

The Estimated Store of Soluble Salts in the Lake Eyre Catchment in Queensland and their Possible Transport in Streamflow to the Lake

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Abstract

Analytical data from 145 samples of deeply weathered and unweathered rocks and 35 soil samples form the basis for a first approximation estimate of the store of soluble salts in the Lake Eyre catchment covering about 500×10^3 km² in Queensland. A simple landscape model is defined to estimate the spatial distribution of the soluble chemical constituents of the various rocks and soils. The estimated quantities of soluble sodium and chloride in the catchment are 14×10^9 and 25×10^9 tonnes respectively. Some weathered rocks also contain appreciable nitrate and ammonium ions. Available data indicate that bicarbonate, sodium and calcium are the dominant ions in stream flood flows, whereas halite and gypsum are the dominant salts in the lake. Precipitation or reconstitution of degraded clays in the suspended load may account for the absence of carbonates in the lake. It is concluded that the weathered and unweathered Cretaceous sedimentary rocks in the catchment contain large stores of soluble salts, and are the most likely sources of the bulk of the salts in the lake.

Introduction

The Lake Eyre Drainage Division covers about 1.2×10^6 km², and is the largest area of coordinated drainage in Australia. It is an internal drainage basin which terminates in the Lake Eyre playa with a surface area of about 9500 km². Most of the water that flows intermittently into Lake Eyre is derived from the catchments of the Georgina and Diamantina Rivers and Cooper Creek which drain the region of higher rainfall in the north-east, principally in Queensland (Fig. 1).

The surface of the main playa, Lake Eyre North, is covered by a salt crust about 20 cm thick on average, but up to 46 cm in places (Bonython 1956; Dulhunty 1977). Bonython (1956) estimated that the crust contains about 360×10^6 t of sodium chloride and 6.4×10^6 t of magnesium and potassium salts, and that a layer beneath contains 3600×10^6 t of gypsum. Bonython suggested that an additional 360×10^6 t of sodium chloride may be trapped in brine in the gypsum layer, giving a total content of 720×10^6 t of sodium chloride. Following the filling of 1974-76, water flowed from Lake Eyre North through Goyders Channel to Lake Eyre South, and after it had evaporated a salt crust formed there for the first time (Dulhunty 1978).

The purpose of this study is to examine the nature of the soluble salts in rocks and soils, and to estimate their total store in landscapes of the three main catchments in Queensland. The possible transport of soluble salts to the lake is also examined in relation to available data on the chemical composition of stream flows before and during the period of flooding in 1974-76.

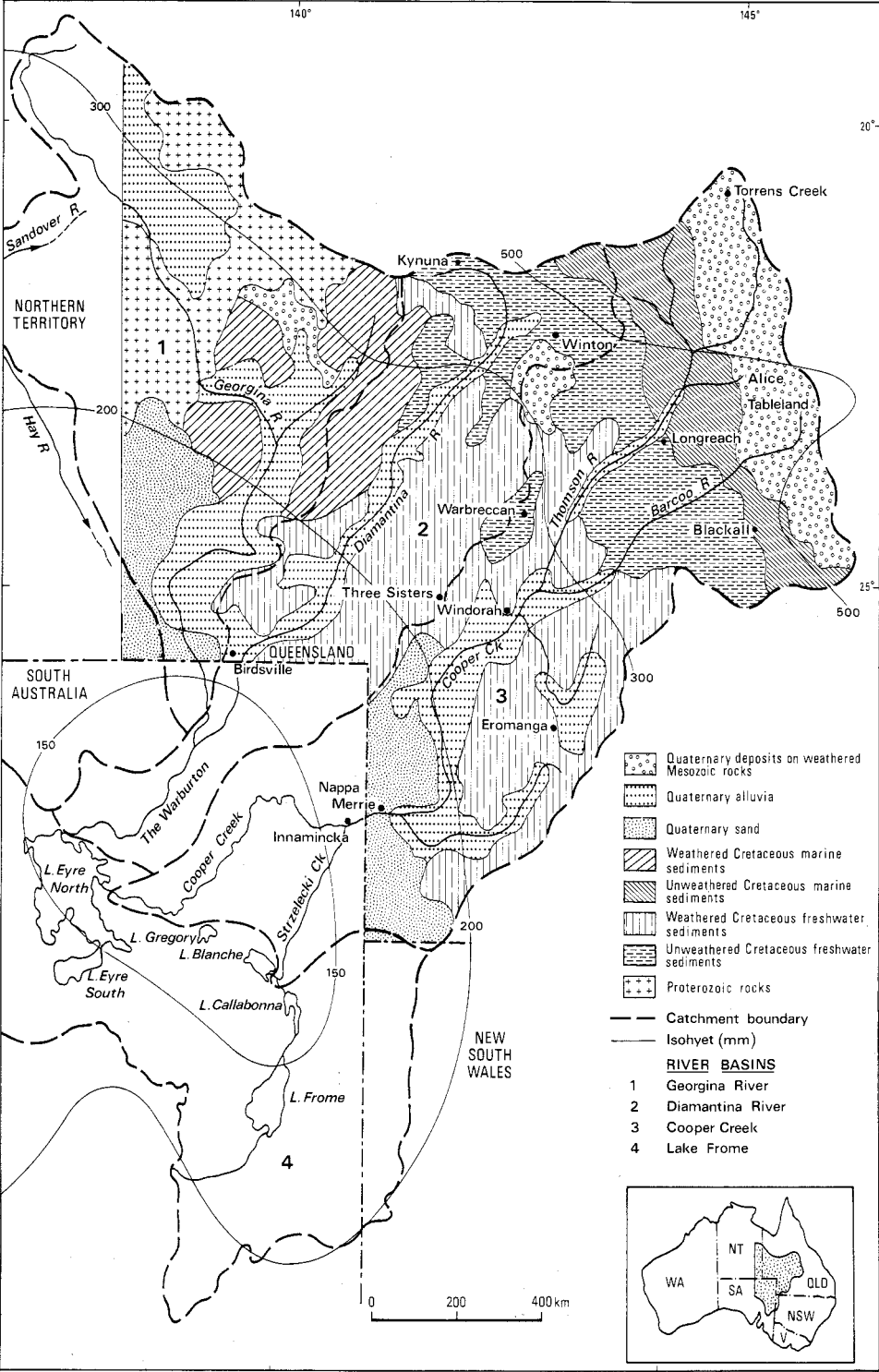


Fig. 1. Generalized geology of the Lake Eyre catchment in Queensland.

