GATUM, DUNDAS TABLELAND, VICTORIA

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INTRODUCTION

Gatum, on the eastern Dundas Tableland in western Victoria, lies approximately 300 km west of Melbourne at 200–300 m above sea level. Seasonal waterlogging, dryland salinity and erosion are major constraints to agricultural production in the Gatum area. To understand the soil–landscape processes causing contemporary land degradation, knowledge of hydrology and its relationship to soil–regolith macro-morphological features (e.g. mottling patterns) are essential. Unfortunately soil–regolith macro-morphological features can reflect both past as well as present hydrology in ancient landscapes such as on the Dundas Tablelands. The construction of appropriate soil-water-landscape 3D models, however, permits distinction between past (relict) and current hydro-pedological processes. The following summary is based on a hydro-pedology/regolith study at Gatum conducted by Brouwer and Fitzpatrick (1998; 2000; 2002a,b) and Brouwer and Anderson (2000).

PHYSICAL SETTING

Geology and Geomorphology

The Dundas Tableland is a flat, dissected surface with a deeply weathered regolith (Figure 1). Valley depths are of the order of 20 m with maximum slopes between 6-8°. Ongoing weathering, possibly since the Permian, has produced deep weathering profiles, with ferricretes and ferruginous gravelly soils overlying mottled and pallid zones that extend to tens of metres depth. Since emplacement, the area has been tectonically stable except for up-doming in the order of 240 m (Joyce, 1991). At Gatum the bedrock geology consists of ignimbrites of the Rocklands Volcanic Group that erupted onto the land surface at around 410 Ma (Early Devonian) (Simpson, 1997, 1998). Depth to fresh basement rock at Gatum varies from more than 20 m to approximately 12 m and fresh basement rock is at a lower absolute level under the drainage lines than under the crests (Lewis, 1985). Above the fresh ignimbrites there is a zone of weathered rock, which, although of low hydraulic conductivity, acts as the main aquifer. Because of its low hydraulic conductivity, groundwater hydraulic heads occur on top of the ignimbrites, in such a way that groundwater catchment boundaries generally coincide with surface catchment boundaries and the groundwater regime is of the local discharge type. Consequently, local changes in recharge will have an effect on local groundwater levels and salinity, and will not be swamped by inflow of groundwater from outside the catchment.

Climate, vegetation and hydrology

The present climate at Gatum is Mediterranean. Annual rainfall averages approximately 630 mm, mostly falling in winter, May to October, when there are also occasional frosts. Average annual

