Deep weathering profile and groundwater characteristics within a low-lying coastal pine plantation, southern Queensland — relationship to water-logging and salinisation

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Summary

Exotic pine plantations are a major landuse within the coastal lowlands of southern Queensland. Seasonal water-logging and the potential for salinity are of significant concern to forest managers. In the northern Tuan State Forest, a typical deep weathering profile is characterised by soils at the top, ferricrete (discontinuous), mottled saprolite, fine saprolite and coarse saprolite at the base. This zonation exerts a major control on the occurrence and geochemical character of groundwaters within the profile. Three groundwater zones are identified: (1) shallow groundwater (fresh) perched on top of the ferricrete or mottled saprolite; (2) intermediate groundwater (brackish) on top of the fine saprolite, and (3) a deep confined groundwater (fresh) aquifer within the coarse saprolite. Water-logging is caused by the perched shallow groundwater and the risk is largely controlled by the depth of restrictive layer that is related to geology. Discharge of the intermediate groundwater at breaks in slope often causes localised salinity. Over the decades, increased water uptake by mature pines has mitigated overall soil salinity induced by clearing of native vegetation for the *Pinus* establishment, but future management should avoid large-scale harvesting as rising water tables of the intermediate groundwater due to increased recharge could re-transport the salts upwards towards the ground surface.

Keywords: plantations; soil; water table; groundwater; salinity; risk; harvesting; *Pinus*; Queensland

Introduction

The coastal lowlands of southern Queensland are a part of a discontinuous belt of lowland country along the seaboard of eastern Australia. Nutrient status of the soils (many of which have a mantle of sand) is low, with wide-spread deficiencies of nitrogen and phosphorus, sporadic deficiencies of potassium, and deficiencies of varying combinations of the minor elements (Coaldrake 1961). Historically, extensive areas within these coastal lowlands, which were generally unsuitable or marginal for agriculture, were acquired by DPI Forestry, now known as Forestry Plantations Queensland, for *Pinus* afforestation (Foster and Costantini 1991).

Since the 1950s, about 110 000 ha of exotic pine plantations have been established in these coastal lowlands (Costantini and Loch 2002). Significant proportions of these plantations are reported being regularly affected by extended periods of seasonal water-logging, mostly during the wet season (November–March). Consequently, logging and other operational activities are restricted during the wet periods[1]. Following large-scale clearing and plantation establishment in the 1970s, extensive areas have become more saline, and the accumulation of excessive salts in the root zone led to increased mortality amongst young pines (Bevege and Simpson 1981).

In Australia, water-logging associated with duplex or texture-contrast soils (Northcote 1979; Isbell 2002) is relatively well understood as it is caused by a perched groundwater occurring on top of more finely-textured B-horizons (Cox 1988; McFarlane and Cox 1992; Cox *et al.* 1994; Cox and McFarlane 1995; Moore and McFarlane 1998), or in some cases, on top of the C horizon, depending on the variation in the subsoil horizontal hydraulic conductivities and textural contrasts (Brouwer and Fitzpatrick 2002a,b). Secondary salinity is often associated with water-logging (Williamson 1998; Rengasamy 2002, 2006; Spies and Woodgate 2005). Notably in the wheatbelt areas of Western Australia, the wholesale clearing of native vegetation has resulted in extensive lands being affected by dryland salinity. Rising water levels provide a transport mechanism whereby salts that are reposited in deep weathering profiles are lifted to the soil surface (Conacher 1982a,b; George and Conacher 1993; Stolte *et al.* 1999; McFarlane and Williamson 2002).

Although perched water tables are a very conspicuous feature in many of the soils in the coastal lowlands of southern Queensland (Coaldrake 1961), there is an obvious lack of literature and knowledge about controls on the perched groundwater, as well as the interaction between the perched and deeper aquifers (Bubb and Croton 2002). Certain soil types in the region, for example gleyed podsolics, are known to have a high potential to become saline (Evans 1967; Bevege and Simpson 1981); the depth where the salts are stored and the mechanisms by which they are transported are, however, poorly understood. Possible relationships between water-logging and salinity are poorly documented in the published literature.

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[1] Eeles, T. (1994) Wet weather loggability coverage. Digital file. Queensland Department of Primary Industries and Forestry, Gympie

The current study was conducted to address these concerns in a chosen area — northern Tuan State Forest (NTSF), a section of the much larger Tuan Toolara State Forest (TTSF, Fig. 1). The forest productivity of NTSF is the lowest within TTSF (Wang *et al.* 2007), presumably due to a higher risk of water-logging and salinity.

The study area is mostly covered by highly weathered material; the weathering profile and groundwaters contained within it were analysed. The study period covered a complete dry–wet season of 2005–2006, and the impacts of landuse changes over a much longer time span were also examined. The outcome of the study contributes to the knowledge of development of shallow water-logging and salinisation within the setting of coastal lowlands which drain into sensitive marine ecosystems such as the Great Sandy Strait. This information will also assist forest management.

Study area

The northern Tuan State Forest is about 300 km north of Brisbane, the capital city of Queensland, and about 5 km to the south-east of the city of Maryborough (Fig. 1). This plantation has a total area of around 100 km^2 and a subtropical climate, typical of SE Queensland (Bureau of Meteorology 2007a). Records at the Maryborough meteorological station show the long-term (1870–2004) average annual rainfall is about 1155 mm (Bureau of Meteorology 2007b). More than 60% of the annual rainfall occurs during the summer wet season from November to March, when summer cyclonic conditions are common. Winters are comparatively dry.

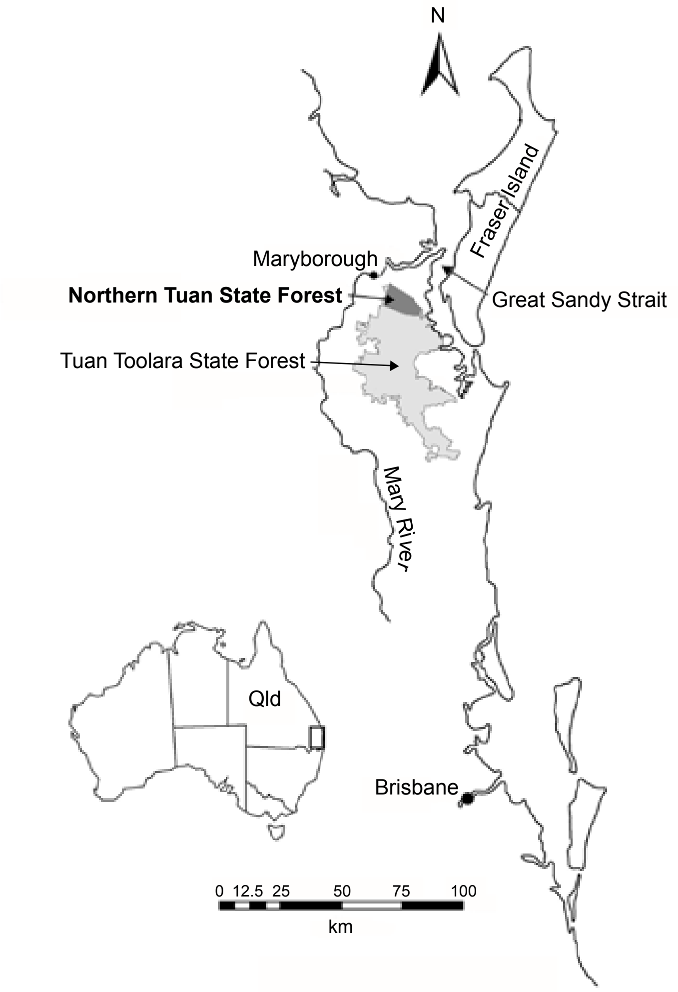


Figure 1. Location of the northern Tuan State Forest on the coastal plain of the Great Sandy Strait, near the mouth of the Mary River

Elevations of NTSF are low overall, up to 50 m but largely less than 30 m above sea level. The terrain gently falls towards the coastline in the east (Fig. 2a). Most of the plantation area has a slope less than 1%. Several tidal creeks flow eastwards, discharging into the Great Sandy Strait; in the north-west, several small streams flow northwards into the Mary River (a large river system, tidal in lower reaches) (Figs 1 and 2a). Surface drainage systems are poorly developed. Many of these are ephemeral, appearing in the wet season; they are characterised during other times of the year as a series of waterholes.