Geology and Geomorphology

Almost the entire catchment of Lake Eyre in Queensland is situated in the Eromanga Basin, which was covered by a shallow sea in the Early Cretaceous. The geology of the region has been mapped by the Bureau of Mineral Resources and the Geological Survey of Queensland (Senior *et al.* 1978), and its structure, stratigraphy and environment are described by Exon and Senior (1976). The following summary description is drawn largely from these sources, and the generalized geology of the region is shown in Fig. 1.

Apart from a relatively small area of basement rocks in the extreme north-west, almost the whole area is underlain by Cretaceous sedimentary rocks of the Rolling Downs Group, which consists of a sequence of commonly calcareous mudstones, siltstones and labile sandstones. These rocks are thought to be largely of andesitic provenance laid down in marine, paralic and freshwater environments. The Winton Formation, the youngest and most extensive unit, is believed to have been deposited under freshwater conditions on a broad coastal plain as the Cretaceous sea withdrew. It is underlain by a sequence of similar argillaceous rocks, the Allaru Mudstone and Mackunda Formation, which were laid down in shallow marine or littoral environments.

The Cretaceous rocks are overlain extensively by Tertiary quartzose sandstones of the Eyre Formation (Wopfner *et al.* 1974; Senior and Mabbutt 1979) and Quaternary sediments derived from reworked, older weathered rocks and materials. Linear dunes and sand sheets with associated swales and clay pans are widespread in the south-west.

Intense chemical weathering in the Tertiary affected the older rocks and a weathered mantle up to 100 m thick covered most, if not all, of the region and kaolinitic profiles with distinctive ferruginous, mottled and pallid zones developed. The Tertiary quartzose sandstones were extensively silicified and formed resistant cappings to the underlying older rocks. Subsequent dissection and erosion left more or less intact remnants of the weathered mantle on divides or where protective silcrete cappings were present. These residual landscapes form extensive plateaux and mesas bounded by steep scarps. The underlying zones of the weathered profiles are extensively exposed on scarps and on pediments below where a range of soil landscapes developed. The less resistant rocks were removed, and deposition of reworked materials by sheet floods and fluvial action partly filled the valleys where layered soils with surface lag gravels of silcrete are common. Over wide areas, particularly in the upper parts of the Diamantina, Thomson and Barcoo catchments, the weathered mantle was completely stripped off to expose the underlying fresh rocks. Clayey alluvia derived from both weathered and fresh rocks were deposited in the broad, almost level floodplains of major streams.

Hydrology

The Lake Eyre Drainage Division comprises seven river basins which are estimated to generate an average annual surface runoff of 3260×10^6 m³ (Department of National Resources 1976). Run-off from three basins enters the playa from Queensland through two discharge points: the Georgina and Diamantina Rivers through the Warburton Creek in the north, and Cooper Creek in the east. Some of the Georgina run-off is generated in the Northern Territory,

but the combined total with the Diamantina represents 57% of the average Divisional total, and Cooper Creek represents a further 15%.

The playa has been completely covered on three occasions in the past 90 years, in 1890–91, 1949–50, and 1974–76 (Bayly and Williams 1973; Vickery 1974). Water enters the playa rather more frequently, but does not cover the full playa floor before evaporating (Bonython 1963).

The average annual rainfall over the catchment is about 250 mm, but ranges from about 120 mm near the lake to over 500 mm in the north-east; annual evaporation from large water bodies in Lake Eyre is about 2000 mm (Tetzlaff and Bye 1978). Surface run-off is principally generated in the upper parts of the rivers, and considerable natural abstractions and diversions occur, so that exceptional conditions are required for surface run-off to reach the terminal playa.

The 1974–1976 flooding filled the main northern basin of Lake Eyre to the greatest depth since European settlement (Dulhunty 1977), enabling it to spill into South Lake Eyre for 6 months and the two acted as a single water body for a further 12 months. The water balance for the whole period was examined by Tetzlaff and Bye (1978), and they estimate that a total inflow, including direct rainfall, of $56 \times 10^9 \text{ m}^3$ occurred. They attribute $38 \times 10^9 \text{ m}^3$ to the Georgina–Diamantina system and only $2 \times 10^9 \text{ m}^3$ to the Cooper Creek.

Flow estimates were also made by the Queensland Water Resources Commission at Birdsville on the Diamantina of $2 \times 10^9 \text{ m}^3$ and at Nappa Merrie on Cooper Creek of $20 \times 10^9 \text{ m}^3$. These figures imply that most of the Georgina–Diamantina flood bypassed the gauged section at Birdsville and that most Cooper water did not reach Lake Eyre. Certainly large volumes of flow in Cooper Creek moved down Strzelecki Creek to Lakes Blanche and Callabonna. There are also extensive floodouts, playas and interdune swales along the lower course of the Cooper. These inconsistencies emphasize the uncertain nature of the estimates of average run-off and the water volumes which reach the terminal playa. A comprehensive analysis of earlier flow data and the behaviour of the Diamantina River and Cooper Creek is provided by Bonython (1963).

