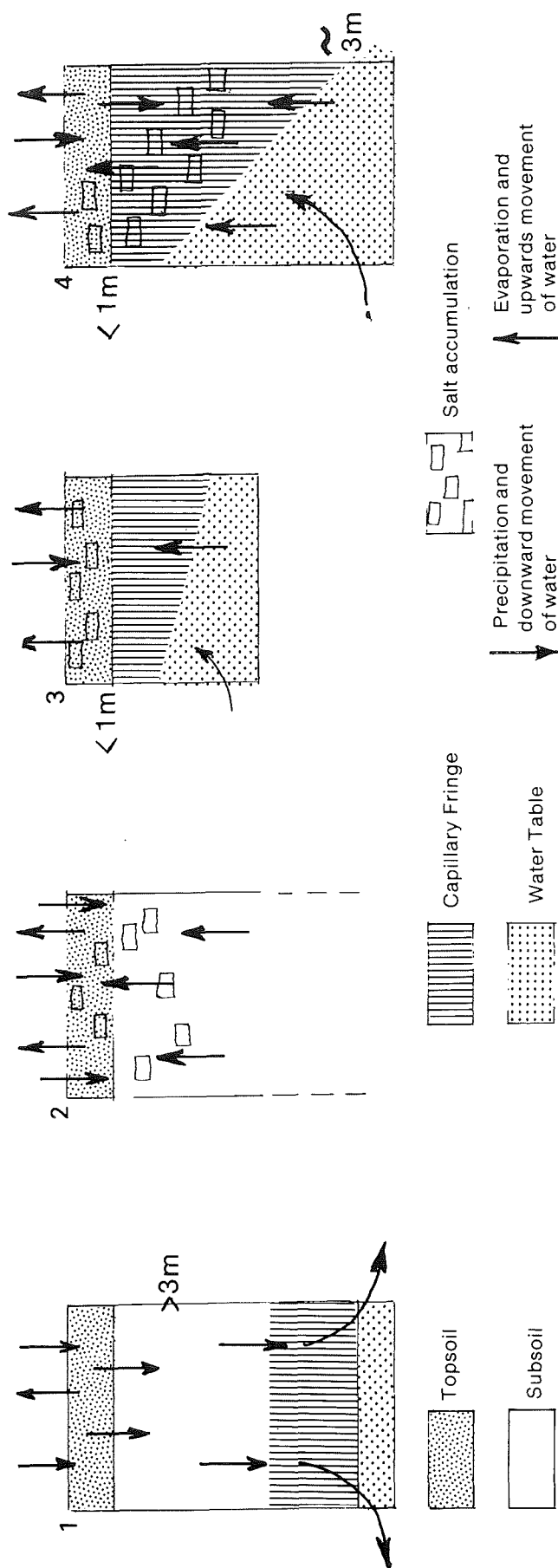
No salt or water imported in ground water

Yaalon (1963), refers to a moisture regime where evaporation exceeds precipitation except for very short periods as 'sub-percolative' (See Figure 17). There is insufficient water to wash salts out of the soil profile and the depth of accumulation coincides with the depth of wetting of the soil. These conditions approximate those for the dry fringe areas of the agricultural districts of Western Australia where early soil surveys have shown salts to have accumulated in the soil profile. Typical soils developed under these conditions and in which groundwater either as seepage or as a watertable has no influence are the Morrel soils of the wheatbelt. Bettenay and Hingston (1964), reported that parna (frequently Morrel) soils in the Merredin district have a mean NaCl content of 0.41 per cent.

Influence of plants on salt movement and accumulation

Early agricultural development in the Western Australian wheatbelt concentrated on finer textured soils. The agricultural practices adopted included bare fallow as a method of releasing nitrogen and for storing soil water for cereal cropping. As a result on soils in which high salt was a natural feature, evaporation from bare fallow encouraged accumulation of salts in the surface.

Smith (1962), set out to determine the effect on salt distribution of removing grass cover from a potentially saline soil. He studied a fine



	1	2	3	4
Type of moisture regime	Normal percolative	Subpercolative	Epercolative	Amphipercolative
Precipitation/evaporation ratio	P>E most of the year	E>P except for very short periods	E>P most of the year	Variable with season
Topography	Flat or sloping low land	Mostly flat	Flat bottomland	Flat bottomland
Permeability of subsoil	Good to moderate	None; dry subsoil	Poor	Poor to fair
Water table	Low	None; dry subsoil	Constantly high	Fluctuating with season
Moisture movement	Outflow of excess moisture	Evaporation of suspended water	Evaporation and ascending movement of imported water	Alternating down movement of imported water
Origin of salts	Weathered and air-borne sea salts leach through the soil profile	Imported by precipitation and released by weathering	Imported by inflowing water	Imported by inflowing water and precipitation
Mode of accumulation	Absorption of Na during possible leaching	At depth of wetting	At surface if water table at 1 m in subsoil if deeper	In subsoil at balance between evaporation and leaching

Figure 17.—Modes of salt accumulation in soils. (Yaalon, 1963).

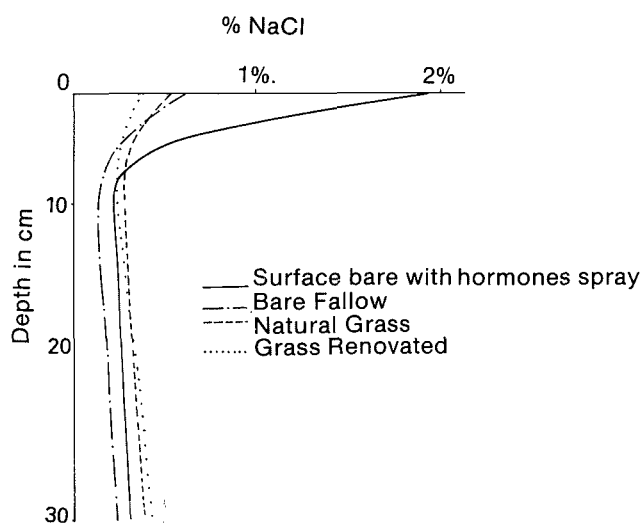


Figure 18.—Effect of land treatment on salt rise. (Smith, 1962).

textured soil in the absence of groundwater influence and his results (Figure 18) indicated that in treatments designed to give a bare surface, but not in those with a grassed surface, salt concentration in the soil surface was significantly higher than in sub-surface layers. A surface bared by hormone sprays reached a much higher level of salt than all other treatments, there being no significant difference between the surface levels in the other three. Smith's results indicated the potential danger of overgrazing saline soils and he suggested that irregularities in grazing may be responsible for development of patchy bare areas. Salt levels at 0.075 m to 0.3 m in the two bare treatments were significantly lower than in the normal pasture plot and the overall lowest salinity was in the cultivated fallow.

It is apparent that the better infiltration under grass demonstrated by Stoneman (unpublished data), and the ability of the grass to reduce surface evaporation and to dry the surface soil out, have been responsible for reducing surface salt accumulation in soil beneath grass. In bare areas, evaporation from the soil surface draws moisture to the surface and results in a high surface concentration of salt.

A comparison of salt distribution in soil beneath bare and grassed areas was obtained by Teakle and Burvill (1938), by conducting a detailed sampling from the surface down to 90 cm over distance of 180 m across a salt-affected

area (Figure 19). The surface soil beneath grass was commonly below 0.05 per cent NaCl while that in bare areas was in some cases above 2 per cent. Differences in salt content extended in many cases to at least 0.9 m. The differences demonstrated between grass and bare soil were most dramatic for the fine textured Morrel soil at Welbungin. Salt differences in a Salmon Gum soil at Ghooli on the Yilgarn Research Station were not as great. Data were not obtained to show whether the saline and non-saline sites differed significantly in texture or infiltration, factors which would influence salt levels and plant cover.

The influence of plants on salt movement is further discussed in the sections dealing with Capillary rise and critical depth, and Control of capillary rise.

Effect of climate on salt movement and accumulation

According to Yaalon (1963), the position of the horizon of maximum salt accumulation in a soil is a function of the seasonal balance of rain and evaporation (in the absence of a water table). Van Schaik and Cairns (1969), observed that for saline soils in Canada gradual leaching of salt is possible if climatic conditions allow for a net downward movement of water in the soil. However, in the Lower Rio Grande Valley in Texas, Lyles and Allen (1966), pointed out that rainfall alone in an area receiving an annual average around 400 to 500 mm was insufficient to remove soluble salts and maintain them at a low level.

Effect of soil on salt movement and accumulation

Reference has already been made to the effect of soil characteristics, such as texture, on the distribution of salts in the landscape before clearing. The same factors affect salt distribution under agricultural use. As indicated by Doering *et al.*, (1964), salts move in solution in soils by either mass transport or diffusion. Mass transport occurs when the water in which salts are dissolved moves within the soil in response to suction or pressure gradients. Diffusion occurs when there is a concentration gradient within the soil solution. Diffusion is normally much slower than mass transport but Doering *et al.*, (1964), have suggested that there may be back diffusion from high surface salt concentrations in arid regions during summer if

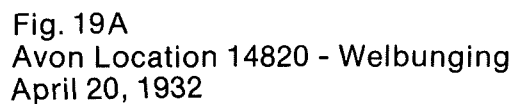


Figure 19B-C.—The distribution of salt in cleared soils which have become affected by salt accumulation in patches. B = bare area, G = grassy or good area, CVs = Circle Valley sand, CVsl = Circle Valley sandy loam, Bsl — Beete calcareous sandy loam. (Teakle & Burvill, 1938).

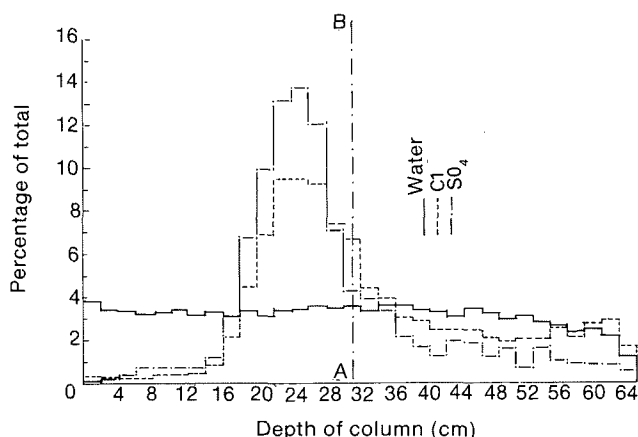


Figure 20.—Movement of a slug of salt and water under vertical infiltration in Yandera loam. Water and anion contents of each 2 cm section is expressed as a percentage of the total in the column. A-B is the water midpoint line. (Evans & Levin, 1969).

the surface remains sufficiently moist in the presence of a shallow water table.

When salt movement in the soil is occurring because of movement of a wetting front Bernstein and Fireman (1957), showed that there tends to be a high concentration of salt in the wetting front. The greater the initial salt content of the soil in their laboratory study however, the less efficient was the movement of salt by the wetting front. It is also likely that movement of salt through undisturbed soils in the field will be less efficient because water may move along preferred paths and the salt will be more intimately mixed with the soil fabric. Nulsen (1980), however, reports that in a ped, a natural soil aggregate of about 0.05 to 0.01 m diameter, salt is at a higher concentration in the outside than the centre of the ped.

Bernstein and Fireman have also drawn attention to the importance of uneven water infiltration in causing salinity problems and such a situation applies to the comparison of salt levels in soil beneath grass and bare areas previously discussed.

Another aspect of infiltration is discussed by Evans and Levin (1969), who applied water to the surface and studied the movement of chloride and sulphate downward in a column of soil treated to eliminate chemical effects. The anions were applied initially as a slug of solution to the soil surface but it was found that the water moved more quickly through the soil than did the slug of salts (Figure 20).

The reason for this effect was explained as the non-steady nature of water movement through soil under infiltration. Wetting under infiltration is not as complete at the wetting front as it is in the case of wetting by capillarity. In soil wet by capillarity the midpoint of the salt slug would have been expected to be the same point as the midpoint of the water, that is A-B in Figure 20. The implications of this work for salt movement in soils in the field may be important as fresh water infiltrating from rainfall could be expected not to leach salts efficiently from the surface of the soil. On the other hand water moving up to the surface to evaporate would be more efficient in its movement of salt than infiltrating water.

The effects of uneven infiltration into soil in grassed areas as compared with bare areas can be compared with movement of the wetting front illustrated by Bernstein and Fireman (1957), for movement of water into a furrow and an adjacent ridge (Figure 21). If the furrow is compared with the grassed area (both being water intake areas) it will be seen that water moves not only downwards but also sideways and upwards into the adjacent dry ridge, which could correspond to the bare area. One mechanism by which the grass and bare areas maintain their differences in salt content is thus built into the system and works to increase the difference.

Detailed studies of the movement of salt in soils in the field near Salmon Gums under light rainfall conditions were made by Teakle and Burvill (1938). They sampled groups of soil with different profile characteristics from cleared areas and adjacent uncleared areas of the same soil type. About 15 000 sampling sites were involved with the results summarised in Table 9. The sandy surfaced soil types exhibited almost complete removal of salt from the surface 0.6 m in cleared areas. Other data indicated a negligible amount of surface accumulation of salts in the form of bare patches. For medium textured soils there was a considerable improvement due to removal of salt from the profile, but heavy textured soils and soils of the Morrel type showed little reduction in salt in the surface. Moreover, heavy textured and Morrel soils were liable to formation of bare patches following clearing.

Movement of salt which occurred in two typical profiles is illustrated in Figure 22, for adjacent virgin and cleared areas. The

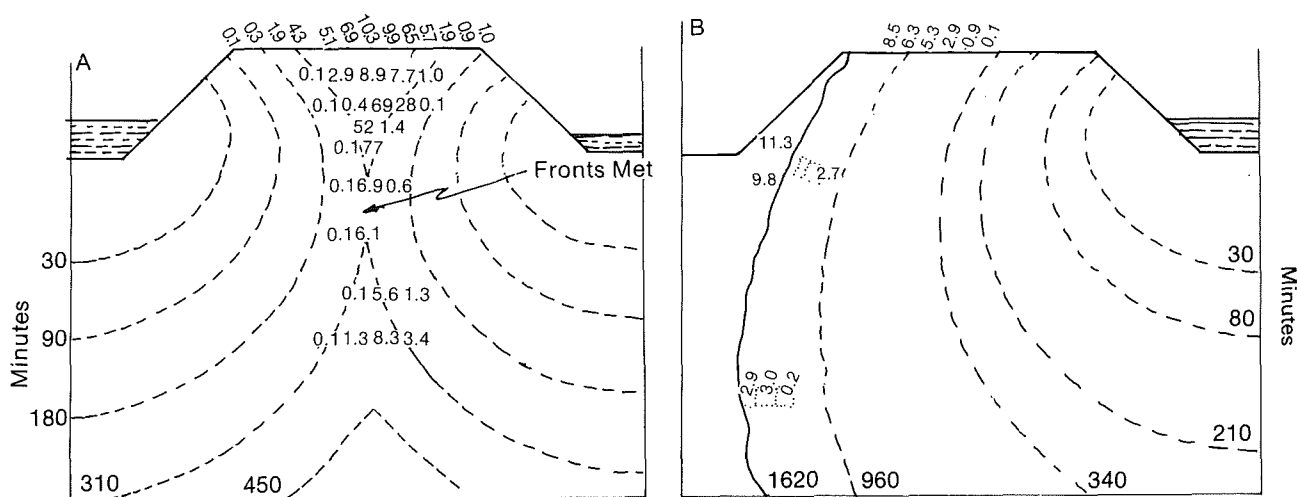


Figure 21.—Salt accumulation ratios in (A) a symmetrically wetted bed (water depth in furrows at 25 and 50 mm as indicated) and (B) a bed irrigated in one furrow only (initial soil salinity (EC) 5 000 Siemens per cm). (Bernstein & Fireman, 1957).

comparison suggests that removal of trees two to five years before sampling resulted in removal of salt from the surface but in East Circle Valley there is no evidence of salt increase in the subsoil.