Three major geological units are present (Fig. 2b):

- Mesozoic Maryborough Formation (Km, mudstone, shale, siltstone and sandstone) forming a highly resistant discontinuous north–north-west trending outcrop within the central study area (Cranfield 1993)
- Tertiary Elliott Formation (Te, sandstone, conglomerate, of variable consolidation) which mantles much of the area
- Quaternary alluvium (Qa, undifferentiated sand, silt, clay and gravels) mostly derived from the Elliott Formation and being confined to drainage systems.

It should be noted that due to its hardness the Maryborough Formation is locally quarried for road base. During our fieldwork we identified Quaternary-aged coastal sands overlying or being admixed with the other deposits towards the east; they are not shown in Figure 2b which is based on a regional 1 : 100 000 geology map (Natural Resources Mines and Energy 2004).

Podsolisation, lateritisation and gleying are the three most common pedogenic processes that have occurred in the study area (Coaldrake 1961). The Elliott Formation has been entirely laterised since the Miocene (Murray 1977). Subsequent erosion has partially stripped this deep weathering profile, exhuming the underlying Mesozoic cover in places (Cranfield 1994). Coaldrake (1961) and Bubb and Croton (2002) described the patterns of soils development within the coastal lowlands of SE Queensland; there is a trend from deep red and yellow earths or red and yellow podsolics on the better-drained upper slope areas through to gleyed podsolics and humic gleys (Stace *et al.* 1968) within lower areas of impeded drainage. Many of the dominant soils show evidence of seasonal saturation in either the A- or B-horizon or both (Stace *et al.* 1968; Northcote *et al.* 1975).

Methods

Establishment of groundwater bores

In September 2005, a network of 33 groundwater bores was established to evenly cover the study area (Table 1 and Fig. 2c), prior to the onset of the summer wet season. Drilling confirmed the widespread presence of a deep lateritic weathering profile that is commonly sandy at the surface and grades into a low-permeability clayey layer at varying depths (Bubb and Croton 2002). Twenty-

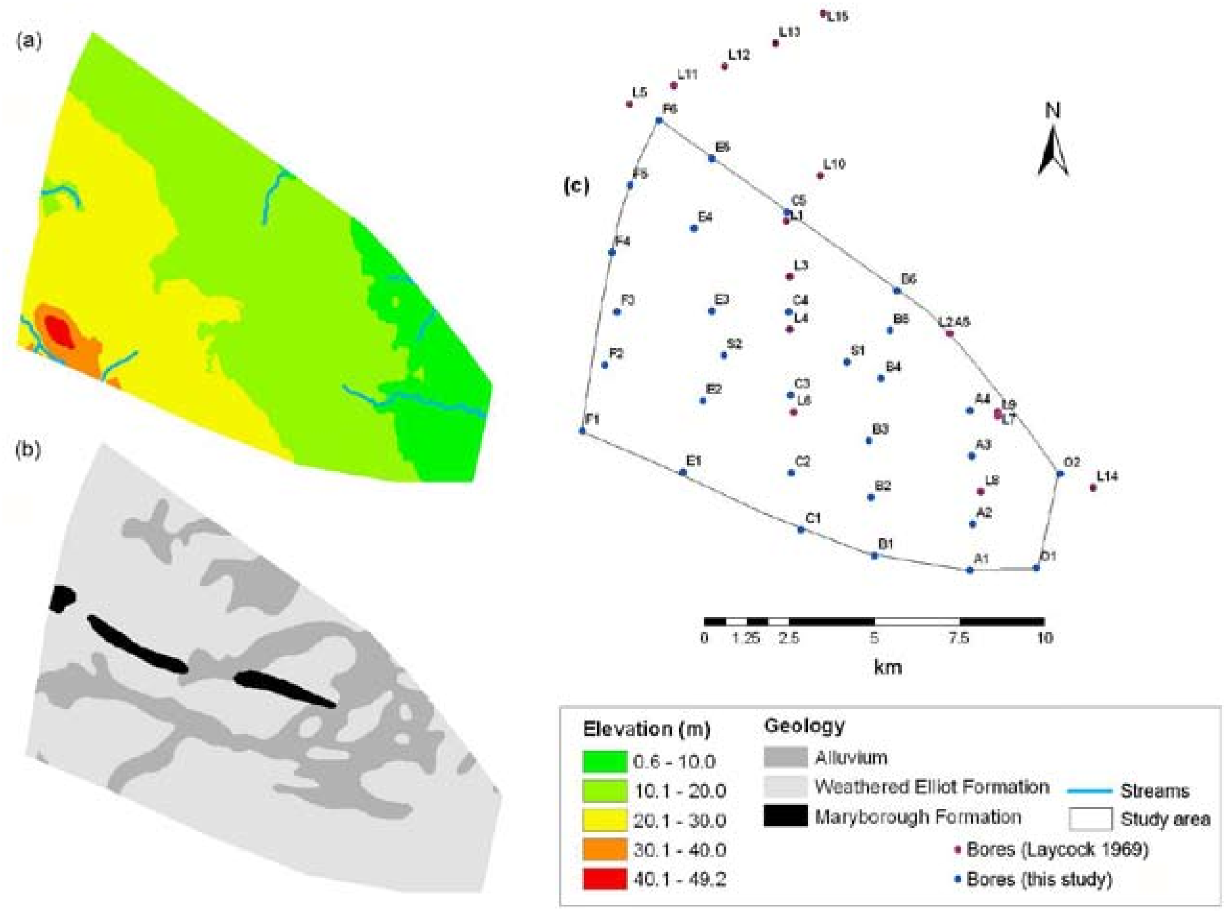


Figure 2. Major features of the northern Tuan State Forest physical setting: (a) surface topography and drainage, (b) surficial geology and (c) layout of test bores utilised in this study

Table 1. Details of the established groundwater bores

Type of bore	Average bore depth (m)	Average screen depth (m)	Number of bores
Shallow	2.2	0.8–2.2	28
Intermediate	4.6	3.1–4.6	4
Deep	12.5	11–12.5	1

eight shallow bores were established for monitoring perched groundwater, presumably formed on top of this clayey layer, or on top of a duripan (ferricrete or silcrete) in cases where the duripan appeared shallower than the clayey layer. Four intermediate-depth bores (B4, C3i, C4 and C5) were slotted within the clayey layer, and one deep bore, C2d, adjacent to the shallow bore C2s, was drilled to 13 m depth and slotted within a sand-gravel aquifer above the bedrock.

The shallow and intermediate-depth bores were drilled by an automated auger and the deep bore was by the rotary wash bore method with water (Brassington 1998). Bores were correctly constructed, cased with 50 mm diameter PVC, and had 1.5 m screened sections, around which they are gravel packed. The bore head is sealed by a concrete pad and downhole packing.

Soil (‘soil’ in this text refers only to the upper part of the weathering profile) and saprolite samples from the drillholes were collected at 0.5 m intervals and at depths where changes were observed. For each sample, a generalised description including colour (matrix and mottles) (Fujihara Industry Company 1967), texture (Wentworth 1922) and segregations was completed.

