The Role of Debris-Flow Deposits in the Development of Dryland Salinity in the Yass River Catchment, New South Wales, Australia

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Abstract: Aeolian deposits known as parna are remobilised as debris flows that occur widely across the Yass River catchment in the state of New South Wales, Australia. The deposits consist of smectite-rich clays that contain varying salt loads and have a grain size that ranges from very fine to fine silt. During the Pleistocene Epoch, debris-flow mechanisms mixed the aeolian material with locally derived windblown sand and fragments of bedrock. Several episodes of debris-flow emplacement are identified, and these may correlate with climatic variations during the Pleistocene Epoch. Multiple episodes of debris-flow deposition and removal probably occurred during this time. Conditions in the catchment prior to clearing represented a meta-stable phase in the erosion of the more recent debris-flow deposits. Destabilisation could have resulted from the onset of a drier climate or by the clearing of deep-rooted vegetation.

According to the conceptual model proposed, the debris-flow deposits have a significant impact on the local groundwater system. Dispersion of the clay and silt in the debris flows and the subsequent release of entrained salt is a major source of salts entering the drainage system. Stabilisation of the debris-flow deposits can only be achieved by allowing the deep groundwater to discharge without contact with these deposits.

Résumé: Les dépôts éoliens connus sous le nom de parna sont remobilisés par des transports solides qui se produisent fréquemment dans le bassin de la rivière Yass, dans l'état des Nouvelles Galles du Sud en Australie. Ces dépôts sont constitués d'argiles riches en smectites contenant des charges variables en sels et ayant une granulométrie de silts très fins à fins. Au cours du Pléistocène, les mécanismes de transports solides se sont produits en même temps que des transports éoliens de sable et de fragments de roches. Plusieurs épisodes de mise en place de transports solides ont été identifiés; ils ont pu être corrélés avec des variations climatiques au cours du Pléistocène. A cette époque, de nombreux épisodes de dépôt et de mobilisation des transports solides sont intervenus. Les conditions régnant dans le bassin avant le lessivage correspondent à une situation métastable dans l'érosion des dépôts de transports solides les plus récents. Cette déstabilisation a pu résulter de la mise en place d'un climat plus sec ou de la disparition des plantes à enracinement profond.

D'après le modèle conceptuel proposé, les dépôts de transports solides ont un impact certain sur les écoulements souterrains à l'échelle locale. La dispersion de l'argile et du silt dans les transports solides et le relargage consécutif du sel entraîné sont la source essentielle de sels entrant dans le système de drainage. La stabilisation des dépôts de transports solides ne peut intervenir que si les eaux souterraines profondes s'écoulent sans contact avec ces dépôts.

Resumen: Los depósitos eólicos conocidos como parna son removilizados como coladas de derrubios ("debris flows") a lo largo del área de captación del Río Yass, en el Estado de Nueva Gales del Sur, Australia. Los depósitos consisten en arcillas ricas en esmectita, con contenidos en sales variables y tamaños de grano que van de limo fino a muy fino. Durante el Pleistoceno, las coladas de derrubios mezclaron el material eólico con arena y fragmentos de roca locales. Se han identificado diversos episodios de coladas de este tipo, que podrían correlacionarse con variaciones climáticas durante el Pleistoceno. Probablemente, durante esta época tuvieron lugar múltiples episodios de deposición y removilización de coladas de derrubios. Las condiciones en el área de captación previas al desbroce del terreno representaban una fase metaestable en la erosión de los depósitos procedentes de coladas de derrubios más recientes. La desestabilización pudo ser el resultado del comienzo de una época más seca o, simplemente, de la desaparición de la vegetación.

Según el modelo conceptual propuesto, los depósitos procedentes de coladas de derrubios tienen una gran importancia en el sistema de flujo subterráneo local. La dispersión de arcillas y limos en las coladas, con la subsiguiente liberación de sales, constituye una de las mayores fuentes de entrada de sales al sistema de drenaje. La estabilización

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de los depósitos de las coladas sólo puede conseguirse permitiendo que las aguas subterráneas más profundas descargen sin llegar a entrar en contacto con estos depósitos.

Introduction

Salts build up in a catchment when their supply exceeds their rate of removal. Salts can be supplied by chemical weathering of rocks; as cyclic salt in rainfall; and as aeolian accessions. Salt is removed from the catchment principally as runoff. Salt removal is, therefore, very sensitive to changes in rainfall patterns. The removal of salt from the Murray-Darling Basin (MDB), Australia, of which the Yass River is an upland tributary, is inhibited by two factors. The first is that tributaries of the system rise in the eastern uplands, where high rainfall occurs, and they flow westward into arid areas, where potential evaporation exceeds rainfall by a factor of more than three. A tendency exists for salts to be relocated from the eastern part to the western part of the catchment, and then to be redeposited. In drought years, the River Murray does not discharge to the ocean, preventing flushing from the basin.