Groundwater discharge from aquifers in the Great Artesian Basin which underlies most of the region occurs from springs, vertical leakage and tubewells (Habermehl 1980). The largest and most active moundsprings are to the west of Lake Eyre, and upward leakage from aquifers is suggested by the groundwater tables which are maintained at high levels around the lake even during long dry periods. The greatest discharge ($1.5 \times 10^6 \text{ m}^3 \text{ day}^{-1}$ in the early 1970's) is from flowing artesian wells, and Habermehl (1980) estimates that 90% is lost by seepage from earth channels and evapotranspiration. Most of the groundwater is of fair quality (500–1000 mg l^{-1}) dominated by sodium bicarbonate, but poor-quality water high in sodium chloride occurs west of Lake Eyre and in the upper Cretaceous Winton and Mackunda Formations in the north-east. Overall, it would appear that groundwater discharge has a very small effect on the salinity of surface waters in the region.

Chemical Composition of Surface Waters

Data on the quantities of dissolved solids in waters entering the lake are available from 19 samples collected from Cooper Creek during the period February 1973 to April 1976, and two samples from the Diamantina collected in March 1971 and

February 1974. These samples were collected and analysed by the South Australian Engineering and Water Supply Department. The average contents of soluble ions in these samples collected during high and low flows at Innamincka and Birdsville are given in Table 1. The pattern of ionic dominance during both regimes was $\text{Na} > \text{Ca} > \text{Mg} > \text{K}$ and $\text{HCO}_3^- > \text{Cl}^- > \text{SO}_4^{2-}$. Two samples collected during low discharges contained dominantly Na^+ and Cl^- , but generally HCO_3^- appears to be the dominant anion, and it remains fairly constant regardless of the flow regime. The flood hydrograph at Innamincka is often multi-peaked, as water is derived from different subcatchments, and the quality may therefore vary according to the origin (R.D.S. Clark, personal communication).

Possible Origins of the Salts in Lake Eyre

Two main hypotheses have been suggested with respect to the origin of the salts in Lake Eyre: atmospheric accessions from the ocean, and rock weathering in the catchment.

Table 1. Average chemical composition of Lake Eyre, Cooper Creek and Diamantina waters
Data supplied by Engineering and Water Supply Department, S.A.

No. of Samples:	L. Eyre North		Cooper (Innamincka)		Diamantina (Birdsville)	
	(June to Dec. 1974) (17)	(Feb. to Dec. 1975) (5)	Flood flows (11)	Low flows (8)	Flood flows (1)	Low flow (1)
Discharge ($\text{m}^3 \text{ s}^{-1}$) (range)	—	—	1175 (160-4000)	7.4 (4.1-23.0)		
pH	7.1	7.1	7.2	7.1	7.4	7.2
EC ($\mu\text{S cm}^{-1}$) 25°C	23800	63500	152	270	63	144
Ca (m.e. l^{-1})	6.89	18.61	0.57	0.76	0.22	0.62
Mg (m.e. l^{-1})	4.36	13.08	0.34	0.44	0.08	0.40
K (m.e. l^{-1})	0.79	1.00	0.17	0.19	0.09	n.a.
Na (m.e. l^{-1})	238.6	695.7	0.66	1.32	0.48	0.55
Cl (m.e. l^{-1})	235.1	698.9	0.20	0.93	0.17	0.45
HCO_3^- (m.e. l^{-1})	1.64	1.79	1.41	1.59	0.70	1.10
SO_4^{2-} (m.e. l^{-1})	15.45	30.31	0.14	0.29	0.14	0.02
SiO_2 (ppm.)	n.a.	n.a.	16	15	n.a.	14

Bonython (1956) considered four possible sources of salts: a relict sea or lake, connate salts, dissolved solids in waters escaping from the Great Artesian Basin and wind-borne oceanic salts. That author suggested that all are likely to have contributed, but that the oceanic contribution is the largest. An annual fallout of about 1 kg of sodium chloride per hectare or a total of 120 000 t over the catchment was assumed. The 360 million t on the dry lake floor could therefore have accumulated in a mere 3000 years if all the salt were transported to the lake. Bonython (1956) regarded the relatively low tonnage of sodium chloride in the lake as a puzzling feature, having regard to the long period, since the 'late Tertiary' when the Lake Eyre depression was probably formed (Brown *et al.* 1968). It was suggested that the low tonnage of salt in the lake could only be explained by deflation; a constant stream of principally airborne and surface-waterborne oceanic salts enters the lake and another stream of different composition constantly escapes from it.

Atmospheric Accessions

Lake Eyre is situated 480–580 km from the ocean, and prevailing winds are from the south (Brookfield 1970). According to Hutton and Leslie (1958) the influence of the ocean on the composition of salts in rain decreases rapidly away from the coast and at about 120 km inland the influence of salts of probable terrestrial origin becomes more apparent. In Western Australia Hingston and Gailitis (1976) concluded that it is difficult to determine how far oceanic salt moves inland from the coast, because no clear distinction can be made between terrestrial and oceanic contributions to ions in precipitation.