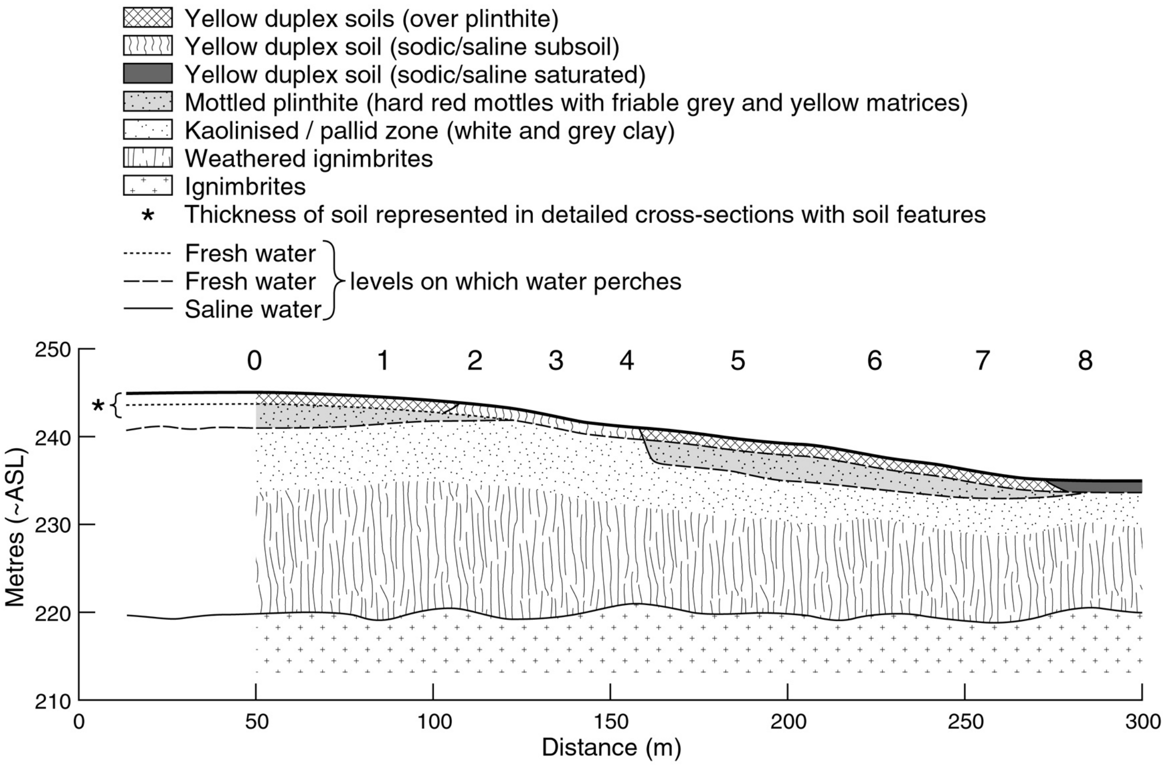

Figure 1. Geological-pedological cross-section at the Gatum study site on the Dundas Tableland, western Victoria. Numbers indicate soil profile pit positions and piezometer installations. (from Brouwer and Fitzpatrick, 2002a)

pan evaporation is approximately 1400 mm. The vegetative cover before clearing for agriculture and for timber for railway sleepers was a Red Gum (*Eucalyptus camaldulensis*) woodland. Local salinity problems already existed then (see Nathan 1999; and Dahlhaus *et al*., 2000). The Red Gum woodland was subsequently replaced by pasture, at first using mostly annual pasture species, in the last 15-20 years also perennial species (mainly *Phalaris*). As a result of tree-clearing, groundwater recharge has increased and the groundwater table has risen at least 10 m into the pallid zone containing the cyclic salts, resulting in widespread salinity problems, mostly in lower parts of the landscape (Lewis, 1985; Brouwer and van de Graaff, 1988).

Soils

The most recent, and still on-going, period of soil development has resulted in mainly sodic yellow and grey duplex and gradational soils being formed in the deeply weathered ignimbrite regolith, saline acid sulfate soils in the valley bottoms, and podzols in the windblown sand dunes. As a consequence of the multi-factorial genesis of these soils, the present landscape is pedologically complex (e.g. Gibbons and Downes, 1964; Dahlhaus *et al*., 1999; Brouwer and Fitzpatrick, 2002a; M. Paine 2003 – this volume; J. Fawcett and co-workers - in press). According to the Soil Classification of Northcote (1979), the soils on the broad crests at Gatum are yellow gradational soils, while the remainder of the toposequence consists of hard, pedal, mottled yellow duplex soils; the bleached A2 (or E) horizons are most conspicuous part way along and at the bottom of the slope (Figure 1). Using the Australian Soil Classification of Isbell (1996), there are Yellow Dermosols on the broad crest and mostly Reticulate Brown Chromosols along the slope, with local ironstone gravel concentrations. Hydrosols with salt accumulations occur part way along the slope and also on the valley bottom. Using Soil Taxonomy (Soil Survey Staff 1999), the toposequence is described as consisting of Typic Plinthoxeralfs on the broad crest and most of the slope, with Aquic Natrixeralfs occurring partway along the slope, and Typic Natraqualfs at the bottom of the slope. The occurrence of the Hydrosols or Natrixeralfs part way along the mid-slope is related to the outcropping there of clayey pallid zone material.