The second factor is that the groundwater systems of the MDB are internally draining. Natural groundwater discharge complexes, or boinkas (Macumber, 1991), occur in the western part of the MDB, and these have become widespread during the past 0.5 million years (Brown, 1989). The River Murray acts as a drain to many of the saline aquifers in the MDB, particularly downstream of Mildura. These two factors combine to produce a natural tendency toward salinity throughout the basin.

At regional or basin scales, salt is stored in the MDB as 1) playa deposits; 2) dissolved salts in groundwater storage; 3) salt derived from the weathering of rocks. 4) cyclic salts stored in soil profiles beneath forest; and 5) salt associated with silty clay deposits, which have been redistributed throughout the catchment by aeolian activity during the Quaternary Period. The sources of salt associated with dryland salinity are discussed widely in the literature (Butler, 1956; van Dijk, 1959, 1969; Gunn, 1985; Gunn and Richardson, 1979; Walker et al., 1988; Salama et al., 1993; Ghassemi et al., 1995).

The Australian Water Resources Council (AWRC, 1976) has defined levels of salinity for use in the classification of groundwater. Four levels are specified: fresh (< 80 mS/m); marginal (80-160 mS/m); brackish (160-480 mS/m), and saline (>480 mS/m). In many parts of the eastern uplands of the MDB, groundwater in the fractured bedrock is not brackish or saline. Jankowski and Acworth (1993) reported an average value of 148 mS/m from 64 chemical analyses in four catchments on the Southern Tablelands. Another source of salt supply is, therefore, required to explain the occurrence of dryland salinity.

In this paper, evidence is presented that the Quaternary-age silty clays deposited upon the basement rocks of Palaeozoic and Silurian age provide a significant source of salt in the Yass River catchment in southern New South Wales (NSW). This area has been studied extensively (Nicoll and Scown, 1993; Bradd et al., 1997) and provides an example of the processes associated with this form of salt storage.

Dryland Salinity in the Yass River Catchment

Catchment Characteristics

The Yass River catchment is on the western margin of the Southern Tablelands of NSW, in the headwaters of the Murray-Darling Basin. The catchment is 122,000 ha and extends from the northern border between the Australian Capital Territory (ACT) and NSW to the township of Yass. The location is shown in *Figure 1*.

The climate is typical of the Southern Tablelands region, with warm summers and cool winters. Although total rainfall (average 642 mm, median 601 mm, and 92 raindays recorded at Yass) is distributed relatively evenly throughout the year (with a slight summer maximum), much of the summer rainfall occurs as high-intensity storms, with an associated lack of effectiveness in recharging the groundwater systems. The winter/spring rainfall occurs as low-intensity frontal systems, which contribute significantly to groundwater recharge.

The Yass River catchment is in the centre of the Lachlan Fold Belt and comprises quartz-rich Ordovician-age greywacke, shale, and slate metasediments, which form part of the Monaro slope and basin sediments (Cas, 1983). Smith (1965) differentiated the Ordovician-age rocks into the basal Pittman Formation and an overlying conformable Picaree Formation. The units are similar in lithology and consist of rhythmically alternating arenite and slate with subsidiary chert and siliceous black slates. Siliceous black slate is common in the Picaree Formation and occurs in the Williams Creek catchment. The Pittman Formation occurs in the Dicks Creek catchment (*Fig. 1*).

The Ordovician-age sediments, in particular, and to a lesser degree the Silurian-age deposits, are characterised by extensive folding, fracturing, and faulting. The sediments have a sub-vertical dip throughout the catchment. Silicification has occurred along many of the fracture zones, resulting in numerous linear quartz reefs, which commonly form the higher ground.

Colluvial material is widely distributed throughout the Yass River catchment, where it occurs as small features in most landscapes. Van Dijk (1959) mapped areas of colluvial material and identified five-soil formation cycles. Major areas of colluvium have been mapped on the adjacent Canberra 1:100,000 geology sheet by Abell (1991), who also refers to widespread colluvium along the east-facing slopes of the Lake George escarpment and on the eastern slopes of Black Mountain in Canberra. Smith (1965) reports the occurrence of colluvium in Murrumbateman Creek in the Yass River valley at Nanima.

