Mallee Dune Seeps

Land, Soil and Water Investigations of Dune Seepage Systems in the South Australian Murray Mallee

In fulfilment of contracts between Natural Resources South Australian Murray–Darling Basin and Juliet Creek Consulting Pty Ltd (NRSAMDB Agreement for Services 1352C and 1361C) and incorporating work completed as part of Rural Solutions SA subcontract 'SAMDB 1247C'.

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Management | Policy | Planning | Landscapes

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Executive summary

Mallee dune seeps are localised perched water areas with expression of water to the land surface. They are part of larger perched water systems. Seep areas are landscape water discharge sites. Seeps are initially fresh to slightly saline, but can become more saline over time.

Seeps most often occur in low-lying areas at the foot of sand dunes, but can occur wherever perched water has surface expression. Seeps are feed by excess dune water (seepage) – water that is not taken-up and transpired by growing plants, evaporated from the land surface, stored as soil or upper regolith moisture, or 'lost' to very deep drainage. Their initial development is also unpredictable, but seems to relate to heavy rainfall years. However, seepage into discharge areas can occur at any time of year, which points to considerable storage of water within upper regolith layers (e.g. within dune cores).

The aim of this document is to report on investigations at two subcatchments in the South Australian Murray Mallee, where dune seeps have formed on productive farmland in recent years (with the seepage problem first impacting upon farm operations in 2005 in both subcatchments – Henschke 2015). This work has been funded by Natural Resources South Australian Murray-Darling Basin.

Mallee dune seepage processes have been investigated via soil characterisation (see Appendices 3 and 6), deep drilling (see Appendices 2 and 5) and land unit mapping (see Appendices 1 and 4). Peisometers (tube wells) have also been installed at water-bearing drilling sites for water pressure and quality monitoring (see Henschke 2015). EM 38 survey information has also been produced as part of a related project, however, electromagnetic data is limited to the top one or two metres and is difficult to interpret without extensive ground-truthing.

Importantly, mallee dune seeps are not associated with regional groundwater, which occurs at considerable depth over much of the Murray Mallee.

Concern has been rising about the development of seeps in the Murray Mallee with recent increases in the extent and severity of seeps reported by a number of landholders and agricultural consultants (e.g. see McDonough 2015a). Many seeps appeared following the high-rainfall year of 2010 (McDonough 2015a). The issue has also been reported upon in local media (ABC Rural 2014; Lawson and Tonkin 2014; Murray Valley Standard 2015), and has been a focus at GRDC Grains Research Updates in Adelaide and Murray Bridge (see Hall 2015a).

The saturated soil of seeps renders them non-arable to semi-arable – partly owing to limited or no germination and seedling emergence because of waterlogging, but also because of the low bearing strength of wet soils and the consequent inability of seep areas to support the weight of farm machinery. Areas of former high productivity become non-productive, and soils can remain

wet throughout the year.

Although many seeps are relatively new, some are at least a few decades old. The appearance of new seeps results from a change in subcatchment water balances. It is thought that the improved control of summer weeds brought about by modern farming techniques (particularly on sand dunes), and a move towards continuous cropping at the expense of annual pasture years within farm land use rotations, has altered the water balance of many subcatchments. Reduced annual water use by plants results in further water additions to seepage, which moves to low-lying areas if there is a low permeability subsoil or upper regolith layer limiting deep drainage and encouraging lateral flow. Wetness can then appear at the land surface in places where low permeability materials occur at shallow depth.

Of great concern is that once seeps form, they can quickly degrade. Initial wetness can cause bare land to form. Lack of vegetative cover can then result in wind or water erosion, with the consequent loss of topsoil making the establishment of plant cover a much more difficult task. Bare land and the presence of wet soil also leads to excessive evaporation and a consequent accumulation of salts on the land surface (see Figure 1). Seep areas can then become more saline over time, especially at the land surface, making the re-establishment of plants more difficult. Highly degraded areas are very difficult to rehabilitate, and can increase in size over time. It is therefore important to maintain land cover at all times to minimise erosion and evaporation.

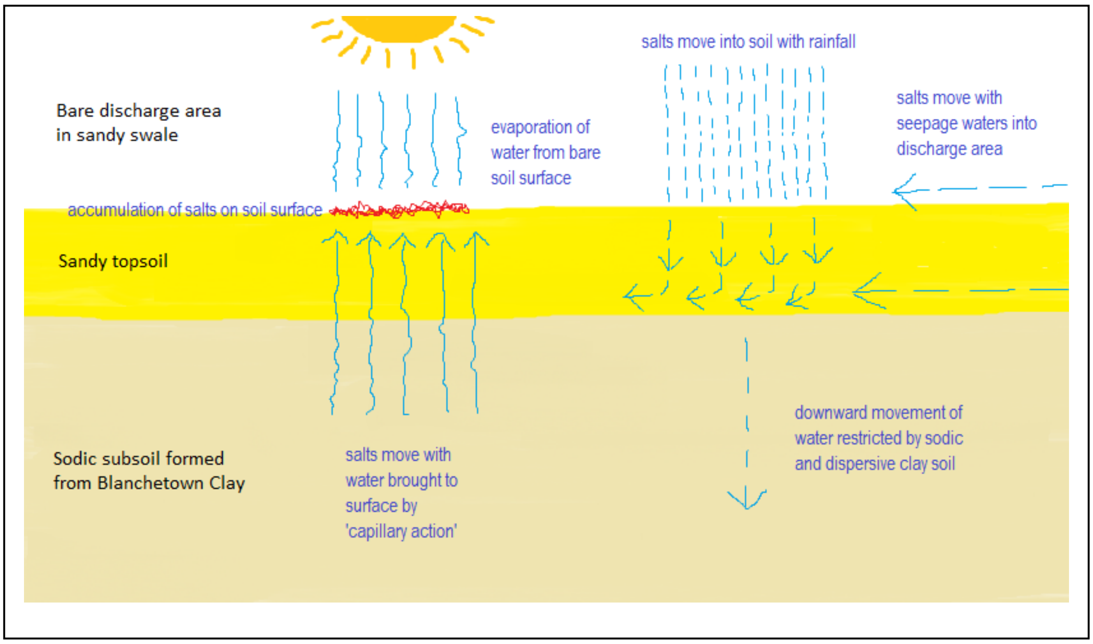

Figure 1: a diagrammatic representation of salt accumulation in a seep (discharge) area.

Project investigations have discovered a very low permeability heavy clay layer at both subcatchments. Water flows upon this material have been encountered. The investigated seeps exist because this material is at shallow depth, forcing water to the land surface. It has been determined via project field work that this material is Blanchetown Clay (see Hall et al. 2009).

Blanchetown Clay and its equivalents occur over much of agricultural South Australia. Within the Murray Mallee it was laid down within ancient Lake Bungunnia and associated satellite lakes between 3 million and 700,000 years ago (see Hall et al. 2009). It is up to 20 m thick, but is quite thin in many areas, and is not continuous over the whole Murray Mallee. Based on the investigations of this project, as well as knowledge gained and information developed by the State Land and Soil Mapping Program (1986–2012: see Soil and Land Program 2007), this is the least permeable layer that exists in the Murray Mallee, and is most probably the layer that causes all dune seeps in the region. The older and very thick Loxton–Parilla Sand (see Hall et al. 2009), although often sodic and clayey, does not seem to generate the same landscape effects.

It is quite a startling thing to have a problem with excess water in such low rainfall farming districts. It is also surprising to find water flows beneath the land surface in environments where lack of rainfall has traditionally been seen as a major impediment to higher crop yields. Dune seeps are a symptom of a much wider issue in mallee dune–swale environments – inadequate utilisation by cultivated plants of annual incident rainfall. A challenge for farming in mallee dune–swale environments is to develop systems that better utilise rainfall on sandy soils.

General recommendations are given in the summary section of this report.

Introduction

Mallee dune seeps are areas of excessive wetness in mallee dune–swale environments. Within the last decade a number of seep areas have appeared across the South Australian Murray Mallee. When these areas become too wet, they are no longer arable – causing some of the most productive farmland in mallee environments to be lost to production.

Understanding of the processes involved has been improved by the investigations described in this report, but the specific causes of the increased landscape water are uncertain. It is suspected, however, that effective control of summer weeds on sand dune areas – as a result of the use of modern farming techniques and herbicides within continuous cropping systems – has created excess water in these low rainfall farming environments. Anecdotal evidence suggests that most dune seep areas have appeared since these technology changes have occurred – although older seep areas are known to exist.

Two subcatchments within the Murray Mallee that contain recently developed seeps have been investigated for this project. The aim has been to gain a better understanding of the processes involved in the development of dune seeps to support the development of management solutions.

Subcatchments have been investigated via:

- characterisation of sites and soil profiles along strategic toposequences within subcatchment areas
- drilling investigations at strategic sites
- stereoscopic air-photo-interpretation (API) of overlapping aerial photographs and the development of land unit maps and watershed boundaries.

Each subcatchment has had land units defined and mapped. This has also included mapping of subcatchment watershed boundaries. Owing to the limited level of soil investigation, however, soil maps were not developed.

The subcatchments investigated were Bonds (Mannum East) and Rose-Thomas (Kulde). Figure 2 gives a general location map of both subcatchments.

As well as soil and regolith (below soil unconsolidated material) investigations, land management–use trials have been instigated at a number of sites as part of related project activities to determine best practice methods of control, amelioration and remediation (e.g. see McDonough 2015b).

A key question has been whether a topsoil dominant water-flow system (upon the subsoil surface), or a much deeper water-flow system (or both), is involved in the development of dune seeps. It is known that regional groundwater is not a casual factor, as this occurs at considerable depth (many tens of metres) over most of the Murray Mallee, as well as at the two project subcatchments.

The investigations of this project, and subsequent better understanding of processes, have enabled development of initial recommendations for Murray Mallee subcatchments affected by dune seepage.

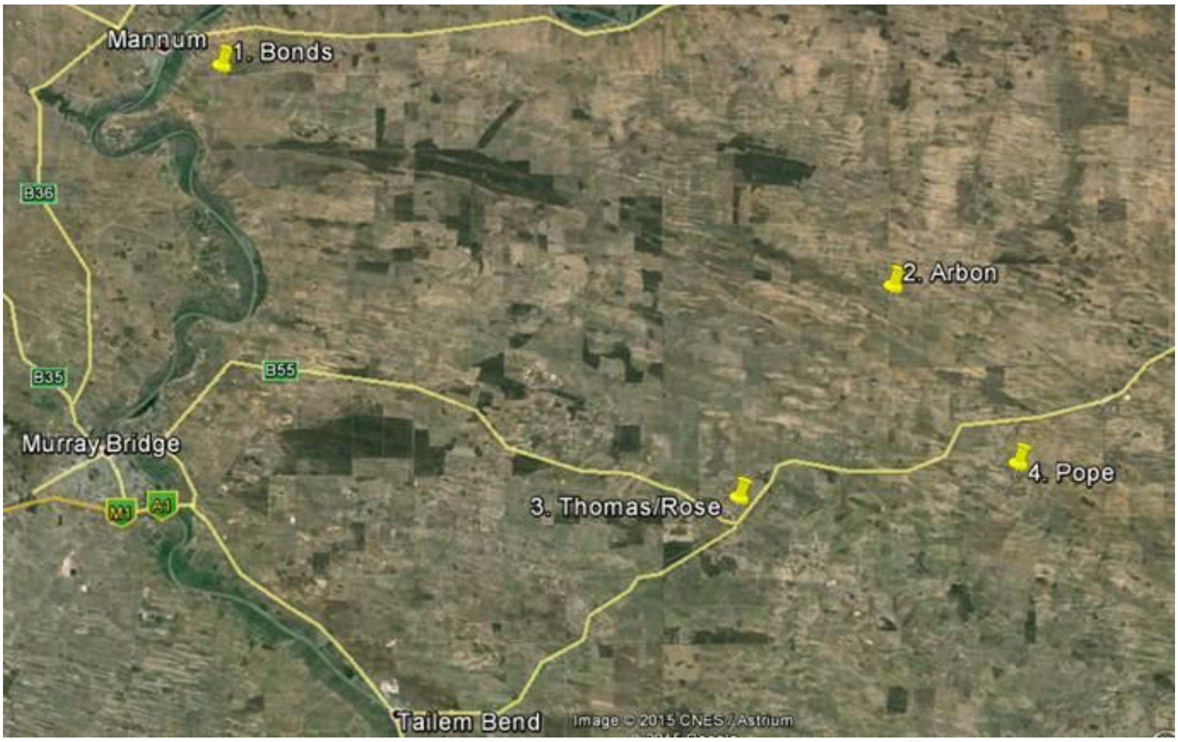

Figure 2: Locations of the Bond and the Rose-Thomas subcatchments, at Mannum East and Kulde, respectively, in the South Australian Murray Mallee.

Methods

This report is based upon initial investigations at the Bond and the Rose-Thomas subcatchments at Mannum East and Kulde, respectively, in the South Australian Murray Mallee (see Appendices 1–6). Work which has been funded by Natural Resources South Australian Murray-Darling Basin.

Soil characterisation has been undertaken to investigate the possible existence of near-surface lateral flow of water along low permeability subsoil surfaces. Soil characterisation also helps to determine the extent of downward movement of water via assessment of the vertical distribution of soluble substances. Moreover, soil characterisation is undertaken to investigate representative soils in detail so that impediments to root and plant growth and production can be better understood, to help devise management solutions.

The siting of soil investigations has been carefully considered, with key considerations being that: main segments of the landscape are selected (e.g. dune crests, lower slopes, low-lying land); sites define a particular toposequence (a down-slope sequence of landform sites); and that it is clear that sites along a toposequence are directly interconnected in terms of water processes within a subcatchment system.

Soil morphological description has been conducted according to national standards (NCST 2009). Moreover, comprehensive chemical analyses have been performed on samples from each described soil layer, again to national standards (Rayment and Lyons 2010). These physical and chemical data help with understanding of land and soil processes, allowing interpretations to be made of soil, landscape and agronomic systems and interactions – such as water movement, storage and use. Chemical analyses of soil samples have been performed at CSBP Laboratories in Western Australia (a nationally accredited soil laboratory).

Drilling was conducted to assess deeper water movement and the presence of deeper layers restricting downward movement of water. Drilling was sited adjacent to selected soil characterisation sites. Descriptions of drilled materials are given in Appendices 2 and 4.