Field monitoring (water levels and physico-chemical parameters)

Field measurements of water levels were undertaken initially in October 2005 and then on a monthly basis from December 2005 to February 2006 to cover the summer wet cycle. Also during this period we measured physico-chemical parameters including electrical conductivity (EC) (μS cm^{-1}), Eh (mV), pH and temperature (°C), except that in December 2005 no measurements of the physico-chemical parameters were made. Water levels were measured using an electrical ‘dipper’ and the physico-chemical parameters by an electrical field meter (TPS WP81).

X-ray diffraction (XRD) analysis

Selected soil and saprolite samples were analysed for mineralogy using XRD. Of these, five samples were selected from the deep drillhole C2d to characterise an entire weathering profile. Seventythree samples from 16 shallow boreholes (O2, A1, A3, A5, C1, C2, C3, C4, C5, F1, F3, F4, F6, S1, S2 and E3) were selected to provide a good spatial coverage of the study area, as well as different geological units (Fig. 2). Ten per cent corundum was added to each sample to identify possible amorphous fractions. Standard procedures for preparing and analysing randomly-orientated powder samples were used (Jenkins and Snyder 1996). A Philips PW 1050 diffractometer equipped with a cobalt anticathode was used for the XRD analysis. The quantification of mineral phases was assisted by SIROQUANT, a quantification program that expresses the composition of crystalline material within a sample as percentage of dry weight.

Soil geochemistry

The soil samples that were analysed by XRD for mineralogy were also measured in the laboratory for soil EC and pH (1 : 5 soil : deionised water suspension) (Rayment and Higginson 1992). As salt damage to newly-established pines can occur where the conductivity is as low as 200 μS cm^{-1} (Bevege and Simpson 1981), this level was adopted in this study as the threshold for the risk of soil salinity.

Groundwater geochemistry

During the February 2006 field trip, groundwater samples were collected using a bailer from five shallow bores from throughout the area (A3, C1, E1, E3 and F1), as well as from the four intermediate and the one deep bore. In the laboratory, major and minor ions were analysed using an inductively coupled plasma–optical emission spectrometry (ICP-OES, Varian, Liberty 200) for cations and an ion chromatography (IC, Dionex Bio-LC) for anions. Alkalinity was determined using a titrimetric method. Standard procedures for sample collection, transport and analysis were followed (Clesceri *et al.* 1998).

Results

Weathering profile

The logs of the deep drillhole C2d together with earlier geological logs from Laycock (1969) confirmed a typical deep weathering profile, which has the following distinctive layers from the ground surface: soil, ferricrete (spatially discontinuous, not present at C2 but observed at many other sites), mottled zone and pallid zone. In this study, the soil-regolith terminology suggested by Nahon and Tardy (1992) is used in which the weathering profile grades upwards from coarse saprolite into fine saprolite, mottled zone and a lateritic residuum (soil and ferricrete). The mottled zone is also termed mottled saprolite, as it contains patches of iron oxides within a matrix of pallid zone saprolite. A summary of the distinctive zones, texture and mineralogy is displayed in Figure 3.

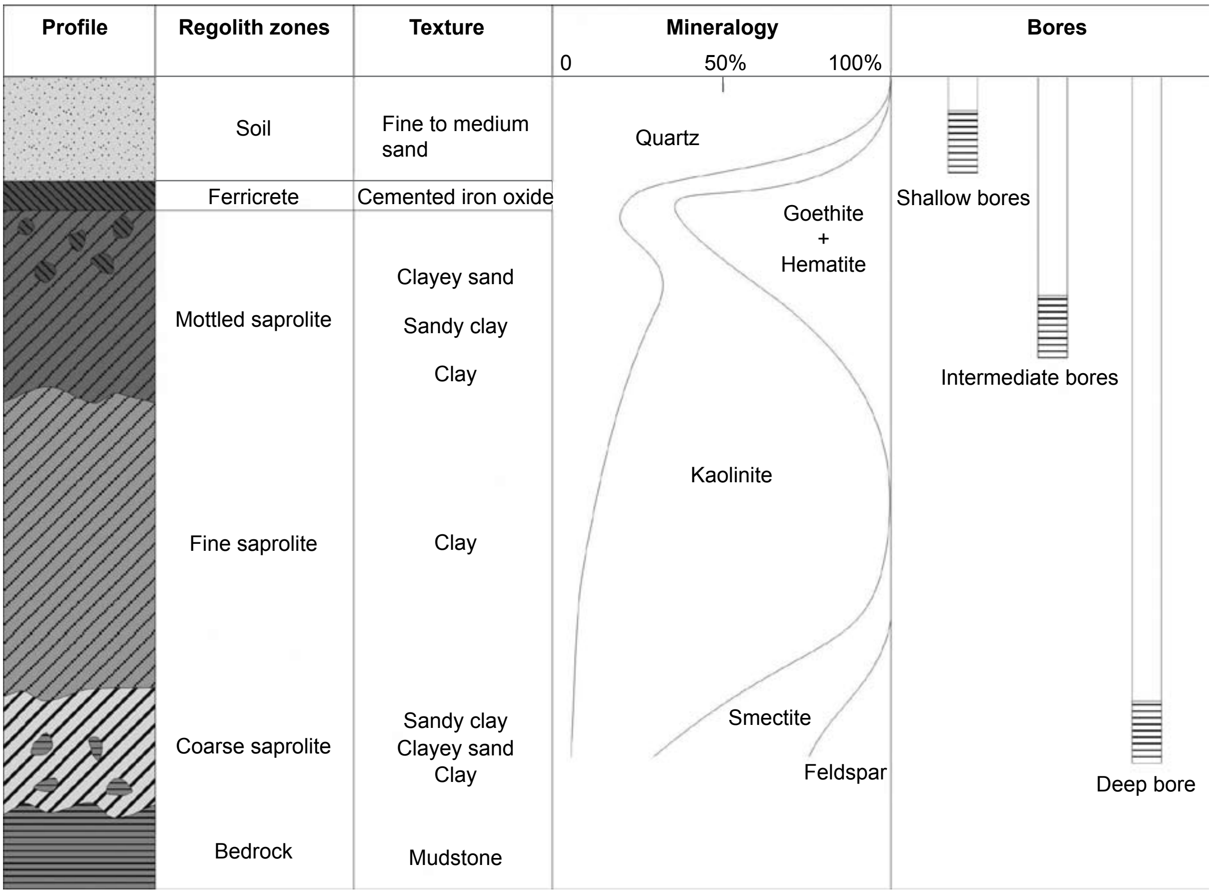


Figure 3. Schematic of the profile showing regolith zone, geological profile, distribution of mineralogy (cumulative %), and the depth of monitoring bores. Detailed mineralogy of samples representing different regolith zones is shown in Table 2.

The soil at the top of the profile is commonly yellowish or greyish fine to medium sand, most of which is quartz. In some places, pisolithic iron nodules can be admixed. Ferricrete, not always present, consists mainly of cemented iron oxide minerals (hematite, goethite and some amorphous phases) together with lesser amounts of kaolinite and quartz. Both the mottled saprolite and the fine saprolite layers are clay-rich. Within the mottled saprolite, the kaolinite content ranges from 26% to 56%, and hematite and goethite content is up to 30%. The fine saprolite, which is depleted of iron oxide minerals, consists of more than 80% kaolinite and minor amounts of smectite. At the base of the profile, the coarse saprolite is sandy to gravely in texture; smectite, rather than kaolinite, is the major clay mineral present, and a large proportion of feldspar is preserved. Detailed mineralogy of representative samples is given in Table 2. The established shallow, intermediate and deep groundwater bores were screened within the soil, mottled saprolite and coarse saprolite layers, respectively.