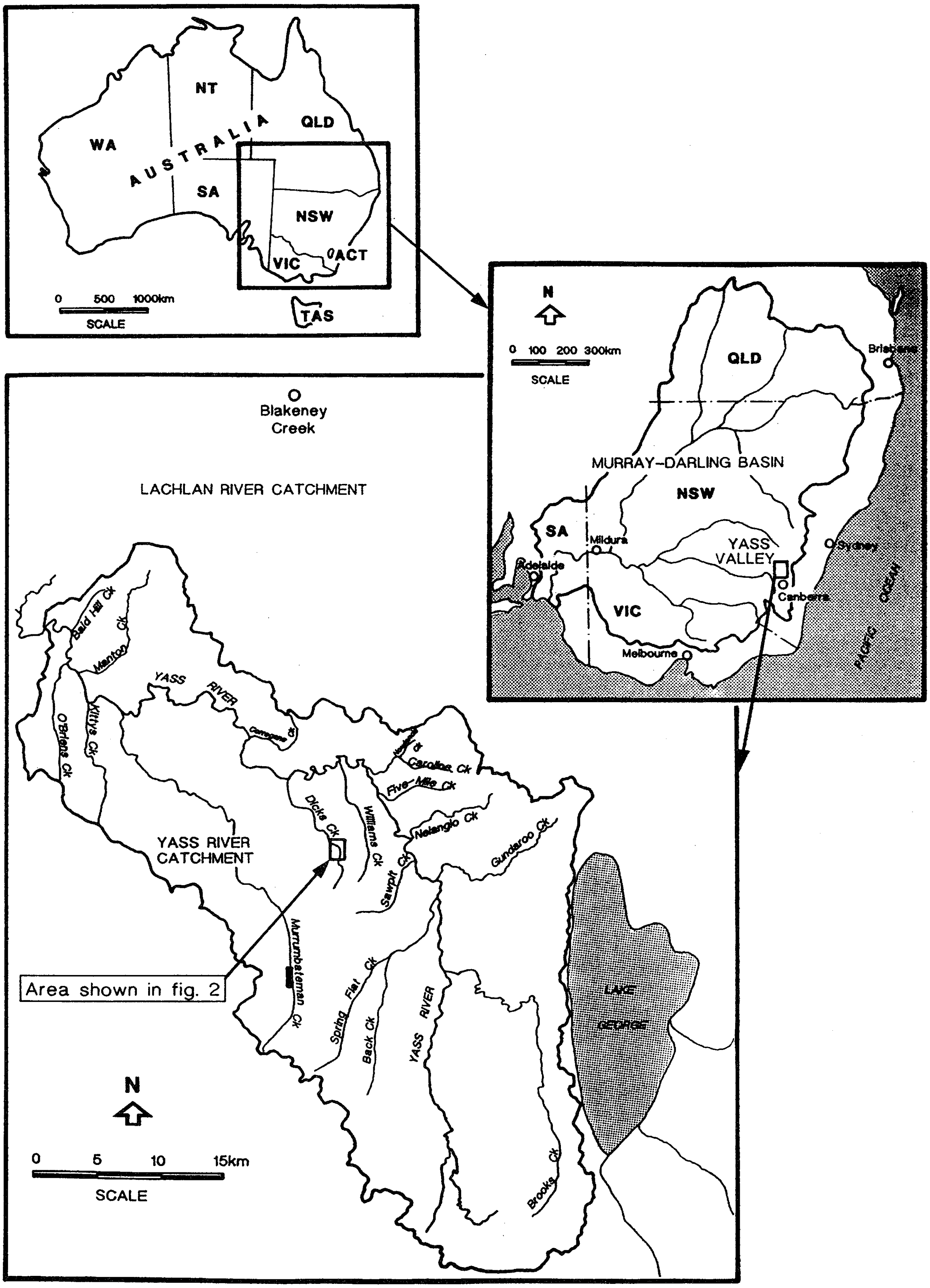

Figure 1. Location of Yass River catchment, New South Wales, Australia.

Dryland salinity is widespread throughout the Yass River catchment and the adjacent southern part of the Upper Lachlan catchment. The first recorded occurrence was in Blakeney Creek in the Lachlan River catchment (*Fig. 1*), where a 40-acre block of land cleared by James Dunley in the 1860's had developed the characteristics of dryland salinity by 1880 (Rex Wagner, pers. comm.). The areal extent of the outbreak has not changed significantly since that time, although downward erosion and gullying have proceeded until the shallow bedrock is now exposed. Dryland salinity was reported in 1902 (Rex Wagner, pers. comm.) on a block in the upper part of Murrumbateman Creek in the Yass River catchment. A heavy clay formed the valley floor and supported grasses before wheat farming commenced in the 1870's. Trees grew on the valley sides. Dryland salinity broke out on the valley floor and was a problem from 1902 onward. The trees on the valley sides were ring-barked between 1910 and 1912 to bring more (replacement) land into production. These early outbreaks of dryland salinity occurred before widespread clearing in the catchment commenced in the early part of the 1900's.

Wagner (1957) mapped salinity occurrences in the catchment and proposed soil-conservation measures to prevent further expansion of the problem. MBDC (1993) reported that 200,000 ha are currently affected by dryland salinity in the MDB and that 1 Mha are at risk.

Field Description

Dryland salinity currently affects approximately 4,000 ha in the Yass River catchment (Nicoll and Scown, 1993). The sites in the Dicks Creek catchment (*Fig. 1*) have been studied by Wagner (1957) and van Dijk (1959, 1969) and have become identified with dryland salinity on the Southern Tablelands, as noted by Charman and Junor (1989) in their review of salinity for the Soil Conservation Service. Features common to these sites are described below, because they must be satisfactorily explained in any proposed conceptual model for salinity development.