Peisometer monitoring wells have been installed at water-bearing drilling sites, and will add to on-going knowledge about mallee dune seepage systems. Well installation details and initial water measurements are given in Henschke (2015).

Land units have been defined to show the extent of various landscape features, including seeps (see Appendices 1 and 3), with subcatchment watershed boundaries also defined.

Land unit mapping shows the nature and extent of particular landscape areas, giving insights into topography, geomorphology, geology, soils, as well as land and soil conditions (such as wetness and salinity). This is based on expert stereoscopic air-photo-interpretation (API) using the most recent and highest resolution aerial photograph stereo pairs (2001 from Mapland). However, as no seeps were evident in 2001, aerial photos from 2013 (Kulde) and 2015 (Mannum East) were used to assess the extent of seepage. Unfortunately, no stereo pairs from these years are available. It should be understood that land unit mapping is based on an extremely limited number of on-ground investigations.

Land unit mapping can be utilised to calculate the actual areas of seeps (hectares and percent of subcatchment), overall productivity losses owing to seepage, the productivity changes arising from management systems that reduce seepage, as well as in water balance models. Soil unit mapping is more useful and accurate for making such calculations, but soil maps can only be produced once a full soil survey is conducted.

Findings and interpretations

Bond subcatchment (see Appendices 1, 2 and 3)

The subcatchment consists of a long hillslope transversely overlain by a series of low ridges and valleys, with sand dunes and sandy sediments superimposed on these. The selection of soil characterisation sites attempts to cover major elements of the toposequence (see Figure 5).

Site MDS-B03 is the highest, situated upon a sandy plateau; site MDS-B02 is on a dunecrest that is situated transversely upon the lower slope of the main hillslope; while site MDS-B01 is in a low-lying area adjacent to a seep area. Two additional sites cover another seep margin area (MDS-B04), and a site on the lower slope of the main hillslope (MDS-B05). The very lowest valley area at the base of the main hillslope contains the vast majority if not all seeps in the subcatchment. Land unit mapping shows this area as land unit 'S2' (see Figure 6).

Soil investigations reveal a typical mallee system dominated by sandy, inherently infertile topsoils that can be water repellent. Slightly heavier textured sandy loam soils occur in and around some seep areas. Subsoils vary from sand (on dunes) to sandy loam and sandy clay loam. Calcrete layers occur in some areas (on rises or in low-lying areas).

An analysis of soil chemical and morphological data can reveal drainage patterns within soil.

Sandy plateau site (MDS-B03)

The lower subsoil has high pH below about 77 cm, while fine carbonate accumulation is significant below 160 cm, indicating that drainage is restricted to some degree, but that the seasonal wetting front typically reaches to well below 1 m. Soil data show no signs of lateral water movement at this site. In-field consistence assessment (moisture content and strength as a function of clay content: see NCST 2009) revealed no saturated soil layers, with the highest moisture contents in the 77–125 cm zone. It is clear at this site that soil water that is not stored in the profile or used by growing plants moves downward rather than laterally.

Deep drilling at this site revealed no layers significantly restricting drainage to a depth of 9.5 m. In the lower part of the drill hole moderately restrictive medium clay material was encountered.

Dune crest / lower slope of main hillslope (MDS-B02)

Soil data indicate a profile that is excessively drained to about 68 cm, but with some slight restrictions below this. It is likely that the seasonal wetting front typically reaches well below 1 m, indicated in part by the beginnings of fine carbonate accumulation from 130 cm. There is no evidence of lateral water movement, and no saturated layers were encountered. It is clear at this site that soil water that is not stored in the profile or used by growing plants moves downward rather than laterally.

Deep drilling at this site revealed a highly restrictive layer to drainage at approximately 6 m, with a bleached saturated layer above this. The restrictive layer is a tight, mottled, heavy clay (Blanchetown Clay). Bleaching of the saturated layer indicates considerable water movement through this layer over time.

Lower slope of main hillslope (MDS-B05)

Soil data indicate that profile drainage is restricted somewhat by the sandy clay loam subsoil, and that some lateral water flow upon this layer is possible (especially indicated by the pale-coloured subsurface layer). It is likely that the seasonal wetting front generally reaches to just below 1 m. However, the subsoil restriction to drainage is not great, and it is likely that most excess water would move downward as deep drainage. No saturated layer was encountered to 190 cm.

No deep drilling was conducted at this site.

Low-lying site adjacent to, and down-slope of seep (MDS-B01)

This is a wet soil with poor drainage. Salinity levels are moderate to moderately low, with the highest in the 22–52 cm zone (an ECe of approximately 6 dS/m). The clay loam subsoil does not constitute a significant barrier to drainage. Deep drilling revealed a highly restrictive layer to drainage at a depth of about 2.5 m that is only about 50 cm thick at this site. This is a tight, mottled, heavy clay (Blanchetown Clay). It is known that this layer is much thicker slightly up-catchment where the main seep area occurs. It is almost certain that the presence of the seep in this area is a function of the relatively shallow Blanchetown Clay layer, which restricts deeper drainage of subcatchment seepage waters that accumulate in this low-lying area. Of interest is the absence of a seep slightly down-catchment from this site, which indicates the likely absence of the Blanchetown Clay layer.

There are indications from chemical and morphological analyses that demonstrate the seep has not been wet for a great number of years. For example, there is no substantial accumulation of organic matter in the surface soil, while the subsoil is whole-coloured and not mottled.

Low-lying site adjacent to seep area (MDS-B04)

This is a wet soil with poor drainage and calcrete pans at shallow depth. Soil data show that lateral seepage occurs across the surface of the calcrete. The presence of calcrete is indicative of an accumulation of calcium carbonate material at this low-lying site from seepage waters over a long period, accompanied by a long-term regime of wetting and drying, signifying that the site has been affected by seepage waters over a long period.

No deep drilling was conducted at this site.

Overall subcatchment

The Bond subcatchment is situated upon a what appears to be a basement rock high that is related to Adelaide Geosyncline formations in the adjacent Mount Lofty Ranges. However, samples form an 80 m drilling core from an uncertain location nearby showed a great thickness of Tertiary-age Loxton-Parilla Sand. The area is overlain with various sediments, the most recent being wind-deposited sandy and calcareous materials. The lower part of the subcatchment is a valley area which probably once flowed towards the nearby River Murray, but owing to local uplift now flows in the opposite direction into a land-locked basin. The subcatchment consists of a long hillslope with superimposed transverse very low ridges which seem to be related to Tertiary age strandlines (old beach ridges). Most of the subcatchment is overlain by sand spreads and dunes.

Deep drilling at toposequence sites has revealed an underlying heavy, tight mottled clay (Blanchetown Clay) at two of three sites (see Appendix 2). No heavy clay was encountered at the high-level sandy plateau site (MDS-B03) with drilling reaching to 9.5 m. In consequence, no saturated layer was encountered. The dunecrest site on the lower slope of the long hillslope (MDS-B02) had heavy clay at approximately 6m, with a bleached and saturated layer upon this. The site adjacent to the seep area (MDS-B01) had a thin heavy clay layer at approximately 2.5 m, with saturated soil above this.

The drilling demonstrated that the main water-bearing system is at depth (e.g. about 6 m on the dunecrest), and that tight, mottled, heavy clay (Blanchetown Clay) forms the base of the subcatchment perched water system (see Figure 3). However, it seems that Blanchetown Clay is not continuous over the whole subcatchment. For instance, the main part of the seep is underlain by relatively thick heavy clay (as viewed from spoil at an excavation site in the seep), while the lower seep edge at site MDS-B01 is underlain by a thin heavy clay layer less than a metre thick (the clay seems to be 'lensing out'), while just a little further down-catchment, no surface expression of seepage is evident, and it is likely that no heavy clay is present.

In this subcatchment, based on the results of initial investigations, it is likely that near-surface lateral flow along subsoil surfaces is not a significant contributor to overall seepage system, and that deeper lateral flow is dominant. This has significance for agronomic and other management options that might be put in place to reduce subcatchment seepage.

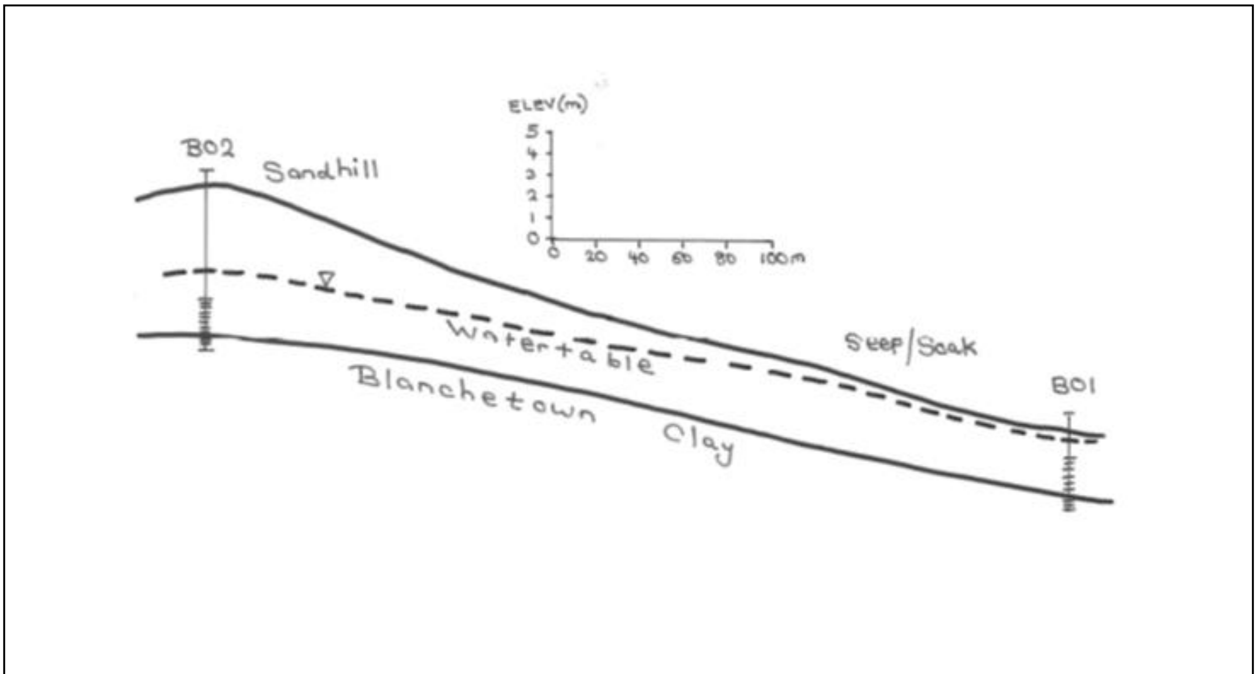

Figure 3: a hydrological cross-section of the lower hillslope section of the Bond subcatchment (from Henschke 2015).

Rose–Thomas subcatchment (see Appendices 4, 5 and 6)

The selected soil characterisation sites (see Figure 7) form a toposequence from a dunecrest to a lower dune slope to a low-lying seep – sites which are thought to be indicative of the wider subcatchment area – and reveal a sandy to sandy loam, inherently infertile topsoil system. Surface soils are sandy outside of seep areas, and are often water repellent (but not strongly so). Topsoil are often very thick (>60 cm). Topsoils also have limited capacity to store and retain nutrients, with waterholding capacities that are only moderate and downward water movement that is largely unrestricted.

Subsoils range from light sandy clay loams to medium clays. Subsoils are brown and mottled – indicating internal soil drainage that is restricted to some extent. Subcatchment subsoils are expected to follow the pattern shown at the characterisation sites of lighter textures (sandy clay loams) on dunes and heavier textures (clays) on lower slopes and in swales.

Interpretations of chemical analyses of subsoil material can reveal drainage potential and history.

Dunecrest site (MDS-R01)

The sandy clay loam subsoil of the dunecrest has relatively high pH and a maximum accumulation of fine carbonate below 110 cm, which indicate that drainage is not excessive and is restricted to some degree, as well as indicating that the seasonal wetting front typically reaches below 1 m.

In contrast, more easily leached materials such as salt (as measured by ECe), sodium (as measured by ESP) and boron show no zone of accumulation in the top 165 cm. This and other indicators show that soil profile drainage within the dunecrest is neither excessive nor greatly restricted, but is well-drained. In-field consistence assessment (moisture content and strength as a function of clay content: see NCST 2009) revealed no saturated soil layers, with the highest moisture contents in the 14–60 cm zone. It is therefore unlikely that large amounts of soil water move along the surface of the underlying sandy clay loam layer, and that the majority of soil water that is not stored in the profile or used by growing plants moves downward rather than laterally.

Drilling revealed a likely saturated layer at approximately 6 m depth, with a tight, mottled, heavy clay encountered just below this at 7 m.

[Drilling at on a southern dune (site MDS-R04) encountered the tight, mottled, heavy clay at about 4.5 m, but no saturated layer upon this].

Lower slope site (MDS-R02)

The lower slope characterisation site possesses more restrictive subsoil layers because of higher clay content, as well as the presence of thin calcrete lamellae and dispersive clays. The existence of a bleached topsoil is confirmation of this. Chemical analyses reveal a maximum fine carbonate accumulation from 98–120 cm, together with a very high pH, a build-up of boron and sodium, and a slight build-up of salt below this. Accumulation of excessive sodium in the subsoil results in dispersive soil that restricts drainage. The results of chemical analyses indicate a seasonal wetting front that typically reaches below 1 m. Consistence assessment (NCST 2009) revealed that the wettest layers were the lower topsoil and the underlying upper subsoil layer. The lower topsoil, while not saturated, was at approximately field capacity, indicating the likelihood of some lateral movement of water when the layer is saturated. Profile internal drainage is imperfect. It is likely that significant amounts of soil water within the profile move laterally, as well as downward.

Drilling revealed a tight, mottled, heavy clay above 6 m, with a saturated layer above this.

Seep site (MDS-R03)

The site on the margins of the seep gives all the indications of having very restricted drainage, with an accumulation of substances throughout the profile.

Salt levels (as measured by ECe) reach their maximum levels in the subsurface layer (a moderate level of 7.3 dS/m at 15–28 cm) and are relatively low below this (<2.5 dS/m). This confirms that this is a 'freshwater' perched seep, but in which salts tend to accumulate over time owing to evaporative processes, especially in areas with no vegetative cover.