Following their field work Teakle and Burvill conducted an experiment in tanks at Merredin. The tanks, about 150 cm deep, and 90 to 120 cm in diameter, were filled with a local sandy-clay-loam soil with Ca and Mg dominating its exchange complex. In three separate tanks

calcium chloride was mixed into the soil at depths of 0.075 to 0.15 m, 0.23 to 0.30 m and 0.53 to 0.60 m from the surface respectively. The tanks were exposed to natural rainfall conditions, and sampled at intervals over the next 6 years. Results are shown diagrammatically in Figure 23 in which the chloride has been expressed as NaCl. At the end of the third year a layer of sand was applied to the surface of that tank in which the salt had been mixed at 0.075 to 0.15 m. Conclusions drawn from the study were, firstly, that under fallow conditions and in

TABLE 9.—Effect of clearing on the salinity of soils of various types in the Salmon Gums area. (from Teakle & Burvill, 1938)

Group	Condition	Total number of sites	Percentage of sites within each range of salt (NaCl) concentration in the soil to depth of 0.6 m				
			Below 0.13. %	0.13 to 0.17. %	0.18 to 0.22. %	0.23 to 0.29. %	above 0.30. %
A.	Virgin	4 324	17.6	14.9	20.2	25.2	22.1
		4 255	78.2	13.0	5.7	1.9	1.2
B.	Virgin	1 901	8.6	8.7	15.3	23.4	44.0
		1 998	45.9	16.2	14.2	11.2	12.5
C.	Virgin	1 950	10.0	8.0	12.7	18.6	50.7
		491	42.6	14.2	11.6	9.0	22.6
D.	Virgin	1 237	7.0	6.3	8.5	15.6	62.6
		837	17.1	14.7	15.0	15.8	37.1

All analyses considered in this table are for 'normal' sites; that is, sites not showing surface evidence of salt accumulation.

GROUP A Sandy surfaced soils (with sandy clay subsoils) include the Circle Valley sand and Scaddan sand.

GROUP B Medium textured soils include the Kumarl sandy loam and the Circle Valley sandy loam.

GROUP C Highly calcareous soils—the Beete calcareous sandy loam.

GROUP D Heavy textured soils include the Kumarl clay loam and the Dowak clay loam.

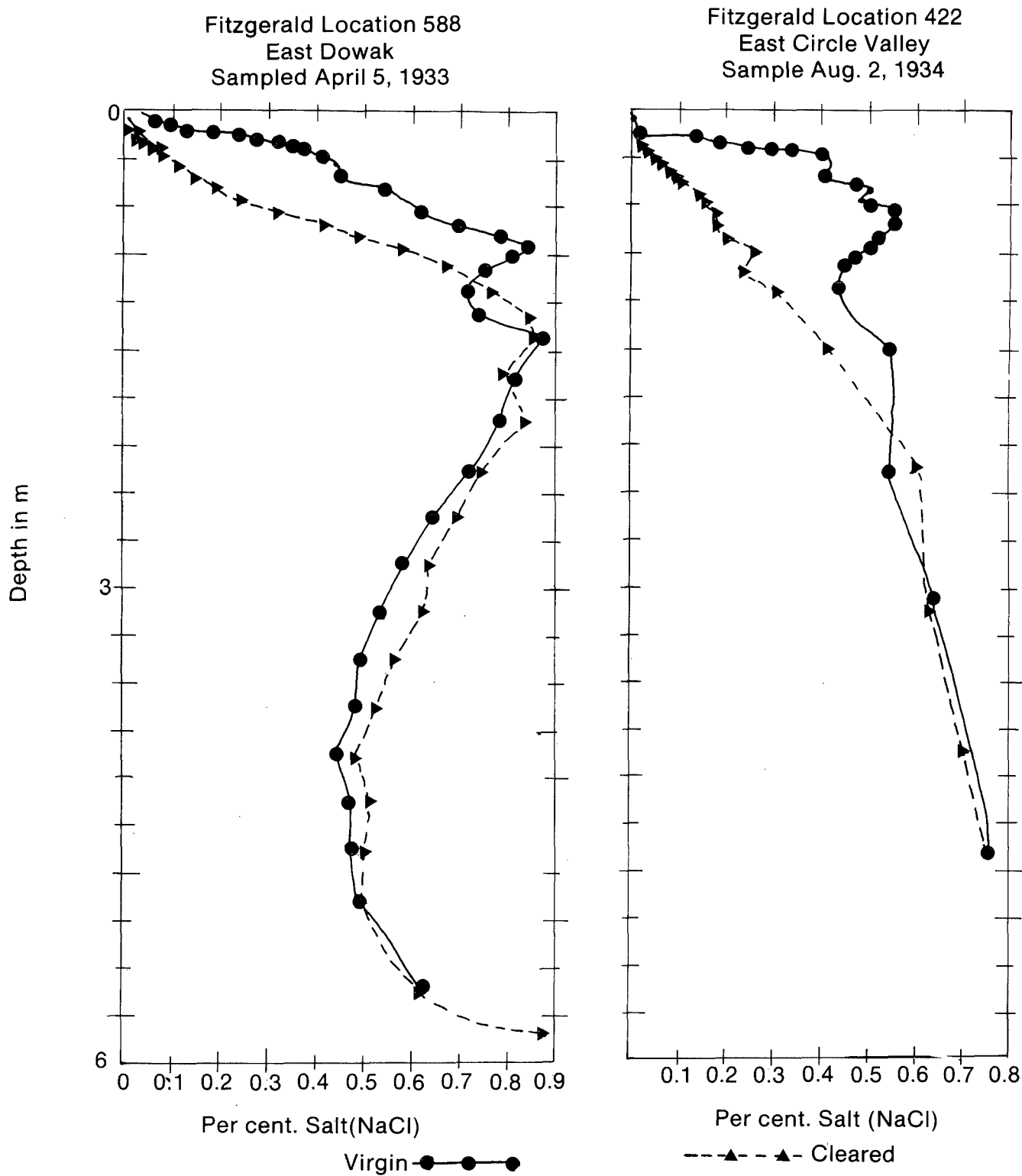


Figure 22.—Salt profiles in cleared and virgin Circle Valley Sand, Salmon Gums, Western Australia. (Teakle & Burvill, 1938).

the absence of groundwater close to the surface, the main movement of chloride was downward. Secondly, that where a saline layer is initially near the surface, there may be sufficient upward movement to be deleterious to crop growth. Thirdly, that a sandy surface promotes moisture absorption and storage and hence greatly accelerates the downward movement of chloride.

Salt and water imported in ground water

A major factor influencing the accumulation of soluble salts in soils is the importation, to certain areas, of salts in the groundwater. In his study of the soils of Australia, Prescott (1931), observed that the distribution of salt, lime and gypsum in soil indicated downward leaching of soluble material as the dominant factor in soil maturation. When the watertable was in capillary reach of the soil surface the process was reversed.

When water evaporates at the soil surface or is used by plants, the salts accumulate at the soil surface or in the root zone respectively. Talsma (1966), observed that in irrigation areas in Australia the development of salinity problems relates to the presence of a permanent watertable. Salt problems of non-irrigated agriculture in both Texas and Canada have been related to the presence of regional groundwater, and both local and regional water movements have been postulated to explain similar phenomena in North and South Dakota, Montana and Wyoming (Doering and Sandoval 1976; Alberta Dry Land Salinity Committee 1976; Carter and Wiegand 1965).

Routes of water and salt movement

In endeavouring to explain the increase of salt in soils and streams in Western Australia, Wood (1924), postulated that water entered the surface, travelled down through the root zone and eventually joined a water bearing layer in which there was an appreciable level of salinity. If water in this layer was at a higher level than that in the valley bottom, it then travelled down into the valley taking salt with it. Wood observed that soil at the surface tended to be sandy, and to overlay sandy clay material which he believed to be less permeable than softer material in the decomposed rock layer at depth.

The water in the aquifer was frequently brackish to saline and he postulated that after clearing more water circulated through to the aquifer than under natural forest, exceeding the amount that could drain away to the coast without raising the watertable. Consequently the watertable rose and underground water could travel through rootholes towards the surface.

The role of preferred pathways such as rootholes has been studied by Nulsen (1980). He found that in some Western Australian soils preferred pathways could account for more than 99 per cent of water flow.

Pennefather (1950), reported that there was insufficient data available on how valleys became waterlogged in the wheatbelt, but that it was apparent that good land became salty due to the approach of saline groundwater to the surface long enough for evaporation and salt accumulation to occur. The excess groundwater problem expressed itself in seepages which occurred in hillsides and in gullies or as the water-logging of broader valleys.

It is apparent from earlier discussion that water not used by plants moves below the depth of rooting and travels through the soil, collecting soluble salts *en route* and contributing them to the groundwater system. The degree of concentration of salts in the system will depend on the rate at which water escapes from the bottom of the root zone, the amount of salt in the soil through which it travels, and the combined salt content of the present groundwater and the new additions.

The position at which the water and salt approach the soil surface sufficiently closely to cause salting depends upon the configuration of underground and surface layers in the catchment. In some cases water and salt pass quickly through deep permeable soils and appear where these soils overlie impermeable material further down slope. In some landscapes soil deposits are in layers and water tends to enter various layers where they commence upslope and leave them where they butt on to impermeable soil or reach the surface themselves downslope. The relative permeability of the soil layers and their hydraulic gradients determine the speed and degree of water movement from one layer to another, taking salt with it.

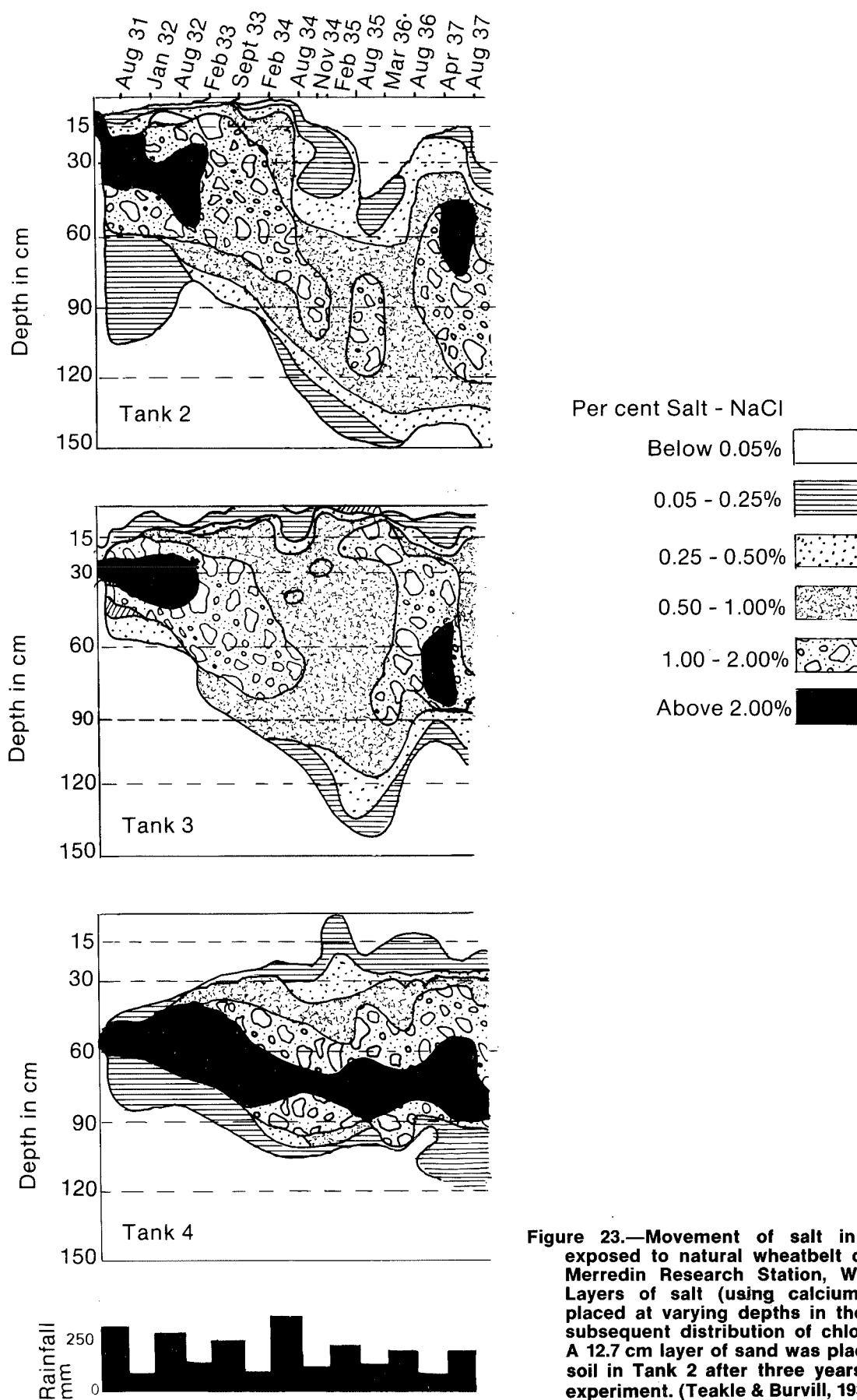


Figure 23.—Movement of salt in soils in tanks exposed to natural wheatbelt conditions at the Merredin Research Station, Western Australia. Layers of salt (using calcium chloride) were placed at varying depths in the profile and the subsequent distribution of chloride determined. A 12.7 cm layer of sand was placed on top of the soil in Tank 2 after three years of the six year experiment. (Teakle & Burvill, 1938).

In some cases groundwater which enters the landscape at a high level may not reappear until it has entered water-bearing layers in the main trunk valleys. In others, it may become evident at changes of slope or changes of material at various points in the landscape. The actual situation in any particular salt occurrence is likely to be complex rather than simple. Moreover, significant factors may not always be obvious, as in the case of lime-filled root channels noted by Mulcahy and Hingston (1961), in the valley floor deposits of the Avon surface. These channels may transport water quickly in an otherwise slowly permeable material. Nulsen (1980), found that a 2 mm diameter channel measured in the field transported as much water as 1.3 m² of clay matrix. West and Howard (1953), also noted for the Murrumbidgee irrigation area that old rabbit warrens and old tree holes were often sites for salt patches because water entered the soil more readily in these areas and created a local high water table.