Dryland salinity occurs in unconsolidated silts and silty clay sediments overlying bedrock. The sediments can be mapped in the erosion gullies that are 4-5 m deep in the catchment. Abell (1991) identified the material as a colluvium in the geological survey report on the Canberra 1:100,000 sheet, the boundary of which is immediately south of the Dicks Creek area but which includes much of the southern part of the Yass River catchment.

Van Dijk (1959 and 1969) and Butler (1971) identified traces of five soil development cycles within the colluvium and produced maps to show the distribution of soils associated with these cycles throughout the Canberra area, including the Yass River catchment. Although later workers have not confirmed the presence of these cycles in detail, and the field relationship between the various cycles is often obscured by the absence of one or more members, the framework established by van Dijkhas has some validity. A clear erosional unconformity separates the lowest member from the underlying bedrock at a several localities. This condition may be observed at the Dicks Creek Site I, where a representative locality is shown in *Figure 2*.

The oldest deposit is referred to by van Dijk (1959) as 'Mugga' and forms a massive over-consolidated clay that commonly contains numerous clasts, many of which are iron stained. Pillans and Bourman (1996) reported that a sample with similar characteristics to the Mugga, from a fan unit on Black Mountain in Canberra, has reversed palaeomagnetic stratigraphy, which indicates an age in excess of 780,000 yr. The Mugga clay shows evidence of desiccation and groundwater flow along fractures.

Van Dijk (1959) identified the remains of four cycles above the Mugga clay. Each cycle represents a phase of erosion and a period of more stable conditions that allowed soil formation. The erosive component of the cycle has commonly removed underlying older-phase material to the extent that a complete sequence as described by van Dijk (1959) is seldom present.

Van Dijk (1959) noted that lime and soluble salts are associated with the K4 (Gundaroo) and K3 (Pialligo) cycles, which comprise extensive hill-wash and mud-flow (diamict) deposits. The K2 (Kurrumbene) cycle deposits also comprise hill-wash and mud-flow (diamict) deposits, but salts are not reported by van Dijk from this deposit.

The Pialligo deposit was assigned a date of 28 ka by Costin and Polach (1973) from radiocarbon dating of detrital wood fragments from a site on the lower slopes of Black Mountain in Canberra. No age data are available for the Yass River catchment. The Gundaroo deposit is characteristically a mottled, over-consolidated clay that acts as a confining bed to groundwater in the underlying fractured rock. Evidence of groundwater penetration is shown by the discolouration of the buff-coloured clay to a pale blue along what appear to be desiccation cracks. The Gundaroo deposit contains the smallest number of clasts. Where the underlying Mugga clay also contains few clasts, it is difficult to distinguish the two.

A characteristic of each of the Pialligo and Kurrumbene deposits is the very large number of angular clasts that occur at different levels. These deposits occur up the valley slopes and thus cannot represent alluvial material. The deposits are also less consolidated and are readily dispersed if exposed to rainfall. By contrast, the Mugga clay often forms the base to erosion gullies, because it is a more competent unit.

The Mugga, Gundaroo, Pilliago, and Kummumbene deposits are all diamicts. Bedrock clasts commonly occur in the clay. These clasts may be angular fragments of bedrock of cobble to boulder size, or smaller pebbles of quartz. They are generally surrounded by a silty clay matrix, but where the number of clasts is large, point contacts may occur. The identification of a diamict facies is significant, because it implies a specific mode of origin for the deposits, which is discussed in detail below.

In valley-floor areas where the deposits are thin, permanent seeps of groundwater from the underlying fractured bedrock systems occur. These seeps are commonly adjacent to gullies, but they occur at a higher elevation. They generally form small