SOIL–REGOLITH CHARACTERISATION

Colour photographs of three typical profiles (G-0, G5 and G8) at different parts down the landscape slope or toposequence at Gatum are shown in Figure 2. Key soil morphological and physico-chemical features of profiles G-0 to G-8 are summarised in Table 1. To understand the lateral linkages and relationships between soil profile features down landscape slopes, we used the systematic structural approach to characterise soil-regolith features at different parts down toposequences (Boulet *et al*., 1982; Fritsch *et al*., 1992; Fritsch and Fitzpatrick, 1994; Brouwer and Fitzpatrick 2000, 2002a). Briefly, we identified and described in the field, by depth interval, in all the profiles along the toposequence, all relevant soil properties, including texture, coarse fragments, structure, matrix colour and mottling. In the office were added chemical and mineralogical properties. Toposequence cross-sections were then drawn that identified uniform layers that contain individual, or sometimes several soil-regolith properties. Subsequently boundaries were drawn around these layers. Each cross-section mapping unit or layer delineated is called a soil feature. A soil feature thus represents a limited range of one or more soil-regolith properties. Maps of different types of soil features were then compared. The key soil-regolith features that help recognise and explain soil formation and interactions between different parts of the toposequence were grouped into the same soil systems using concordant relationships: i.e. where there is a concordant relationship spatial distributions and boundaries mostly coincide, and hydrological processes, chemical processes and/or parent material will be the same. Soil features were separated into different soil systems using discordant relationships; in such cases spatial distributions show no or only partial overlap, boundaries do not coincide but touch or cut cross each other, and processes and/or parent material will be different (Figure 2). Each soil layer displayed in the cross-section or toposequence was then linked to past or present soil and hydrological processes. In Figure 2 speckled shading for instance represents present soil sodicity; red arrows indicate present saltwater flow; and blue arrows indicate present freshwater flow.

REGOLITH EVOLUTION

The Dundas Tableland has undergone a number of weathering, erosion and deposition cycles and possibly faulting during tectonic uplift. This has resulted in the formation of various "palaeo-horizons" (e.g. plinthite and pallid zone) and paleo-features (e.g. mottles, glaebules and cutans) occurring at or close to the surface in different parts of the landscape, and acting as parent material for soil development. We summarise our results on the occurrence and transformation of various soil-regolith features below.

Mottling patterns in plinthite

Using the terminology of Soil Taxonomy (Soil Survey Staff, 1999), plinthite (Greek *plinthos* = brick) or laterite refers to an iron-rich, humus-poor material produced by an accretion of iron oxide in a platy, polygonal or reticulate pattern (Figure 2 – Profile I). Plinthite may be crushed by hand or cut with a spade but, on drying, hardens irreversibly to petroplinthite. Mottle colour varies greatly both within and between soil profiles (Figure 2B; Table 1). The Fe oxides are strong pigmenting agents and are largely responsible for defining the colour patterns in the plinthite. Soil colours caused by Fe oxides and their spatial distribution have been used as a basic tool for assessing soil and landscape hydrology.

Plinthite in soils on the crest (G0 to G1) has red (2.5YR) mottles with no rinds at depth (>1m). With decreasing depth (0.8-1.0 m, i.e. well below the top of yellow Bt1 horizon) the red mottles become progressively yellower (5YR) at their edges (i.e. red with thin brown rinds) to eventually have strong brown colour

Table 1. Summary of soil features, hydro-pedological/regolith weathering processes at Gatum.