Some water runs off, especially during heavy rain, and may cause flooding of low-lying areas. Farmers frequently associate flooding with salt problems because both occur in similar situations. Flood waters may enter the soil and saturate it down to the level of free groundwater or a confining layer if they are of sufficient volume and duration. As a result a perched watertable will be formed and will add to reclamation problems.

Movement of water under pressure

Where water enters a particular layer of soil material or a rock crevice faster than it can escape, pressure will develop within that water-bearing layer. The pressure at any point is equal to the vertical difference in height between the point where the water has built up to in the layer and the point at which the layer is tapped. In a thick layer of relatively low permeability

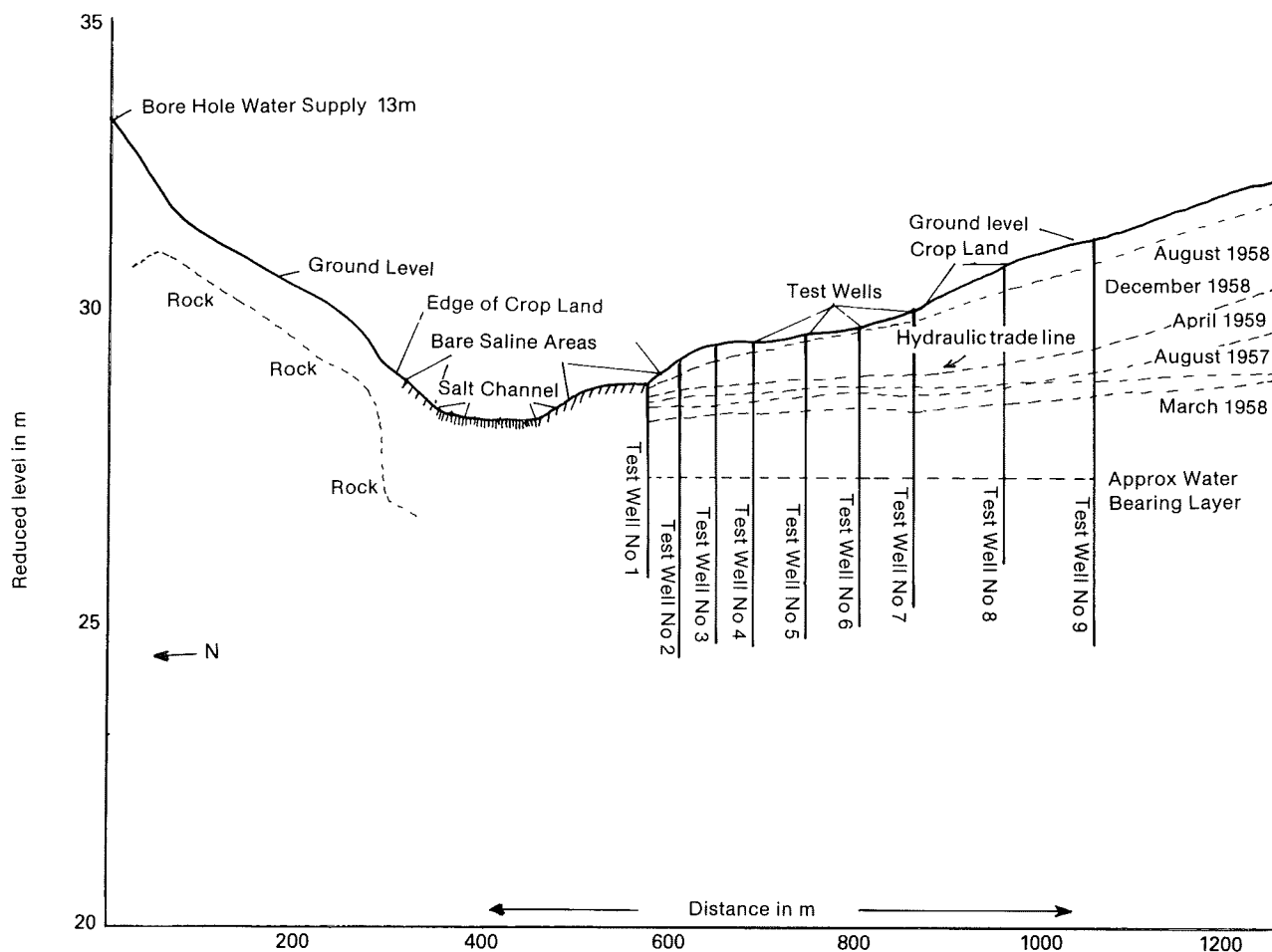


Figure 24.—Seasonal fluctuations in test wells in a salt-affected valley on the property of W. Heinrich, Carnamah, Western Australia. (Smith, 1962).

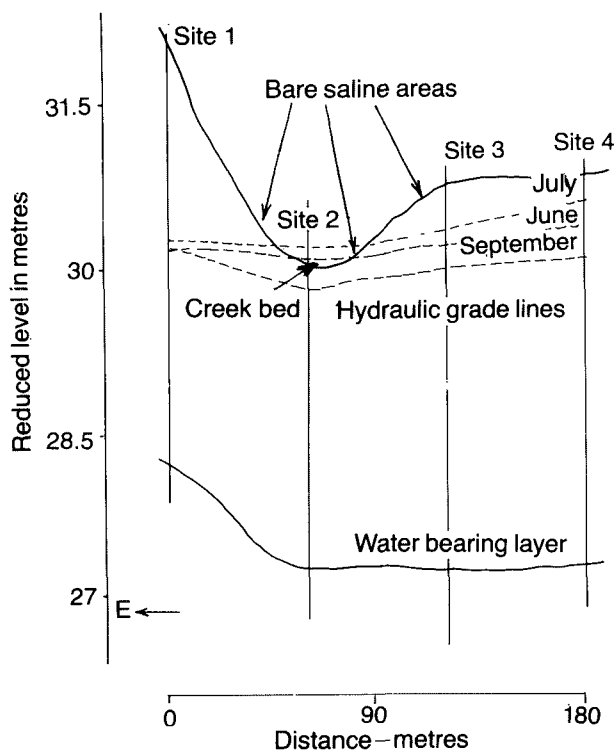


Figure 25.—Groundwater investigations, valley cross-section, on the property of J. Starceovich, Korbel, Western Australia. (Smith, 1962).

there will be differences of pressure within the layer itself and these will indicate directions in which water is tending to flow within the layer. If water is escaping through the layer in its passage through the landscape there will be a drop in pressure in the layer.

It is not necessary for the confining boundaries of a water bearing layer to be entirely impermeable for pressure to develop, and in fact an impermeable layer in a soil landscape is very uncommon. The distribution of salt to great depth in the fine textured subsoil of the laterite horizons in the agricultural areas of Western Australia bears testimony to the fact that these layers, though relatively impermeable, are nevertheless sufficiently permeable for salt to have permeated their whole depth. Similar considerations apply to the fine textured deposits in the broad valleys.

Movement of groundwater under pressure in Western Australian landscapes has been studied by Smith (1962), using test wells near Carnamah and Korbel, Figures 24, 25. The wells were lined with galvanised piping jointed at intervals but not necessarily sealed against water movement. Smith considered that he was able to show the greatest hydraulic head encountered within the water bearing layers.

Attempts were also made by means of batteries of wells to different depths to determine the vertical component of water movement. The results were regarded as unsatisfactory, but greatest hydraulic pressures usually occurred at depth, never shallow.

The study showed that there were extensive groundwaters beneath the valley and that these approached the surface in saline areas. The groundwaters rose in the test wells to heights greater than the depth at which water was first encountered during boring, indicating a degree of confinement of the water, and that water was tending to flow towards the soil surface. There was also a gradient of increasing salinity from the highest point in the landscape to the valley floors. The hydraulic gradient indicated that water was tending to flow within the water bearing layer from the high country towards the valley floors.

The gradient in salinity may be taken as an indication either that water is lost from the water-bearing layer in the course of its passage down the landscape, perhaps by root activity or by vapour loss, or that salt is contributed to the groundwater from deposits within the water-bearing layer. Such deposits are indicated by soil sampling data which indicate the storage of salt in fine textured soil materials to considerable depth.

The hydraulic head for the Carnamah property is illustrated in Figure 24 which shows the appreciable seasonal fluctuations in the hydraulic grade line. The greatest fluctuation was at the highest elevation in the landscape that was sampled and was of the order of 3 m. It was concluded from these fluctuations that water was entering the upper end of the water-bearing layer and that it was escaping from the lower end or being lost by evapotranspiration at a sufficient rate to prevent accumulation from year to year. For any given level of input at the upper end of the water-bearing layer there will be an equilibrium pressure level at the lower end which may be sufficiently high to allow salt accumulation to occur. In Figure 24 the depth of the water-bearing layer at the edge of the salt affected area is of the order of 150 cm, which is sufficiently close to the surface for salt accumulation to occur in some soils. On the Korbel property (Figure 25) Smith's test wells showed that in the bed of the drainage line the hydraulic head in June and July was above the ground surface.

Where water in a relatively permeable layer is beneath less permeable material and is under pressure there will be a continuous tendency for the water to move upwards through the less permeable material. The tendency will be exerted to the height of the hydraulic head of the water in the water-bearing layer (aquifer). Movement of water beyond that height will depend on capillary forces not on pressure from beneath. Flaws in the soil fabric, such as cracks or old root channels, will provide preferred routes for the movement of water under pressure through the overlying layer. However, capillary rise will tend to occur within the soil fabric and will not occur as readily in cracks and other larger holes. The rate at which water moves through the overlying confining layer will depend upon the degree of pressure exerted from beneath and the permeability of the confining layer. In areas where pressure brings the water sufficiently close to the surface for capillary action to occur up to the soil surface, surface accumulations of salt will occur.

The movement of salt and water through a wheatbelt landscape has been discussed in general terms so far but Bettenay *et al.*, (1964), have examined the hydrology and salinity of soils and landscapes in the Belka area in considerable detail. As in the York-Quairading area, the soils highest in the landscape tend to be those formed on the old laterite profile. These

soils (the Ulva association) have high permeability and water moves down the profile and forms a water table perched upon the duricrust layer—see Figure 26. If the duricrust intersects the surface the water seeps out and forms a saline area.

Examples of salt profiles of the various soil associations under both non-saline and saline conditions are shown in Figure 27 and the salt contents of the various soil associations are shown in Table 10.

Finer textured soils of the Booraan, Merredin, Collgar and Belka associations tend to shed or retain water rather than allow it to leach their profiles. Salt therefore accumulates (Bettenay *et al.*, 1964). These soils also overlie massive heavy clay of low porosity and very low permeability. The authors state that “the permeability of these materials is extremely low and would prevent any significant seasonal accession of water to the aquifer from above. However, in response to the positive pressure of capillarity and the evaporation gradient towards the surface, there is a slow upward movement of saline water through the aquiclude”. In the valley floors, because the confining material is shallower, salt accumulation from the groundwater in the aquifer occurs at the soil surface.

Movement of saline water in the aquifer along the valley is stated to amount to only centimetres in a year but, in general, Bettenay

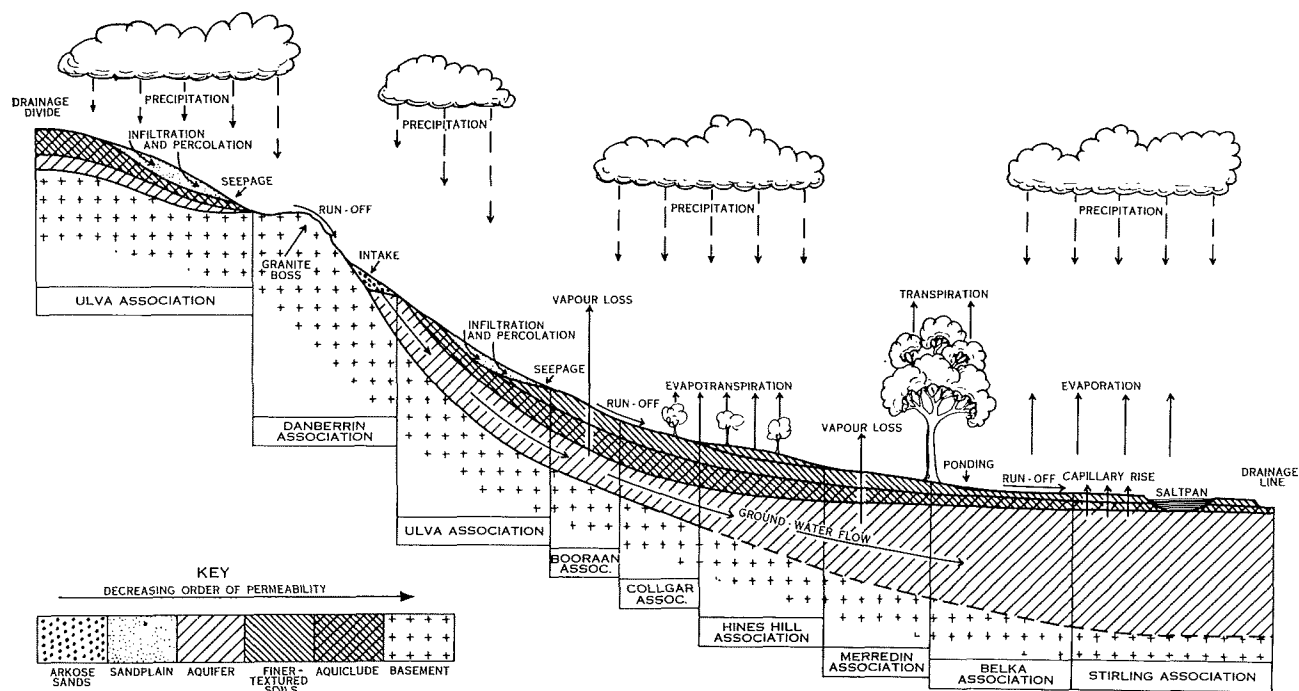


Figure 26.—Hydrologic cycle in the Belka Valley, Western Australia. (Bettenay, Blackmore & Hingston, 1964).