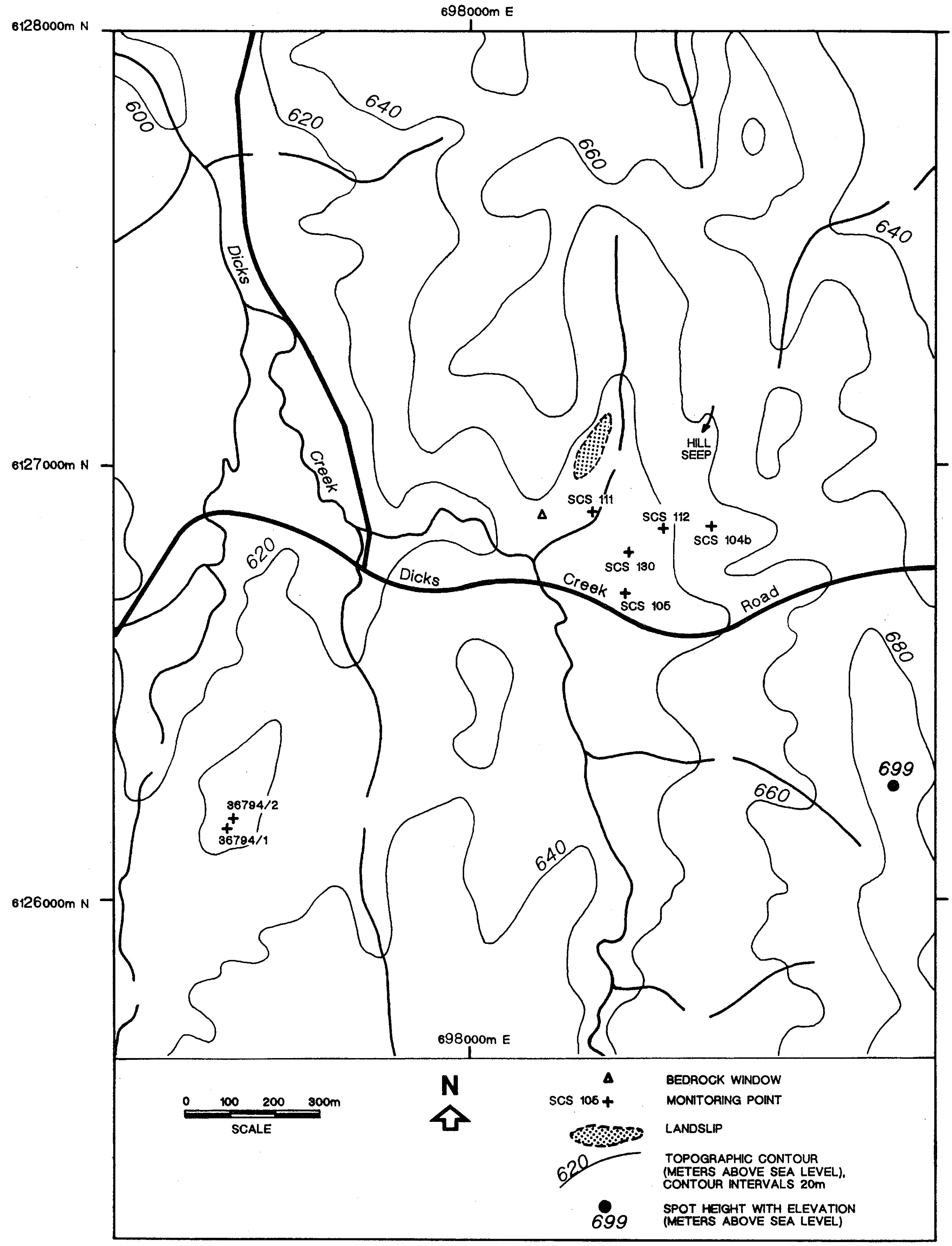

Figure 2. Locations of piezometer sites in Dicks Creek catchment.

mounds and support good plant growth, because the seeps are not saline. Flowing artesian groundwater from the bedrock aquifers is a common characteristic of the salinity sites. A bore at Dicks Creek Site I (36791/4) flows at approximately 5 L/s and has a head that ranges from 2-3 m above ground surface. Piezometers installed into the base of the clays also exhibit heads above ground level and permanently weep small quantities of water. Jankowski and Acworth (1993) detailed the fractured bedrock groundwater chemistry in these areas and demonstrated that the seepage water is of the same chemistry as the underlying bedrock aquifer water. Measurements of hydraulic head in nested bores in the fractured bedrock confirm the presence of a positive (upward) hydraulic gradient, and it is concluded that a significant vertical hydraulic gradient is a characteristic of dryland-salinity sites.

Where the clay in the younger deposits (K4-K2) has been exposed by erosion at a salinity site, desiccation cracks form readily within hours of rainfall. A characteristic of the exposed surface of the clay in these deposits is a blister crust that forms after rainfall and contains gas. The surface of the blister is formed by an algal mat. Seepages and piezometers in these areas frequently show evidence of degassing (Chadwick, 1993).

The NSW Department of Land and Water Conservation (DLWC) installed approximately 200 shallow piezometers throughout the Yass River catchment as a part of the Yass Valley Salinity Abatement Demonstration Programme. Where these piezometers are completed within the clay, they generally have high values of fluid conductivity. Nicoll and Scown (1993) mapped the soils developed upon these clay formations as shallow, gravelly, or deep soloth/solodics.

Various hypotheses have been proposed for the origin of the clays. The simplest is that the clays represent weathering products of the underlying bedrock and are typical pallid-zone clays similar to those developed on weathered granites (Wright, 1992). The identification of diamict facies occurring above an erosional unconformity is evidence against this hypothesis. Detailed studies of the physical and chemical properties of the clays have been carried out (Herwantoko, 1991; Broughton, 1992; Calvert and Acworth, 1994), and the results suggest an aeolian source for the material.

Debris-Flow Deposits

The evidence for the presence of debris flows in the landscape on the Yass River catchment is based upon field observations of diamicts in the erosion gullies. Debris-flow formation could not have occurred unless a substantial component of fine-grained material was available for mixing with water. Aeolian dust is the probable source of this material.