Water levels

Daily rainfall records over a five-month period from October 2005 to February 2006 (Bureau of Meteorology 2006) are shown in Figure 4. Rainfall started to recover from the previous dry season during October, increased further in November, and peaked in December. Following this, an almost symmetrical decrease occurred over January and February. This is atypical for southern Queensland, where most rain occurs in January to February. Groundwater levels are compared with the daily rainfall amounts. Although no continuous water level measurements were made, patterns of water level variations observed from discrete field measurements display the general trend (Fig. 4).

Of note is the water level within the deep bore C2d which showed little variation over the study period, but a slight increase during the summer wet season can still be seen.

The greatest variability in water levels occurred within the shallow bores during the prolonged dry and wet periods (see C2s and C3s, Fig. 4). Most of the shallow bores were dry in October; perched groundwater tables built up only after the intense rainfalls in December. Over the following two months, the rainfall continued but less intensely; some of the perched water levels started to decline (e.g. C2s), while some others continued to rise (e.g. C3s). In late February, however, most water levels decreased and some of the bores had become dry again.

Most of the intermediate bores had water levels measurable throughout the dry-wet period. They (e.g. C3i) showed patterns of water level variation similar to those of the shallow bores (e.g. C3s) (Fig. 4), but their heads were generally lower.

Physico-chemical characters

Physico-chemical measurements of groundwaters during three rounds of field monitoring (October 2005, January and February 2006) are summarised in Table 3. Some bores became dry during this period and consequently no water samples were available. In October 2005, only two shallow bores (C1 and E1) and two intermediate bores (C3 and C4) were sampled. The number increased to 16 in January for the shallow bores and to 15 in February 2006. For the intermediate bores, three bores (B4, C3 and C4) were sampled in January and all four in February. Variation in the bores sampled should be taken into account when considering temporal changes in parameters for groundwaters of different depths shown in Table 3.

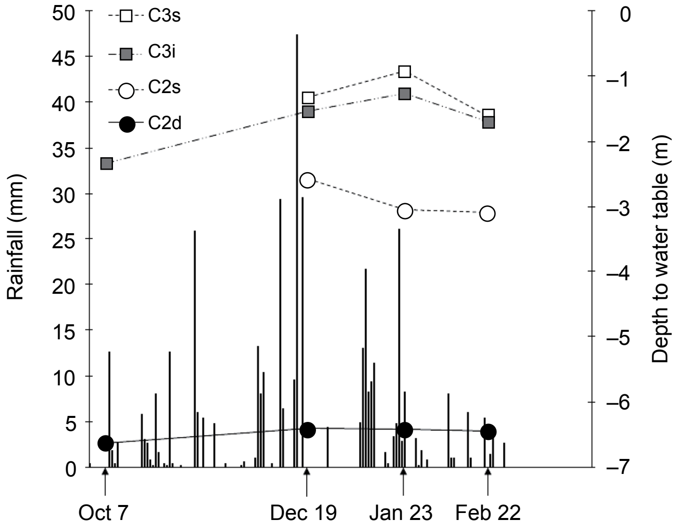


Figure 4. Relationship of borehole water levels to total daily rainfall over a summer wet season of 2005–2006 (Bureau of Meteorology 2006). The lines linking the measurement points are intended to facilitate visual comparison, not to imply the actual water level change between the measurement dates

Table 2. Mineralogical composition of selected samples from XRD[A]

Bore ID	Depth (m)	Regolith zones	Quartz	Feldspars[B]	Kaolinite	Smectite	Hematite	Goethite	Laumonite	Amorphous
C2d	0.0	Soil	96.4	–	–	–	–	–	–	3.6
C4	0.5	Ferricrete	27.0	–	12.1	–	26.0	34.9	–	–
C2d	1.5	Mottled saprolite	41.3	–	26.1	–	10.6	22.0	–	–
C2d	2.0	Mottled saprolite	19.6	–	56.5	–	10.1	13.3	–	0.4
C2d	3.0	Fine saprolite	10.9	–	86.9	1.3	–	–	–	0.9
C2d	11.0	Coarse saprolite	6.3	28.3	13.3	48.3	–	–	2.1	1.7

[A] Only samples that are used for depicting the mineralogy curve in Figure 3 are listed.

[B] Feldspars include albite and microcline.

Although the EC values of the intermediate groundwater vary dramatically from site to site (lower than 1000 μS cm^{-1} at B4 whereas close to 10 000 μS cm^{-1} at C5), the median value (4248 μS cm^{-1}) is about seven times that of the shallow groundwater (598 μS cm^{-1}) and five times that of the deep aquifer (799 μS cm^{-1}). In addition, the pH of the intermediate groundwater is correspondingly the lowest (4.3). The shallow groundwater is less but also acidic (5.7), while the deep groundwater is more typical of common circum-neutral groundwater pH (6.5). The intermediate groundwater is also distinguishable with the highest Eh (338 mV) compared to the shallow groundwater median at 148 mV and the deep groundwater median at 168 mV. Temperatures of the groundwaters show a reasonable trend of decreasing values with depth.

Groundwater geochemistry

Sodium and chloride are the major cations and anions found in all the groundwater samples (Table 4), reflecting primary recharge from coastal rain. Water chemical type varies with geology: Na-Cl and Na-Cl-HCO_3 are typical for the weathered Elliott Formation and Maryborough Formation; for the Quaternary alluvium, however, significant amounts of Mg, Fe and SO_4 were present in the groundwater.

Previous records of groundwater geochemistry of deep groundwater bores from Laycock (1969) and typical seawater and stream water from Cox *et al.* (1996) were compared with results from the current study (Fig. 2). The ratios of two major anions (Cl and HCO_3) were plotted against the ratios of two major cations (Na and Ca) (Fig. 5), which depicts grouping of, and transition between, different water bodies (Hem 1992). As the general positions of seawater and fresh stream water show a mixing line I, most bores from this study and also from Laycock fall along a parallel line II of elevated Na content with the bores E3 and F1 reflecting direct infiltration and the intermediate bores on the other end of concentration. Bores C2d and E1 show further Na enrichment and Ca depletion. On the *x*-axis, the ratio of Na : (Na+Ca) is largely between 0.9 and 1.0. The groundwater bodies are better differentiated by the anions on the *y*-axis. The four intermediate groundwater samples have the highest ratio of Cl : (Cl+HCO_3) at 1.0. The ratio for the deep groundwater samples ranges between 0.6 and 1.0, and for shallow groundwater samples it is either below 0.6 (e.g. E1, E3 and F1) or above 0.9 (e.g. C1 and A3). The higher-ratio (> 0.9) samples show a trend towards the intermediate groundwater, presumably due to mixing with intermediate groundwaters.