Location on topo-sequence	Topsoil features A & E horizons (<0.3 m)	Subsoil features B & C horizons (>0.3 m)	Soil-regolith processes: hydrological and weathering
Crest, upper slope (G0 to G2)	**Matrix Colour**: dark brown over brown **Glaebules**: magnetic and non-magnetic	**Matrix Colour**: brownish yellow turning to grey and light brown at depth, with strong brown and red mottles respectively **Glaebules**: mostly non-magnetic **Roots**: Relict tree root holes **Platy** at depth **Cutans** reddish brown and black	**Topsoil:** infrequent periodic saturation or ponding of fresh perched water. **Subsoil:** frequent periodic saturation or ponding of infiltrating rainwater on the top of the unaltered part of the relict mottled zone where platy structure is still coarse ("plinthite on crest"), and above which there has been at least a partial change in non-matrix soil colours: from black to reddish brown in the cutans, and from red to reddish yellow or strong brown in the mottles. Some salt influx (via cyclic salt accession by wind) as well as leaching.
Waning mid-slope (G3 to G4)	**Matrix Colour**: dark grey brown over grey brown **Glaebules**: trace, magnetic	**Matrix Colour:** white and brownish yellow **Glaebules**: none **Roots**: Occasional relict tree root hole **Prismatic structure** at depth **Cutans** dark brown	**Topsoil:** frequent periodic saturation, fresh perched water, mostly lateral flow but some downward vertical flow. **Subsoil:** frequent periodic saturation caused by water perching on relict "pallid zone" subsoil clay and not by deeper groundwater. Leaching of salt causes clay dispersal and development of a restricting clay layer.
Straight mid-slope (G5)	**Matrix Colour**: dark grey brown over brown **Glaebules**: none	**Matrix Colour:** brownish yellow turning to grey and light brown at depth, with red and reddish yellow mottles respectively **Glaebules**: mostly non-magnetic **Platy** close to top of B **Cutans** black	**Topsoil:** infrequent periodic saturation, fresh perched water, mostly lateral flow but some downward vertical flow. **Subsoil:** frequent periodic saturation caused by perched water on unaltered part of the relict mottled zone quite close to the top of the B ("plinthite on midslope"), and possibly also by (perched) water coming in laterally and/or from below. Some conversion of red mottles to strong brown at top of B and possibly to reddish yellow in lower part of B. Black cutans unchanged. Clay illuviation and weak redox conditions leading to partial dissolution of hematite and primary goethite and precipitation of light brown mottles (secondary goethite).
Waning lower slope (G6-7)	**Matrix Colour**: dark grey brown over grey brown **Glaebules**: trace only, magnetic and non-magnetic, in G7	**Matrix Colour:** brownish yellow turning to grey and light brown at depth, with red and reddish yellow mottles respectively **Glaebules**: non-magnetic **Platy** close to top of B. **Cutans** black turning to pale at depth	**Topsoil:** infrequent periodic saturation. **Subsoil:** frequent periodic saturation caused by perched water on unaltered part of the relict mottled zone ("plinthite on midslope") and frequent periodic saturation in lower parts of the subsoil caused by high saline groundwater. Possibly conversion of red mottles to reddish yellow in lower parts of B horizons. Also, black cutans changed to pale in lower parts of B horizons by redox processes in shallow saline groundwater tables.
Flat (G8)	**Matrix Colour**: dark grey brown over pale brownish grey. **Glaebules**: non-magnetic.	**Matrix Colour:** pale brown and brown and saline clays with many grey/yellow mottles **Glaebules**: magnetic and non-magnetic in top of B. **Cutans** dark brown in mi-d and lower B	**Topsoil:** frequent saturation. **Subsoil:** very frequent to permanent saturation caused by high saline groundwater, fresh lateral flow and some fresh perched water. Alluvial/colluvial deposits. Red-brown coloured streaks of ferrihydrite on surfaces of peds and cracks. Dissolution of yellow coloured mottles containing goethite.