Aeolian Dust Deposits

Butler (1956) was the first to identify substantial accumulations of aeolian dust deposits (parna). These deposits are tentatively identified with the main arid phase of the last glaciation in this region (15-25 ka BP), when sand-dune mobilisation was at a maximum. The period of maximum aridity is considered to have been 17.5-16.0 ka BP (Bowler, 1976; Bowler, 1983). McTainsh (1989) suggested that the optimum site for dust entrainment is in the marginal desert areas and made the point that the Murray-Darling system, which receives recharge along the Dividing Range and discharges into the arid interior, may be expected to be a prime site for dust generation. McTainsh (1989) identified three environments in which the generation of dust is optimised.

Sources of Dust

Alluvial flood plains

The River Darling deposits much of its bedload in the anabranch systems of the Channel Country. The gradients of rivers in this region are extremely low (approximately 1:14,000 between Gunnedah and Adelaide). The low gradient implies that the sediments in the rivers are very fine. Irregular floods create overbank deposits that are readily susceptible to dust entrainment as the deposits dry.

Dunefields

The orientation of sand-dune systems has been correlated with the probable wind directions that occurred during glacial maxima (Wasson, 1986). Dune sands are derived from the same source material as the dust and represent the material that the wind can only move by saltation. The presence of sand dunes downwind from dust sources implies that a large volume of dust has also been entrained in the same direction.

Analysis of palaeoclimatic data and examination of dune system orientation were used by several authors (Bowler, 1976; Sprigg, 1982; and Wasson, 1986) to propose that dust was transported from the western part of the MDB to the eastern part during the Pleistocene Epoch. Work on modern dust deposits by McTainsh (1989) and Keifert and McTainsh (1995) indicates that this dust path remains active.

The main sand-dune systems in NSW occur in the western part of the MDB; however, local sources of material may also provide dust and sand, as Nott and Price (1991) have shown from the eastern shore of Lake George, about 30 km east of Yass (*Fig. 1*). The power of winds in the southeastern dust path is indicated by the dune deposits that have been blown eastward from the shore of Lake George, up and over the local catchment divide, to accumulate on the lee slope in the next catchment.

Groundwater discharge systems (playa lakes)

The discovery of lunettes (Bowler, 1973; Bowler, 1983) identified playa lakes as a major source of dust material. Clay on the playa floor flocculates in response to high concentrations of gypsum and halite, with the result that silt-sized particles are formed (Macumber, 1991). The lunettes, which occur on the downwind side of playas, are a mixture of sand and silt grains and they represent the larger particles left behind as the dust is transported away. Macumber (1991) carried out detailed mapping of the evolution of playas in northern Victoria, and he observed, for example, that the floor of Raak Boinka has been lowered by as much as 1 m by deflation. Playa lakes occur widely in western NSW and provide a significant source of both clay and salt for transport eastward as dust.

Dust Deposition

The carrying power of the wind is apparent from the deposits of the southeastern dust path; these deposits were identified in marine cores taken from the ocean floor east of Australia (McTainsh, 1989), and recent reports describe Australian dust in New Zealand.

Dust is transported downwind until it is trapped in some manner. The dust may slowly settle out, be rained out, or be deposited where the speed of the wind is reduced for some reason. Local turbulence from eddies created by the winds passing over the hills and ridges of the Tablelands causes dust deposition in the lee of ridges. The dominant orientation of ridges in the Tablelands is approximately at right angles to the dust path and thus forms a dust trap.

Identification of Dust Deposits

Clear sources of dust have been identified upwind of the NSW Tablelands. However, a major problem with the identification of aeolian material is that after deposition as a loess, it readily becomes reworked and incorporated in the soil. McTainsh (1989) described grain-size criteria for the identification of an aeolian component of soils. Walker et al. (1988) identified aeolian accessions on a granite soil using soil morphology and particle-size distribution criteria.

Butler and Hutton (1956), Beattie (1970), and Walker and Costin (1971) measured grain sizes on modern dust deposits and reported mean diameters of 4 mm (phi scale value of 8), with a maximum likely size of 40 mm (phi scale value of 4.6). These are the Wentworth sizes representing very fine to medium silt. The well sorted units at the Dicks Creek site show a grain-size population consistent with an origin as aeolian material (phi scale value of 6-8). Some samples contain two grain-size populations. Either a predominantly aeolian material is mixed with a smaller component of coarser grain-size material, or predominantly coarse grain-size material is mixed with only a minor aeolian component. A ternary diagram showing the percentage contributions of sand, silt, and clay for surface grab samples of Mugga/Gundaroo units at Dicks Creek is shown in *Figure 3.*

Clay identification was carried out using XRD techniques for the surface grab samples from the Dicks Creek site and also from auger samples taken from bore locations (SCS 112, SCS 104b, and SCS 130), shown in *Figure 2.* The results of these analyses are presented in *Figure 4.* The presence of smectites in the clays sampled at Dicks Creek is an indicator of an aeolian origin (Keifert and McTainsh, 1995). Smectite is not sourced by weathering of the Palaeozoic-age shales and sandstones that form the bedrock (Grim and Guven, 1978), and smectite is destroyed by metamorphism. Therefore, the source of smectite identified in the clays must lie outside of the local catchment area. Further evidence is provided by the widespread occurrence of Mugga-like deposits in the adjacent southern part of the Lachlan River catchment, overlying igneous rocks (Broughton, 1992), and in the Canberra area (Abell, 1991).