There are a number of indications from chemical and morphological analyses that demonstrate the seep has not been wet for a great number of years. Firstly, the soil lacks high organic carbon content in the surface soil and, secondly, the nature of the mottling of the subsoil does not indicate excessive wetness, and is similar to that of the lower slope and dunecrest sites. Of interest is that no layer was seen to be saturated (on the day of description), although water was evident on the land surface in the scalded part of the seep a few metres away. The layer from 47–62 cm (the upper subsoil) was the wettest – all layers were at field capacity or greater. When the site was excavated, water began to trickle in from the top of the clay layer just upslope, while some water entered via a crack in the pit face at a depth of about 1 m. After one day the excavated hole was half-full of water. The site has very poor to poor drainage, indicating the presence of a restrictive layer that holds up drainage at relatively shallow depth.

Following drilling investigations (see Appendix 5), such a restrictive layer was discovered at a depth of approximately 2 m – a tight, mottled, heavy clay believed to be Blanchetown Clay material.

Air-photo-interpretation (API) revealed that the closed depressions that form seep areas seem to be blocked by slightly raised calcrete bench areas, both in the study subcatchment and in an adjacent subcatchment (see Figure 8).

Overall subcatchment

The Rose–Thomas subcatchment subsoil and related deeper materials exhibit many of the characteristics of 'Loxton–Parilla Sand' (intimately mixed sand and clay deposited as foreshore strandlines in Tertiary times – see Hall et al. 2009). However, subsequent deep drilling in the subcatchment revealed an underlying heavy, tight, mottled clay at depth, which is 'Blanchetown Clay' (an ancient lake bed deposit – see Hall et al. 2009). As Blanchetown Clay overlies Loxton–Parilla sand in the geological sequence, the overlying material cannot then be 'true' Loxton–Parilla sand. However, much reworking of materials has occurred through the ages, and it is possible that reworked Loxton–Parilla Sand, in conjunction with younger siliceous sands and carbonate materials, has been deposited upon the Blanchetown Clay (a phenomenon that has been encountered at other soil characterisation sites in the Murray Mallee – see Soil and Land Program 2007; Hall et al. 2009).

Deep drilling at toposequence sites revealed saturated layers upon underlying heavy, tight mottled clay at all three sites (see Appendix 5) – surprisingly this even included the dunecrest (see Figure 4).

The drilling demonstrated that the main water-bearing system was at depth (e.g. about 6 m on the dunecrest), and that a tight, mottled, heavy clay (Blanchetown Clay) forms the base of this system. Nonetheless, lateral flow along subsoil surfaces would not be insignificant as a contributor to overall seepage (e.g. as indicated by the lower slope site).

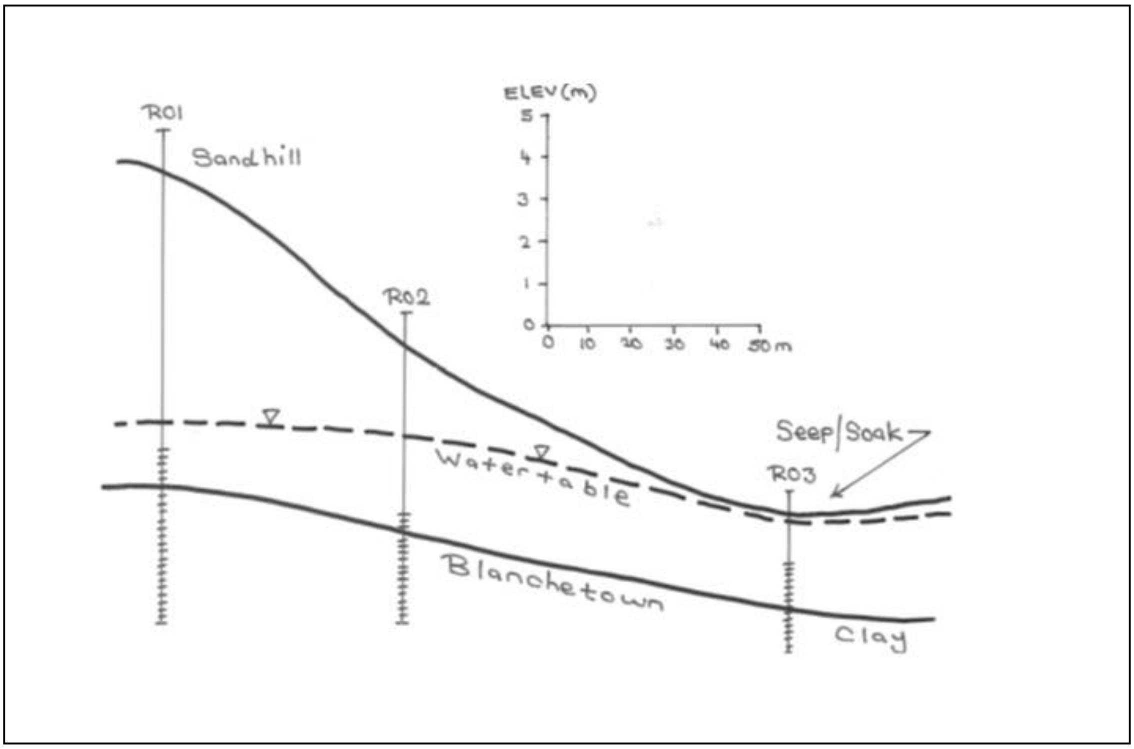

Figure 4: a hydrological cross-section of the Rose–Thomas subcatchment (from Henschke 2015).

Summary and recommendations

It has been established from drilling and soil investigations that relatively deep drainage and lateral water flows are the major processes contributing to the formation of mallee dune seeps in both the Bond and the Rose–Thomas subcatchments. At the Bond subcatchment it is likely that near-surface lateral flows upon subsoils are insignificant across most the area, with possibly minor occurrences on some lower slopes. At the Rose–Thomas subcatchment, it is likely that near-surface lateral flows contribute a small but significant part of seepage waters, especially on lower slopes. This finding has impacts for the development of management solutions to control and reduce seepage and seep areas. Over much of each subcatchment, it is unlikely that annual crop plants can impact directly upon seepage flows, as they occur at considerable depth. Even some perennial plants might not reach and access seepage waters at depths of around 6 m. This means that plant selection and siting to reduce seepage needs to be carefully planned.

The seepage systems at both subcatchments are localised perched water flow systems with a base of Blanchetown Clay. Seeps arise where Blanchetown Clay has a near surface presence in low-lying areas. Although in other areas of the Murray Mallee seeps have been observed on lower slopes, break-of-slope areas, and other higher-level land associated with sand dunes. Infertile, deep sandy soils (especially on dunes) are the main source of seepage waters, owing to the ease with which water can move beyond the rootzone and general inadequate plant water use. Dune cores may also act as reservoirs and sources of water throughout the year.

The recommendations given below are in two main parts: those that deal with management and rehabilitation of seep areas; and those that deal with subcatchment-wide management changes that attempt to improve plant water use and so reduce seepage and discharge. Other possible engineering-type options are also discussed.

Good advice is to use rainfall where it falls (personal comment: Michael Brougham), especially when the land lost to seepage is potentially much more productive than the deep sandy soils from which much of the excess water originates.

Seep management and rehabilitation

The first approach is to manage seeps as separate areas, with the main priority to maximise soil water use, prevent erosion, and minimise evaporation from the land surface to prevent salt accumulation. It is critical to maintain cover to prevent degradation of seep areas. This can be achieved by growing any suitable vegetative cover on the discharge site (e.g. tall wheat grass, puccinellia or saltbush) and/or by planting suitable trees or shrubs on the margins of the site (or even within the seep, depending on species). Even hay or other material can be spread to protect bare soil until plants can be established. An excellent publication detailing the management of salty and wet land and the selection of suitable species is *Saltland Pastures for South Australia* (2007), compiled by Craig Liddicoat and Jock McFarlane. The quicker seeps are dealt with the easier rehabilitation will be. Old, degraded sites take considerably more effort to repair, and may never return to their former state.

The main problem with this approach is that it does not tackle the cause of the problem, which is inadequate water use on adjacent or nearby sandy soils. It also sections-off an area of the farm, alienating it from standard farm management. Such approaches also accept that former high productivity land is lost to production.

Whole of subcatchment management

The best, but more challenging approach, is to manage whole subcatchments to maximise plant water use. This may mean managing areas of deep sandy soil (usually on sand dunes) separately to the rest of the paddock, and the introduction of deep-rooted, high-water-use perennials into the farming system (e.g. lucerne). It could even mean a complete rethinking of farming systems – for many years now, it has been the vison of some researchers (e.g. see Stirzaker et al. 2000; Bryan et al. 2007a; Bryan et al. 2007b) that mallee landscapes could become mosaics of land use matching land capability, with a mix of perennial and annual crops and pastures matched to soil and landform; no longer dominated by rectangular paddocks and farming practices that take limited account of variations in soil type or landform. This remains a long-term vision.

Various agronomic approaches could be utilised to increase crop growth and plant water use, thereby minimising seepage (e.g. the use of slow release fertilisers on infertile sandy soil or improved management of non-wetting soil) – but such changes, although important, are usually incremental. Improving the capacity of infertile deep sandy soils to retain nutrients for plant use is the main aim.

Of interest is that continuous annual cropping systems with high-level summer weed control make virtually no use of out-of-growing-season rainfall that moves through the soil beyond the rootzone. This means that when heavy rain falls in summer, significant amounts may end up contributing to seepage. This signifies that plant water use would be maximised if plants were grown all year round, which means the use of perennials or summer crops.

The fact that mallee dune seepage is associated with localised groundwater flow systems and relatively small catchment areas means that a farm-level whole-of-subcatchment approach can be effective. This is very different to a situation where regional groundwater systems are associated with discharge and the actions of individual farmers have minimal impact.

One landscape approach is to introduce additional trees and shrubs into the landscape. It has been estimated that a significant proportion of a catchment needs to be planted to perennial vegetation (e.g. at least 20%) before a noticeable impact is made on discharge areas associated with dryland salinity (Henschke et al. 2010). It is possible that a similar area would need to be planted to perennials within the investigated subcatchments to bring all seep areas back to arability, although the placement and nature of perennials utilised is important, and further investigations are required.

It has been proposed, nonetheless, that small but strategic plantings of very-high-water-use trees – such as slightly upslope from a seep area – could be used to 'intercept' underground seepage waters before they reach a seep discharge area, with roots drawing water from the saturated layer. This approach needs more testing, but is likely to work only where subcatchment areas contributing to seepage are very small. It could also be limited in usefulness where seepage waters are too deep for roots to reach.

Soil modification with clay

Soil modification with clay is a key method of improving the water storage and nutrient retention capacities of sandy soils, and thereby improving plant water use, and minimising the excess water that contributes to seepage. Such an approach can lead to substantial increases in plant water use and yield. Methods such a clay spreading, delving and spading can be utilised. On deep sandy soils clay spreading with incorporation (often using a spader) is the only method possible. The economics of clay spreading depend on the depth and/or distance to a clay source. The effectiveness depends on rate, method of spreading, degree and depth of incorporation, and clay characteristics. Considerable information is available about clay spreading (e.g. see Leonard 2011). It is likely that the proportion of a subcatchment requiring clay modification to remedy dune seeps would be similar to the proportion requiring perennial vegetation. However, this would vary with subcatchment characteristics, methods and clay type. The new horizons program conducted by Primary Industries and Regions SA is providing more knowledge and information about the effectiveness of soil modification with clay (see <http://pir.sa.gov.au/consultancy/major_programs/new_horizons>).

The do nothing approach

A legitimate option is to make no management changes and to leave seeps as sacrifice areas. However, such a tactic would likely result in unsightly, degraded areas at the worst affected sites, which could easily expand in extent.

Other options

- There is the possibility of utilising the excess water discharging into swale areas for other purposes (e.g. for stock water or irrigation). Further investigations are required.
- One response by farmers to the presence of seeps and localised perched water flow systems is to drill through the low permeability Blanchetown Clay layer and allow seepage waters to 'drain away' to very deep drainage. The feasibility or practicality of such an option is unknown and further investigations would be required.

Possible further investigations

- Investigations and field experimentation (e.g. using lysimeters to measure actual plant water use and soil drainage) at selected sites and catchments to determine the cause of the development of new mallee dune seeps (e.g. are they caused by control of summer weeds within continuous cropping systems?). Information gained could then be utilised along with land unit or soil mapping information to develop whole-of-catchment water balance models.
- Further soil investigations and drilling could be conducted to confirm the nature of dune seepage systems at other sites in the Murray Mallee.
- Development of recommendations and further investigations with respect to managing seep areas once they have formed.
- Remote or proximal sensing (e.g. ground-penetrating radar) could be employed to map the extent of Blanchetown Clay in selected catchments.
- Soil survey and mapping of selected catchments to develop a sound spatial basis for calculating catchment water balances and agronomic and economic impact of management changes
- Calculation of broad water balances for selected catchment/s to support development of management strategies, and to determine the proportion of incident rainfall 'lost' to seepage.
- Calculation of agronomic (yield) and economic impact of ameliorative strategies for mallee dune seeps.
- Mapping of dune seeps across the South Australian Murray Mallee to assess the extent of the issue.
- An economic evaluation of the impact of seeps across the Murray Mallee.

- Mapping the occurrence of Blanchetown Clay across the whole Murray Mallee.
- Use of State Land and Soil Information Framework datasets to model and map potential for dune seep development.
- Continuation and expansion of investigations into agronomic practices to increase plant water use and decrease seepage across the Murray Mallee.
- Further assessments, trials and recommendations on the use of perennials in mallee landscapes.
- Assessments, trials and recommendations with respect to the use of summer crops in mallee landscapes.
- Assessments and recommendations for clay spreading in relation to controlling mallee dune seeps.

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Appendices

Appendix 1 – figures (Bond subcatchment)

Figure 5: Bond Subcatchment (Mannum East) in the South Australian Murray Mallee: showing sites investigated via soil characterisation and drilling (with a 2001 aerial photograph as background).