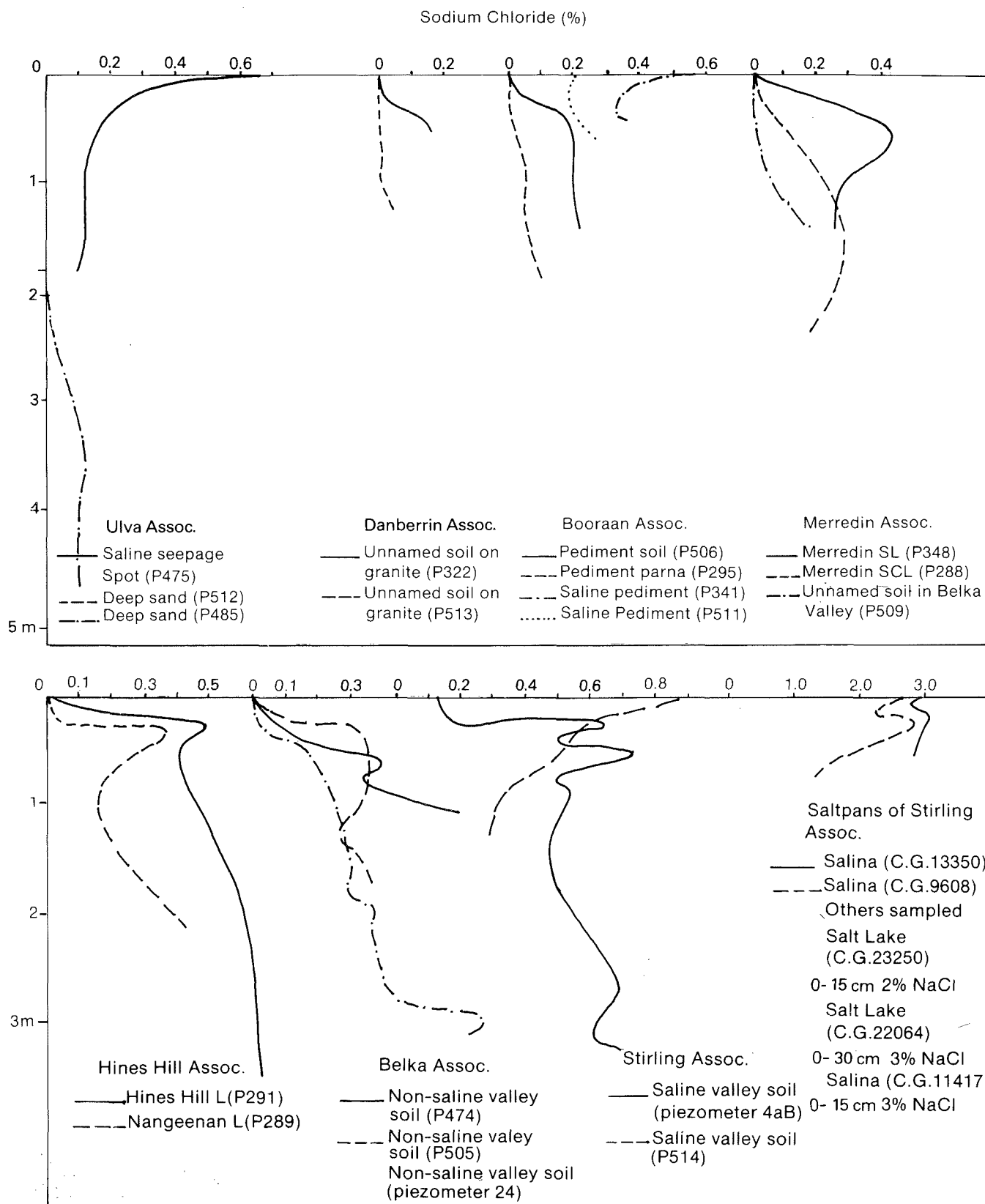


Figure 27.—Salt content of representative soils in the Belka and Merredin Valleys. (Bettenay, Blackmore & Hingston, 1964).

TABLE 10.—Area, percentage composition of soil units, and estimated salt distribution, Belka Valley, Western Australia

Soil association and description	Area (ha)	Percentage composition of area	Description of sediments (depth m)	NaCl* (%)	NaCl (t/ha)	Total NaCl (t)	Percentage of total NaCl
Danberrin; skeletal soils and rock outcrops	14 843	8.6	Soil 0.9	0.05	8	1.02×10^6	< 0.1
Ulva; sand and gravel plains	82 296	47.8	(a) Sands 1.5 (b) Duricrust 1.5 (c) Pallid zone	< 0.01 < 0.01 0.16 †	— — 429.0	.429 37.70×10^6	32
Booraan; pediment soils	34 234	19.9	(a) Soil 0.9 (b) Pallid zone 4.5	0.10 0.16 †	12.5 107.9	120 4.18×10^6	4
Belka; non-saline valley Soils	26 000	15.1	(a) Soil 0.9 (b) Pallid zone 24	0.40 0.63 ‡	527 2257.9	2310 60.18×10^6	53
Colligar	8 407	4.9	(a) Soil 0.9 (b) Pallid zone 18	< 0.01 0.16 †	— 429.0	429 3.57×10^6	3
Meredin; non-saline	2 583	1.5	(a) Soil 0.9 (b) Pallid zone 24	0.20 0.42 §	25.1 1505.3	1530 3.98×10^6	4
Stirling; saline valley soil and very small area of salinas	2 207	1.3	(a) Soil 0.9 (b) Pallid zone 24 Salinas 0.6	0.50 0.63 ‡ 3.0	67.7 2257.9 25.1	2325 5.10×10^6 very small	5
Hines Hill; panna soils	1 551	0.9	(a) Soil 0.9 (b) Pallid zone 4.5	0.20 0.16 †	27.6 107.8	135 0.20×10^6	< 1
Total area: 172 131		Average NaCl: 652 t/ha		Total NaCl: 112.2×10^6 tonnes			

* Estimated from the average salinity of aquifer waters and assuming 18% moisture.

(Extracted from Bettenay, Blackmore and Hingston, 1964.)

† Water under sand and gravel plains 150 m-equiv. Cl /L

‡ Waters under Belka association, 600 m-equiv. Cl /L

§ Waters under Merredin association, 400 m-equiv. Cl /L

et al. found the aquifer to be responsive to rainfall. If there was a saturated aquifer the response to rainfall was rapid. If the aquifer was not saturated there was a delay between the commencement of rainy periods and the registering of rainfall events in piezometers, during which the aquifer became filled with water. The most rapid loss of pressure at the lower end of the aquifer was noted where the aquiclude was cut by salt pans.

In their discussion of the details of the soils of the Belka valley Bettenay and Hingston (1964), described earlier stream levees and fine textured flood plains which have developed on the floors of the valley but have subsequently been modified by wind action. They describe these soils as characteristically secondary solonchaks formed by the invasion of the soil by saline groundwater. The soils comprise low sandy ridges winding through extensive clay plains.

The position of the Belka surface relative to deep tertiary weathering and to later deposits is shown in Figure 14. As riverine deposits are characteristically bedded and contain lenses of coarser material it is likely that they sometimes contain perched water due to flooding. However, the main cause of the salt problem is the saline groundwater in the pallid zone below. Groundwater pressures below soils with pallid zone subsoils have been shown to reach 3 metres above ground level in studies at Quairading (Henschke personal communication).

The degree to which water, arriving at a particular part of the landscape, either enters the soil and goes straight downwards, enters the soil and moves laterally, or flows over the top of the soil, depends on the relationship between the rate of rainfall and the rate at which the water can enter and move downward in the soil. If downward water movement in soil is restricted to a rate slower than that at which water is arriving at any particular layer from the layer above, there will be an accumulation of free water in the soil and a tendency for water to move laterally. Once the possibilities for lateral flow have been saturated, water will bank up further in the soil and may run out on the soil surface.

Conacher (1975), has claimed that shallow lateral water flow in soils (which he defines as through-flow) is a cause of soil salinity. In his discussion of the role of through-flow, Conacher draws a sharp distinction between it and the flow in any deeper layers and denies that confined groundwater has a major role in the formation of salt-affected areas in the wheatbelt. In the field study made to support his hypothesis, Conacher examined numerous salt-affected areas and reported on the nature of their soil layers to a depth of about a metre or less, in most cases. The soils are reported to have been waterlogged and levels of salinity were shown to increase towards the centres of the salt-affected areas.

Conacher stated that soil layers beneath the depth of sampling were relatively impermeable and therefore any deeper layers of water-bearing material would not be contributing to the salinity problem. However, data were not presented to indicate the duration of surface waterlogging. No piezometric studies on deeper soil layers were undertaken and the possibility of upward leakage of deeper water through root channels was not investigated.

Conacher established that shallow seepage in some soils close to salt-affected areas may contribute to the waterlogging of saline areas. It does not follow however that all seepage areas are due only, or even primarily, to shallow seepage. Many seepage areas remain moist well into the summer, by which time the soils upslope have dried out to an appreciable depth. Furthermore, the presence in many seepage areas of small bubbling eruptions of water indicates that water is being released under pressure. These observations indicate that water continues to move into the seepage areas from deeper layers after shallow downslope movement has ceased.

Many farmers report that seepages commence to flow late in the summer or early in autumn, before there has been any rain, and certainly before there is an opportunity for shallow seepage. The reason for this phenomenon is not clear. It is possibly related to the fact that trees or other perennial vegetation on the catchment from which the seepage arises have their transpiration needs reduced by the onset of cooler weather. It may be that because the evaporative demand is reduced at the seepage patch, whatever moisture was flowing into the area is no longer evaporated and actually forms moist streams on the soil. Alternatively, owing to the slow flow of water through the aquifer system the flow of the seepage may lag behind the water input. The peaks and troughs in groundwater pressure have been shown to be about half a year out of phase with seasonal rainfall at Bakers Hill (Williamson and Bettenay, 1979) and Quairading (Henschke personal communication). Whatever the explanation of the phenomenon, it does not allow Conacher's explanation to be used generally for all salt-affected areas.

Capillary rise and critical depth

Salt accumulation takes place once groundwater comes so close to the surface that the capillary fringe reaches the soil surface.

Teakle *et al.*, (1940), pointed out from the results of their soil survey in the Lakes District, that it was apparent that soil salinity was not necessarily related to the proximity to salt lakes, but rather to the texture and structure of the soil and to the depth of the saline watertable. A saline watertable at shallow depth prevents effective leaching of salt from the soil, even in irrigation areas (Basco and Fekete, 1968) and causes secondary salination of horizons of soil above the groundwater.

The depth to watertable used in this discussion is the depth at which free water is first encountered when a hole is sunk into the soil. In dense clay subsoils, owing to the slow rate of flow, it may be necessary to leave the hole for some hours for free water to become evident.

Referring again to the work of Yaalon (1963), for moisture regimes 3 and 4 (Figure 17), groundwater influences the accumulation of salts in the soil. In the former case, which Yaalon refers to as "epepercolative" evaporation exceeds precipitation for most of the year but owing to the presence of a shallow watertable the capillary fringe intercepts the soil surface where evaporation causes salt to accumulate. The main accumulation of salt is at the soil surface if the watertable is at a metre or less but in the subsoil if the watertable is deeper. In the fourth set of conditions, described by Yaalon as "amiphipercolative" (which would correspond to Western Australian climatic conditions) the ratio of evaporation to precipitation depends upon the season. The watertable fluctuates with the season and there is alternate downward and upward movement of water in the soil. Salts are imported by the inflowing water, and by rainfall, and accumulate in the subsoil at a depth determined by the balance between evaporation and leaching. The depth of the watertable is a critical factor in determining the severity of salting (see also Nulsen, 1980).

For the Lower Rio Grande Valley area in Texas, Carter and Wiegand (1965), describe salt problems developing from the presence of a shallow watertable which varies in depth from 0.3 to 2.4 m below the surface in areas receiving annual rainfall of about 660 mm. On a nearby study area receiving 400 to 500 mm of annual rainfall Lyles and Allen (1966), describe salt problems developing in a clay loam soil with a watertable ranging from 0.75 to 3.0 m. For Western Australia Teakle and Burvill (1945), report that there are many instances where the

saline water table has risen from 6 m or more before clearing, to within 1 to 2 m of the surface. They regard 1.5 to 1.8 m as a critical depth for soil salinisation. Pennefather (1950), indicated records which show that the watertable in Western Australia wheatbelt valleys was at 4.5 to 9 m soon after clearing—recent test wells show it may often now be at about a metre.

It is important to consider what is the critical depth for a watertable and Teakle and Burvill (1938), quoted various studies in which estimates of maximum possible capillary rise ranged from 3 m to as much as 3.2 km. The greatest depth at which they noticed an apparent influence of a saline watertable was 3 to 3.3 m in the Lake Brown area.

The maximum depth of groundwater above which salinisation occurs was described by Volobuev (1946), as the "critical level". He recognised that factors which could influence salt accumulation included the salinity of the groundwater, the physical properties of the soil, and management practices such as tillage and irrigation. He regarded the mechanical composition of the soil as especially important, quoting 1.2 to 1.3 m as dangerous for a clay soil but 1.3 to 1.5 m depth as the dangerous level for a watertable in a loamy soil.

For the Mugan region in Russia, Volobuev divided watertable depth into three orders of hazard.

The first order, from 0 to 1.1 m watertable depth, was associated with intense accumulation of salt in the surface layers of the soil and was lethal to agricultural crops.

Second order 1.1 to 1.5 m watertable depth gave dangerous salt accumulations in the root zone, but there was a possibility of control by agronomic measures under certain favourable conditions.

Third order 1.75 to 2.25 m groundwater depth was that position at which groundwater was involved for the first time in evaporation from the surface. Slight salinisation might take place but it would be easy to control by agronomic measures. By inference groundwaters deeper than 2.25 m caused no problem.

The critical levels appropriate to a particular region depend on the balance between evaporation and precipitation. Van Schaik and Stevenson (1967), have indicated that in southern Alberta, if the rainfall between June 1 and November 1 exceeds 150 mm, and if the

watertable is deeper than 1 m there is a net downward movement of water. If the watertable is shallower than a metre there is a net upward movement. With the watertable at 1 m in the autumn, upward water migration during the winter, with subsequent evaporation in spring could add to salt accumulation at the soil surface.

Surface additions of water were effective in keeping salt down in isolated soil columns in the Murrumbidgee irrigation area (West and Howard, 1953). It was found that if the watertable was maintained at 50 cm from the surface by adding water to the top of the soil column, salt was washed from the surface and did not return. If, however, the watertable was maintained at 1 m by adding water from below, there was a small increase in salt in the surface 10 cm of soil. The authors were surprised at the small amount of salt which accumulated and postulated that for the levels of salt accumulation reached in the field, there needed to be some circulation of water involving lateral movement.

For the Mirrool irrigation area Groenewegen (1959), reported that saline soils occurred where the watertable was closer to the surface than 1.8 to 2.4 m. He found a marked difference in chloride accumulation between permeable and slowly permeable soils. Under conditions conducive to surface salt accumulation the chloride concentration in permeable soils decreased with depth, while in slowly permeable soils it increased with depth. Movement of salts in the slowly permeable soils appeared to be slow.

The effect of soil on the rate of salinisation was observed to be extremely important in the Murrumbidgee irrigation area (Talsma, 1962). In areas with the watertable at 1.5 m the rate of salinisation of the soil with high capillary conductivity was over ten times that of soil with low capillary conductivity. Where the watertable was at 0.6 m the rates of salinisation were equal on the two soils.

Subsequently Talsma (1966), examined the influence of capillary conductivity on salt accumulation in more detail. He found that two soil properties were important in determining water transfer to the soil surface: the first was the relationship between suction and moisture content of the soil, and the second the relationship between the capillary conductivity of the soil and its moisture content.