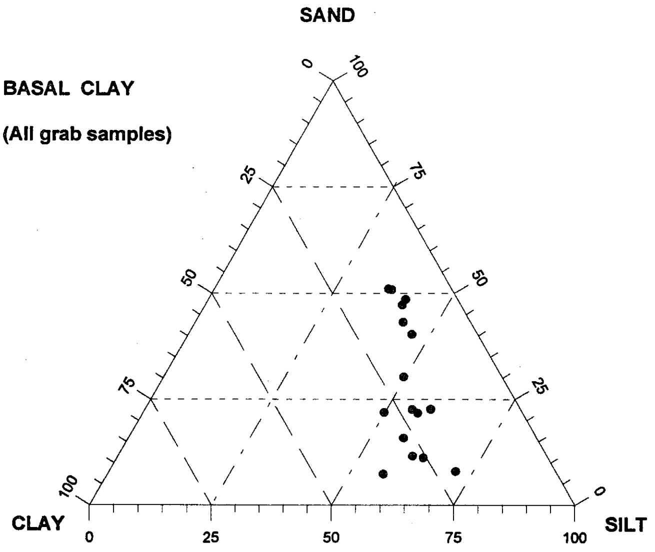

Figure 3. Distribution of sand, silt, and clay in the basal clay at Dicks Creek.

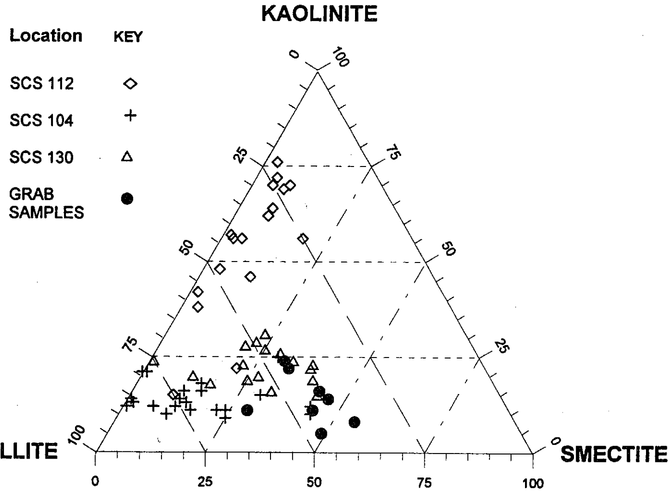

Figure 4. Clay components of grab samples from the basal clay and from three piezometers at Dicks Creek.

In summary, the grain-size data, the clay-type data, the presence of an erosional unconformity, the widespread existence of the deposits, and the position of the Yass River catchment in the southeastern dust path, combine to produce a strong argument for an aeolian origin of this material. Recycling of the dust occurs as the material, initially moved east by the wind, is again transported west by the rivers.

Debris-Flow Genesis and Identification

The presence of diamicts can be explained by one of four processes: as a glacial till; by dropstones from an ice sheet over water; by a debris flow associated with dust from volcanic eruptions; or by a debris flow associated with the hydroconsolidation of loess deposits.

No evidence exists to suggest that the first three processes operated during the Pleistocene Epoch within the Yass River catchment. Attention is, therefore, focussed on the hydroconsolidation of loess deposits. This process is characteristic of the loess deposits in China (Derbyshire, 1983). When moisture contents in the loess approach saturation due to rainfall, a catastrophic collapse of the loess structure occurs, with the subsequent formation of a debris flow. Failure on slopes may also occur before complete saturation of the deposit is reached by landslips along basal slip planes.

The term "loess" is generally used to refer to aeolian deposits of glacially derived silt; however, Chinese loess deposits (Derbyshire, 1983), indicate multiple phases of loess transport that often include an alluvial component. Derbyshire (1983) also reported that much of the loess in southeastern Asia was derived by frost shattering and not by glacial action. During the glacial maximum, frost shattering may have added a significant additional component to the aeolian dust load on the Tablelands.