Table 3. Physico-chemical measurements of the different groundwater bodies

Depth of bore	Time	EC (μS cm^{-1})	pH	Eh (mV)	T (°C)
Shallow	Oct 2005	245 to 2533	5.1 to 5.5	85 to 113	21.7 to 22.5
	Jan 2006	133 to 1574	5.1 to 6.9	–51 to 261	23.4 to 27.2
	Feb 2006	164 to 2580	4.6 to 6.5	–48 to 293	24.8 to 29.5
	Median	**598**	**5.7**	**148**	**26**
Intermediate	Oct 2005	2767 to 4083	3.1 to 3.4	202 to 220	20.7 to 21.5
	Jan 2006	811 to 4770	4.1 to 4.7	241 to 291	23.8 to 25.1
	Feb 2006	1177 to 9560	4.1 to 4.4	260 to 420	25.0 to 27.2
	Median	**4248**	**4.3**	**338**	**25.1**
Deep	Oct 2005	515	6.4	33	22.0
	Jan 2006	812	6.9	127	23.0
	Feb 2006	785	6.0	208	23.9
	Median	**799**	**6.5**	**168**	**23.5**

Table 4. Groundwater geochemistry[A] (February 2006)

Bore ID	Depth	Geology[B]	EC	pH	Na	Ca	Mg	K	Fe	Cl	SO_4	HCO_3	Water type
A3	Shallow	Te	895	5.7	191.7	1.3	10.1	1.6	28.4	288.0	24.7	22.0	Na-Cl
C1	Shallow	Qa	1172	5.5	460.5	1.4	74.4	0.3	0.9	981.4	137.8	16.2	Na-Mg-Cl
E1	Shallow	Qa	263	5.1	28.4	0.3	1.9	0.5	9.8	34.4	3.7	23.9	Na-Fe-Cl-HCO_3
E3	Shallow	Km	188	5.6	26.1	3.7	1.4	8.9	1.1	26.8	7.0	29.7	Na-Cl-HCO_3
F1	Shallow	Qa	483	5.8	64.8	7.4	5.0	0.2	0.4	52.1	51.5	37.5	Na-Cl-SO_4
B4	Intermediate	Te	1177	4.4	234.0	1.1	22.8	0.0	2.1	346.7	31.5	0.0	Na-Cl
C3	Intermediate	Te	4560	4.0	893.0	5.4	42.4	0.0	0.4	1438.1	40.6	0.0	Na-Cl
C4	Intermediate	Te	3860	4.1	647.6	0.7	37.0	1.2	0.0	910.8	185.9	0.0	Na-Cl
C5	Intermediate	Qa	9560	4.4	1751.0	6.8	239.8	5.2	0.0	3133.8	292.5	0.0	Na-Mg-Cl
C2	Deep	Te	785	6.0	147.2	2.3	6.8	0.3	0.1	158.6	8.8	97.6	Na-Cl-HCO_3

[A] Data are in mg L^{-1}, except for EC in μS cm^{-1} and pH

[B] Te — Elliott Formation; Km — Maryborough Formation; Qa — Quaternary alluvium

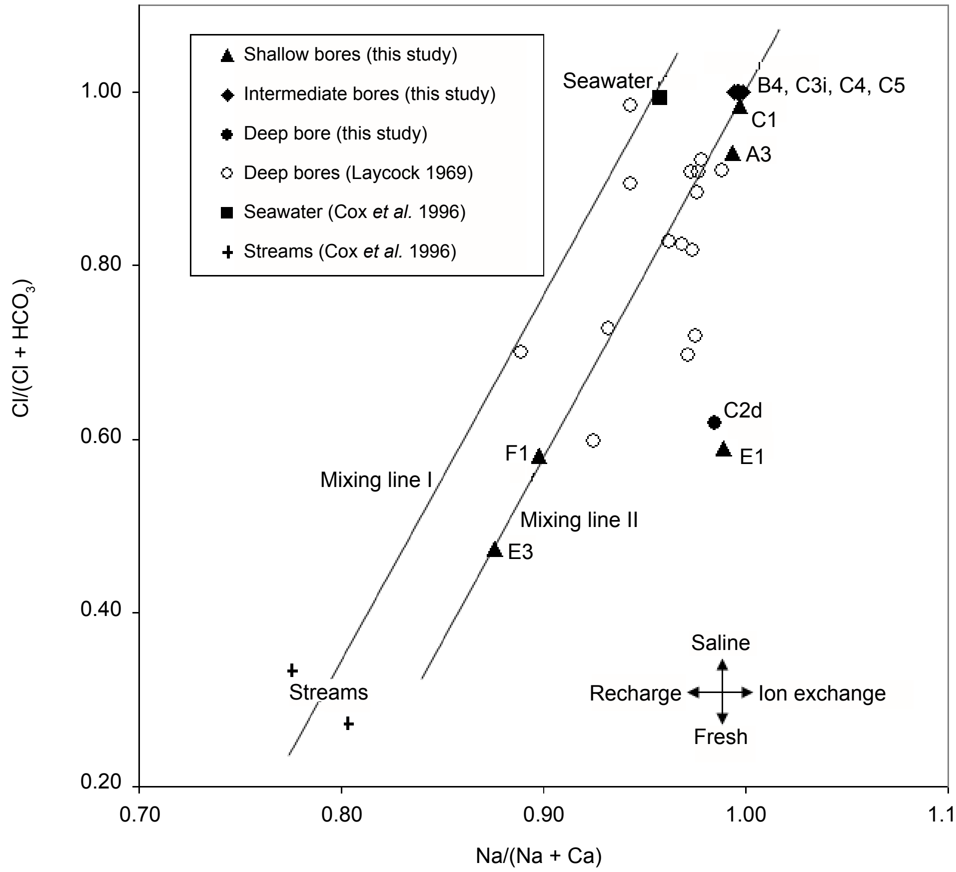


Figure 5. Variability of two major anions (Cl and HCO_3) versus two major cations (Na and Ca). The mixing line I is delineated by the seawater and typical fresh stream water in the southern Queensland (Cox *et al.* 1996). The mixing line II is defined by the groundwater samples from this study and Laycock (1969)

Soil mineralogy, EC and pH

All weathering profiles show a general tendency of increasing clay content with depth (Fig. 6). An abrupt increase by 20% appears to indicate the appearance of the mottled saprolite, at depths mostly between 1 and 1.5 m. At site A1, the depth is about 2.5 m, which is due to an overlying layer of Quaternary-aged coastal sand about 1 m thick. Close to the alluvium, the increase of clay content is more abrupt. An increase from almost zero to nearly 50% is common. The depths of this increase are greater close to drainage channel (e.g. C1 and F1) and become much shallower with distance from the streams (e.g. A5 and C5). Segregated ironstone gravels can exist within the surficial soil (e.g. F1 and A5); but the underlying clay layers do not contain iron oxides.

The spatial distribution of ferricrete (or duricrust) is closely associated with the outcropping Maryborough Formation (Fig. 2b). At sites S3, C4 and F4, iron-oxide contents are as high as 60–80%. Ferricrete tends to occur at depths of around 0.5 m, resulting in a restrictive layer at shallower depth.

Profiles of the soil EC and pH measurements show systematic variation with depth for most of the sampled sites (Fig. 6):

- overall, there is a positive correlation between soil electrical conductivity and clay (kaolinite) content, with EC generally rising at depths where the kaolinite content increases, which is most obvious at sites A3, C1, C3, C4 and C5
- negative correlations are observed for the pH and EC values. In most of the profiles, the zone of lowest pH corresponds approximately with the zone of highest salt content.