The relationship between suction applied to a soil and the capillary conductivity of water remaining in the soil is shown in Figure 28. This

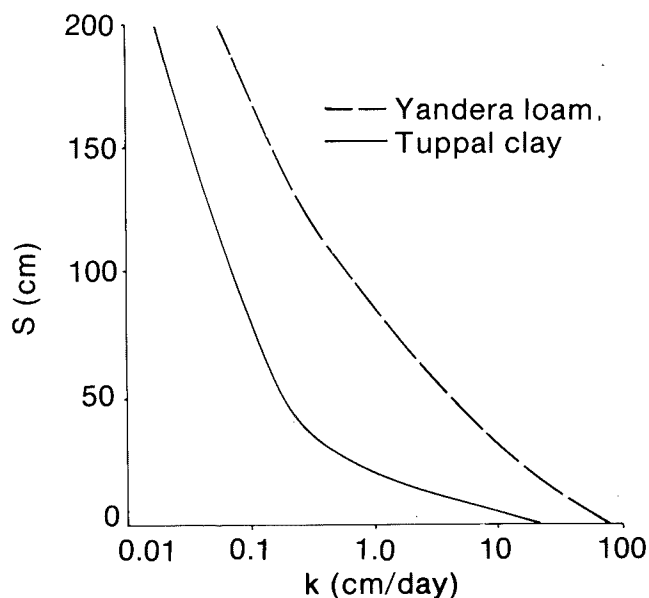


Figure 28.—Capillary conductivity (k), suction (s), relationships, derived from field experiments for two soil types. (Talsma, 1966).

relationship was derived from field experiments for two different soils, a loam and a clay. It may be seen that when the soils are both at a suction of one metre the loam has almost ten times the capillary conductivity of the clay. At all suctions on the graph the loam is higher in capillary conductivity than the clay although there is some variation in the differences observed.

In Figure 29 the same loam and clay soils are compared in terms of the depth at which a watertable needs to be present in order to supply a given rate of evaporation. It may be seen that to maintain an evaporation rate of 0.7 cm per day at the soil surface the watertable would need to be at 45 cm in the clay but could be at 113 cm in the loam. If this depth limit was exceeded in these soils a vapour barrier would develop at the surface and the salinisation rate would be reduced. If the watertable in the clay was increased to 113 cm it would only be able to supply water to the surface at a rate of 0.13 cm per day. If the evaporation rate at the surface exceeded this level a vapour barrier would develop. As Talsma states: "The salinity hazard of the loam soil is much greater than that of the clay soil and watertable control to a greater depth is necessary in the loam to prevent serious salinisation from groundwater".

The curves in Figure 29 show that at high rates of evaporation demand a relatively small change in the depth of the watertable will cause a marked reduction in surface salinisation. However, at evaporation rates of less than 0.2 or 0.1 cm per day substantial increases in the depth of the watertable are necessary to prevent the

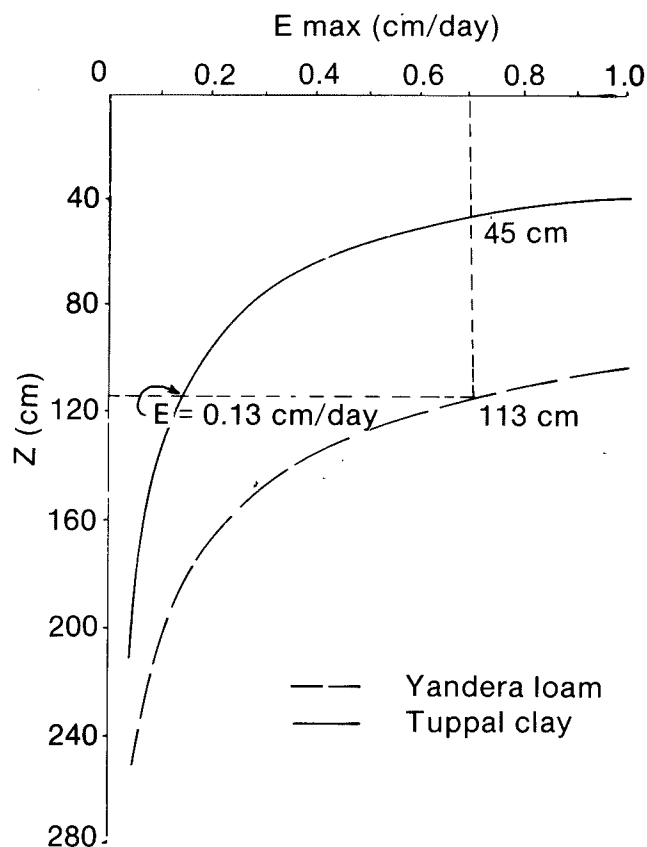


Figure 29.—Maximum flux rates in relation to watertable depth for two soil types. (Talsma, 1966).

accumulation of salt at the surface. Talsma suggests that the critical depth for groundwater for any soil should be the depth at which the upward flow rate is reduced to 0.1 cm per day. This rate, he says, is generally lower than the potential evaporation rate over the greater part of the year in most irrigation regions. In Western Australia evaporation in the central wheatbelt ranges from about 0.2 cm per day in winter to 1 cm per day in summer (Commonwealth Bureau of Meteorology 1958). For the clay and loam soils in Talsma's study the critical depths of 0.2 cm per day evaporation rate would be approximately 100 and 170 cm respectively. These depths correspond to the moderately to severely salt-affected classes in the study by Nulsen (1980).

Criteria used by Talsma to express the potential of a soil for capillary rise are a function of factors such as pore space and texture. Ijjas (1969), has examined the effect of compactness and initial moisture content of soil on the process of capillary rise. He used fine and medium grained sands compacted to different degrees and with different initial moisture contents in his study in the laboratory. In Figure 30 the capillary rise in medium grained sand, compacted to various degrees and with different moisture contents, is shown over a 12 hour

period. It will be seen that for dry sand ($W = 0\%$) the height of capillary rise was progressively greater for sands at 50.3, 38.6 and 35.2 per cent porosity respectively. It may be concluded that compaction produces finer soil pores which are capable of causing higher capillary rise.

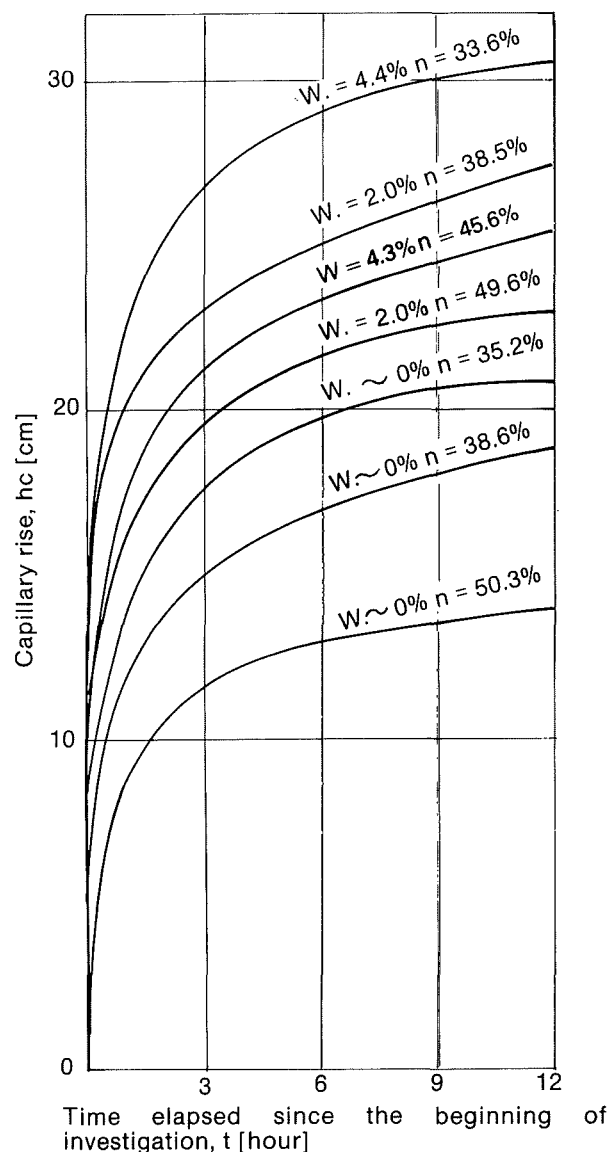


Figure 30.—Curves of the capillary rise in a medium grained sand soil at varying initial moisture content (w) and porosity (n) ($D_{10} = 0.13$ mm and $U = 2.3$). (Ijjas, 1969).

For sand at 38.6 per cent porosity, the height of capillary rise after 12 hours was increased from 19 to 27 cm by increasing the initial water content from 0 to 2.0 per cent. In Figure 31 the progressive rise by capillarity in medium grained sand compacted in layers has behaved according to the degree to which it was compacted. Pohjakas (1966), showed that in saline-alkali soils in Saskatchewan liquid and

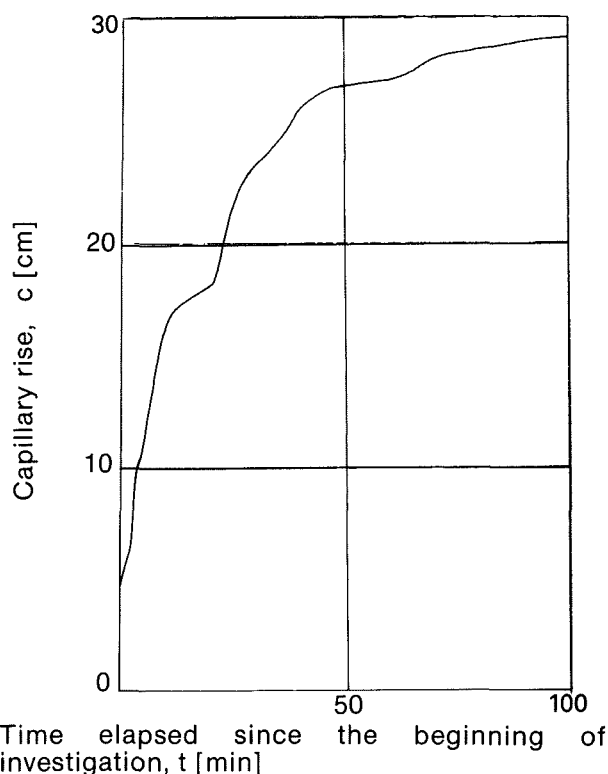


Figure 31.—Curve of capillary rise in a medium grained sand soil compacted in layers ($D_{10} = 0.13$ mm and $U = 2.3$). (Ijjas, 1969).

plastic limits were lowered and as a result compaction occurred more easily.

The implications of the work of Talsma and Ijjas are that factors such as compaction of the surface soil or moistening of the surface soil to re-establish capillary rise, is likely to increase the accumulation of salt at the soil surface by capillarity. Malcolm (1961), and Bettenay *et al.*, (1964), have noted that waterlogging may cause the death of plant cover and may maintain the surface soil in a moist condition in spring and early summer and thereby lead to increased salting. Farmers have reported that in the northern wheatbelt, summer thunderstorms frequently appear to increase salting. A possible cause of this effect would be the establishment of capillary rise from the subsoil at a time when plant growth is absent.

The effect of agronomic practices on capillary rise has been studied by various workers. Ferguson (1965), reported that bare summer fallow allowed salt crusts to form resulting in seedling damage, whereas intensive cropping caused salts to accumulate in the root zone. He suggested using fallow with stubble mulch to reduce evaporation and salt accumulation. If fallow years alternated with cropping in a rotation Leo (1963), suggested that a "pumping

and priming" action of the two systems resulted in more rapid salinisation of the soil. In their studies of salt changes under reed canary grass, plastic sheeting and summer fallow, all with saline groundwater at 0.9 m, Van Schaik and Milne (1963), found salt levels in the top 0.6 m were unchanged under fallow and plastic but rose markedly under grass.

In a four year study in North Dakota by Sandoval and Benz (1966), with a water-table at 0.5 to 3 m cultivated bare fallow, barley and grass did not appreciably affect the salinity of the top 0.15 m. However, salt was leached from

the 0.15 to 0.6 m layer beneath the fallow plots by rainfall (500 mm annual average).

Lüken (1962), investigated the effects of mulch, manure, fertiliser and, a synthetic soil conditioner, Krilium, on soil salinity. Only Krilium treatment caused reduced salinity in the surface 0.15 m, while summer fallow favoured surface salt accumulation.

Apparent contradictions in studies on the effects of fallow and plant growth on salt accumulation are probably due to differences in soil type, season and site hydrology. Therefore recommended measures must be tested under the conditions in which they will be used.

TREATMENTS FOR SALT LAND

Catchment measures to minimise salt encroachment

Clearing control

Native vegetation is removed to allow agricultural production, so some form of clearing control may be desirable if it is known that clearing certain areas will have serious effects on salinity. For instance, in the soil surveys conducted in dry areas of Western Australia, extensive areas of soil naturally high in salt were delineated as too salty for agricultural development. Where clearing and potential salt encroachment relate to the same site avoiding salt problems may be possible by excluding saline soils from development.

It is more difficult to develop methods of predicting what saltland may be caused by clearing of other areas. Moreover, the area of saltland caused by any particular area of clearing is usually far smaller than the area cleared, so that it is not an attractive proposition to aim to control clearing in order to prevent salt encroachment, even where the two areas may be on the same property. It is even more difficult where the clearing of land and the development of saltland are on different properties and where there is a delay of some years between clearing and salt encroachment.

There are probably other reasons for avoiding clearing in the wheatbelt for which a stronger case can be made than for the prevention of salt encroachment, for example, flora and fauna conservation. There may also be specific cases, such as the protection of dams, or other improvements on farms, where special consideration of the benefits of clearing control may be worthwhile.

Replanting non-saline land to trees or shrubs

There has been considerable interest recently in using perennial plants such as trees and shrubs for reducing the salinity of the stream flow into water supply reservoirs in the Darling Ranges. Such measures aim at protecting the capital investment in reservoirs and reticulation schemes by maintaining the quality of the water involved or increasing the number of usable rivers and thus increasing good quality water reserves available.

Where replanting is to be considered as a treatment on non-saline land for reducing salinity of nearby saline land the economics are not as attractive and similar difficulties to those raised previously apply. It would generally be expected that a greater area of land would need to be planted to perennial species than the area

from which a benefit in reduced salinity would be expected. If there are other reasons for planting trees or shrubs, such as for shelter, windbreaks, aesthetic purposes, or commercial timber, plantings could be sited on areas believed to be the intake of aquifers causing saltland. Small blocks of trees can be planted immediately upslope of small seepages to intercept and use the water. Trees planted widely spaced are likely to use more water per tree than trees in clumps, but they will also reduce the yield of crops or pastures on a larger area of intervening land.

Agricultural practices on non-saline land

In South Australia, it is recommended that water use may be encouraged on hills by use of lucerne (*Medicago sativa*) (Matheson, 1968) but this plant has proved better adapted to conditions in South Australia than Western Australia where long hot dry summers present a problem. However, R. A. Nulsen (personal communication) has shown that there are significant differences in water use by annual plants which could be used to reduce groundwater levels.

Bare fallow was one of the earliest practices suspected of causing an increase in salt encroachment. Because fallow is designed to increase the amount of water stored in the soil it will also increase the amount of water percolating to the groundwater and thereby increase the likelihood of development of salinity problems related to excess groundwater. Overseas workers (USDA, 1971 and Benz *et al.*, 1976) have also drawn attention to the undesirable effects of fallowing on salt seepages and groundwater levels respectively.

Whereas bare fallowed soil stores water, plant cover uses up water during transpiration thereby decreasing the likelihood of salinity problems.