(7.5YR and even 10YR) near the top of the B-horizon (Figures 2B and 2C, and Table 1). Goethite is the pigmenting agent in the yellowish (10YR - 7.5YR) mottles near the surface, whereas a mixture of hematite and goethite is present in the reddish (2.5 YR and 5YR) mottles occurring at depth on the broad crest and upper slope ("plinthite on crest", no ground water table present – Figure 2). On the midslope ('plinthite on slope') strong brown mottles are only present in the top 0.15 m of the B-horizon of profile G-5. Redox processes are less pronounced in the plinthite on the mid-slope than in the plinthite on the crest. This is most likely because soils on the mid-slope have greater lateral interflow and surface run-off than soils on the crest with deeper infiltration of water. The plinthite on the slope also has a different structure to that on the crest and may be of a different origin (different ignimbrite flow). Yellowish red mottles occur at depth in profiles G-5 to G-7 possibly because of the presence of a perched groundwater table at depth (see Brouwer and Fitzpatrick 2002a,b). The perched groundwater table fills the soil pores with water and dissolved oxygen in the water is depleted by microbial activity. Redox sensitive Fe oxides (hematite) occurring along the pore walls are then reduced/dissolved, and soluble Fe(II) diffuses into the soil matrix where it is ultimately re-oxidized by trapped O_2. With repeated cycles of saturation-reduction and drying-oxidation, patterns of Fe-oxide depletion and accumulation develop. The