Discussion

The weathering profile and three groundwater bodies

Deeply weathered regolith profiles that contain distinctive layers including soil, (ferricrete), mottled saprolite, fine saprolite and coarse saprolite are widespread in the inter-tropical belt between latitudes 35°N and 35°S, such as in Australia, Africa, India and South Africa, where the regolith is considered to have been produced by intense weathering over long periods (Tardy and Roquin 1992; Anand and Paine 2002). The distinctive zonation developed within these typical deep weathering profiles has a substantial control on groundwater hydrological processes (Ollier and Pain 1996). Typically, permeability is high near the surface, decreases rapidly in the mottled and fine saprolite, and increases again in the coarse saprolite (Thomas 1994). This permeability trend with depth is reflected in this study by the mineralogical variation. Kaolinite content is almost zero close to the top in the sandy soil, increases to around 26–56% in the mottled saprolite, and to more than 80% in the fine saprolite, and then drops to around 10% within the coarse saprolite. This mineralogical profile (Fig. 3) also indicates a decrease in weathering intensity

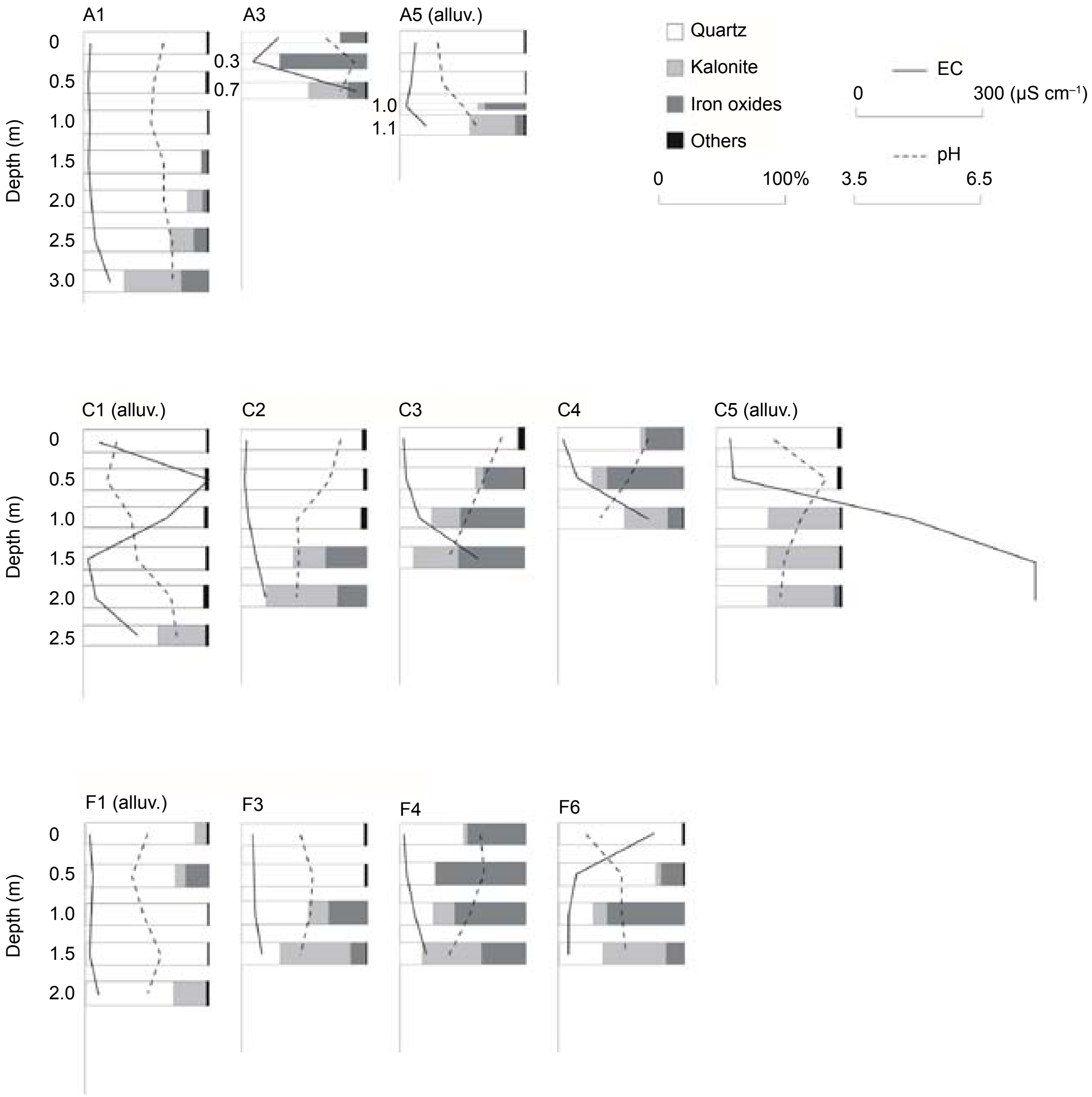


Figure 6. Stacked bar charts of mineralogy (100%) based on XRD analyses with depth, as well as EC and pH trends. Boreholes A5, C1, C5 and F1 are within Quaternary alluvium and the others are within weathered Elliott Formation

with depth, observed as the existence of primary minerals at deeper levels.

The downward flow of water is restricted at three levels: at the top of the ferricrete or mottled saprolite, at the top of the fine saprolite, and at the unweathered bedrock (Fig. 7). All the groundwater samples have the ratio of Na : (Na+Ca) between 0.9 and 1.0, which confirms the weathered Elliott Formation as being non-calcareous and essentially siliceous (Ellis 1971). Considerable amounts of Mg, Fe and SO_4 were present in groundwater samples within alluvium (Table 4), which may be derived from the fringing Grahams Creek Formation pyroclastic and volcaniclastic sandstones in the south-west. The deep bore C2d may have passed through the weathered Elliott Formation and into underlying Grahams Creek Formation, as a small percentage of laumonite was identified in the lower sample of C2d (Table 2).

Both the shallow and intermediate groundwaters are acidic as is common for plantation settings, as organic matter such as fallen leaf litter decomposes to produce organic acids that infiltrate the groundwater (Drever 1997). Head differences between the shallow and intermediate bores (e.g. C3s and C3i in Fig. 4) show that there is a potential of recharge from the shallow to the intermediate groundwater. Water seeping through the restrictive layer may be via tree root channels which have been detected at depths of several metres in the clay layer. Stolte *et al.* (1999) modelled subsurface flow conditions in a salinised catchment in south-western Australia and found that recharge by flow through these macropores occurs only where perched aquifers develop and allow the macropores to be activated. The shallow groundwater is generally less acidic than the intermediate groundwater and has a higher content of HCO_3 and therefore a lower Cl : (Cl+HCO_3)