The analyses by Hutton (1962) of 22 rainwater samples collected at a station 100 km north of Alice Springs during the period October 1957 to January 1962 are shown in Table 2. The station is located about 800 and 1000 km from the northern and southern oceans respectively and about 650 km north-west of Lake Eyre. The prevailing wind is from the south-east (Brookfield 1970). The samples were collected mainly during the October to December periods. During periods of no

Table 2. Average ionic composition (ppm) of 22 rainwater samples collected 100 km north of Alice Springs (after Hutton 1962)

	EC ($\mu\text{S cm}^{-1}$) 20°C	Ca	Mg	K	Na	Cl	HCO ₃	SO ₄
Mean	19	0.87	0.37	0.47	0.85	1.36	3.26	2.13
s.d.	14.4	0.60	0.38	0.45	0.98	1.75	1.58	1.44

rain, dust may have been removed from the gauge, but generally the water analysed would have had some contribution from dry fallout (J. T. Hutton, personal communication). As indicated by the standard deviations in Table 2, the ionic composition is highly variable; chloride, for example, ranged from 0.07 to 7.09 ppm. On a weight basis, the pattern of ionic dominance indicated is $\text{Ca} \geq \text{Na} > \text{Mg} > \text{K}$ and $\text{HCO}_3 > \text{SO}_4 > \text{Cl}$, which differs markedly from that in seawater.

At Katherine, located about 260 km from the coast in the Northern Territory, Wetselaar and Hutton (1963) found that 1.1 and 1.8 kg ha⁻¹ of sodium and chloride respectively were deposited annually in rain. As the ratios of the ions found in the rainwater were dissimilar to those in seawater, these authors concluded that most of the material is part of a terrestrial cycle and not a true accession. A similar conclusion may be drawn from the evidence given above in respect of the station north of Alice Springs, particularly in view of the extensive areas of saline, calcareous desert loam soils to the south-east where the prevailing winds originate. Evaporites, including halite, in the Bitter Springs Formation are also exposed at the surface east of Alice Springs (Wells 1980).

From the evidence available, it is therefore by no means certain that accessions of oceanic salts occur at a mean rate of 1 kg ha⁻¹ year⁻¹ over the entire catchment, and no information is available on the residence time of such salts in the various landscapes.

Rock Weathering

An alternative source of the salts that accumulated in Lake Eyre is the weathering of rocks in the catchment. Bonython (1956) suggested that connate salts may have been weathered out from old marine sediments. Wopfner and Twidale (1967) stated that the salt in the lake 'has undoubtedly been derived from the rocks which crop out in the catchment area'. This statement was challenged by Bayly and Williams (1973) on the grounds that no explanation was offered as to how such large absolute and relative amounts of sodium and chloride could have originated from the weathering of these rocks.

In the Lake Frome playa about 300 km south-east of Lake Eyre, sodium and chloride were found by Draper and Jensen (1976) to be the dominant ions in the hypersaline surface and subsurface waters. In view of the much higher Cl/Br ratio (1283) relative to that of seawater (292), these authors considered that the salts in Lake Frome have been derived from a combination of sources with weathering of saline rocks, deposition of cyclic salts and weathering of normal rocks the most important in that order. Connate waters and artesian water have been of less importance. A sample collected from Lake Eyre in April 1981 after a minor flooding indicated a similar high Cl/Br ratio of 1045 (R. J. Wasson, personal communication).

Minor occurrences of evaporites in the Eromanga and Georgina Basins are recorded by Wells (1980). In the Eromanga Basin, evaporites, including gypsum, occur in Cainozoic sediments over 100 m thick and are possibly the result of seasonal evaporation of floodwaters during the Tertiary and Quaternary (Senior 1970).

Contents of Soluble Ions in Rocks and Soils

The quantities of soluble ions in the various rocks and soils in the Lake Eyre Catchment in Queensland have been estimated on the basis of analytical data from 145 samples of weathered and unweathered rocks collected from surface outcrops, shallow bores and drill holes. The sampling sites were located mainly in the Eromanga Basin, but some were in the Surat Basin to the east, where the geology and geomorphic history are very similar (Exon and Senior 1976). Laboratory methods and analytical results for 81 samples were reported in a previous study by Gunn and Richardson (1979), and 64 additional rock samples were collected in this study. The contents of soluble ions were estimated from saturation extracts, and the analyses do not reflect the high contents of salts of low solubility such as gypsum and carbonates which are commonly present in the soils of the region. The study is therefore concerned primarily with the readily soluble salts, mainly sodium chloride. The chemical data on the various rock types and on 35 soil samples collected from landscapes underlain by weathered and unweathered rocks are summarized in Tables 3 and 4. The imbalance between cations and anions in some groups of samples may be due to errors in the sulfate estimation, particularly in gypseous materials. Four of the eight samples from surface outcrops of weathered freshwater rocks contain appreciable ammonium and nitrate which are not shown in Table 3.

A feature of some mottled and pallid zones in Cretaceous sedimentary rocks is their high content of nitrate and ammonium. Analyses of five samples collected from surface outcrops (Table 5) indicate that the presence of these ions is correlated

with strongly to extremely acid reaction, high EC_e values (averages 37.9 mS cm^{-1}) and, in some cases, high levels of magnesium and potassium. The origin of this nitrogenous material is of some interest, particularly as the host rocks have been subjected to intense weathering and chemical alteration. All the samples were collected from scarps at the margins of residual mesas, and it is possible that the

Table 3. Mean EC_e and contents of soluble ions in weathered and unweathered Cretaceous rocks

Rock type and sampling depth	No. of samples	EC_e (mS cm^{-1}) at 25°C	Ca	Mg	K (m.e. l^{-1})	Na (saturation extracts)	Cl	HCO_3	SO_4	SP ^A
Weathered marine sediments										
Surface outcrops	3	48.7	22.7	254.3	0.72	310.0	589.0	0	8.4	43.1
Shallow bores (2–5 m) and drill holes (4–87 m)	42	8.9	8.5	25.2	0.94	68.2	81.6	0.16	23.2	80.2
Weathered freshwater sediments										
Surface outcrops	8 ^B	15.4	34.3	53.5	5.4	85.7	92.0	0	8.0	64.3
Shallow bores (2–5 m) and drill holes (5–52 m)	42	6.1	5.7	15.5	0.50	43.3	52.0	0.08	16.1	83.4
Unweathered marine sediments										
Drill holes (15–145 m)	43	6.1	9.9	14.6	0.91	54.4	23.6	2.71	54.4	70.4
Unweathered freshwater sediments										
Drill holes (24–139 m)	7	10.6	10.5	7.1	0.6	93.3	102.9	2.1	12.8	96.5

^A SP, saturation percentage.