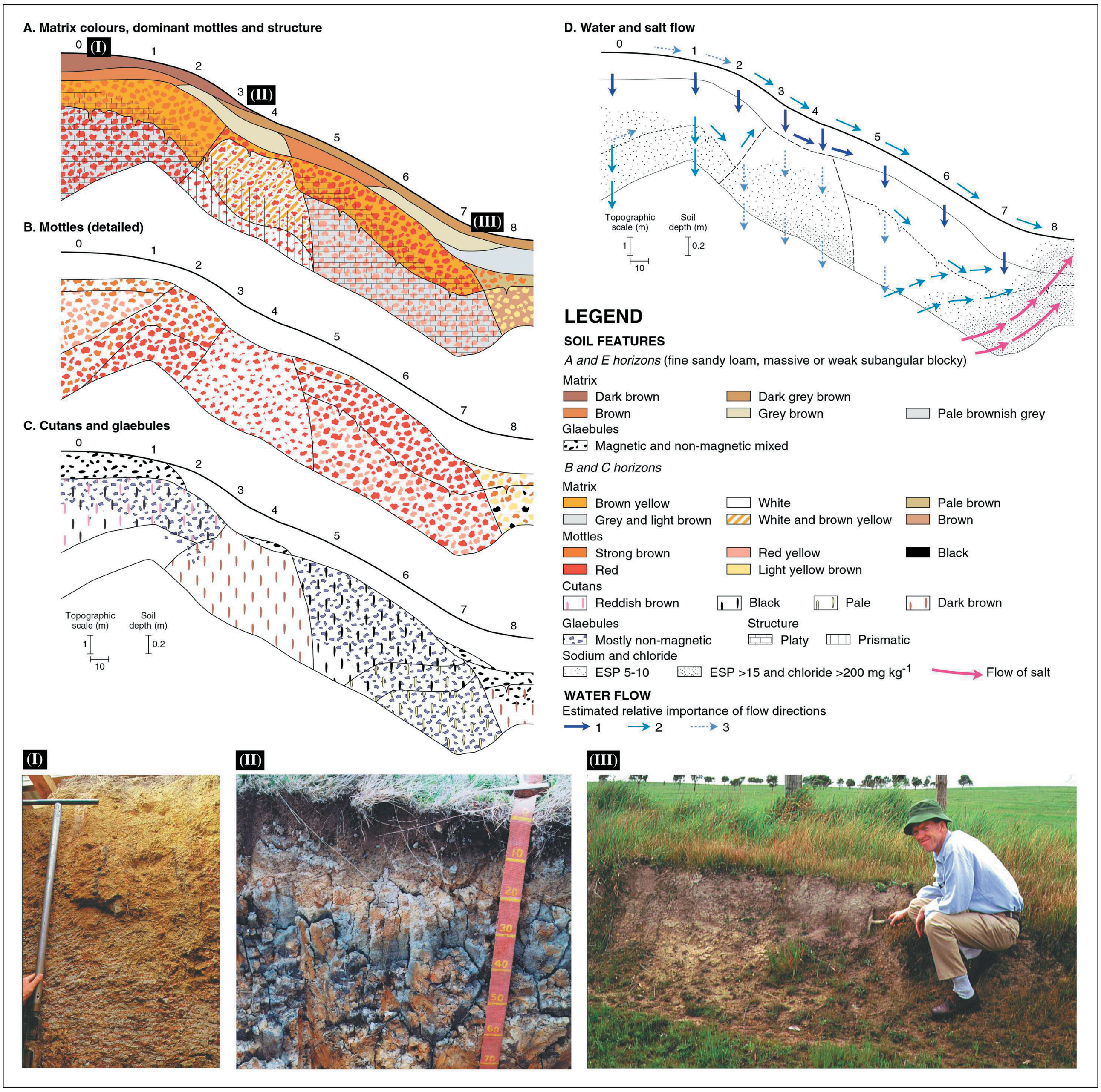

Figure 2. Soil features at Gatum. Numbers indicate piezometer installations and soil profile pit positions. (from Brouwer and Fitzpatrick, 2000; 2002a, b)

upper limit of the reddish yellow mottles in profiles G-5 to G-7 is largely parallel to the soil surface rather than parallel to a presumed perched groundwater table. It is therefore also possible that the yellowish red mottles in the lower part of the B-horizons of G-5 to G-7 were never red to start with.

Light yellow brown and black mottles are found throughout the B-horizon of G-8, indicating a long duration of saturation (Vepraskas *et al*., 1994). Red mottles are completely absent from G-8. This and other differences point to the G8 profile not having undergone the humid tropical weathering (lateritisation) that the other profiles (G0 to G 7) underwent.

Soil structure patterns

Wherever soil structure of the B- and C-horizons is not indicated as being platy or prismatic, it is angular blocky (Figure 2A and Table 1). In plinthite, the original platy structure is still present in the lower parts of the B- and in the C-horizons. The transformation from platy to angular blocky structure has not progressed as deeply as the transformation from a grey soil matrix with red mottles to a yellowish brown matrix with strong brown mottles (cf. profiles G-0 to G-2, and G-5 to G-7, in Figure 2A). The transformation of the soil structure therefore appears to take longer than the transformation of iron minerals. The change in soil structure is most likely caused by changes in hydrology, with extreme wetting and drying causing shrink-swell to occur and the transformation of the platy structures. The 'onion peel'-type patterns in the mottled zone on the crest (Brouwer and Van de Graaff 1988) indicates that the original platy structure may be traced back to the geologic structure of the pyroclastic parent material

Glaebule distribution

More than 2% ironstone glaebules are found in the top of the plinthite-containing subsoil on the crest (yellowish brown B-horizon of G-0 to G-2), and virtually throughout the plinthite on the mid-slope (G-5 to G-7) (Figure 2C). These glaebules appear to have been formed in situ, because they have an angular shape. In the pallid subsoil layer at G-3 and G-4 no glaebules are found because no iron is present for glaebules to be formed from. In the alluvial/colluvial profile at G-8, the glaebules in the subsoil are derived from upslope because they are more rounded, suggesting transportation, and because glaebules are absent from the lower parts of the B-horizon of G-8.

Pallid zone patterns

Deep weathering of ignimbrites has resulted in the accumulation of layer silicates, which grade upwards to form a pallid zone with white matrix and relatively few mottles (Figure 1). In the upper part of the pallid zone, weathering has led to white coloured clay with sporadic remnant quartz crystals from the original parent material (profiles G-3 and G-4 in Table 1 and Figure 2). It is in the pallid zone that cyclic salts have accumulated over thousands of years, now forming a salt store of the order of 500 tonnes per ha (e.g. Brouwer and Van de Graaff 1988).