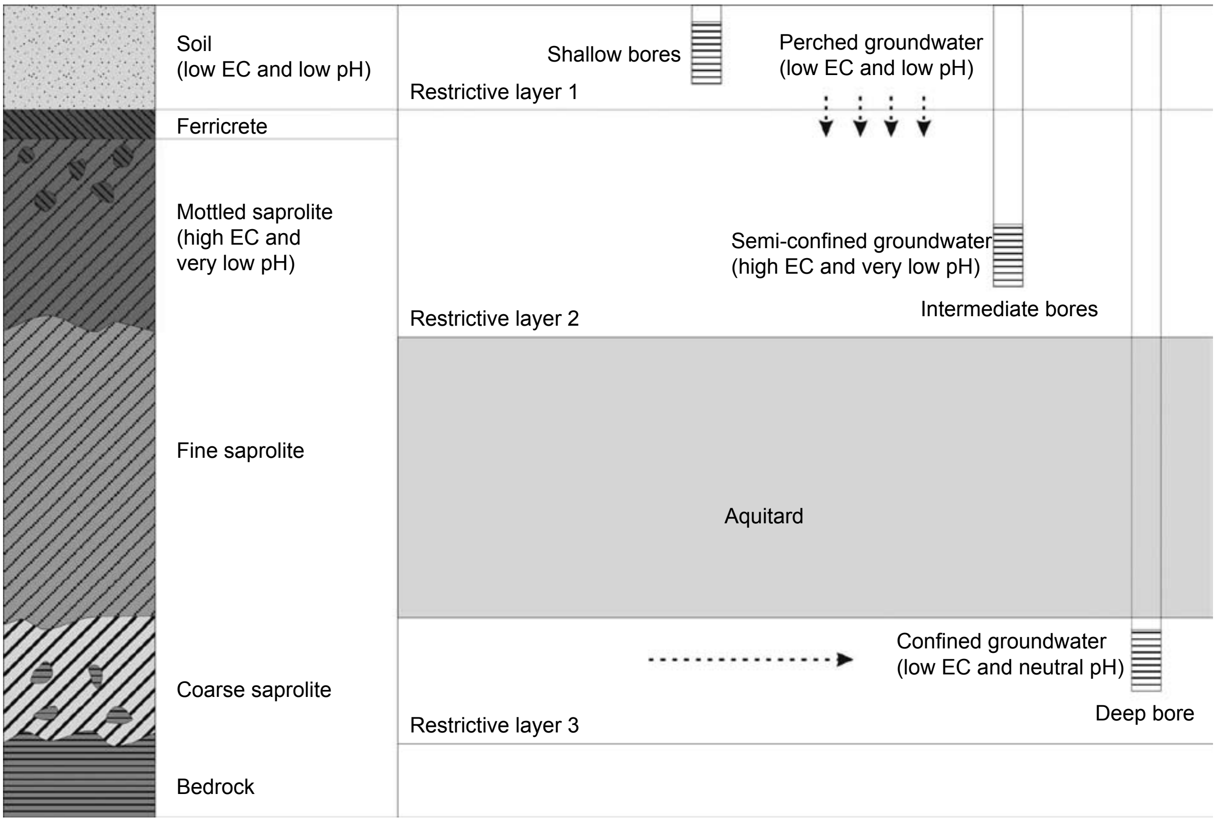


Figure 7. Schematic of the relationship between layered regolith profiles and groundwater hydrology (see Table 3 for EC and pH ranges)

ratio, which is generally related to shallow biogenic activities; CO_2 dissolves into water directly from plant roots and, more importantly, by the microbial degradation of soil organic matter (Younger 2007).

A weak response to local rainfall variation has also been observed for the deep groundwater, which may suggest some vertical connectivity between the intermediate and deep groundwater but it is unlikely in this study as the salinity of the intermediate groundwater is much higher than that of the deep groundwater (Table 3). There are however wide variations in the EC values of the intermediate groundwater, from being relatively fresh to brackish, which is related to the clay content of the saprolite and the slotting depths of the bores within the saprolite. Increasing groundwater salinity deeper in the saprolite is expected, continuing the trend that was shown in the soil–saprolite EC profiles (Fig. 6). Salts are most concentrated in the fine saprolite. In addition, as the layer of fine saprolite is essentially kaolinite, the deep groundwater within the coarse saprolite is considered to be hydrologically confined and recharged at some distance.

Some of these findings are similar to those found in a salt-affected duplex soil toposequence in western Victoria (Brouwer and Fitzpatrick 2002a,b), in which three groundwater bodies occur in the weathering profile: a perched soil water within the B-horizon (as opposed to on top of the B-horizon in many duplex soils), a second perched or semi-confined groundwater on top of the pallid zone (i.e. fine saprolite), and the permanent aquifer on top of the bedrock. It was, however, the deep groundwater that was saline and the intermediate-depth groundwater occurring within the mottled zone (i.e. mottled saprolite) that was fresh.

Given that it is widely accepted that the kaolinised pallid zone of deep weathering profiles is the major repository of soluble salts (Dimmock *et al.* 1974), the salt concentration of groundwaters above and below this salt-store zone would be dependent on the direction of the water movement through this zone. If the deep aquifer is semi-confined and recharged from the upper layers, it is reasonable that groundwater moving slowly through the pallid zone would bring the salts downwards and render the deep groundwater salty. On the contrary, where the deep groundwater is confined and recharged horizontally, the salts contained within the pallid zone would have to remain at that level or move upwards with a rising water table; the deep groundwater would therefore not be affected. It is the latter case in the study area.

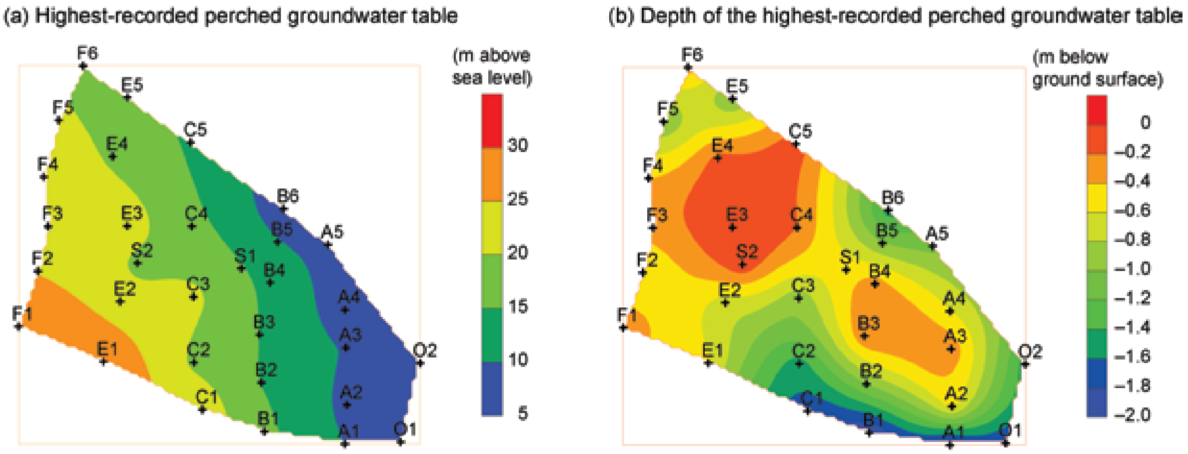
The perched groundwater and depth of restrictive layer

Water-logging is caused by the perched groundwater, with rainfall being the main recharge source. Over the study period, the highest perched groundwater level occurred either in December 2005 or in January 2006 depending on site drainage factors such as slope, soil texture and linkage to the intermediate groundwater. A convenient way of assessing the risk of water-logging is by analysing the depths of the highest-recorded perched groundwater table, which simulates the maximum degree of saturation that has been observed during the whole wet season. A comparison between the surface topography (Fig. 2a) and the highest-recorded perched groundwater table (Fig. 8a) suggests similarity in the flow patterns of surface runoff and underground throughflow. Generally, due to the flat landscape, lateral movement of water is negligible. Evapotranspiration was found to be the major output flux in similar settings further south (Bubb and Croton 2002), possibly together with recharging of the intermediate groundwater through macropores.