Water use by plant cover is influenced by the degree of plant cover on the ground, the length of time during which the cover is present, climatic conditions, and various other factors such as the light-reflecting properties of the plant material and the roughness of the plant cover. Measures aimed at increasing water use should aim to maintain a dense cover of plant material over as long a period as possible, but especially when evaporative demand is high. It has been emphasized, that rainfall should be used where it falls in order to maximise production, minimise erosion problems, and prevent seepages and boggy and dry areas in paddocks (Lightfoot, 1952; Marsh, 1952; Watson, 1961).

It is advocated that rainfall should be used rather than allowed to contribute to rising salt watertables. Three means of maximising water use on hillslopes are listed by Watson (1961).

- Maintaining a good plant cover on the soil.
- Encouraging good soil structure so that rainfall will soak readily into the soil.
- Adopting contour cultivation and if necessary contour earthworks to encourage water to soak in.

Watson observed that improved water absorption on higher slopes may result not only in better plant growth but also in an increase in groundwater supplies which may be useful for stock water. This observation highlights the dilemma facing anyone who tries to influence salt encroachment by changes of land use on the catchment. If water is allowed to run off during winter, it will cause waterlogging of soils in the valleys and flats. The resulting waterlogging is likely to lead to bare and moist areas in spring and these may lead to an increase in salting. On the other hand, if the water is encouraged to soak in on the slopes, it is likely to lead to an increase in groundwater either as seepages or as rising groundwater levels in the valleys, both of which lead to salting. Since retention of water on hills by good pastures, good cropping practices and use of the principles of soil conservation farming is likely to lead to improved production on the hills, it may be recommended apart from any influence it may have on the salt problem.

Workers in Canada and the U.S.A. have studied the effects of water use by crops on saline seep development. Brown and Ferguson (1973), found that alfalfa (lucerne) on the catchment dried out the subsoil and was probably able to prevent the outbreak and spread of seeps. Annual cereal cropping which dried out the soil to 1.2 to 2.1 m was also capable of reducing or halting seep spread, but had little prospect of eliminating already formed seeps. A cereal-fallow rotation was found by Doering and Sandoval (1976), to encourage seep development whereas alfalfa, natural grass and annual cropping were methods of using more water.

A novel approach to using more water is used in the Nobelford Reclamation Project by Oosterveld and Zentner (1976). They have used irrigation equipment to redistribute surface run-off for crop use on drier parts of the watershed. As a result more water is used and groundwater levels are lowered. Some pump drainage is also

involved in the scheme which has been calculated to give an economic benefit compared with continuous cropping.

Prospects for increasing water use on catchments in Western Australia currently depend on emphasizing crops such as wheat and lupins, which are deep-rooted, and planting back a proportion of catchments to trees or other perennial vegetation. However, longer seasoned, deeper rooted or perennial crops may be grown, provided they either equal annual conventional crops in yield or offer some other advantages which are judged worthwhile. Practices such as heavy grazing and fallow, to reduce the use of water which has already penetrated the soil on the hills may need to be avoided to discourage salting.

Workers in the United States of America (USDA, 1971; Webster, 1976) have observed that higher rates of nitrogen fertiliser can increase water use and may assist in reduction of seepages. Experiments in Western Australia on sandy soils at Wongan Hills have shown that water use by wheat can be increased by applying nitrogen fertiliser (Tennant, personal communication). However, at high rates of nitrogen, yield reductions are likely to occur. Fertiliser rates are normally designed for giving optimum returns from crops but if an additional benefit such as reducing salt encroachment can be gained from using more nitrogen on crops on hills, an increase in fertiliser nitrogen may be justified.

There may be selected soil types or topographical situations where nitrogen could be used to encourage water use, but practices of this nature could not be expected to have a permanent effect. They would only operate during the year they were applied and the actual effect if any on the saltland may occur in a later year.

Conacher (1974), and Whittington (1975), have suggested that salt encroachment may be reversed with deep interceptor drains installed on the catchments of saline areas. They assume that salting is caused by shallow sub-surface flow of unconfined water down the slope causing waterlogging and surface salinity following evaporation lower down the slope or on the flat. Water caught in the interceptor banks is said to enter the deeper groundwater and not influence salting because it cannot return to the surface.

The interceptor drain system is essentially a modification of normal soil conservation methods, but with the drain behind the contour banks deepened, and with the banks relocated to

positions where the subsoil is sufficiently close to the surface to be penetrated by the interceptor drain. An effort is made during construction to push up subsoil behind the bank to prevent water movement through the bank.

In response to such claims the author has dug deep test holes in saline soils in Western Australia at Morawa, Wongan Hills, Cadoux, Tammin, Quairading and South Carolling to investigate movement of groundwater in these areas. In every case saline groundwater has been found to leak through preferred pathways in clay and cemented material on its way to the ground surface in saline soils rather than to flow at shallow depths. Piezometers at Morawa, Wongan Hills, Quairading and South Carolling have also been shown by the author and Nulsen, Henschke and Stoneman (personal communication) to indicate movement of groundwater from below saline soils towards the surface. (See also Division of Resource Management, 1980).

Data from the CSIRO research station at Bakers Hill and widespread drilling and observation by CSIRO confirm the importance of preferred pathways and groundwater under pressure (Bettenay, personal communication) rather than shallow lateral flow of water as the cause of salt encroachment.

Cases are reported by Soil Conservation Officers of the Western Australian Department of Agriculture where use of normal soil conservation works has cured hillside seepages. There are also reports from farmers of improved growth on saline flats due to the use of contour banks or shallow drains to reduce waterlogging. Some improvement in saline areas from the use of interceptor banks can therefore be anticipated because they serve as surface drains and thereby reduce flooding and waterlogging. Much cheaper structures built with a grader could normally perform the same function.

In view of the causative role of upward leakage of saline groundwaters in most saline areas no substantial effects of interceptor banks on groundwater levels can be expected. In the Narrogin district Negus (1981), has tested the use of grader cut interceptors. The interceptors penetrated through the surface soil into dense clay subsoil and water was observed to flow in the V-ditch in the clay. However no change was observed over six years in the salt-affected area on five properties and on one property the salt-affected area extended 20 m upslope from the interceptor. The effects on saline areas of installations of interceptors are being monitored

by Stoneman and Henschke at Meckering, South Carolling and Quairading (Western Australian Department of Agriculture research). No significant reduction in the areas of salt-affected land have been observed.

At Batalling Creek, south-west of Williams, the relative contributions of surface, sub-surface and deep flow to the salinity of streamflow have been investigated by the Public Works Department (1979). Four to seven per cent of the chloride being discharged into the creek came from shallow sub-surface seepage although shallow seepage contributed five times as much water as deep flow.

To the extent that shallow seepage is contributing to a salt problem by encouraging winter waterlogging, and to the extent that run-off is causing waterlogging of salt affected areas, maximum water use on hillsides by good plant cover supported by contour cultivation and such structures as may be necessary to lead excess water away safely during heavy rain will assist the salt problem. However, in areas where these measures encourage an increase in deep percolation, some increase in seepage flow or valley waterlogging may be expected.

Reclamation of saline soils for normal crops and pastures

There are two basic steps in reclamation of salt-affected soils. The first is to control groundwater in cases where its presence is influencing the accumulation of salts at the soil surface. The second is to encourage salts to move downwards in the soil instead of accumulating at the surface. In the second case, success may depend on groundwater being controlled first. The ultimate purpose of such reclamation measures is to return land to normal crops and pastures if possible and to do so at a cost justified by the return obtained from the reclaimed land. However, as concluded by Peck (1978), in a review of salt problems, although several reclamation measures have been investigated little of practical significance has so far developed.

Groundwater control

A possibility for groundwater control is the use of some form of drainage. The purpose of drainage is to lower the groundwater so that accumulation of salts at the soil surface by capillary rise no longer occurs under normal management, that is the watertable must be lowered to below the "critical" depth of 1 to 2 m for most soils.

Effective drainage is only achieved when the drains are installed at the correct depth and spaced to draw down the watertable below the critical depth over the whole area. The spacing depends to a marked degree on the permeability of the soil, which is low in the case of many Western Australian saline areas.

The possibility of using drainage for the reclamation of salt-affected soils in the wheatbelt has been mentioned by the Royal Commission on Mallee Belt and Esperance Lands (1971), Teakle (1929, 1937 and 1938), and Burvill (1950). However, as observed by Burvill, drainage does not appear to be a practical solution in the flat wheatbelt valleys and he compared the cost of drainage with the cost of effective drainage in vine areas on Mallee soils in Victoria. A comparable figure today would be of the order of \$1 000 (1979) per hectare. It is unlikely that drainage for groundwater control in the broad fine-textured valleys of the wheatbelt would be an economic proposition as drains would need to be about 2 m deep and disposal of effluent water would require deeper collector drains or pumping.

There may be specific situations where some form of groundwater control by drainage may be practicable. For example, Bettenay (1978), reports substantial salt discharge from a drain installed in a seepage area at Bakers Hill. The drain was 3 m deep and had 50 mm drainage pipe in sand in the bottom. The effects on soil salinity are being observed. In the Calingiri area many salt affected valleys are sand filled and a relatively cheap drain may be effective in reducing salt levels. There are also situations where the flow of seepage water may be cut by means of a drain across the slope above the seepage. Such drains must be sunk to a sufficient depth to cut all of the groundwater supplying the seepage but as this may not be contained in a single water-bearing layer in many cases careful investigation of the source of water causing the problem is essential before starting work.

In saline areas caused by leakage from artesian aquifers in U.S.A. Benz *et al.* (1976), found no benefit from drains 2.1 m deep. However, aquifer pumping to lower groundwater levels was found to be an economic proposition.

Deep pumping from a 19 m thick sandstone aquifer at a rate of 2 250 L hr⁻¹ for 179 days reduced the groundwater pressures for a radius of 8 km. The reduction in pressures was sufficient to lower the saline watertable below

the critical depth for capillary rise and the land was successfully cropped. However, soil hydraulic conductivities in North Dakota calculated from Benz *et al.* data are about 36 m day⁻¹ and are appreciably higher than in Western Australia so the method may not be effective here. Bettenay *et al.*, (1964), found K values (hydraulic conductivity) of 0.006 to 0.62 m day⁻¹ for a range of sites in the Belka Valley but reports that limited areas have greater permeability (Bettenay unpublished data).

In the Kerang district in Victoria rapid reclamation of badly salt-affected soil was obtained by ponding fresh water on top and pumping from a sand layer at 7.2 m (Garland and Jones 1963). Essential features of this method are, firstly, the fresh water supplied to the top to wash the salt through the profile, and secondly, the availability of a sandy aquifer at depth from which to pump water rapidly. This situation does not apply to wheatbelt saltland. Moreover, as noted by Garland and Jones (1961), the saline watertable was still present after removal of salt from the surface soil and it was not known how long it would take for the surface soil to become re-salinised.

An appreciable expenditure may be justified for draining saline groundwater in certain cases and Bleazby (1917), reports that to save railway water supplies salt creeks were diverted around storages. Cases also arise on farms where dams, house yards, and other capital investments may be threatened by saline groundwater. Special investigation of the cause of salting and methods of groundwater control are justified in cases of this nature. Cole (personal communication) reports that saline areas in orchards have responded to deep drainage.

In general the prospects for deep drainage in saline soils in the agricultural areas of Western Australia are poor owing to the impervious nature of the subsoil. Specific cases must be considered on their merits, taking due account of economic factors. Salt encroachment in the sandier areas of the coastal plain, for example Eneabba, may be amenable to treatment by pumping or deep drains although silting would be a problem with the latter unless drainage pipes are used.

The control of surface water and mitigation of flooding is more easily achieved. Waterlogging reduces water uptake by plants and increases chloride uptake (West and Black of 1978), and West (1978) found a seven fold

increase in leaf chloride in apple trees due to imposing waterlogging as well as salt, instead of salt alone.

Additional water on a saline soil may improve leaching, as reported by Benz *et al.*, (1976), or raise groundwater levels as in irrigation areas in many countries. George (1979), reports the development of a groundwater mound in salt affected areas on the Esperance Downs Research Station.

In many saline areas the hydraulic pressure gradients are towards the surface and contributions to groundwater from flooding are limited to temporary perched watertables in the topsoil. The combination of water rising from beneath and entering the soil from above provides a saturated soil condition unsatisfactory for plant growth and leads to bare soil with a high surface concentration of salt. Where deeper groundwater can be removed by pumping surface additions may cause leaching but in most cases it is desirable to reduce the flooding of saline land by provision of soil conservation measures on the slopes, and flood mitigation measures on valley floors.

Using plants to control ground water

Growth of perennial plants in areas with a shallow saline watertable may lower the groundwater level (Greenwood and Beresford 1980), but the effect is likely to be temporary. While it is possible to grow plants in saline areas they use less water than in fresh situations (West 1978), and it is therefore better to plant in non-saline areas if the aim is to use more water.

Control of capillary rise

Grazing control on saline land

Smith (1962), showed the effect on surface salt accumulation of removing vegetation from potentially saline soil. He regarded soil bared by grazing as more likely to become saline than soil bared by cultivation, and therefore placed great emphasis on grazing control, particularly during spring when the soil was moist and evaporative demand moderate. The compacting effect of trampling by stock also encourages capillary rise so that grazing should be restricted as far as possible to late summer and autumn when soils are less readily compacted and there is less likelihood of capillary rise.

Avoid fallow

Fallow is recognised as being likely to increase surface salt, and its use has been recommended against by Burvill (1950), Lüken (1960), and Smith and Stoneman (1971). The possibility of using fallow with stubble mulch and ponding of winter rainfall to reduce soil salinity should be further investigated for sites on which the watertable is relatively deep and surface management has an important influence on salt rise.

Cultivate to encourage plant cover

Some saline soils tend to seal at the surface owing both to their high exchangeable sodium levels, and to the compaction of the surface by raindrop impact and grazing animals. Cultivation to break the seal in spring can either be delayed until the growth of annuals has ceased, or can be applied only to bare areas where plant cover will not be killed. Cultivation after annuals have stopped growing during the summer and autumn may be used on bare or grassed and patchy saline areas as a preparation for the opening rains.

Cultivation before the opening rain assists rain to reduce the salt content of the surface soil in preparation for the sowing of plants. Malcolm (unpublished data) found that areas cultivated in early May had a mean EC (electrical conductivity of the saturation extract) of 22.8 mS cm^{-1} (milli Siemens per centimetre) compared with 43.6 mS cm^{-1} for uncultivated areas when both were sampled after rain in late May. Even short term reductions in salinity of this magnitude may significantly assist plant establishment.

The value of cultivation for reducing the salt content of soil was examined by Smith and Stoneman (1970). It was found that autumn cultivation improved the efficiency of leaching by winter rain but had little effect on the return of salt to the soil surface in spring and summer. The experiment was conducted on bare saline soil and the implications for saltland management were described as follows: "Cultivation before the winter period is desirable to achieve the maximum leaching by rain and to avoid killing volunteer plants already germinated. For the latter reason, additional spring cultivations, while retarding the rate of upward movement of salt, are impracticable in saltland reclamation". It was recommended that seeding of saltland should be done after surface concentrations had been reduced by winter rains and machines should be chosen and speeds of working used to reduce the

kill of plants already germinated. A rotary hoe was used in the experiment but it was suggested that cultivation methods which left a rougher surface would provide greater encouragement for seed trapping and water infiltration.