In these pallid zone subsoil horizons, white and light grey colours persist where the prismatic structure has already been converted to angular blocky. Arguably, this is because there is less iron present in the pallid material, causing a change in colour to yellowish brown to take longer.

Cutan patterns

Cutans are prominent in many of the profiles, indicating illuviation of clay and organic carbon from overlying horizons in the past and present. The cutans are particularly abundant in the pallid zone material, where they are dark brown and cover all the ped faces. They are somewhat more pronounced every 0.3-0.6 m laterally, pointing to larger units within the prismatic structure of the pallid zone (cf. Lewis 1985). Brown cutans also occur in profile G-8. Very dark (black) cutans are found throughout the B-horizon of profile G-5 and in the upper parts of the B-horizon of profiles G-6 and G-7 (plinthite on mid-slope). In the plinthite on the crest, cutans are less clear but still quite noticeable and both black (2.5YR) and reddish brown (5YR) in colour. The reddish brown cutans are probably conversions of black cutans. This conversion could be related to the general yellowing of the soil from above, showing the same shift in hue from reddish to yellowish as for the converted mottles. As with the mottles, the changes in colour of the cutans indicate that the cutans were not formed under present hydrological conditions, only changed by them. In profiles G-5, 6 and 7 no reddish brown cutans were observed.

The pale (light grey) cutans in the lower parts of profiles G-6 and G-7 appear to be conversions of the black cutans found higher up in the same profiles. The pale cutans, too, show a slight yellowing (from 5YR to 7.5 YR), in addition to a pronounced increase in value relative to the black cutans. This zone of colour change in the cutans borders on the area of very wet conditions in profile G-8, and has an upper boundary, which is not parallel to the soil surface (Figure 2C). The pale colour of cutans in lower parts of profile G-6 and throughout the B-horizon of profile G-7 is most likely caused by present, seasonally saturated, and possibly saline, conditions. These conditions are related to water coming in laterally and/or up from below into profiles G-6 and G-7.

HYDRO-PEDOLOGICAL/REGOLITH PROCESSES AND LAND USE IMPLICATIONS

Contrary to a commonly held view, seasonal waterlogging in near-surface soil horizons is not always caused by restricting clay layers occurring at the top of B-horizons (first restricting layer indicated in Figure 3). Rather, ponding of infiltrating rainwater in profiles G-0, 1 and 2 (plinthite on the crest) occurs on the top of the coarse platy mottled plinthite at a depth between 0.6 and 1.0 m. It is, by and large, equivalent to the depth to which partial changes of non-matrix colours have progressed: cutans have partially changed from black to reddish brown, and mottles have changed from the original red to more yellow or brown (Munsell colour changes from 2.5YR to 5YR and 7.5YR, and even 10YR) (Figure 2B). The fact that ponding occurs on a layer well into the B horizon, rather than at the top of the B, improves the potential for subsurface drainage of the broad crests.

In profiles G-5, 6 and 7 (plinthite on midslope/footslope) seasonal waterlogging also occurs above the plinthite layer at the top of the B-horizon (possibly at approximately 40 cm depth). The plinthite in G-5, 6 and 7 appears to have a different parent material to G0 – G2.

Tree root holes and interpedal cracks in the restricting plinthite layers are major preferential pathways for water to flow downward. Tree root holes were found in all profile pits and in all parts of the landscape. Most of the infiltrating rain water has to move laterally over the less permeable part of the B horizon to a roothole, before being able to move downward again. Lateral movement is obviously easier the greater the horizontal conductivity of the overlying horizons. This means that, in situations as at Gatum, deep-ripping to reduce surface soil saturation is likely to lead to increased deep infiltration, rising deep water tables, and increased salinity problems (Brouwer and Van de Gaaff 1988). Sowing perennial pastures to increase evapo-transpiration and thereby reduce deep infiltration may also be counterproductive: the perennial pastures may reduce run-off even more than they increase evapotranspiration, thereby causing a net increase in deep infiltration (Brouwer 1989).