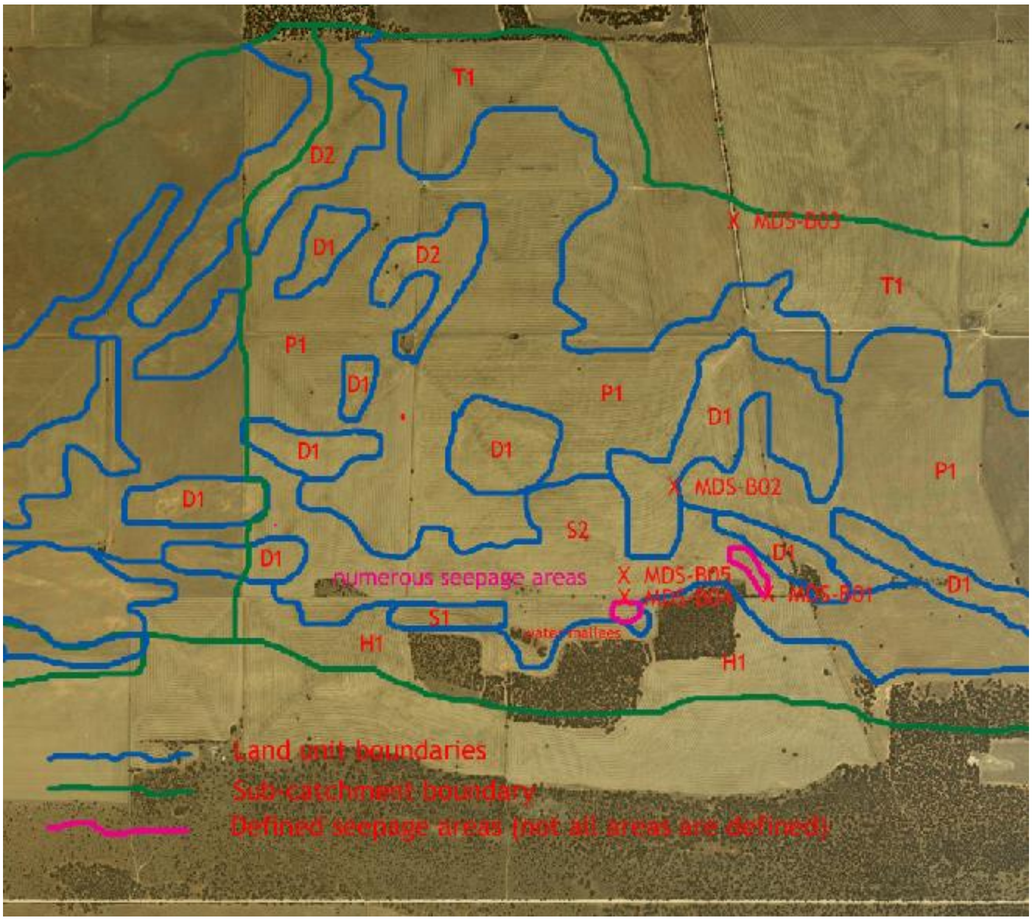


Figure 6: Bond Subcatchment at Mannum East in the South Australian Murray Mallee: showing land units and subcatchment watershed boundary (with a 2001 aerial photograph as background).

Land unit development is based on stereoscopic Air-Photo-Interpretation (API) of 2001 aerial photographs, an interpretation of 2015 aerial photographs (non-stereo), a very limited number of on-ground investigations, and State Land & Soil Mapping Program descriptions of the area (Soil and Land Program 2007).

D1 = prominent sand dunes and rises (lower elevation)

D2 = prominent sand dunes and rises (higher elevation)

T1 = sandy plateau and upper slopes

H1 = hillslopes

P1 = undulating plains

S1 = closed depression

S2 = low-lying areas with numerous semi-arable to non-arable seep (two of the main seeps are indicated in pink)

Appendix 2 – drilling reports (Bond subcatchment)

Notes: It needs to be noted that drilling is a very uncertain business, and that materials disturbed by the drill head do not necessarily travel up the augur to the land surface at an even rate or, in some cases, do not travel up the rotating augur at all (e.g. heavy clay and wet materials), and that it is often uncertain which depths specific materials are derived from. However, it can be reasonably assumed that materials deposit at the land surface in sequential order. Depths given below, therefore, are indicative only. Colours are also mostly indicative, as materials of different colours are mixed, however, the tight mottled heavy clay material encountered was viewed intact.

Site MDS-B01 – Drilling Report (17/6/2015)

The drill site is several metres from the MDS-B01 soil characterisation site.

Easting 354 626 Northing 6130 635

Position: valley / depression / flat

Depth (cm)	Material
50	loamy sand / brown / moderately moist / loose / moderately calcareous / -
100	sandy clay loam / strong brown / moderately moist / weak / moderately calcareous / -
150	sandy light medium clay / strong brown / moderately moist / weak / highly calcareous / -
200	light medium clay / yellowish red / moist / weak / highly calcareous / slightly dispersive
250	light medium clay / yellowish red / moist / weak / moderately calcareous / slightly dispersive
----------------------- discontinuity -----------------------	
300	heavy clay / dark red, strong brown and olive / moderately moist / strong / moderately calcareous / -
----------------------- discontinuity -----------------------	
350	light medium clay / yellowish red / moist / firm / non-calcareous / -
400	medium clay / yellowish red / moderately moist / firm / non-calcareous / -
500	medium clay / yellowish red / moderately moist / very firm / non-calcareous / -
550	medium clay / yellowish red / moderately moist / very firm / non-calcareous / -
600	medium clay / yellowish red / moderately moist / firm / non-calcareous / -
----------------------- discontinuity -----------------------	
700	silty clay loam / yellowish red / moderately moist / very weak / non-calcareous / -
800	fine sandy silty clay loam / yellowish red / moderately moist / very weak / non-calcareous / slightly dispersive
850	fine sandy silty clay loam / yellowish red / moderately moist / very weak / non-calcareous / slightly dispersive
950	fine sandy silty loam / yellowish brown / moist / very weak / non-calcareous /

	slightly dispersive
1000	fine sandy silty loam / yellowish brown / moist / very weak / non-calcareous / non-dispersive
1100	fine sandy silty clay loam / strong brown / moderately moist / very weak / non-calcareous / slightly dispersive

There were strong indications that the 200–250 cm layer was water bearing. A quite thin layer of tight, mottled, heavy clay directly underlies the water-bearing layer; it has extremely low permeability, and is confirmed as a layer of Blanchetown Clay material.

Site MDS-B02 – Drilling Report (18/6/2015)

The drill site is approximately 20 metres from the MDS-B02 soil characterisation site.

Easting 354 436 Northing 6131 005

Position: upper dune slope which is superimposed on the lower slope of a very long hillslope

Depth (cm)	Material
50	loamy sand / yellowish brown / moist / loose / non-calcareous / -
100	loamy sand / yellowish brown / moist / loose / highly calcareous / -
150	loamy sand / yellowish brown / moist / loose / highly calcareous / -
200	clayey sand / yellowish brown / most / loose / highly calcareous / -
250	light sandy clay loam / brownish yellow / moist / very weak / highly calcareous / -
300	heavy sandy loam / yellowish brown / moist / very weak / highly calcareous / -
350	light sandy clay loam / yellowish red / moist / weak / highly calcareous / -
400	light sandy clay loam / yellowish red / wet to moist / weak / slightly calcareous / moderately dispersive [some semi-hard calcrete]
450	light sandy clay loam / brownish yellow / moist / weak / highly calcareous / - [calcrete layer]
500	sandy clay loam / reddish yellow / moist / weak / slightly calcareous / -
600	light sandy clay loam / very pale brown / wet / loose / non-calcareous / -
----------------------- discontinuity --	
650	heavy clay / dark red, strong brown and olive / moderately dry / strong / non-dispersive

The bleached layer directly above the heavy clay was saturated. The heavy clay is confirmed as Blanchetown Clay. There was also evidence that some lateral water flow occurs in the 350–400 cm layer.

Site MDS-B03 – Drilling Report (18/6/2015)

The drill site is approximately 7 metres from the MDS-B03 soil characterisation site.

Easting 354 493 Northing 6131 883

Position: high-level sandy plateau

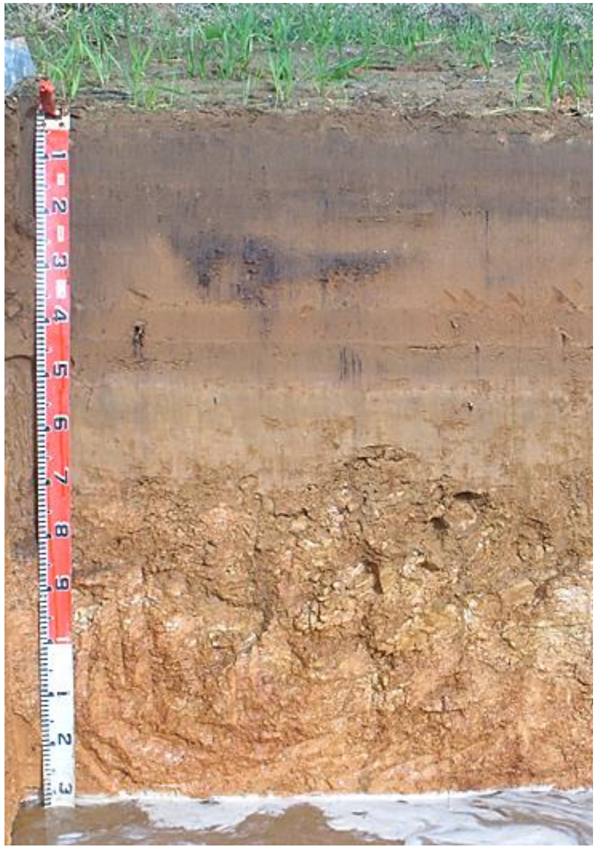
Depth (cm)	Material
50	light fine sandy loam / dark brown / moderately dry / loose / non-calcareous / -
100	light fine sandy loam / brown / moderately moist / loose / slightly calcareous / -
150	fine sandy loam / brown / moderately moist / very weak / moderately calcareous / -
200	fine sandy loam / brown / moderately moist / very weak / moderately calcareous / -
250	fine sandy loam / yellowish brown / moderately moist / very weak / highly calcareous / - [some calcrete]
300	fine sandy loam / yellowish brown / moderately moist / very weak / highly calcareous / - [some calcrete]
350	fine sandy clay loam / light yellowish brown / moderately moist / weak / highly calcareous / -
400	fine sandy clay loam / brownish yellow / moderately moist / weak / highly calcareous / -
450	fine sandy clay loam / reddish yellow / moderately moist / very weak / highly calcareous / - [some hard carbonate]
500	heavy fine sandy loam / strong brown / moderately moist / very weak / highly calcareous / non-dispersive [some hard carbonate]
550	fine sandy light clay / strong brown / moderately moist / weak / highly calcareous / -
-	light medium clay / strong brown / - / - / moderately calcareous / - [some semi-hard calcrete]
-	light medium clay / strong brown / moderately moist / firm / moderately calcareous / - [some semi-hard calcrete]
-	medium clay / strong brown / moderately moist / very firm / moderately calcareous / non-dispersive
-	medium clay / strong brown / moderately moist / very firm / moderately calcareous / -
-	medium clay / strong brown / moderately moist / very firm / moderately calcareous / -
-	medium clay / yellowish red and strong brown / firm / slightly calcareous / slightly dispersive

Total drilling depth was 9.5 m. It became uncertain what depths material was derived from in the lower part of the hole, so depths are not given. Evidence of a water-bearing layer was not encountered.

Appendix 3 – soil characterisation sites (Bond subcatchment)

WET SANDY LOAM OVERLYING A BROWN LIGHT CLAY

Wet, thick, light sandy loam topsoil over a whole-coloured brown light clay subsoil with some hard carbonate



Subgroup soil	Soil N3 (wet soil) (Hall et al. 2009)
Landform	Low hills with an overlying dunefield
Substrate	Whole-coloured clay loamy sediment
Native Vegetation	Mallee scrub (to approximately 10 m)
Position	Depression/flat within a valley
Site	Bond subcatchment:

Site No:	MDS-B01	1:50 000 mapsheet:	6728-2 (Mannum)
Hundred:	Younghusband	Easting:	354 646
Section:	-	Northing:	6130 641
Date:	28-29/7/2015	Annual rainfall:	300 mm

Low-lying site in a depression/flat slightly down-catchment of, and adjacent to, a major seep.

Soil Description

Depth (cm)	Description
0–12	Soft, dark brown, non-repellent, light sandy loam with single grain structure. Clear boundary to:
22–52	Strong brown, light sandy loam with single grain structure. Clear boundary to:
52–70	Strong brown, moderately calcareous, moderately dispersive, light clay with weak subangular blocky structure. Clear boundary to:
70–100	Strong brown, moderately calcareous, dispersive, clay loam with weak subangular blocky structure and 20–50% hard carbonate fragments (6–60 mm diameter). Clear boundary to:
100–140	Strong brown, moderately calcareous, slightly dispersive, clay loam with weak subangular blocky structure and 20–50% hard carbonate fragments (6–60 mm).

No layer was saturated. The wettest layers were at field capacity (layers 1 & 2). Active water seepage was observed within cracks of layer 4; and there was also some seepage across the surface of this layer from upslope.

Australian Soil Classification

Oxyaquic Hydrosol. Before becoming wet, he soil would have classified as a: Supracalcic, Subnatric, **Brown Sodosol**; thick, non-gravelly, loamy / clayey, shallow.

Summary of Properties

Drainage The soil profile is poorly to very poorly drained, and is wet for most of the year, owing to seepage from the higher subcatchment area.

Fertility Fertility levels are high, owing to the accumulation of substances in this low-lying area.

pH Owing to the accumulation of substances in this low-lying area, soil pH is strongly alkaline throughout the profile.

Rooting depth Root were observed to 52 cm.

Barriers to root growth

Physical There are no significant physical restraints to root growth.

Chemical Chemical restraints to root growth are many and include strong pH, high boron and sodium levels and moderate salinity levels. Profile wetness also presents a barrier to root growth.

Waterholding capacity Plant Available Waterholding Capacity is estimated to be approximately 50 mm (moderately low) [Workings: 0.22x120 + 0.3x100].

Seedling emergence Good. Although waterlogging and moderate salinity levels may affect seedling emergence.

Workability Good.

Erosion potential

Water Low.

Wind Moderately low. Risk is reduced by low-lying positon and wetness.