Little information is available on the ability of seeds of plants, such as annual ryegrass and cereals, to survive in the field under saline conditions and to germinate once the salt has been removed. However, Teakle (1937), and Matheson (1968), have specifically recommended that planting should be delayed until opening rains have reduced the salt content of the soil.

The particular value of annual ryegrass as a plant for achieving a cover on salt affected soil was discussed by Shier (1952). The planting of annual ryegrass and its regular renovation by cultivation was found to be effective in reducing salt levels in the soil and in spreading plant cover over bare areas at Salmon Gums in Western Australia.

Mulches

In their study of salt movement in bare saline soils Smith and Stoneman (1970), included a sand mulch treatment. They found that the sand cover, which was about 5 cm thick and placed on uncultivated soil, was highly effective in enabling salt to be leached from the top 30 cm during winter, and in preventing its return during spring and summer. Organic mulches of animal manure or of cotton bur have also been reported to be highly effective in achieving salt leaching and saltland reclamation (Teakle 1929, Fanning and Carter 1963).

Unfortunately, mulches tend to be a very expensive approach to saltland reclamation although for small troublesome areas close to a source of suitable mulch they may be practicable.

Deep ploughing

Research on solonchic soil in Canada (Cairns and Bowser 1968, Rasmussen *et al.*, 1972) indicates that deep ploughing to about 55 cm brings about chemical reclamation of soil. The ploughing is designed to mix the lime rich horizon in the sub-soil with other soil layers. Although deep ploughing is very expensive and conventional machinery will not achieve the depth required, shallower ploughing is ineffective. The method would only be applicable to soils in which a lime or gypsum layer is developed.

It has not been shown whether there are any particular areas in Western Australia where deep ploughing might be useful, but in Canadian experiments it was superior to application of heavy rates of gypsum and special fertiliser treatments, and it increased yields on non-saline, as well as saline soils of the solonchic type.

Subsoiling

Suggestions have been made that deeper than normal cultivation may be beneficial to salt-affected areas in the wheatbelt, mostly because of the improved water infiltration. Burvill (1950), stated that he had seen no evidence to show that subsoiling improved growth on saltland as compared with the growth obtained from working to ordinary depths with a plough or scarifier.

Ridges and bed shapes

The special bed shapes developed by Bernstein and Fireman (1957), for growing row crops are not practicable for the establishment of a continuous cover over saline areas. Fanning and Carter (1963), also report that for areas treated with a ridge and furrow system less leaching was achieved than under cotton bur mulch. Salt was readily removed from beneath the furrows but accumulated under the ridges. However, use of a ridge to assist in establishment of shrubs is discussed later.

Land levelling and water ponding

Lyles and Allen (1966), report that levelling the microrelief in saline areas eliminated differences in rainfall infiltration and improved salt removal from the top 90 cm of soil in the Lower Rio Grande Valley area in Texas. Greater efficiency was achieved in salt removal by constructing small dykes around raised saline areas and impounding run-off on the areas. The method was applicable where salt spots occurred on the higher sections of the microrelief. The overall balance of salt remained unaffected and areas with a complex pattern of spots could not be treated.

It was noted by Fanning and Carter (1963), that the degree of salt removal from soil covered by a cotton bur mulch was superior to that which would be expected from using the same amount of water and ponding it on the ground. Ponding techniques have also been used by the New South Wales Soil Conservation Service

and will be discussed in connection with the establishment of shrubs. Water for ponding may be obtained by water spreading techniques or by construction of a ponding bank, but the success of the technique depends on the degree to which the salinity is caused by proximity of the watertable. Capillary rise through the summer from a shallow watertable may annul ponding benefits.

Gypsum and other amendments

The main benefits to be expected from use of gypsum are replacement of exchangeable sodium by calcium but for this to occur the sodium has to be leached from the soil. Gypsum usually improves the infiltration of water into soil, but under low rainfall conditions the amount of leaching water available may still be insufficient to give satisfactory leaching and replacement of sodium. In their study of salt movement in saline soils in the wheatbelt Smith and Stoneman (1970), included a treatment involving the application of 12.5 t ha^{-1} of gypsum with autumn cultivation. They concluded that the gypsum treatment had no measurable effect on salt movement at any stage of the experiment.

Subsequently Stoneman (1973), failed to show a significant effect of gypsum at 15 t ha^{-1} on leaching of chloride from mildly saline soils. Evidence of a beneficial effect of gypsum was reported by Milthorpe and Newman (1979), who applied gypsum at 2.5, 5 and 10 t ha^{-1} to a sodic scalded soil on the Lachlan flood plain in New South Wales. Major improvements in cereal yields and soil condition were obtained, but for sustained effects beyond five years the higher rates were necessary.

In their deep ploughing experiments in Canada Rassmussen *et al.*, (1972), found that neither gypsum at 36 t ha^{-1} nor subsoiling was as effective in reclaiming saline soils as 0.9 m deep ploughing. However, all such treatments would be expensive and very significant productivity increases would be needed to justify the costs.

It has not been shown to date that under Western Australian wheatbelt conditions salt problems are lessened by application of gypsum.

Fertilisers

Fertilisers are not a cure for salt problems and unfortunately there is no magic substance which can be added to the soil to "neutralise"

the effects of salt on plants and soil. As mentioned by Burvill (1950), however, growth of cover on saltland can be encouraged by addition of fertiliser, although whether it is worth adding fertiliser will depend on the severity of salting and the type of soil. On Western Australian saline soils, plant growth is usually limited by salt and/or waterlogging rather than by fertility. Conventional rates of fertiliser are recommended on mildly salt affected areas and nitrogen fertiliser gives profitable returns when applied to Puccinellia stands if they are harvested for seed (Clarke and Malcolm, 1976).

Flood mitigation

Flooded areas and salt affected areas tend to coincide because the lowest lying areas are those which are flooded, and they usually have saline groundwaters at the shallowest depth. Adverse effects of flooding can be mitigated by shallow surface drains or low banks to prevent water spreading over large flat areas, but care must be taken not to concentrate the flow of water on to neighbours' properties, and to avoid soil erosion. The use of interceptor banks is discussed in the section on agricultural practices on non-saline land.

It was noted earlier that under some conditions ponding water on saline soils may improve conditions for plant growth. Whether an improvement occurs depends on the salt content of the ponded water and whether leaching of the soil is possible. Good subsurface drainage would further assist the leaching process.

Revegetation of saltland

In the wheatbelt, measures discussed previously may return mildly salt affected areas to productivity with normal crop and pasture plants under continued good management. However, moderately and severely salt affected land will not be sufficiently improved by these measures for reliable production to be obtained from the usual farm plants. On these areas the planting of salt tolerant forage plants is recommended (Malcolm, 1969).

Plant selection

Apart from areas which can be regarded as beds of permanent or ephemeral salt lakes, natural saline soils are covered with some form of vegetation. Frequently the vegetation is useful for grazing, especially as a drought

reserve and therefore, if the the right plants can be found, soils which become salt-affected can be revegetated and production obtained.

In Western Australia Teakle and Burvill (1945), reported favourable results on saltland with trailing (creeping) saltbush (*Atriplex semibaccata*) and *A. paludosa* (probably this species was what is now called *A. bunburyana*). Bluebush (*Maireana brevifolia*), old man saltbush (*A. nummularia*) and creeping saltbush were also recommended by Smith and Malcolm (1959), but for waterlogged saltland, samphires (*Halosarcia* spp.) are recommended (Malcolm and Cooper, 1974).

Salt water couch (*Paspalum distichum*, previously *P. vaginatum*) has been recommended for many years for wet seepages (Burvill and Marshall, 1951) and for drier seepages and watertable saltland the Turkish grass *Puccinellia cilyata* is available (Clarke and Malcolm, 1976).

In 1966 a programme of collection and testing of salt tolerant forage plants was initiated to improve production from saltland (Malcolm, 1971; Malcolm and Clarke, 1971 and 1973). Although a special effort was made to obtain material of *Puccinellia* spp., testing failed to show any introduced material superior to the commercial cultivar Menemen. Salt water couch remains the best plant for wet seepages and samphire for waterlogged saltland.

For dryland salt, bluebush is superior to all other plants because of its ability to spread naturally and to withstand grazing. The testing programme has also identified several *Atriplex* spp. superior to old man saltbush and creeping saltbush in a number of respects. Progress in the programme has been reported by Malcolm (1974 and 1979a).

Because of the range of conditions in wheatbelt saltland, a range of plants is required to give vegetative cover. Most need a degree of salt tolerance greater than that of regularly used forage plants. During one growing season the author sampled 18 wheatbelt sites used for testing shrubs and grasses and found an average salinity of the saturation extract of 25 mS cm⁻¹ (and 0.6% NaCl) with a range from 3 to 96 (and 0.12 to 3.27% NaCl). At only one site were the salinity levels all below 18 mS cm⁻¹, the upper tolerance limit quoted for forage crops in USDA Handbook 60.

Factors influencing the selection of a salt tolerant forage plant for a particular site include rainfall, degree of winter waterlogging, degree

TABLE 11.—A guide to the selection of salt tolerant forage plants for saltland types in Western Australia

Saltland type and conditions		Degree of salt affectedness*		
		Mild	Moderate	Severe
Seepage	Summer wet	<i>Strawberry clover</i> ** <i>Paspalum dilatatum</i> couch, kikuyu	<i>Salt water couch</i>	<i>Salt water couch</i>
	Not summer wet	<i>Puccinellia</i> , barley	<i>Puccinellia</i>	<i>Puccinellia</i>
Saline valley floors	> 375 mm rainfall.	<i>Puccinellia</i> , barley	<i>Puccinellia</i> , saltbushes	<i>Samphire</i>
	<375 mm rainfall. Commonly flooded in winter	<i>Puccinellia</i> , saltbushes, barley	<i>Puccinellia</i> , samphire, saltbushes	<i>Samphire</i>
	Seldom flooded in winter	Barley, bluebush, saltbushes	<i>Puccinellia</i> , saltbushes, bluebush, <i>Puccinellia</i>	<i>Samphire</i> , saltbushes, <i>Puccinellia</i>
Dryland salinity		Barley, bluebush, saltbushes	<i>Bluebush</i> , saltbushes	<i>Bluebush</i> , saltbushes

* The degrees of salt affectedness are defined in the text.

** The recommended plant is italicised, others listed are also capable of reasonable growth.

*** Barley has not been recommended for mild areas which are likely to be so frequently winter waterlogged that results would seldom be worthwhile.

of summer moisture and severity of salting. In Western Australia the severity is most easily judged in the field from the annual plant cover:

- Mildly affected saltland has a cover of sea barley grass (*Hordeum marinum*) and a reduced occurrence of clover, medics and non-salt tolerant grasses. It often gives a reasonable crop with six-row barley.
- Moderately affected saltland has a patchy occurrence of bare and grassed areas and only carries a profitable cereal crop if seasonal conditions are especially favourable.
- Severely affected saltland is completely bare or only carries highly salt tolerant vegetation such as samphire. Cereal crops will not grow on severely affected saltland.

Using this classification and the information in Table 11 plants suited to particular areas of saltland may be selected. Recommendations in the table may not fit all circumstances but are intended as a guide. In a particular case it may be desirable to plant trial areas of the several plants listed, subsequently expanding the area of that which proves best.

No specific saltbushes (*Atriplex* spp.) are recommended in the table because testing is still in progress. Factors now being assessed include long term survival, colonising ability, grazing recovery, palatability, ease of establishment, seed production, yield and nutritional value. Species in current testing programmes have been selected from a much wider range and are listed in Table 12 together with brief comments on their characteristics and performance.

TABLE 12.—Some characteristics* of saltbushes (*Atriplex* spp.) currently under test

Common name	Botanical name	Colonising ability	Vigour	Growth habit	Relative palatability	Seed production
Silver saltbush	<i>A. bunburyana</i>	excellent	good	fair	fair	good
Grey saltbush	<i>A. cinerea</i>	poor	excellent	good	excellent	good
Quail brush	<i>A. lentiformis</i>	fair	excellent	fair	fair	excellent
Old man saltbush	<i>A. nummularia</i>	poor	good	fair	fair	good
Marsh saltbush	<i>A. paludosa</i>	good	good	excellent	good	good
River saltbush	<i>A. rhagodioides</i>	poor	excellent	excellent	excellent	good
Wavy leaf saltbush	<i>A. undulata</i>	fair	excellent	excellent	good	excellent
Bladder saltbush	<i>A. vesicaria</i>	good	fair	good	fair	fair

* The ratings are given on a subjective basis and serve mainly to indicate that different species are superior in different characteristics.

Best overall growth has been achieved by *A. undulata* and *A. rhagodioides* which are the subject of further study to devise establishment methods and determine grazing yields. Other species are still under test for the following reasons; *A. bunburyana* because of superior colonising ability; *A. cinerea* because of speed of ground cover development, *A. lentiformis* because of good performance in the northern wheatbelt, *A. nummularia* as a control and because of good longevity and high salt tolerance, *A. paludosa* because of excellent ground cover and good performance and *A. vesicaria* because of its importance in natural pastures.

The performance of the species listed is sufficiently encouraging for the development of reliable harvesting and establishment methods to be proceeding.

Seed supplies

Salt water couch produces little seed and must be established vegetatively. Seed of *Puccinellia* is available but it is relatively expensive and some farmers reduce costs by harvesting their own seed. The seeds do not shed early and may still be harvested quite late in the season. However, their fineness necessitates close settings for threshing, a fine screen and very low draught.

A field scale method of harvesting seed of samphire is discussed by Malcolm and Cooper (1974). A forage harvester is used to chop and gather the succulent but ripe-seeded bushes and the material is spread on bare ground to dry. A side delivery rake is then used to separate larger twigs and the resulting mixture of segments of seedheads and small pieces of broken bush can be used without further treatment, or, after a threshing or it may be threshed and cleaned. Threshing appears to assist field establishment.

It is possible to obtain small amounts of seed of bluebush and several of the saltbushes by hand collection in the wheatbelt, but bluebush seed must be dried and stored dry to maintain viability (Malcolm, 1961a). Drying agents are essential for long term storage (a year) of bluebush seed.

Mechanical harvesting methods are being developed for bluebush and saltbushes, and seed production plots of the most promising saltbush species have been planted for mechanical harvesting. Seed of some saltbushes is commercially available.

Establishment

- Salt water couch is normally planted from stolons in the early spring. Planting can be mechanised to a degree by placing the pieces in a furrow and covering by ploughing another furrow. A Bermuda grass sprig planter may also be used, or broadcast runners may be rotary-hoed in to a shallow depth.
- *Puccinellia* is established by sowing seed in autumn. The ground should be given an early cultivation, preferably before the opening rain, to assist rainfall penetration and salt leaching before sowing. Where weed control is not needed (i.e. on bare areas) satisfactory establishment is sometimes obtained by sowing areas before the opening rain. Clarke and Malcolm (1976), and Negus (private communication) have both reported on establishment methods and Negus has studied the value of spraying for weed control and obtained good responses.