^B Add NH_4 , 6.3; NO_3 , 68.8.

Table 4. Average contents of soluble ions in clay soils formed on fresh and weathered rocks

Parent rock	No. of samples	Depth (cm)	pH	EC_e (mS cm^{-1}) at 25°C	Ca	Mg	K (m-equiv. l^{-1})	Na (saturation extracts)	Cl	HCO_3	SO_4	SP
Fresh	14	0–30	7.5	0.7	0.86	0.34	0.22	2.88	0.06	4.04	4.16	105.5
	7	30–90	7.5	2.6	1.66	1.12	0.23	17.79	4.96	3.16	24.66	104.2
Weathered	6	0–30	7.1	3.5	9.7	2.6	0.31	21.6	30.5	1.6	2.8	92.8
	8	30–150	7.2	13.2	23.4	13.5	0.55	89.5	114.4	1.1	12.2	94.7

Table 5. Soluble ions in weathered rocks with high contents of nitrate and ammonium

Note: HCO_3 was absent in all samples

Sample No.	Geol. form ^A	Locality	pH	EC_e (mS cm^{-1}) at 25°C	Ca	Mg	K (m-equiv. l^{-1})	Na (saturation extracts)	Cl	SO_4	NH_4	NO_3	SP
94	Kld	Torrens Ck	3.6	76.0	2.0	610	0.5	350	962	23.0	16.1	87.3	43.3
121	Kw	Winton	3.9	38.0	115	119	14.4	190	94	29.7	34.6	355.0	37.3
331	Kw	Warbreccan	5.8	9.5	19.0	42.0	1.7	39	67	14.0	0.2	26.6	105.9
353	Kw	Three Sisters	4.7	24.0	29.0	4.2	5.6	175	168	0.7	12.0	131.0	59.5
358	Kw	Eromanga	5.1	42.0	76.2	218	19.2	251	352	3.7	6.5	188.0	57.6

^A Kld, Lower Cretaceous Doncaster Member; Kw, Cretaceous Winton Formation.

nitrogen ions had concentrated by seepage in these situations where high contents of other soluble salts are also commonly found (Gunn and Richardson 1979). Four samples were from the Cretaceous Winton Formation which consists of a complex, bedded sequence of argillaceous sediments which, in the unweathered state, contain lignified plant debris and thin lignite seams (Exon and Senior 1976). It is possible therefore that the NO_3 and NH_4^+ ions were derived largely from this organic source.