Laboratory Data – MDS-B01

Hori-zon	Depth cm	Texture	N NH_4^+ mg/kg	N NO_3^- mg/kg	pH H2O	pH CaCl2	CO3 %	EC 1:5 dS/m	ECe dS/m	Org C %	P Avail. mg/kg	P Buff Index	K Avail. mg/kg	S (KCl) mg/kg	Boron mg/kg	Trace Elements mg/kg (DTPA)				Sum cations meq/100g	Exchangeable Cations meq/100g					ESP
																Cu	Fe	Mn	Zn		Ca	Mg	Na	K	Al	
A1	0–22	sl-	<1	10	9.8	8.7	0.24	0.35	4.67	0.32	43	32.4	218	52	9.31	0.36	19.8	1.5	3.2	6.5	2.14	1.04	2.72	0.56	0.08	41.6
A2	22–52	sl-	<1	17	9.5	8.4	0.62	0.42	5.95	0.19	30	27.9	179	65	9.15	0.42	19.2	0.7	0.6	8.6	3.89	0.83	3.29	0.43	0.15	38.3
Bt	52–70	lc	<1	10	9.8	8.7	10.5	0.51	3.05	0.21	7	131	442	56	14.99	0.51	9.7	0.7	0.8	20.1	7.46	4.68	6.73	1.13	0.09	33.5
Btk	70–100	cl	<1	11	9.7	8.4	24.6	0.40	2.73	0.24	2	168	571	65	16.83	0.57	9.9	0.6	1.1	21.8	6.75	7.90	5.56	1.46	0.08	25.6
C	100–140	cl	<1	7	9.5	8.4	47.7	0.52	2.40	0.13	<2	154	425	65	17.22	0.79	6.9	0.2	0.5	17.8	5.80	6.10	4.68	1.09	0.08	26.4
Approx. Critical/Ideal Values			-	-	6–8	5.5–7.5	0	<0.7–1.85	<4–8	>1–2	>25–35	100–200	>80–120	>6–8	1–15	>0.2	>2.5	>1–2	>0.5–1.0	>15	75% CEC	20% CEC	<6% CEC	5% CEC	<5% CEC	<6

Note: (1) Sum of Cations approximates the Cation Exchange Capacity (CEC), a measure of the soil's capacity to store and release major nutrient elements.
(2) Exchangeable Sodium Percentage (ESP) is derived by dividing the exchangeable sodium value by the CEC, in this case estimated by the Sum of Cations.

DEEP SILICEOUS SAND

Deep siliceous sand with minor lamallae and earthy segregations, as well as moderate fine and hard carbonate below 1 m.

Subgroup soil Soil H2 (siliceous sand) (Hall et al. 2009)

Landform Low hills with an overlying dunefield

Substrate Whole-coloured sandy material

Native Vegetation -

Position Upper dune slope (near crest)

Site Bond subcatchment:

Site No:	MDS-B02	1:50 000 mapsheet:	6728–2 (Mannum)
Hundred:	Younghusband	Easting:	354 412
Section:	-	Northing:	6131 001
Date:	28–29/7/2015	Annual rainfall:	300 mm

On an upper duneslope that is superimposed transversely on the lower slope of a long hillslope. Within a wheat crop, with newly planted lucerne within 20 m.

Soil Description

Depth (cm)	Description
0–12	Loose, dark yellowish brown, non-repellent, clayey sand with single grain structure. Abrupt boundary to:
12–50	Brownish yellow, loamy sand with single grain structure and minor heavier-textured lamellae. Abrupt boundary to:
50–68	Yellowish brown, clayey sand with single grain structure. Sharp boundary to:
68–100	Brownish yellow, clayey sand with single grain structure and 10–20% nodular non-clayey segregations with slightly higher clay content than the main soil matrix. Gradual boundary to:
100–130	Brownish yellow, moderately calcareous, clayey sand with single grain structure. Gradual boundary to:
130–175	Brownish yellow, moderately calcareous, light sandy clay with single grain structure and 10–20% hard carbonate fragments (20–60 mm diameter).

Australian Soil Classification

Calcareous, Arenic, **Brown-Orthic Tenosol**; thick, non-gravelly, sandy / sandy, deep.

Summary of Properties

Drainage The soil profile is rapidly drained – indicated in part by evidence of leaching of phosphorus below the surface soil.

Fertility Cation exchange capacity levels (as shown by sum of cation figures) are very low to 50 cm, and low below this, indicating very low capacity to retain, store and provide nutrients to plants.

pH Soil pH is acidic in the surface soil, then alkaline to 100 cm, and strongly alkaline below this.

Rooting depth Roots were observed to 68 cm.

Barriers to root growth

Physical There are no physical barriers to root growth.

Chemical General low fertility is the only chemical barrier to root growth.

Waterholding capacity Plant Available Waterholding Capacity is estimated to be approximately 69 mm (moderately low). [Workings: 0.12x110 + 0.56x100].

Seedling emergence Good. Although potential for water repellency and restricted seedling emergence, as well as potential for sand-blasting of seedlings are issues.

Workability Good.

Erosion potential

Water Low.

Wind Moderately high. Loose sandy surface and sand dune crest position increase risk. Maintenance of surface cover is required to minimise erosion.

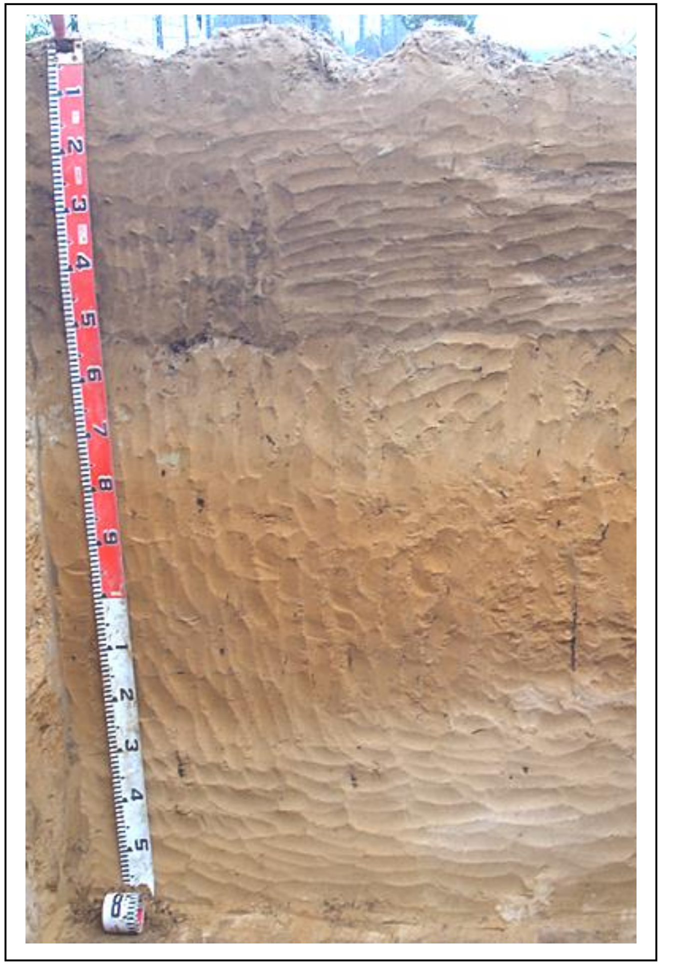
Laboratory Data MDS-B02

Hori-zon	Depth cm	Texture	N NH4+ mg/kg	N NO3- mg/kg	pH H2O	pH CaCl2	CO3 %	EC 1:5 dS/m	ECe dS/m	Org C %	P Avail. mg/kg	P Buff Index	K Avail. mg/kg	S (KCl) mg/kg	Boron mg/kg	Trace Elements mg/kg (DTPA)				Sum cations meq/100g	Exchangeable Cations meq/100g					ESP
																Cu	Fe	Mn	Zn		Ca	Mg	Na	K	Al	
A1	0–12	cs	1	26	6.0	5.2	0.2	0.06	0.66	0.62	25	15.9	121	2.6	0.44	0.24	42.8	1.99	2.48	3.6	2.49	0.74	0.04	0.25	0.06	1.1
A2	12–50	ls	<1	2	8.7	7.9	0.2	0.04	0.36	0.05	13	10.6	88	1.5	0.26	0.15	11.1	0.57	0.15	2.6	1.65	0.53	0.02	0.23	0.17	0.8
Bw1	50–68	cs	<1	1	7.7	6.7	0.2	0.02	0.32	0.06	3	15.7	159	1.1	0.52	0.09	5.80	0.40	0.19	5.4	3.26	1.41	0.04	0.41	0.24	0.7
Bw2	68–100	cs	<1	1	9.1	7.9	0.38	0.06	0.30	0.05	<2	13.4	97	1.6	0.56	0.19	4.22	0.36	0.15	6.1	4.27	1.26	0.04	0.25	0.30	0.7
Bk1	100–130	cs	<1	2	9.2	8.2	0.75	0.06	0.27	0.05	<2	13.8	90	1.4	0.60	0.16	5.15	0.35	0.16	5.6	4.02	1.01	0.03	0.23	0.29	0.5
Bk2	130–175	sl-	<1	3	9.4	8.4	4.37	0.09	0.40	0.05	<2	41.6	211	2.4	1.34	0.14	5.68	0.38	0.24	9.6	6.19	2.66	0.07	0.54	0.16	0.7
Approx. Critical/Ideal Values			-	-	6–8	5.5–7.5	0	<0.7–1.85	<4–8	>1–2	>25–35	100–200	>80–120	>6–8	1–15	>0.2	>2.5	>1–2	>0.5–1.0	>15	75% CEC	20% CEC	<6% CEC	5% CEC	<5% CEC	<6

Note: (1) Sum of Cations approximates the Cation Exchange Capacity (CEC), a measure of the soil's capacity to store and release major nutrient elements.
(2) Exchangeable Sodium Percentage (ESP) is derived by dividing the exchangeable sodium value by the CEC, in this case estimated by the Sum of Cations.

DEEP SANDY LOAM

Deep sandy loam with moderate fine and hard carbonate at depth.



Subgroup soil	Soil M1–G1 (deep sandy loam) (Hall et al. 2009)
Landform	Low hills with an overlying dunefield
Substrate	whole-coloured sandy loam material
Vegetation	-
Position	High-level sandy plateau
Site	Bond subcatchment:

Site No:	MDS-B03	1:50 000 mapsheet:	6728–2 (Mannum)
Hundred:	Younghusband	Easting:	354 482
Section:	-	Northing:	6131 885
Date:	28–29/7/2015	Annual rainfall:	300 mm

Soil Description

Depth (cm)	Description
0–12	Loose, dark yellowish brown, non-repellent, light sandy loam with single grain structure. Clear boundary to:
12–27	Dark yellowish brown, light sandy loam with single grain structure. Clear boundary to:
27–52	Dark yellowish brown, light sandy loam with single grain structure. Abrupt boundary to:
52–77	Yellowish brown, sandy loam with single grain structure. Clear boundary to:
77–125	Yellowish brown, moderately calcareous, light sandy loam with single grain structure. Clear boundary to:
125–160	Brownish yellow, moderately calcareous, sandy loam with single grain structure and 2–10% hard carbonate fragments (6–20 mm diameter). Clear boundary to:
160+	Light yellowish brown, moderately calcareous, slightly dispersive, light sandy clay loam with single grain to weak structure and 20–50% hard carbonate fragments (20–60 mm).

Australian Soil Classification

Calcareous, Regolithic, **Brown-Orthic Tenosol**; thick, non-gravelly, loamy / loamy, deep.

Summary of Properties

Drainage The soil is well drained to rapidly drained. Excessive drainage is especially indicated by some leaching of phosphorus below the surface soil. A minor restriction to downward movement of water occurs below 1 m.

Fertility Cation exchange capacity levels (shown by sum of cation figures) for the various soil layers indicate relatively low levels of fertility in the top metre, with increasing levels below this. The upper metre has limited capacity to retain, store and provide plant nutrients. This points to the importance of maintaining and enhancing surface soil organic matter content, which provides the main store of plant nutrients.

pH Soil pH ranges from slightly alkaline in the surface soil, to alkaline below this, and then strongly alkaline below 1 m.

Rooting depth Roots were observed to 52 cm.

Barriers to root growth

Physical There are no physical barriers to root growth.

Chemical Owing to excessive drainage in the top metre, there is no accumulation of toxic elements.

Waterholding capacity Plant Available Waterholding Capacity (PAWC) is estimated to be 58 mm (moderately low). [Workings: 0.12x120 + 0.4x110].

Seedling emergence Good. Some problem could occur owing to sand-blasting of seedlings by wind-driven sand.

Workability Good.

Erosion potential

Water Low.

Wind Moderate. Elevated position increases risk. Maintenance of surface cover is required to minimise erosion.