Seasonal waterlogging was exacerbated in the mid-slope profiles (G-3 and G-4) developed from pallid zone material (second restricting layer indicated in Figure 3). On this mid-slope where the pallid zone material comes to the surface, the first and second perched watertables merge and cause hillside seepages to occur. Such hillside seeps can occur where surface topography gives no indication of their likely presence. The effects of such hillside

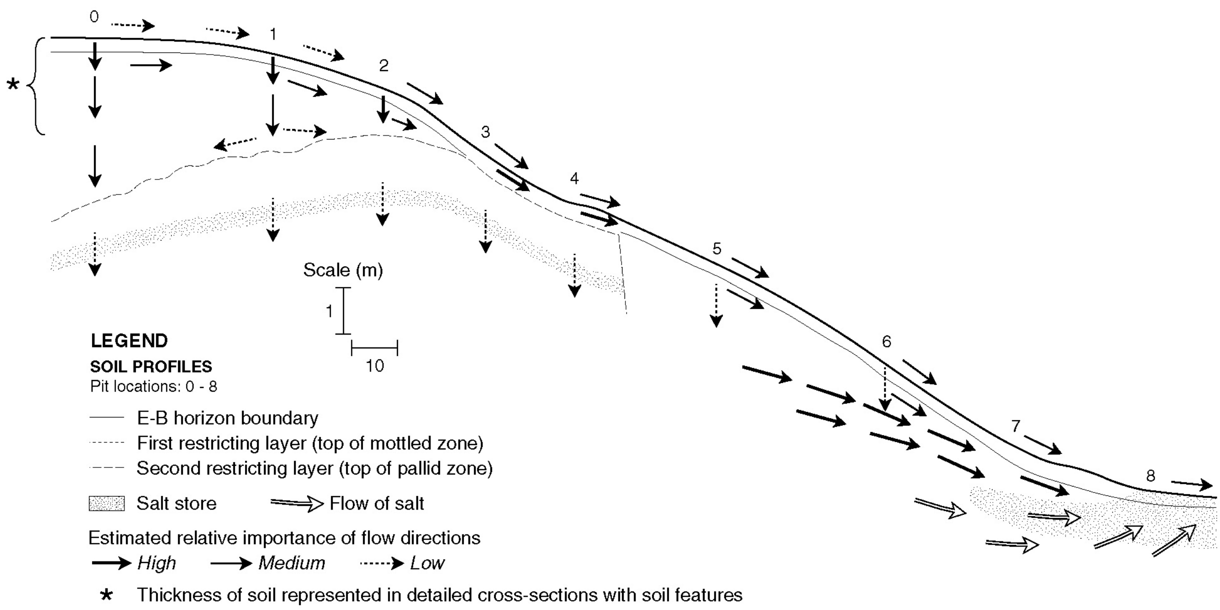

Figure 3. Hydrological cross-section of the toposequence at Gatum. The numbers indicate piezometer and profile pit positions and piezometer installations. (from Brouwer and Fitzpatrick, 2002b)

seeps may be reduced by installing a cut-off drain or planting trees just upslope of them.

The permanent saline ground watertable rests on the fresh bedrock. Fresh bedrock occurs at a depth of >20 m under the broad crests, but much closer to the surface in the lower parts of the landscape (Figures 1 and 3). It is there that salinity problems are most severe. These salinity problems are exacerbated where there is also lateral inflow of fresh water from one or both of the perched fresh water tables (e.g. profile G-8 in Figures 1 and 3). But even under the broad crests the saline water table can rise to within 4 m of the surface, causing the occurrence of saline seeps relatively high in the landscape (though not in the toposequence studied).

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