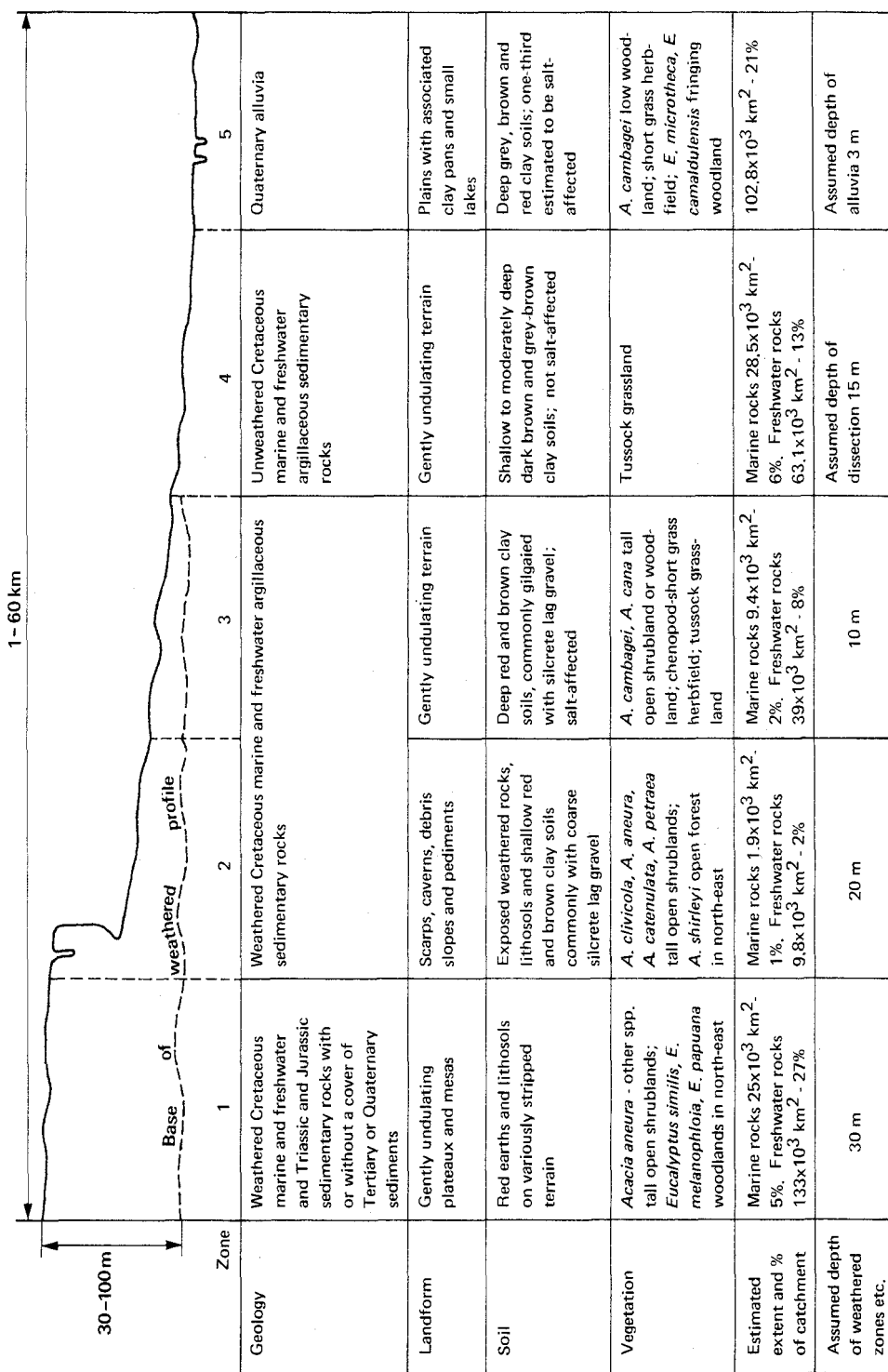


Fig. 2. Principal attributes and estimated extent of major landscape units in the Lake Eyre catchment in Queensland.

Landscape Model

To estimate the total store of soluble salts in the region, it is necessary to extend the available analytical data on the various rocks and soils to the range of landscapes in which they occur. For this purpose, a simple landscape model has been defined on the basis of surface morphology and interpretations of the pedo-geomorphic history. The model comprises five main elements or zones shown diagrammatically in Fig. 2 and illustrated in Fig. 3. Many other minor zones occur, and the actual pattern is clearly much more complex than it is possible to indicate here.

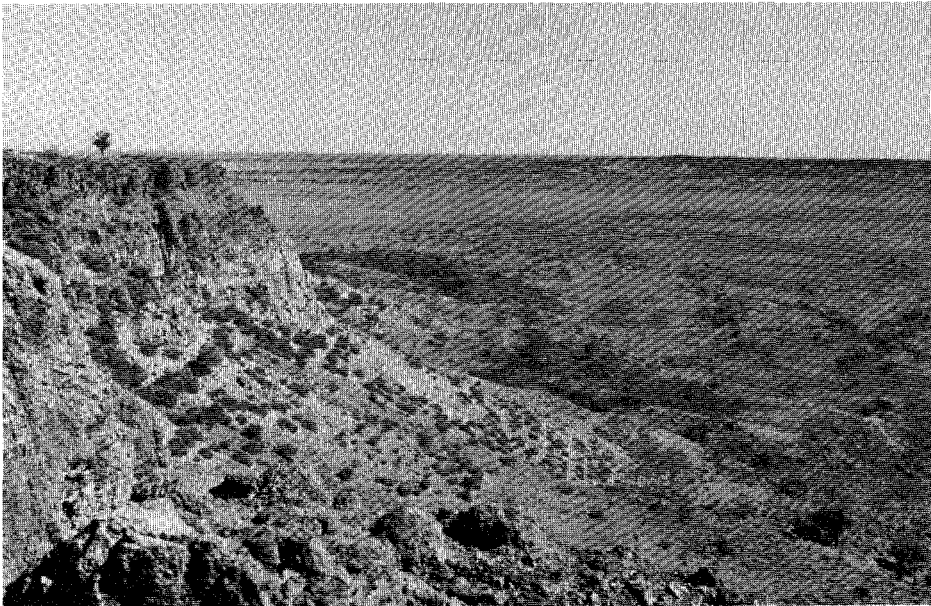


Fig. 3. A residual mesa north of Warbreccan with capping of Tertiary quartz sandstone over weathered Cretaceous Winton Formation. The main elements are the plateau, scarp, debris slope, pediment and gently undulating terrain on the valley floor.

The most elevated zone comprises plateau and mesa summits bounded by steep scarps with exposures of weathered rocks. Below the scarps are debris slopes and footslopes, generally with gravelly soils and surface lag gravels or cobbles of silcrete. Where broad valleys have developed on weathered rocks, the footslopes grade to gently undulating or almost level plains, with deep brown or red clays under woodlands of *Acacia cambagei*, *A. cana* or chenopod-short grass herblands. Where the weathered mantle has been stripped off, gently undulating plains with dark brown or grey-brown clays have developed, and in the lowest situations are broad, channelled alluvial plains with deep clay soils under *A. cambagei* and mixed open herblands or low shrublands. The five zones are estimated to cover about 85% of the catchment in Queensland, which is about 500×10^3 km² in extent. The remaining 15%, consisting of Quaternary sands and Proterozoic rocks, has not been taken into account. The estimated extent of the broad geological units were obtained by measurement of the areas mapped in Fig. 1. The spatial distribution and extent of the various landscapes shown in Fig. 2 are similar to those in the land

system maps of Dawson (1974), and Mills and Boyland (1976), which cover about half the catchment.

A range of grey, brown and red clay soils occurs extensively in various landscapes in the region. These soils have formed *in situ* on strongly weathered and 'fresh' argillaceous parent rocks and on colluvial and alluvial materials derived from them. They have been described by Hubble and Reeve (1970) and Dawson and Ahern (1974), and were examined during a rapid reconnaissance in this study. On the basis of this information, the physical and chemical properties of these soils are discussed in relation to their probable modes of formation and contents of soluble salts.

Residual Clay Soils on Argillaceous Sedimentary Rocks

Two broad groups of clay soils occur in this category, those formed on fresh, unaltered rocks, and those on rocks or materials that have been affected by deep weathering. There are gradations between these groups, and there is often no clearcut division. These soils are considered in terms of their depth, colour, salt content and clay mineralogy.