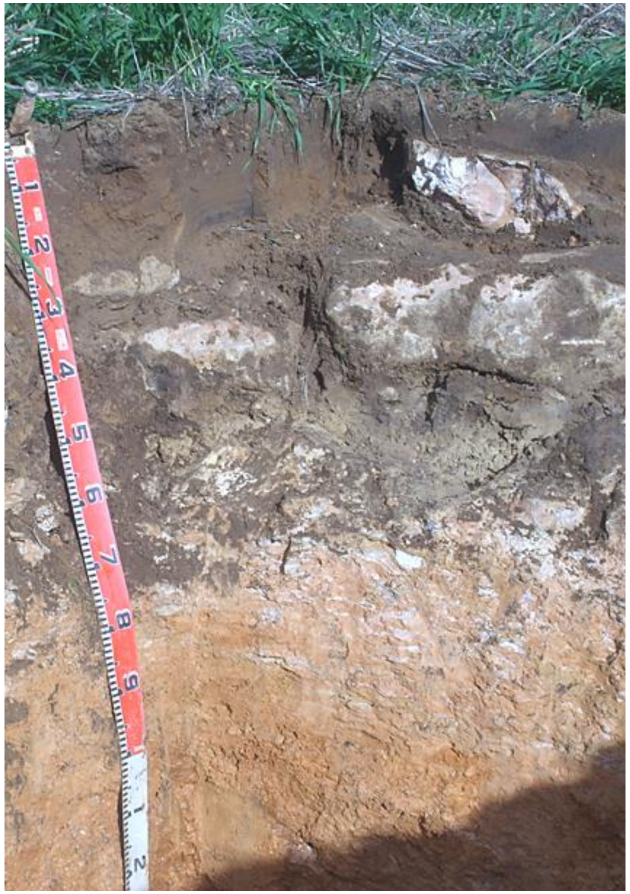
Laboratory Data – MDS-B03

Hori-zon	Depth cm	Texture	N NH_4^+ mg/kg	N NO_3^- mg/kg	pH H2O	pH CaCl2	CO3 %	EC 1:5 dS/m	ECe dS/m	Org C %	P Avail. mg/kg	P Buff Index	K Avail. mg/kg	S (KCl) mg/kg	Boron mg/kg	Trace Elements mg/kg (DTPA)				Sum cations meq/ 100g	Exchangeable Cations meq/100g					ESP
																Cu	Fe	Mn	Zn		Ca	Mg	Na	K	Al	
Ap	0–12	sl-	<1	15	7.8	7.2	0.26	0.06	0.73	0.64	24	16.8	203	2.9	0.62	0.23	11.3	0.70	2.32	6.6	5.30	0.76	0.04	0.45	0.04	0.6
A12	12–27	sl-	<1	7	8.8	8.0	0.23	0.06	0.53	0.41	22	15.8	194	2.8	0.75	0.50	9.49	0.22	0.73	6.6	5.39	0.61	0.02	0.49	0.08	0.3
A13	27–52	sl-	<1	8	8.6	7.7	0.27	0.05	0.58	0.41	12	17.2	210	2.2	0.94	0.25	9.02	0.24	0.23	7.2	5.96	0.62	0.03	0.44	0.11	0.4
Bw1	52–77	sl	1	5	8.8	8.0	0.32	0.07	0.50	0.21	4	20.7	129	2.5	0.71	0.13	16.8	1.41	0.19	5.6	4.32	0.69	0.05	0.33	0.17	0.9
Bw2	77–125	sl-	<1	9	9.2	8.3	3.86	0.08	0.48	0.17	<2	42.0	219	2.9	1.10	0.16	9.29	0.38	0.10	10.5	8.15	1.59	0.05	0.56	0.16	0.5
BCk1	125–160	sl	<1	12	9.4	8.4	6.99	0.10	0.66	0.08	<2	46.7	291	2.8	1.33	0.25	6.75	0.17	0.30	10.0	6.64	2.41	0.10	0.75	0.10	1.0
BCk2	160+	scl-	<1	10	9.7	8.6	18.0	0.21	1.05	0.17	<2	216.8	522	5.8	5.84	0.43	7.66	0.44	0.28	15.2	6.93	4.80	2.06	1.34	0.10	13.5
Approx. Critical/Ideal Values			-	-	6–8	5.5–7.5	0	<0.7–1.85	<4–8	>1–2	>25–35	100–200	>80–120	>6–8	1–15	>0.2	>2.5	>1–2	>0.5–1.0	>15	75% CEC	20% CEC	<6% CEC	5% CEC	<5% CEC	<6

Note: (1) Sum of Cations approximates the Cation Exchange Capacity (CEC), a measure of the soil's capacity to store and release major nutrient elements.
(2) Exchangeable Sodium Percentage (ESP) is derived by dividing the exchangeable sodium value by the CEC, in this case estimated by the Sum of Cations.

WET SHALLOW SANDY LOAM OVER CALCRETE

Wet, shallow sandy loam over a thick calcrete pan with whole-coloured sandy clay loam substrate.



Subgroup soil	Soil N3 (wet soil) (Hall et al. 2009)			
Landform	Low hills with an overlying dunefield			
Substrate	Whole-coloured sandy clay loam			
Vegetation	-			
Position	Valley/closed depression/margin of seep area			
Site	Bond subcatchment:			
	Site No:	MDS-B04	1:50 000 mapsheet:	6728–2 (Mannum)
	Hundred:	Younghusband	Easting:	354 098
	Section:	-	Northing:	6130 607
	Date:	28–29/7/2015	Annual rainfall:	300 mm

Soil Description

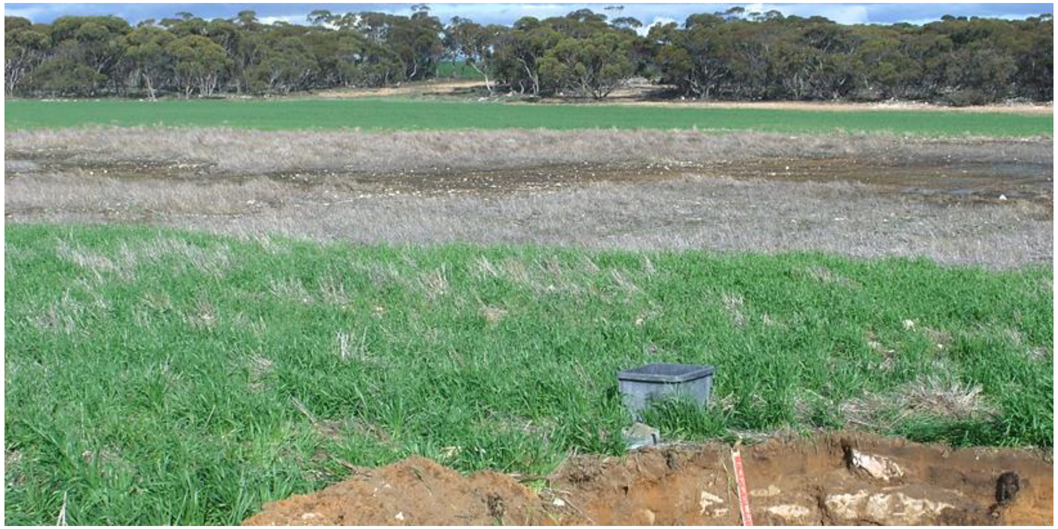
Depth (cm)	**Description**
0–12	Soft, dark brown, non-repellent, light sandy loam with weak structure. Clear boundary to:
12–22	Strong brown, light sandy loam with single grain structure and 10 – 20% hard carbonate fragments (>60 mm diameter). Abrupt boundary to:
22–45	Saturated, pale brown, slightly calcareous, slightly dispersive, bleached, light sandy loam with abundant hard carbonate fragments (>60 mm). Abrupt boundary to:
45–70	Calcrete pan. Clear boundary to:
70–90	Calcrete pan. Clear boundary to:
90–140	Brownish yellow, slightly calcareous, moderately dispersive, light sandy clay loam with weak structure.

Australian Soil Classification

Oxyaquic Hydrosol. Before becoming wet, the soil would have classified as a: Calcareous, Petrocalcic, **Bleached-Leptic Tenosol**; thick, gravelly, loamy / -, shallow.

Summary of Properties

Drainage The soil profile is poorly drained. Soil may remain wet for many months.



pH Soil pH is alkaline in the surface soil and, owing to the accumulation of substances in this low-lying area, strongly alkaline below this.

Rooting depth Roots were observed to 45 cm.

Barriers to root growth

Physical Calcrete pans present a barrier to root growth.

Chemical Wetness, particularly in layer 3 presents a barrier to root growth, as does the strong pH below the surface soil.

Waterholding capacity Plant Available Waterholding Capacity (PAWC) is estimated to be approximately 37 mm (low). [Workings: 0.12x120 + 0.2x0.8x100 + 0.18x0.4x100].

Seedling emergence Good.

Workability Moderate. Calcrete fragments impact upon workability.

Erosion potential

Water Low.

Wind Moderately low. Low-lying position reduces risk.

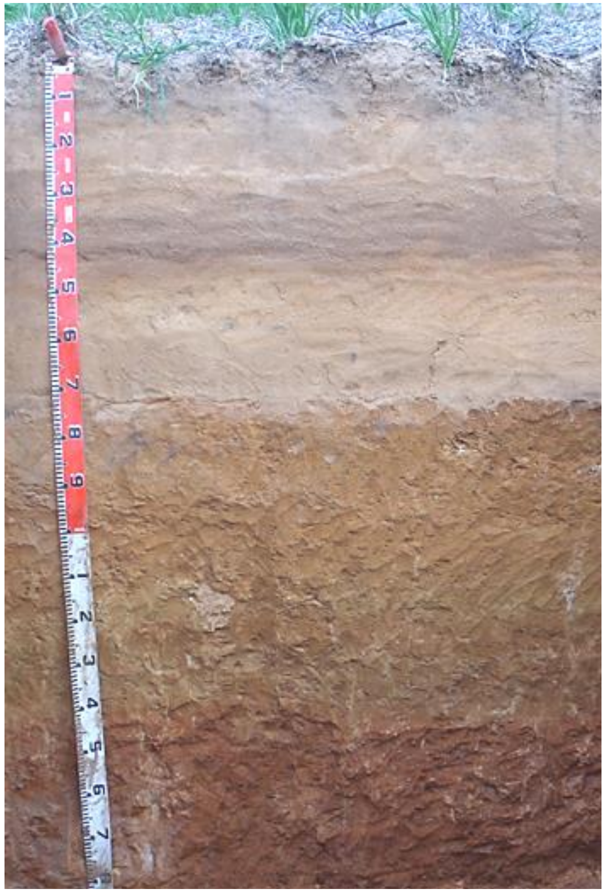
Laboratory Data – MDS-B04

Hori-zon	Depth cm	Texture	N NH_4^+ mg/kg	N NO_3^- mg/kg	pH H2O	pH CaCl2	CO3 %	EC 1:5 dS/m	ECe dS/m	Org C %	P Avail. mg/kg	P Buff Index	K Avail. mg/kg	S (KCl) mg/kg	Boron mg/kg	Trace Elements mg/kg (DTPA)				Sum cations meq/ 100g	Exchangeable Cations meq/100g					ESP
																Cu	Fe	Mn	Zn		Ca	Mg	Na	K	Al	
A1	0–12	sl-	2	41	8.5	7.9	0.35	0.21	1.47	1.12	38	19.0	276	11.0	2.48	0.35	16.9	1.74	4.70	8.4	5.55	1.41	0.68	0.71	0.05	8.1
A2	12–22	sl-	<1	12	9.5	8.5	0.37	0.11	1.44	0.19	24	25.1	229	7.9	3.31	0.34	11.5	0.24	0.71	5.6	3.24	0.80	0.92	0.54	0.14	16.3
A2k	22–45	sl-	<1	10	9.8	8.7	10.2	0.24	1.69	0.56	8	102.4	293	15.2	6.83	1.05	14.3	2.04	1.52	15.1	8.50	4.03	1.79	0.75	0.07	11.8
Bkm1	45–70	-	calcrete pan																							
Bkm2	70–90	-	calcrete pan																							
C	90–140	fscl-	<1	7	10.0	8.7	60.2	0.23	0.99	0.15	<2	159.7	406	11.6	9.61	0.60	9.2	0.48	0.83	14.5	5.91	5.32	2.19	1.04	0.02	15.1
Approx. Critical/Ideal Values			-	-	6–8	5.5–7.5	0	<0.7–1.85	<4–8	>1–2	>25–35	100–200	>80–120	>6–8	1–15	>0.2	>2.5	>1–2	>0.5–1.0	>15	75% CEC	20% CEC	<6% CEC	5% CEC	<5% CEC	<6

Note: (1) Sum of Cations approximates the Cation Exchange Capacity (CEC), a measure of the soil's capacity to store and release major nutrient elements.
(2) Exchangeable Sodium Percentage (ESP) is derived by dividing the exchangeable sodium value by the CEC, in this case estimated by the Sum of Cations.

SAND OVER SANDY CLAY LOAM

Very thick sand over fine sandy clay loam with minor carbonate at depth.



Subgroup soil	Soil G1 (sand over sandy clay loam) (Hall et al. 2009)
	Low hills with an overlying dunefield
Substrate	Whole-coloured sandy loam and calcrete
Vegetation	-
Position	Lower slope of very long hillslope
Site	Bond subcatchment:

Site No:	MDS-B05	1:50 000 mapsheet:	6728–2 (Mannum)
Hundred:	Younghusband	Easting:	354 099
Section:	-	Northing:	6130 702
Date:	28–29/7/2015	Annual rainfall:	300 mm

Soil Description

Depth (cm)	Description
0–10	Loose, brown, non-repellent*, clayey sand with single grain structure. Sharp boundary to:
10–30	Brown, loamy sand with single grain structure. Clear boundary to:
30–48	Brown, loamy sand with single grain structure. Clear boundary to:
48–70	Brownish yellow, loamy sand with single grain structure. Abrupt boundary to:
70–74	Strong brown, moderately dispersive, light sandy clay loam with weak to moderate structure. Sharp boundary to:
74–110	Strong brown, slightly calcareous, moderately dispersive, heavy fine sandy clay loam with weak structure. Gradual boundary to:
110–140	Strong brown, slightly calcareous, moderately dispersive, light fine sandy clay loam with weak structure and 2–10% hard carbonate fragments (6–20 mm diameter). Sharp boundary to:
140–190	Yellowish red, moderately dispersive, heavy fine sandy clay loam with moderate structure. Abrupt boundary to:
190+	Very hard calcrete pan.

* within a patch of crop impacted by water repellency.

Australian Soil Classification

Hypocalcic, Subnatric, **Brown Sodosol**; very thick, non-gravelly, sandy / clay loamy, deep.

Summary of Properties

Drainage The soil profile is well drained to moderately well drained. Some restriction to downward water movement occurs at the topsoil–subsoil interface; while the sandy topsoil shows signs of excessive drainage with some leaching of phosphorus below the surface soil.

pH Soil pH is acidic in the surface soil, then alkaline to 74 cm, then strongly alkaline below this.

Rooting depth Roots were observed to 110 cm, with most in the top 30 cm.

Barriers to root growth

Physical There are no significant physical barriers to root growth in the top metre. A very hard calcrete pan occurs at 160 cm.

Chemical Chemical barriers to root growth occur below 1 m, where there is some accumulation of toxic elements (e.g. boron and sodium). Of interest is that salinity levels are high below 74 cm (in subsoil layers).

Waterholding capacity Plant Available Waterholding Capacity (PAWC) is estimated to be approximately 80 mm (moderate). [Workings: 0.1x120 + 0.2x110 + 0.4x0.5x100 + 0.4x0.5x140].

Seedling emergence Moderate. There are no physical barriers, however, this is a patch of soil affected by water repellency and resulting reduced seedling emergence. There is also potential for sand-blasting of seedlings.

Workability Good.

Erosion potential

Water Low.

Wind Moderate. Maintenance of surface cover is required to minimise erosion.