Puccinellia is very susceptible to competition during establishment, especially from sea barley grass. Where competition is likely it is important to control weeds effectively by either spraying, burning or cultivating. Often on saltland the ground is soft when wet and bogging is likely. In these circumstances an initial cultivation before the rains will stimulate germination of weeds which can be controlled by spraying just before sowing.

The seed is small and should be broadcast on the surface of the soil at about 2 kg ha⁻¹. There is some evidence that higher rates give denser stands but good stands can be obtained at 2 kg ha⁻¹, and seed is expensive. (Farmers who produce their own seed may be prepared to sow at rates up to 6 kg ha⁻¹.) It can be mixed with superphosphate without adverse effects and the two broadcast together, as long as there is no more than a day or two delay.

The seed should not be buried deeper than one centimetre, and on a roughly cultivated surface may be left broadcast on the surface. Rains will bury it sufficiently whilst harrowing buries it too deeply. Where the seedbed is flat and fine a light harrowing may be worthwhile.

Growth will be improved by a dressing of about 25 kg ha⁻¹ N applied at sowing time. In limited trials superphosphate benefited

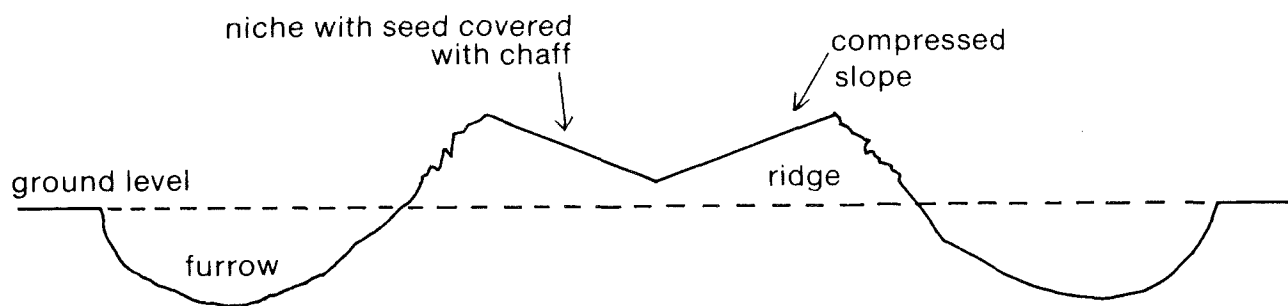


Figure 32.—Cross-section of furrow, ridge and planting niche produced by the Mallen Niche Seeder.

Puccinellia establishment but dressings in later years gave no response (Negus personal communication).

It is essential to exclude stock from the time of sowing until at least the following January and unless establishment and growth are good it is better not to graze at all in the first year.

Where existing barley grass is dense Negus (1979), recommends a four-step system for successful establishment as follows:

- Burn off dry barley grass
- Apply Spray Seed® four to six weeks after the opening rains (Spray Seed is a registered ICI formulation with 12.5 per cent Paraquat and 7.5 per cent Diquat.)
- Cultivate for the first time and sow Puccinellia seed a day or two after spraying.
- Fence off the Puccinellia pastures.

Once well-established, Puccinellia can be grazed for about six months each year, preferably from about March through to August. From August onwards the Puccinellia is allowed to recover to develop a good ground cover and to set seed.

- Samphire establishment has not been researched in detail but satisfactory results have been obtained by spreading the seed on the surface of cultivated ground in autumn. The seeds of two varieties were shown by Malcolm (1964), to be of low salt tolerance. Nevertheless, samphire rapidly colonises bare saline soils under natural conditions if a seed source is available and if protection from grazing is afforded. There is evidence that surface sowing is superior to sowing at about 2.5 cm (Malcolm and Cooper, 1974).

- Bluebush and saltbushes are difficult to establish on saline soils. A detailed review of the subject was made by Malcolm (1972), resulting in a new machine, the Mallen Niche Seeder, being invented specifically for planting salt tolerant forage shrubs from seed on saline soils (Malcolm *et al.*, 1980; Malcolm and Allen, 1981).

In one operation the Mallen Niche Seeder ploughs a furrow and forms a small ridge, presses a niche on the ridge and places seed covered with mulch in the niche. In Figure 32 a cross-section of the furrow and niche is shown. The figure shows a ridge made with an opposed disc ridger. An earlier system using a mouldboard plough was less successful.

The furrow is intended to catch water and cause water to be stored in the subsoil close to the growing shrub to aid survival and growth. The bank allows the planting site to be raised above the general ground level to avoid waterlogging or flooding problems, and to help leach salt from the niche. The niche provides a sheltered planting site with a firmed base on which the seed can be placed and the pressed side slopes cause run-off to be concentrated where the seed is placed. Water penetration and salt leaching are promoted by the mulch which also reduces evaporation and soil crusting. Some favourable results have been obtained using a chaff mulch but recent tests with vermiculite indicate that it is better. A marked increase in establishment by spraying with black water-based paint or bituminous emulsion which cause an increase in soil surface temperature has been obtained in field trials.

- The seed and mulch are placed intermittently along the row to allow the bushes to grow 2 to 3 m across. Spacing

and seed rates are adjustable and by sowing shrubs on a 3 x 3 m spacing one bag of chaff is enough for about one hectare.

- Results with the Mallen seeder have indicated that it is capable of giving markedly better establishment of bluebush and saltbushes than the old method of spreading seed on cultivated ground. Establishment varies with time of sowing. Autumn cultivation, which encourages salt leaching during rainfall prior to seeding, gives an increase in establishment.

Management and grazing

The most important factor in saltland revegetation is protection from grazing. Saltland forage plants should not be grazed in spring and early summer as they are making their most vigorous growth and producing seeds. Usually the need for grazing protection makes special fencing necessary, but where the area of saltland in a paddock is large relative to the area of non-saline land it is possible to manage the paddock to maintain a cover of salt tolerant forage without fencing.

Protection from grazing in spring also allows annual plants to make maximum growth, thereby assisting in providing a cover for the soil.

Bluebushes and saltbushes in south Western Australia are green when other feed in paddocks is dry so in the first year or two strict grazing control is necessary to allow the young shrubs to become established and develop a good root system. Later it may be necessary to control grazing in order to allow the older shrubs to throw new seedlings to thicken the stand.

Young seedlings are most susceptible to grazing during the spring and early summer. By autumn a substantial root system has usually developed and the seedlings are more likely to be bitten off than pulled out.

Grazing control is also necessary to allow recovery of grazed shrubs. Under wheatbelt conditions green forage from shrubs is normally most useful in late summer to early winter when other feed is dry and unattractive.

A careful watch must be maintained on the overall salt intake of animals grazing salt-tolerant perennial shrubs. Salt in the feed may be diluted by ensuring that stock have access to abundant fresh water and areas of dry grass or stubble. The intake of salty feed may also be diluted by feeding hay.

The salt level is highest in samphire and lowest in bluebush, with saltbushes intermediate.

Bluebush is known to contain high levels of oxalate but under wheatbelt conditions problems arising from this may be avoided by diluting the intake of bluebush with dry annual pasture, stubble or hay.

Samphire plants normally contain about 20 per cent chloride (or 30 per cent common salt) on an oven-dry basis. A major consideration in grazing management is therefore to avoid excessive salt intake by the grazing animals. Because sheep are more tolerant than cattle samphire is better suited to grazing by sheep.

The precautions necessary when allowing sheep to graze samphire are similar to those which should be adopted when moving sheep from a fresh to a salty drinking water supply. Sudden large intakes should be avoided and special care should be taken with ewes and young sheep. It is important to provide water with a low salt content, otherwise the overall salt intake by the animal is likely to be too high. Providing these precautions are observed useful grazing can be obtained from samphire.

The most practicable way to ensure that sheep do not eat excessive quantities of samphire is to have other feed available, or to feed hay. In some areas it is possible to sow *Puccinellia* in the samphire stand in order to provide an alternative feed. Samphire is normally of most use for late summer and autumn grazing because other feeds are scarce at this time of the year. Grazing at this time avoids the summer growth and seed production period.

Mature stands of samphire subjected to late summer and autumn grazing management tend to thicken and improve. In time they are normally invaded by annual pasture species which provide a useful supplement to the samphire.

Puccinellia, if well established, may be grazed heavily and is highly palatable even in its dry summer condition. Continuous heavy grazing prevents thickening of stands from natural seeding and reduces the vigour of established plants. There is a need for more research on methods of managing *Puccinellia* to maintain a dense vigorous stand and Clarke and Malcolm (1976), report on fertiliser responses of *Puccinellia* as follows:

Response to nitrogen varies according to the fertility of the soil and the rainfall in the area. For example, where rainfall is more than 500 mm, 30 kg ha⁻¹ of nitrogen will increase yields of dry matter by up to 1 t ha⁻¹. This response has been maintained up to 100 kg ha⁻¹ although 70 kg ha⁻¹ applied during winter would be a more general recommendation.

In lower rainfall areas response to 30 kg ha⁻¹ N or equivalent can be up to 800 kg ha⁻¹ of dry

matter. This fertiliser rate is generally recommended where rainfall is less than 500 mm per annum.

Superphosphate can be beneficial in the first year of sowing, especially if the area has had little superphosphate. It is unlikely to give any response in later years unless on new land in high rainfall areas where nitrogen is being applied.

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Glossary of Terms

- AQUICLUDE**—a layer of material which, although porous and capable of absorbing water slowly will not transmit it fast enough to furnish an appreciable supply.
- AQUIFER**—a stratum or layer below the surface of the earth capable of transmitting water.
- BELKA VALLEY**—a valley about 80 km long and 30 km wide situated about 240 km east of Perth.
- BREAKAWAY**—exposed broken edge of iron-cemented layer in laterite profile, usually a small cliff above a steep slope.
- CALCAREOUS**—rich in lime (calcium carbonate).
- CAPILLARY CONDUCTIVITY**—physical property related to the readiness with which unsaturated soil transmits water.
- CAPILLARY RISE**—upward movement of water in the soil from the saturated zone (watertable) as a result of surface tension forces in the pores (fine holes) in the soil. The smaller the pores the greater the possible height of capillary rise but the slower the rate of rise.
- COUNTRY ROCK**—the unweathered rock material underlying the soil and weathered rock or outcropping at some points.
- CRABHOLES** (also known as gilgais)—naturally occurring ridge and hollow formation in some clay soils. Hollows are often about 0.5 m deep.
- CRITICAL DEPTH**—the depth from which water will rise to the surface by capillary rise from the watertable in sufficient quantity to cause a salt problem.
- DEPOSITIONAL MATERIAL**—soil material which has been moved by wind or water and deposited elsewhere in the landscape.
- DIFFUSION**—of salts in water occurs from areas of high concentration to areas of low concentration. It is a very slow process.
- DISPERSED**—clay is dispersed in water when the individual particles are separated. Dispersed soils settle as an impermeable crust and do not retain their crumb structure when wet.
- DURICRUST**—the iron-cemented layer commonly exposed at breakaways.
- EROSIONAL SURFACES**—parts of the landscape from which soil or rock material is being removed, not necessarily in the short term. Evidence of erosion in the nature of gullies and sheet eroded areas may be lacking.
- EVAPORATION**—change of water from a liquid to a gas (vapour) form and its subsequent loss to the atmosphere.
- EVAPOTRANSPIRATION**—the sum of water loss from the soil by evaporation and by transpiration from plants.
- EXCHANGEABLE**—used to refer to some chemical ions such as sodium, calcium and magnesium which may become attached to electrically charged positions on clay particles. If there are changes in the concentration of the ions in the soil water (e.g. if a soil becomes saline) the ions on the clay may exchange for ions in solution.
- FERRUGINOUS CONCRETIONS**—lump of soil material cemented together by iron rich material. Compounds of aluminium and silica are usually also involved in the cementation.
- FLOCCULATED**—clay is flocculated in water when the individual particles are gathered together in groups which do not readily break up. Flocculated soils retain their crumb structure when wet.
- GIMLET**—*Eucalyptus salubris*.
- GRADIENT**—rate of change of elevation, see pressure gradients and suction gradients.
- GROUNDWATER**—is used in this publication to mean water in the soil or subsoil at a sufficient content (usually saturated) to move under gravity or to flow upwards as a result of pressure from beneath.
- HYDRAULIC CONDUCTIVITY**—is a measure of the ability of a soil to allow water to flow through.
- INFILTRATION**—refers to the movement of water into the soil surface.
- LATERITE**—ironstone gravels and boulders and their associated clayey subsoils.

- LATERITISATION**—the process of weathering of soil minerals and leaching and concentration of iron rich material at a certain level in the soil.
- MALLEE**—*Eucalypt* with a lignotuber and growth habit of several stems arising at ground level. Numerous species have mallee form.
- MASS TRANSPORT**—movement of salts in solution in the soil due to gravity or pressure or suction gradients.
- MERRIT**—*Eucalyptus floetanae* and *E. celastroides*.
- MICRO-TOPOGRAPHY**—differences in elevation of a minor scale, e.g. crabholes, ploughed banks or furrows.
- MORRELL (red)**—*Eucalyptus longicornis*.
- MORRELL (black)**—*Eucalyptus melanoxylon*.
- NaCl**—sodium chloride, common salt.
- PALLID ZONES**—the white or mainly white kaolin (clay) rich subsoils which occur beneath many lateritic soils often to great depth.
- PARENT MATERIAL**—the rock or other material from which a soil is formed.
- PED**—a discrete cohesive natural lump of soil.
- PEDIMENTS**—erosional slopes beneath high points in the landscape.
- PERMEABILITY**—soil property governing the movement of air or water through its mass.
- PIEZOMETERS**—tubes inserted in and sealed into the ground but with their bottom end open. The pressure of water in the soil at the bottom of the tube causes water to rise in the tube. The height to which the water rises is a measure of the hydraulic pressure at the bottom of the tube.
- PORES**—spaces in the soil. Water and air movement occur in the pores.
- PRESSURE GRADIENTS**—occur between positions in the soil between which there is a difference in hydraulic pressure. Water will move from high to low pressure positions unless prevented.
- ROOT CHANNELS**—in land which previously carried trees or shrubs the rotting of roots may result in channels being left in the soil.
- SALMON GUM**—*Eucalyptus salmonophloia*
- SALT**—in most of the soils and waters in the Western Australian wheatbelt 75 per cent of the salt present is common salt (NaCl). Other salts present are in roughly the proportions found in sea water.
- SALT PANS**—bare salt affected areas carrying a salt crust in summer and often covered with water in winter.
- SALT PROFILES**—salt content of the soil from the surface down to a stated depth.
- SOLONETZ**—a soil the formation of which has been influenced by excess soluble salts. Typically solonetz soils have high clay levels in the subsoil which is columnar in structure.
- SPILLWAYS**—areas of sandy soil formed when sand from high level areas spills into valleys and forms deposits akin to high level deltas.
- SUCTION GRADIENTS**—occur between positions in the soil between which there is a difference in soil water suction, e.g. dry as against damp soil. Water will move from positions of low suction (wetter) to position of higher suction (drier) unless prevented.
- SURFACE DRAINAGE**—drains provided to assist water lying on the soil surface to escape to the natural watercourse.
- TRANSITIONAL ZONE**—the layer of partly weathered material between the pallid zone and the underlying rock.