The fresh labile sandstones, siltstones and mudstones of the Rolling Downs Group which underlie almost the entire region are black to bluish grey, and all contain clay which is predominantly montmorillonite (Senior 1977). Where the weathered mantle that covered the region at one time has been removed completely to expose these underlying fresh rocks, the soils that have formed on them are generally only moderately deep (60–90 cm), surface horizons are dark brown to very dark grey-brown, and they are not, or are only slightly, affected by salinity ($EC_e < 4 \text{ mS cm}^{-1}$). Sodium is the dominant cation throughout the soil profiles, and bicarbonate and sulphate are the dominant anions in surface and subsurface horizons respectively. Chloride contents are very low. Analyses by the Australian Mineral Development Laboratories (AMDEL) indicate that montmorillonite or randomly interstratified material is the dominant clay mineral and kaolinite and quartz are accessory. These soils are most extensive in the upper catchments of the Barcoo, Thomson and Diamantina Rivers, but they also occur in scattered areas to the south where the weathered mantle has been stripped completely.

In contrast, the cracking clay soils formed on weathered rocks or layered parent materials derived from them, are deep to very deep, red or reddish brown, and they generally contain moderately high quantities of soluble salts in subsoils (Table 4). Sodium and chloride are the dominant ions throughout. X-ray diffraction analysis by AMDEL of nine samples indicate that kaolinite, montmorillonite and randomly interstratified material (montmorillonite with illite interstratification) are generally co-dominant. Quartz is accessory and goethite is occasionally present in trace amounts.

The major differences between these two groups of soils are in their colour, depth and salinity; the deep clay soils on weathered rocks have reddish hues and moderately high contents of soluble salts with high proportions of chloride. The greater depth, reddish colours and much higher contents of kaolinite clay are consistent with their formation on parent rocks that have been affected, at least to some degree, by deep weathering under more humid climatic conditions in the past; the development of the shallower dark soils on fresh rocks is compatible with their less-altered state under the present semi-arid to arid climate. Whitehouse (1940)

referred to 'chestnut coloured' soils in proximity to lateritic residuals, and greyish brown soils in areas remote from them. The much higher chloride contents of the deep red soils almost certainly reflect the accumulation of soluble salts in the lower zones of deeply weathered profiles.

Clay Soils in Transported Materials

Extensive areas of grey, brown and red clay soils occur on the floodplains of Cooper Creek, the Diamantina and Georgina Rivers and their tributaries, and are associated with numerous claypans, salt pans and adjacent small lakes. The soils in these landscapes are described by Dawson and Ahern (1974). The red and brown clays occur mainly on the more elevated alluvial plains of tributary streams which are bordered by variously dissected terrain underlain by deeply weathered rocks. Analytical data by Dawson and Ahern (1974) indicate mean values for TSS (1 : 5 soil : water suspensions) and Cl^- of 0.56% and 0.23% respectively in the subsoils of six profiles. The grey clay soils occur mainly in backswamps and alluvial plains of major streams which are subject to flooding. Analytical data of 12 profiles indicate mean values for TSS and Cl^- of 2.1% and 0.22% respectively.

Table 6. Estimated storage of soluble ions in major land zones

Land zone ^A	Rock type	Estimated extent (km ²)	Ca	Mg	K	Tonnes $\times 10^6$			
						Na	Cl	HCO ₃	SO ₄
<i>Weathered</i>									
1	Marine	25 000	198	340	60	1 678	3 123	8	1 303
	Freshwater	133 000	764	1 351	148	6 568	12 319	22	4 890
2	Marine	1 900	127	94	1	219	636	—	12
	Freshwater	9 800	139	141	40	398	731	—	63
3	Marine	9 400	25	43	7	210	392	1	163
	Freshwater	39 000	75	132	15	642	1 204	2	478
<i>Unweathered</i>									
4	Marine	28 500	113	93	22	764	463	105	1 502
	Freshwater	63 100	467	157	50	3 914	6 446	292	1 161
5	Alluvia	34 000					308		
Total			1 908	2 351	343	14 393	25 314	430	9 572

^A See Fig. 2.

Claypans, scalds and salt pans associated with the alluvial plains are also generally salt-affected (mean values for 12 profiles are TSS 1.92% and Cl^- 0.32%) (Dawson and Ahern 1974).

Estimated Store of Soluble Ions

Estimation of the total store of soluble ions in the various landscapes of the Lake Eyre catchment in Queensland is based on several assumptions: (1) that the rock and soil samples collected are representative of the landscapes, (2) that the mean values obtained by the analysis of the various rock types approximate the true mean values with respect to their chemical composition, (3) that the estimated extent and spatial distribution of the landscapes and depths of weathered zones, as shown in Fig. 2, are substantially correct.

Estimates of the total store of soluble ions are given in Table 6. The estimates are based on the mean values for the various rock types given in Table 3, their estimated extent and conservatively assumed depths (Fig. 2). Bulk densities of 1860 and 2100 kg m⁻³ were assumed for weathered and unweathered sedimentary rocks respectively, and are average values obtained from determinations on nine samples. The calculations indicate that sodium and chloride are the dominant soluble ions in the landscapes, and that large quantities of sulfate are also present. The estimate of 308×10^6 t of chloride shown for the alluvial soils in Zone 5 is based on data derived from analyses by Dawson and Ahern (1974).

Discussion and Conclusions

The evolution of the landscapes in the Lake Eyre catchment of Queensland is primarily the result of differential stripping of the weathered mantle that covered most of the region at one time. As in other parts of the continent, the pattern and depth of stripping are due to differences in geology, depth of weathering, relief and possibly climate (Churchward and Gunn 1983). As a result of uplift (Exon and Senior 1976) and/or the absence of silicified cappings, stripping has been most extensive in the north-east of the catchment where the weathered mantle has been removed almost completely to expose unweathered argillaceous rocks of marine and freshwater origin on which dark brown clay soils developed. As a result of stream incision and scarp retreat, stripping of the mantle in mid-catchments has left more-or-less intact remnants on interfluvies with a cover of red earths and/or silcrete, and has exposed the underlying weathered zones. It is estimated that about half the catchment in Queensland is covered by deeply weathered rocks (Zones 1, 2 and 3; Fig. 2).