Laboratory Data – MDS-B05

Hori-zon	Depth cm	Texture	N NH4+ mg/kg	N NO3- mg/kg	pH H2O	pH CaCl2	CO3 %	EC 1:5 dS/m	ECe dS/m	Org C %	P Avail. mg/kg	P Buff Index	K Avail. mg/kg	S (KCl) mg/kg	Boron mg/kg	Trace Elements mg/kg (DTPA)				Sum cations meq/100g	Exchangeable Cations meq/100g					ESP
																Cu	Fe	Mn	Zn		Ca	Mg	Na	K	Al	
1A11	0–10	cs	2	18	6.0	5.0	0.24	0.06	0.53	0.64	22	12.4	123	2.3	0.30	0.52	42.0	3.02	2.07	2.5	1.61	0.52	0.02	0.25	0.07	0.8
1A12	10–30	ls	2	11	8.5	7.5	0.19	0.05	0.38	0.14	23	10.2	88	2.0	0.25	0.29	40.3	1.21	0.38	1.8	1.06	0.41	0.02	0.21	0.09	1.1
2A1	30–48	ls	<1	2	8.3	6.8	0.20	0.02	0.29	0.13	15	10.0	130	0.6	0.27	0.41	11.0	0.02	0.29	2.8	1.85	0.50	0.02	0.31	0.10	0.7
2A2	48–70	ls	<1	2	8.6	7.5	0.20	0.02	0.33	0.05	5	8.8	83	0.6	0.26	0.54	9.37	0.20	0.27	2.2	1.37	0.39	0.03	0.19	0.17	1.4
2A3	70–74	scl-	<1	3	8.9	7.6	0.25	0.06	17.7	0.06	<2	24.0	314	1.0	2.29	0.44	10.4	0.15	0.21	7.7	2.71	2.98	0.97	0.80	0.20	12.7
2Bt1	74–110	fscl+	<1	3	9.9	8.9	3.74	0.23	44.5	0.07	<2	76.9	492	2.4	10.8	0.82	9.24	0.42	0.44	16.0	6.33	5.74	2.46	1.26	0.17	15.4
2Bt2	110–140	fscl-	<1	4	10.0	8.7	9.31	0.28	62.2	0.09	<2	101.5	427	3.1	15.8	0.75	8.97	0.52	0.32	15.0	6.06	4.69	2.95	1.10	0.16	19.7
3B	140–190	fsl+	<1	4	10.0	8.7	1.08	0.31	65.9	<0.05	<2	55.1	473	2.4	21.4	0.67	9.68	0.19	0.23	12.7	3.38	3.80	4.13	1.21	0.18	32.5
3Bkm	190+	-	calcrete pan																							
Approx. Critical/Ideal Values			-	-	6–8	5.5–7.5	0	<0.7–1.85	<4–8	>1–2	>25–35	100–200	>80–120	>6–8	1–15	>0.2	>2.5	>1–2	>0.5–1.0	>15	75% CEC	20% CEC	<6% CEC	5% CEC	<5% CEC	<6

Note: (1) Sum of Cations approximates the Cation Exchange Capacity (CEC), a measure of the soil's capacity to store and release major nutrient elements.
(2) Exchangeable Sodium Percentage (ESP) is derived by dividing the exchangeable sodium value by the CEC, in this case estimated by the Sum of Cations.

Appendix 4 – figures (Rose-Thomas subcatchment)

Figure 7: Rose-Thomas Subcatchment at Kulde in the South Australian Murray Mallee: showing sites investigated via soil characterisation and drilling (with a 2013 aerial image as background).

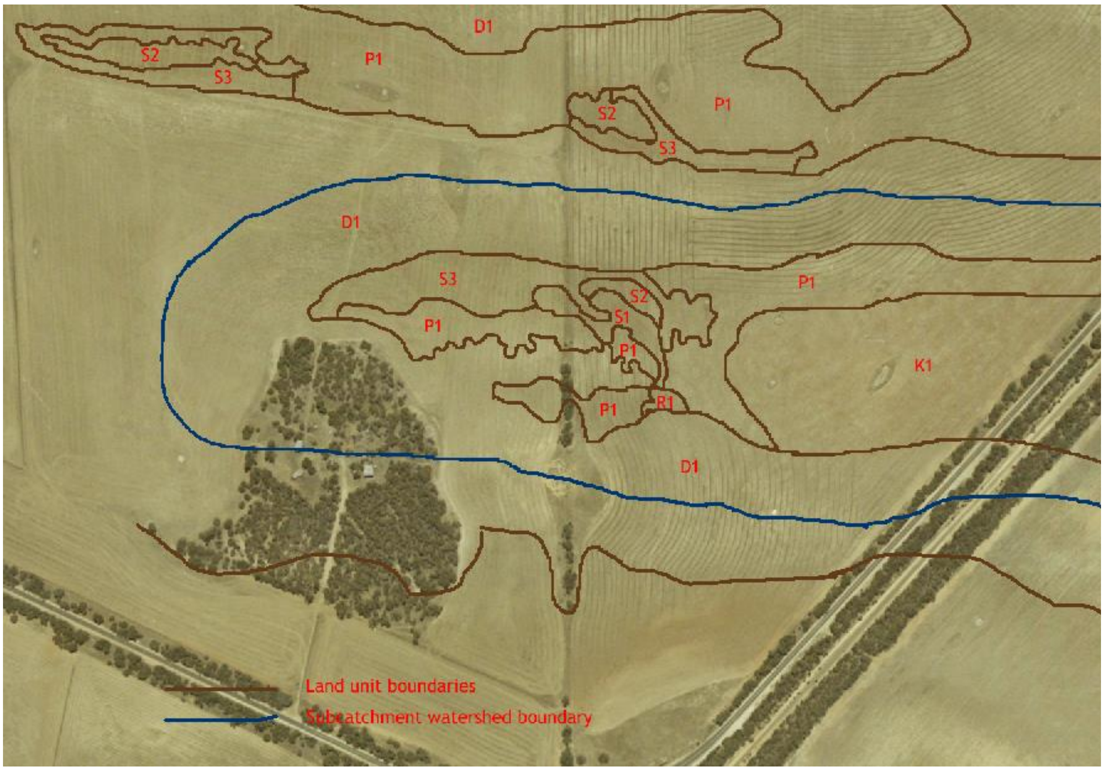


Figure 8: Rose-Thomas Subcatchment at Kulde in the South Australian Murray Mallee: showing land units and subcatchment watershed boundary (with a 2001 aerial photograph as background).

Land unit development is based on stereoscopic Air-Photo-Interpretation (API) of 2001 aerial photographs, an interpretation of 2013 aerial photographs (non-stereo), a very limited number of on-ground investigations, and State Land & Soil Mapping Program descriptions of the area (Soil and Land Program 2007).

D1 = sand dune areas

P1 = lower slopes and plains, often with calcrete at shallow depth

K1 = plains dominated by calcrete at shallow depth

S3 = flats, plains and lower slopes with signs of wetness

S2 = low-lying, secondary seep areas: semi-arable to non-arable

S1 = low-lying, primary seep areas: the most severely affected areas; non-arable (given the current subcatchment water balance); mostly scalded, and eroded by channel erosion in places; surface water observed. This area is affected not only by seepage from adjacent slopes, but also by seepage and overland flow from the larger 'S3' seep to the west.

R1 = low-lying, flow-on area: area seasonally affected by over-flow from the main seep area (S1); semi-arable.

Appendix 5 – drilling reports (Rose-Thomas subcatchment)

Notes: It needs to be noted that drilling is a very uncertain business, and that materials disturbed by the drill head do not necessarily travel up the augur to the land surface at an even rate or, in some cases, do not travel up the rotating augur at all (e.g. heavy clay and wet materials), and that it is often uncertain which depths specific materials are derived from. However, it can be reasonably assumed that materials deposit at the land surface in sequential order. Depths given below, therefore, are indicative only. Colours are also mostly indicative, as materials of different colours are mixed.

Site MDS-R01 – Drilling Report (10/6/2015)

Easting 378 315 Northing 6109 333

Position: dune crest (northern)

Depth (cm)	Material
50	loamy sand / dark yellowish brown / moderately moist / loose / - / -
-	loamy sand / very pale brown / moist / loose / - / -
-	sandy loam / yellowish brown / moist / very weak / - / -
-	light sandy clay loam / brownish yellow / moist / weak / - / -
-	sandy light clay to sandy medium clay / yellowish brown / moist / firm / - / - [some hard carbonate]
-	sandy medium clay / strong brown / moist / firm / slightly calcareous / - [some hard carbonate]

Total drilling depth was 10.5 m. It became uncertain what depths material was derived from in the hole, so depths are not given. There was a likely saturated layer at approximately 6 m. A tight, mottled, heavy clay was encountered at approximately 7 m.

Site MDS-R02 – Drilling Report (10/6/2015)

Easting 378 312 Northing 6109 281

Position: lower dune slope

Depth (cm)	Material
-	loamy sand / dark yellowish brown / moist / loose / - / -
-	loamy sand / very pale brown / moist / loose / - / -
-	sandy clay loam / yellowish brown / moderately moist / weak / - / -
-	sandy light clay / yellowish brown / moist / weak / - / -
-	sandy light clay / yellowish brown / moist / weak / moderately calcareous / -
-	sandy light clay / yellowish brown / wet to moist / very weak / moderately calcareous / -
-	sandy light clay / yellowish brown / wet / loose / moderately calcareous / moderately dispersive
----------------------- discontinuity	---
-	heavy clay / - / - / - / - / -

Total drilling depth was 6 m. It was uncertain what depths material was derived from in the hole, so depths are not given. A tight, mottled, heavy clay was encountered at approximately 6 m and above; and a saturated layer was encountered to an uncertain height above this.

Site MDS-R04 – Drilling Report (11/6/2015)

Easting 378 315 Northing 6109 030

Position: upper dune slope (southern)

Depth (cm)	Material
50	loamy sand / yellowish brown / moist / loose / - / -
100	loamy sand / light yellowish brown / moist / loose / - / -
150	loamy sand / light yellowish brown / moist / loose / - / -
200	loamy sand / very pale brown / moderately moist / loose / - / -
250	loamy sand / yellowish brown / moist / loose / - / -
300	[calcrete layer]
350	heavy sandy loam / yellowish brown / moist / very weak / moderately calcareous / -
400	sandy light clay / yellowish brown / moist / weak / moderately calcareous / moderately dispersive
------------------------ discontinuity	---
450	sandy medium heavy clay / yellowish brown and greenish grey / moderately moist / firm / moderately calcareous / -
550	heavy clay / dark red and greenish grey / moderately moist / strong / moderately calcareous / slightly dispersive

A tight, mottled, heavy clay was encountered at approximately 450 cm.

Site MDS-R05 – Drilling Report (11/6/2015)

Easting 378 418 Northing 6109 177

Position: depression / on edge of seep

Depth (cm)	Material
50	sandy loam (organic rich) / dark brown / wet / loose / slightly calcareous / -
100	sandy loam / very pale brown / wet / loose / moderately calcareous / - [some hard carbonate]
200	sandy clay loam / brownish yellow / wet / loose / moderately calcareous / - [some hard carbonate]
------------------------ discontinuity	---
300	heavy clay / yellowish red, light olive brown and greenish grey / moderately moist / strong / moderately calcareous / -

A tight, mottled, heavy clay was encountered below approximately 200 cm. The soil profile was saturated above this.

Appendix 6 – soil characterisation sites (Rose-Thomas subcatchments)

SAND OVER SANDY LOAM / OVERLYING A BROWN MOTTLED SANDY CLAY LOAM

Medium thickness sandy surface soil on sandy loam subsoil which overlies brown mottled sandy clay loam with fine carbonate at depth.

Subgroup soil	Soil G1 (sand over sandy loam / overlying sandy clay loam material) (Hall et al. 2009)
Landform	Dunefield / Undulating rises
Substrate	Mottled sandy clay loam
Vegetation	Mallee scrub (to approximately 10 m)
Position	Dunecrest
Site	Rose-Thomas subcatchment:

Site No:	MDS-RO1	1:50 000 mapsheet:	6827–4 (Wynarka)
Hundred:	Hooper	Easting:	378 327
Section:	-	Northing:	610 9332
Date:	14/5/2015	Annual rainfall:	Approx. 350 mm

Soil Description

Depth (cm)	**Description**
0–12	Loose, brown loamy sand with single grain structure. Abrupt boundary to:
12–14	Light yellowish brown, bleached, loamy sand with single grain structure. Abrupt boundary to:
14–30	Brownish yellow, light sandy clay loam with heavier-textured, dark yellowish brown lamellae and massive structure. Gradual boundary to:
30–60	Brownish yellow, sandy loam with a few heavier-textured lamellae and massive structure. Gradual boundary to:
60–90	Yellowish brown, sandy loam with massive structure. Abrupt boundary to:
90–110	Slightly calcareous, brownish yellow, strong brown and olive yellow, light sandy clay loam with massive structure. Clear boundary to:
110–165	Highly calcareous, reddish yellow, light sandy clay loam with massive structure.

Australian Soil Classification

Basic, Regolithic, **Brown-Orthic Tenosol** / overlying calcareous, mottled, sandy clay loam; medium, non-gravelly, sandy / loamy, moderate.

Summary of Properties

Drainage Moderately well drained. Soil profile may remain wet for up to a week after heavy or prolonged rainfall.

Fertility The sandy surface soil has very low Cation Exchange Capacity (as estimated by the Sum of Cations), but this increases down the profile with increasing clay content.   In addition, Phosphorus Buffering Index is low throughout the profile, but it does reach satisfactory levels below 110 cm. These analyses indicate a low capacity to store and retain nutrients. There is some leaching of phosphorus to 30 cm, which is indicative of excessive leaching. Organic carbon levels are very low in the topsoil, as are sulfur and boron levels.

pH Slightly acidic surface soil overlies alkaline soil which almost reaches strongly alkaline levels in lower layers.

Rooting depth Roots were observed to 90 cm, with few below 30 cm.

Barriers to root growth

Physical There are no significant physical restraints to root growth and downward water movement to 165 cm, although the soil is relatively hard below 110 cm.

Chemical Chemical restraints to root growth include very low fertility levels below 30 cm, and very high pH below 60 cm.

Waterholding capacity Plant Available Waterholding Capacity is estimated to be approximately 45 mm, which is moderately low. [Workings: (0.12x100)+(0.02x80)+(0.16x150)+(0.30x120x0.1)+(0.30x120x0.1)].

Seedling emergence Good. The sandy surface soil provides good seed–soil contact and no barrier to seedling emergence.

Workability Good.

Erosion potential

Water Low.

Wind Moderate wind erosion potential. Surface protective cover is required to prevent erosion.