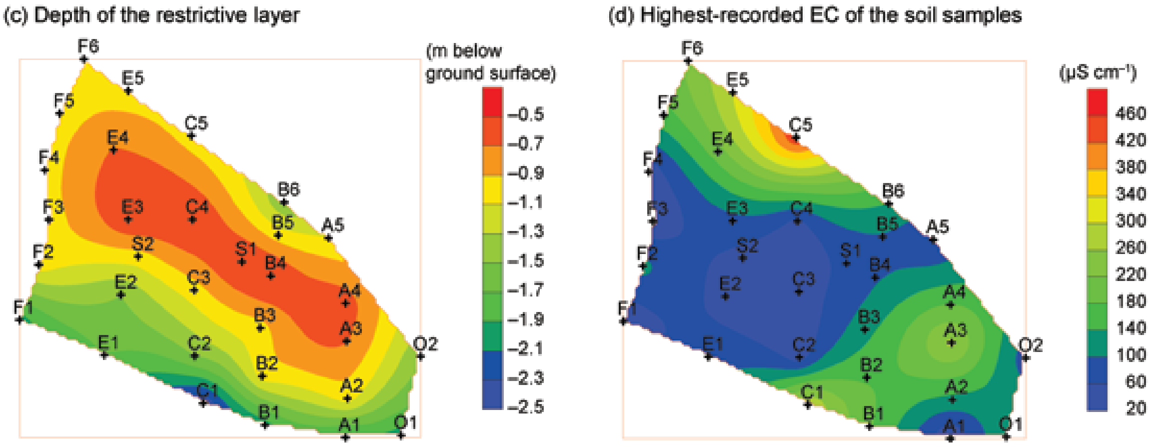
The depths of the highest-recorded perched groundwater levels were interpolated (Fig. 8b). Apparently most of the study area had experienced a water level within 1 m of the ground surface during the wet months. The highest risk occurs north-west to the centre of the area delineated by the bores S2, C4, C5 and E4, where the water table has reached within 20 cm of the surface and ephemeral surface water bodies were observed. Other high-risk areas consist of a zone in the east enclosed by the bores B3, B4 and A3, as well as the south-western corner. Generally, the risk of water-logging decreases towards the south and the north or further east. This spatial pattern of the risk of water-logging was found to be closely related to the pattern of the depths of restrictive layer (Fig. 8c). Cox and McFarlane (1995) noted that in duplex soils, a decrease in the thickness of the A-horizon topsoil caused an increase in water-logging potential. In this study, the depths of the restrictive layer identified from each bore location based on texture and mineralogy (clay content) correlates with the outcropping of the Maryborough Formation (see Fig. 2b); the depth to the restrictive layer increases outwards from the outcrop. The reason for the shallower depths associated with the Maryborough Formation is that the unit is rich in iron and has favoured the development of ferricrete, which tends to occur at shallower depth than the mottled saprolite. Slight differences in the pattern of Figure 8b and 8c may indicate the effects of other factors such as some dramatic changes in surface topography. For example, at the south-western corner, a hill up to almost 20 m high (Fig. 2a) north-east of the bore of F1 may act as a barrier to lateral water flow towards the hill direction (Fig. 8a). This increased the risk of water-logging at the site of F1, although the restrictive layer is relatively deep (Fig. 8c).

The salinity dynamics

As a general rule, salts are stored in the mottled saprolite and more significantly in the fine saprolite. The fact that the deep groundwater occurring on top of the bedrock is fresh suggests that the major source of salts has been from upper levels such as coastal rainfall (Chartres 1993; Shaw *et al.* 1994) rather than


(a) Highest-recorded perched groundwater table

(b) Depth of the highest-recorded perched groundwater table


(c) Depth of the restrictive layer

(d) Highest-recorded EC of the soil samples

Figure 8. Comparison and analysis of the interpolated parameters that are related to the development of water-logging and soil salinity: (a) highest-recorded perched groundwater table (m above sea level) over the study period; (b) depth of the highest-recorded perched groundwater table (m below ground surface); (c) depth of the restrictive layer (m below ground surface), and (d) highest EC within soils

the bedrock weathering (Gunn 1967; Gunn and Richardson 1979). As the study area is a transitional zone located between hill ranges and costal-shoreline marine deposits, it is affected by both these environments. At the sites A3, C1, C3, C4 and C5, the EC increases more dramatically from the upper soil layer to the saprolite than at the other sites, which may suggest existing tidal influences or relict salinity from previous high sea levels.

For each borehole site that salinity has been measured at different depths, the highest EC value of all the soil samples at and above the restrictive layer was taken as being indicative of the risk of soil salinisation at that site; the values were interpolated spatially (Fig. 8d) and compared with the water-logging potential (Fig. 8b). No apparent correlation between the risk of water-logging and risk of salinisation was seen. The perched groundwater may even dilute the salt concentration unless the increased recharge to the intermediate groundwater and therefore rising water table of the intermediate groundwater has resulted in a mixing of the two groundwater bodies. In the Western Australian wheatbelt, most salt scalds are adjacent to ephemeral stream channels (Conacher 1982a); this was not observed in the study area.

Bevege and Simpson (1981) established that salt damage to newly established pines occurs where soil electrical conductivity is as low as 200 μS cm^{-1}. Soil EC measurements undertaken in this study show that bores C1 and F6 are the only sites where soil saline conditions have developed (Fig. 5). These sites are located either at the lower end of a slope or at a break of slope. The source of this salinity is considered to be the discharge from intermediate groundwaters higher up the slope. The EC measurements at F6 show a gradient with the values increasing towards the surface, which is possibly due to capillary rise and an evaporation effect. At C1, however, the value of EC peaks at 0.5 m and then drops towards the surface. This implies that the capillary rise of groundwater at this site has reached a depth of only 0.5 m and that the surface soils have not been salt-affected.

Landuse changes play a significant role in changing salinity profiles by influencing the recharge and therefore the water table variations of the semi-confined intermediate groundwater. Following the large-scale vegetation clearing of this area in the 1970s, 1200 ha of the northern Tuan State Forest was classed as having a high potential for soil salinity (Bevege and Simpson 1981). Those high-risk zones included areas to the south-east of C5, between S1 and B4 and to each side of C3 to C4 (Fig. 2c); these areas have therefore not been planted. However, salinity measurements taken on current soil samples from neighbouring drillholes (i.e. C3, C4, C5, B4 and S1) suggest that there is no existing salinity problem around these sites. In other words, clearing the land prior to the plantation establishment initially increased the potential for developing salinity, but with the increased water uptake of mature pines there has been a decrease in the level and extent of salinity. Large-scale harvesting may have the same effects as the land clearing, and therefore should be avoided. Instead, harvesting in scattered coupes may be preferred.

Conclusions

Wide-spread seasonal water-logging occurs in the coastal lowlands of southern Queensland where increasingly extensive areas have been occupied by exotic pine plantations. The deeply weathered regolith profiles examined in the northern Tuan State Forest have the following distinctive zones: soil, (ferricrete), mottled saprolite, fine saprolite and coarse saprolite. The soils are generally sand-rich, while the saprolite is clay-rich, largely kaolinite. During the wet season, shallow groundwater is perched above the ferricrete or mottled saprolite. Intermediate-depth semi-confined groundwater occurring within the mottled saprolite is recharged from the shallow perched groundwater probably via preferential pathways. A deeper confined aquifer is present within the coarse saprolite at the base of the weathered profile, which consists mainly of smectite and felspars.

The three groundwater bodies identified exhibit distinctive chemical characters. The shallow groundwater is low in EC and slightly acidic, which reflects typical shallow plantation settings. The intermediate groundwater has high salinity and is low in pH, and the deep groundwater is low in EC and the pH is circum-neutral. Sodium and chloride are the major cation and anion, present in all the groundwaters. As the weathering profile is essentially siliceous, all the groundwaters show a depletion of Ca relative to Na. The considerable amount of minor elements (Mg, Fe and SO_4) present in groundwaters within the Quaternary alluvium distinguishes this unit from Tertiary (Elliott Formation) and pre-Tertiary (Maryborough Formation) geological units.

Water-logging is caused by the perched groundwater. The spatial pattern of the piezometric heads of the shallow bores mirrors the surface topography. In a flat terrain where lateral flow of water is negligible, the risk of water-logging is largely controlled by the depth of the restrictive layer; increased water-logging is associated with decreased depth of the layer of ferricrete or clayey saprolite. The spatial distribution of the depth of the restrictive layer reflects geology, with the depths decreasing close to the Maryborough Formation, which is iron- and silica-rich; the greater abundance of these elements has favoured the development of ferricrete and possibly silcrete at relatively shallow depths.

Salinity profiles show a positive relationship between salt and clay content, i.e. higher EC within the clay-rich saprolite and lower EC within the soil. Compared to conditions when the plantation was newly established, the salinity level and extent has largely decreased, probably due to the high water demand of mature pines. The only two observed saline sites are related to discharge of the intermediate salty groundwater. Under current conditions, soils with higher salinity are not those with higher risk of water-logging, unless there is mixing of the perched and intermediate groundwater bodies. The fresh deep groundwater in the coarse saprolite has no bearing on salinity development, which is distinguished from the general findings for many other geographic regions of Australia.

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