In common with other regions of Australia, the Lake Eyre catchment has been subjected to major fluctuations in climate since the mid-Tertiary. In the late Pleistocene, Lake Eyre was about 17 m deep (King 1956) and occupied an area at least three times its present extent (David and Browne 1950; Wopfner and Twidale 1967; Twidale 1980). The extensive gypcrete deposits to the west and south-west of the lake may have accumulated in this ancestral lake (Twidale 1980) and are possibly the major sources of the gypsum in the lake. The fine-grained sedimentary rocks in the basin have remained virtually undisturbed since the Cretaceous and the landscapes have possibly been influenced by atmospheric salt accessions for long periods. However, if this were so, it would be expected that much greater volumes of salts would have accumulated in the lake and in soils formed on fresh rocks exposed by stripping.

Estimates of the total store of soluble ions in the catchment are based on available analytical data of the mean contents of the various rocks and soils and extended spatially to the landscapes that have been identified (Fig. 2; Tables 3 and 4). In view of the small number of samples, methods of analysis and broad assumptions that have been made, these estimates must be regarded as no more than a first approximation of the total volume of soluble material in the catchment. The estimates indicate that sodium and chloride are invariably the dominant ions in the mottled and pallid saprolite in the lower zones of weathered profiles. The highest values occur in surface outcrops on scarps and in caverns (Zone 2, Fig. 2). Sodium and chloride are also the dominant ions in unweathered freshwater sediments, but sodium and sulfate are generally predominant in unweathered marine sediments.

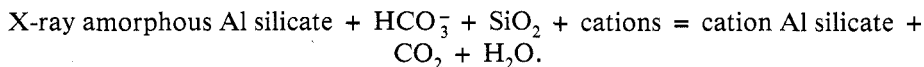
The weathered and unweathered rocks in the region undoubtedly contain large stores of soluble salts, but the rates at which they are released under the prevailing semi-arid to arid conditions are not known. It is likely that the highest rates of release are from the weathered rocks exposed on scarps and narrow pediments in strongly dissected terrain, such as the upper and middle parts of the Diamantina catchment, where run-off rates are high and large blocks of saprolite derived by slumping are disintegrated. In years of average or below average rainfall, it is likely that soluble salts are transported in run-off and stream flow over relatively short distances to waterholes, anastomosing distributaries, clay pans and minor floodouts. During occasional very wet periods, overflow covers these landscapes and salts which accumulated in upper reaches are eventually transported downstream. In view of the wide frequencies (1 in 50 to 100 years) at which flooding occurs in Lake Eyre, the movement downstream of salts in solution is likely to be slow and sporadic.

Although unweathered rocks of both marine and freshwater origin contain appreciable quantities of soluble ions, the dark brown and grey-brown clay soils formed on them are not salt-affected. This is probably due to the small volumes of rock that are involved and to the removal of chloride even under the prevailing semi-arid conditions. On the other hand, there is an apparent close correlation between salt-affected soils and deeply weathered parent materials or rocks, in which soluble salts had accumulated in lower zones. If the nitrate and ammonium ions present in some weathered rocks (Table 5) were derived from lignite seams in the unaltered rocks prior to weathering, then these ions must also have accumulated as a result of rock weathering.

Although analyses of only two samples of Diamantina water are available, in view of the marked similarities in the geology and geomorphic history of the catchments, it seems reasonable to assume that the chemical composition of Diamantina-Georgina floodwater is similar to that of Cooper Creek (Table 1). Assuming that $40 \times 10^9 \text{ m}^3$ were discharged into Lake Eyre by these streams during the flood period, it may be calculated that the following quantities of dissolved ions in tonnes $\times 10^3$ were present in the floodwaters at sampling sites upstream of the lake:

Ca^{2+} 460	K^+ 270	Cl^- 290	SO_4^{2-} 280
Mg^{2+} 160	Na^+ 610	HCO_3^- 3450	SiO_2 620

If all the chloride and sulfate combined with equivalent amounts of sodium and calcium respectively (i.e. $478 \times 10^3 \text{ t NaCl}$, $397 \times 10^3 \text{ t CaSO}_4$), together with some magnesium and potassium salts were deposited in the lake, the disposition of the large excesses of other ions not present in the lake needs to be accounted for. As suggested by Mackenzie and Garrels (1966) in respect of dissolved constituents carried by streams to the oceans, it is possible that the excess cations, silica and the large amounts of bicarbonate react with degraded aluminosilicates of the suspended load in floodwaters and with clays on the extensive floodplains north and east of the lake to form new minerals. The type of reaction suggested is:



Alternatively, the bicarbonate is precipitated from the solutions before they enter the lake.

On the assumption that 478×10^3 t of sodium chloride are deposited in Lake Eyre during floodings at a frequency of about once every 50 years, 1460 similar events or 73×10^3 years would be required for the accumulation of the 700×10^6 t presently in the lake. If a proportion of the sodium chloride is regularly removed by deflation from the dry lake bed, then a longer period would be required. Evidence of dry windy conditions in the past indicate that some of the salts present in landscapes of the region may have been derived from atmospheric accessions, and a small proportion of the salts in Lake Eyre may have originated from groundwater discharge from moundsprings. However, in view of the apparently large stores of soluble salts in the rocks of the region, it is considered that they are the most likely sources of the bulk of the salts in the lake.

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