Laboratory Data – MDS-R01

Hori-zon	Depth cm	Texture	N NH_4^+ mg/kg	N NO_3^- mg/kg	pH H2O	pH CaCl2	CO3 %	EC 1:5 dS/m	ECe dS/m	Org C %	P Avail. mg/kg	P Buff Index	K Avail. mg/kg	S (KCl) mg/kg	Boron mg/kg	Trace Elements mg/kg (DTPA)				Sum cations meq/100g	Exchangeable Cations meq/100g					ESP
																Cu	Fe	Mn	Zn		Ca	Mg	Na	K	Al	
1A11	0–12	ls	1	9	6.2	5.5	0.29	0.030	0.36	0.63	25	16.4	125	2.2	0.27	1.18	42.7	1.37	1.31	2.34	1.52	0.42	0.02	0.27	0.11	0.85
1A2e	12–14	ls	horizon not sampled owing to insufficient thickness																							
1B21w	14–30	scl-	3	2	8.3	7.5	0.43	0.040	0.38	0.18	5	28.2	189	1.9	0.69	0.63	3.38	0.11	1.04	7.19	5.44	0.90	0.04	0.48	0.33	0.56
1B22w	30–60	sl	1	1	8.9	8.0	0.73	0.047	0.32	0.05	<2	29.9	133	1.3	0.88	0.50	2.67	0.08	0.47	6.88	5.42	0.80	0.03	0.34	0.29	0.44
1B23w	60–90	sl	<1	<1	9.1	8.1	0.82	0.048	0.26	0.07	<2	31.6	114	1.2	1.19	0.43	2.19	0.10	0.47	7.23	5.29	1.32	0.04	0.29	0.29	0.55
2Bt	90–110	scl-	1	<1	9.1	8.2	1.19	0.058	0.27	0.06	<2	41.9	249	1.1	2.12	0.41	4.70	0.64	0.89	9.25	5.74	2.61	0.05	0.64	0.21	0.54
2Btk	110–165	scl-	2	1	9.1	8.3	11.8	0.084	0.38	0.11	<2	115.2	322	1.8	2.50	0.50	2.95	0.66	0.39	10.3	6.77	2.51	0.06	0.82	0.14	0.58
Approx. Critical/Ideal Values			-	-	6–8	5.5–7.5	0	<0.7–1.85	<4–8	>1–2	>25–35	100–200	>80–120	>6–8	1–15	>0.2	>2.5	>1–2	>0.5–1.0	>15	75% CEC	20% CEC	<6% CEC	5% CEC	<5% CEC	<6

Note: (1) Sum of Cations approximates the Cation Exchange Capacity (CEC), a measure of the soil's capacity to store and release major nutrient elements.
(2) Exchangeable Sodium Percentage (ESP) is derived by dividing the exchangeable sodium value by the CEC, in this case estimated by the Sum of Cations.

VERY THICK BLEACHED SAND OVER BROWN MOTTLED CLAY

Very thick sandy topsoil with some bleaching, overlying slightly dispersive brown mottled clay subsoil with fine and hard carbonate.

Subgroup soil	Soil G3 (thick sand over clay) (Hall et al. 2009)
Landform	Dunefield / undulating rises
Substrate	Mottled sandy clay
Vegetation	Mallee scrub (to approximately 10 m)
Position	Lower duneslope (4% slope)
Site	Rose-Thomas subcatchment:

Site No:	MDS-R02	1:50 000 mapsheet:	6827–4 (Wynarka)
Hundred:	Hooper	Easting:	378 328
Section:	-	Northing:	6109 282
Date:	14/5/2015	Annual rainfall:	Approx. 350 mm

Soil Description

Depth (cm)	Description
0–18	Loose, water repellent, brown loamy sand with single grain structure. Abrupt boundary to:
18–60	Very pale brown and brownish yellow, sporadically bleached, sand with single grain structure. Clear boundary to:
60–80	Brownish yellow loamy sand with single grain structure and minor heavier-textured lamellae. Sharp boundary to:
80–98	Yellowish brown, strong brown and olive yellow, light clay with massive structure. Gradual boundary to:
98–120	Yellowish brown, strong brown and olive yellow, slightly dispersive, moderately calcareous, light medium clay with approximately 20% hard carbonate fragments (2–20 mm) and laminae, as well as massive structure. Gradual boundary to:
120–170	Yellowish brown, strong brown and olive yellow, slightly dispersive, fine sandy

medium clay with massive structure.

Australian Soil Classification

Mottled-Sodic, Supracalcic, **Brown Chromosol**; very thick, non-gravelly, sandy / clayey, moderate.

Summary of Properties

Drainage The soil profile is imperfectly drained. Soil may remain wet for several weeks after heavy or prolonged rainfall.

Fertility The very thick sandy topsoil has very low Cation Exchange Capacity (as estimated by the Sum of Cations) – with almost none recorded in the bleached layer from 18–60 cm, and low Phosphorus Buffering Index. This indicates that the topsoil has little capacity to store and retain nutrients. There is evidence of leaching of phosphorus to 80 cm (the base of the topsoil), which is indicative of excessive leaching. Topsoil levels of organic carbon, potassium, sulfur and boron are also low. The capacity of the subsoil to retain nutrients is much greater owing to higher clay content.

pH Acidic surface soil overlies alkaline subsurface layers, which in turn over subsoil that grades from alkaline to strongly alkaline at depth.

Rooting depth Roots were observed to 60 cm, with few below 18 cm.

Barriers to root growth

Physical There are no significant physical constraints to root growth above 98 cm. Below this the soil is slightly dispersive and relatively hard, with high sodicity levels below 120 cm. Also, the subsoil contains a series of discontinuous, thin calcrete lamallae, which present a barrier to root growth.

Chemical General topsoil infertility inhibits root growth. It is also highly probable that seasonal water perched upon the subsoil also restricts root growth to deeper layers.

Waterholding capacity Plant Available Waterholding Capacity is estimated to be approximately 52 mm, which is moderate. [Workings: (0.18x100)+(0.42x80)].

Seedling emergence Good. The sandy surface soil provides good seed–contact and no barrier to seedling emergence. Although the surface soil exhibits water repellence.

Workability Good.

Erosion potential

Water Low.

Wind Moderate wind erosion potential. Surface protective cover is required to prevent erosion.

Laboratory Data – MDS-R02

Hori-zon	Depth cm	Texture	N NH4+ mg/kg	N NO3- mg/kg	pH H2O	pH CaCl2	CO3 %	EC 1:5 dS/m	ECe dS/m	Org C %	P Avail. mg/kg	P Buff Index	K Avail. mg/kg	S (KCl) mg/kg	Boron mg/kg	Trace Elements mg/kg (DTPA)				Sum cations meq/100g	Exchangeable Cations meq/100g					ESP
																Cu	Fe	Mn	Zn		Ca	Mg	Na	K	Al	
A11	0–18	ls	2	9	5.8	4.9	0.30	0.03	0.36	0.35	26	15.1	40	2.0	0.20	0.91	36.8	2.72	0.70	1.9	1.44	0.25	0.02	0.10	0.09	1.05
A21j	18–60	s	3	2	6.7	5.7	0.28	0.02	0.15	0.07	13	8.0	25	0.7	0.12	0.58	16.2	0.66	0.18	<1.0	0.71	0.12	<0.01	0.06	0.10	<1.0
A22	60–80	ls	2	6	7.0	6.5	0.27	0.02	0.33	<0.05	8	7.3	47	1.2	0.19	0.68	7.81	0.60	0.32	1.67	1.12	0.29	0.02	0.12	0.12	1.20
B21t	80–98	lc	5	3	8.8	7.9	1.56	0.07	0.32	0.08	2	62.4	315	1.5	3.49	0.58	4.94	0.59	0.68	12.24	6.56	4.38	0.26	0.81	0.23	2.12
B22tk	98–120	lmc	3	5	9.2	8.3	16.3	0.10	0.52	0.21	<2	143.2	348	2.6	6.66	0.56	6.51	0.61	0.90	16.24	9.30	5.20	0.63	0.89	0.22	3.88
C	120–170	fsmc	2	3	9.6	8.5	3.28	0.19	0.90	0.08	<2	75.4	355	1.5	10.3	0.50	6.36	0.59	0.46	13.97	5.36	5.46	1.99	0.94	0.22	14.2
Approx. Critical/Ideal Values			-	-	6–8	5.5–7.5	0	<0.7–1.85	<4–8	>1–2	>25–35	100–200	>80–120	>6–8	1–15	>0.2	>2.5	>1–2	>0.5–1.0	>15	75% CEC	20% CEC	<6% CEC	5% CEC	<5% CEC	<6

Note: (1) Sum of Cations approximates the Cation Exchange Capacity (CEC), a measure of the soil's capacity to store and release major nutrient elements.
(2) Exchangeable Sodium Percentage (ESP) is derived by dividing the exchangeable sodium value by the CEC, in this case estimated by the Sum of Cations.

WET SANDY LOAM OVER SANDY CLAY LOAM

Thick sandy loam topsoil with abundant hard carbonate in the lower part, over sandy clay loam subsoil with fine and hard carbonate.

Subgroup soil	Soil N3 (wet soil) (Hall et al. 2009)
Landform	Dunefield / Undulating rises
Substrate	Mottled light clay
Vegetation	Mallee scrub
Position	Closed depression
Site	Rose-Thomas subcatchment:

Site No:	MDS-R03	1:50 000 mapsheet:	6827–4 (Wynarka)
Hundred:	Hooper	Easting:	378 340
Section:	-	Northing:	6109 235
Date:	14/5/2015	Annual rainfall:	Approx. 350 mm

Soil Description

Depth (cm)	**Description**
0–15	Soft, dark brown, sandy loam with massive structure. Clear boundary to:
15–28	Slightly calcareous, brown sandy loam with massive structure. Clear boundary to:
28–47	Moderately calcareous, yellowish brown, heavy sandy loam with abundant hard carbonate nodules (20–60 mm). Clear boundary to:
47–62	Moderately calcareous, reddish yellow sandy clay loam with massive structure and abundant hard carbonate fragments (2–60 mm). Clear boundary to:
62–95	Highly calcareous, strong brown, yellowish brown and dark red, clay loam. Clear boundary to:
95–115	Highly calcareous, reddish yellow, pink and yellowish red, light clay with 20–50% hard carbonate fragments (6–60 mm).

Australian Soil Classification

Natric, Calcarosolic, **Oxyaquic Hydrosol**; thick, non-gravelly, loamy / clay loamy, shallow.

Summary of Properties

Drainage Poorly to very poorly drained. Soil may remain wet most of the year.

Fertility The position of this soil in the landscape, the fact the soil is wet, and that subcatchment flows terminate in this area, means that numerous substances accumulate within the profile. Consequently, sulfur, potassium and boron levels are high to adequate. However, toxic substances also accumulate here (see below). Interestingly, organic carbon levels are low, which indicates that this area has not been wet over the long term (the farmer Peter Rose indicates that excessive wetness was first noticed in this area in 2005).

pH Given that this area is part of a closed depression where subcatchment waters accumulate – bringing numerous substances with them, including alkaline-inducing ones – pH levels are strongly alkaline throughout the profile.

Rooting depth Roots were observed to 47 cm.

Barriers to root growth

Physical All layers are dispersive and highly sodic, however, moist soil conditions would indicate that there are no significant physical barriers to root growth.

Chemical Chemical barriers to root growth are significant. Strong pH levels restrict roots, as do raised salinity levels (especially in the subsurface layer from 15–28 cm) and high sodium levels.

Waterholding capacity Plant Available Waterholding Capacity (PAWC) is estimated to be approximately 50 mm, which is moderate. However, excessive wetness renders this area unsuitable for crop production – so PAWC could be considered 0 mm. [Workings: (0.15x120)+(0.13x120)+(0.19x120x0.7)].

Seedling emergence Satisfactory to poor. The sandy loam surface soil provides no barrier to seedling emergence. However, excessive wetness and chemical toxicities may limit germination and emergence of crop species.

Workability Poor. Excessive wetness leads to reduced trafficability.

Erosion potential

Water Moderately low. Erosion can occur in this low-lying area via channel flow.

Wind Moderately low. Bare scalds can be affected by wind erosion, with areas deflated in the process.

Laboratory Data – MDS-R03

Hori-zon	Depth cm	Texture	N NH_4^+ mg/kg	N NO_3^- mg/kg	pH H2O	pH CaCl2	CO3 %	EC 1:5 dS/m	ECe dS/m	Org C %	P Avail. mg/kg	P Buff Index	K Avail. mg/kg	S (KCl) mg/kg	Boron mg/kg	Trace Elements mg/kg (DTPA)				Sum cations meq/100g	Exchangeable Cations meq/100g					ESP
																Cu	Fe	Mn	Zn		Ca	Mg	Na	K	Al	
A11	0–15	sl	<1	4	9.9	8.7	3.44	0.269	3.83	0.36	5	64.2	266	35.0	9.42	0.58	20.2	3.46	0.32	12.06	5.74	2.11	3.40	0.68	0.13	28.19
A12	15–28	sl+	<1	9	9.8	8.9	0.66	0.614	7.31	0.55	12	26.4	165	122.4	7.58	0.74	41.9	2.28	2.25	9.74	4.29	1.22	3.75	0.42	0.06	38.50
A3k	28–47	sl+	1	7	9.8	8.5	36.3	0.229	2.47	0.31	5	138	316	43.0	8.24	0.73	13.9	4.15	0.66	14.89	7.20	3.35	3.45	0.81	0.08	23.17
B21wk	47–62	scl	<1	6	9.8	8.6	53.7	0.315	2.50	0.20	3	165	276	48.0	6.79	0.81	9.23	2.69	0.37	14.67	7.20	3.43	3.26	0.71	0.07	22.22
B22wk	62–95	cl	2	6	9.9	8.5	37.3	0.273	1.70	0.14	<2	141	472	43.7	13.67	0.78	9.40	2.45	0.47	17.61	5.74	5.91	4.66	1.21	0.09	26.46
B3k	95–115	lc	1	5	9.9	8.3	47.4	0.340	1.30	0.11	2	150	400	36.6	13.71	0.77	8.72	1.44	0.42	15.43	5.74	4.20	4.41	1.03	0.05	28.58
Approx. Critical/Ideal Values			-	-	6–8	5.5–7.5	0	<0.7–1.85	<4–8	>1–2	>25–35	100–200	>80–120	>6–8	1–15	>0.2	>2.5	>1–2	>0.5–1.0	>15	75% CEC	20% CEC	<6% CEC	5% CEC	<5% CEC	<6

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