In this paper, the debris-flow deposits are proposed to have been created by hydroconsolidation of dust (clay and silt) accumulations. Under this hypothesis, the debris flows would have accumulated in valley floors and would have entrained clasts of the local bedrock. Local supplies of sand from small creeks and lakes would also be moved upslope, away from the local source area, as small dunes, similar to the process identified at Lake George (Nott and Price, 1991). These sands would become part of the debris flow; they are identified as water-carrying sand lenses in borehole sections. The path taken by the debris flow would have been strongly influenced by the pre-existing topography and by any constrictions in the topography. A ridge of harder rock along the path of the debris flow would cause a damming effect leaving a greater thickness of clay behind the ridge. The colluvial deposits described by Smith (1965) are interpreted as debris-flow deposits. Abell (1991) suggested a mode of origin as a scree in a cold, arid climate associated with the last glaciation in southeastern Australia, and the deposits are considered to have arisen as a result of solifluction originating from widespread hillslope instability during seasonal freezing and thawing on a landscape bare of vegetation. Under the processes proposed herein, the hillslope instability was significantly enhanced by dust accumulation leading to debris flows.

The dust probably included salts deflated from playas. This salt would have mixed with the clay particles during deposition. Although a proportion of the salt would have been flushed from the deposit during the movement of the debris flow, complete flushing and removal of salts from the material would not have occurred, particularly if transport occurred more as a landslip or slump.

Van Dijk (1959) reported that many of the soil units he identified on the Southern Tablelands had the characteristics of hill-wash and mud-flow deposits. The source of material for these deposits was not reported.

Distribution of Debris Flows

Accumulations of aeolian material would have preferentially occurred on the lee slopes of hills. At the end of the period of aridity, rainfall increased and caused the landslips and debris flows, which resulted in the redistribution of the aeolian material. The location of what is probably a landslip at Dicks Creek Site I is shown in *Figure 2*. This sequence of events also provides an explanation for the occurrence of some fans that are overfit for the size and relief of the catchment. The dust accessions provide the missing source of mass for the fans, which are interpreted as debris-flow deposits.

Age of Debris Flows

With the exception of the last 50,000 yr, the climatic record over the Tablelands during the Quaternary Period is not well resolved. Australia experienced multiple arid/glacial phases during this period. The oscillation from wet to dry and back to wet would have created many episodes of dust entrainment. Several episodes are probably represented on the Tablelands. However, much of the dust deposited during the end of each glacial maximum was probably moved westward by erosion during each inter-glacial time. This prospect has a direct bearing on the management of the dryland salinity problem, which is discussed in a later section.

The transition from wet to dry conditions caused dust entrainment during period 35-25 ka BP. The Pialligo clay (K3) was possibly created during this period, as indicated by the radiocarbon dates reported by Costin and Polach (1973). Additional debris-flow deposits would have accumulated on top of the lower clay during the period since 16 ka BP, which would be represented by the Kurrumbene deposits. The upper debris-flow deposits contain a much greater proportion of clasts than do the lower units. Clast generation proceeded rapidly during the glacial maximum as the result of freeze/thaw processes.

The age of the Gundaroo deposit probably pre-dates the last glacial maximum and possibly represents an earlier glaciation. The Mugga clay would then represent an earlier phase of Pleistocene glaciation. However, because no confirmed dates are available for the Yass River catchment, the timing of diamict facies deposition remains speculative and further work is required to date the various phases of deposition.

The above discussion provides evidence for an aeolian origin of the material in debris-flow deposits in the Yass River catchment. Field observation suggests a strong association between these units and the occurrence of salinity in this area (Nicoll and Scown, 1993). Below, a mechanism is proposed by which salinity could develop on these debris-flow deposits. As part of this analysis, an understanding is required of the groundwater flow systems developed in the Yass River catchment prior to debris-flow deposition.

Groundwater Flow Systems Prior to Debris-Flow Emplacement

Tóth (1963) and Freeze and Witherspoon (1967) demonstrated in theoretical analyses of basin groundwater flow that local, intermediate, and regional flow systems develop as a consequence of surface topography and regional slope. As predicted by these analyses, local and intermediate flow systems occur in the Yass River catchment, with recharge on hilltops and discharge in valley floors (local flow system) or to the Yass River (local and intermediate flow systems). These conditions are demonstrated by the hillslope and catchment potentiometric data presented by Nicoll and Scown (1993).

In a local flow system such as that represented by the subcatchment at Dicks Creek, the elevation of the water table in the recharge area fluctuates in response to changes in recharge. The elevation of the discharge point in the valley floor is controlled by the fixed head represented by the local drainage. An increase in recharge leads to an increase in water levels in the recharge zone and to an increase in the discharge flux in the fixed-head zone on the valley floor. When drilling into the floor of a local system, upward groundwater pressures are observed, the result of curvature of flow lines, as indicated by Fetter (1994, p. 277). This curvature of the flow lines is a necessary requisite to explain the characteristic development of upward groundwater discharge that is observed at salinity sites. Groundwater does not reside long in a local flow system, and the hydraulic heads respond rapidly to recharge. The discharge occurs a short time after rainfall at hillslope seepages or at springs, which represent discharge points, and it forms the baseflow component to streams.

A simple two-dimensional local flow system is shown in *Figure 5* to demonstrate the generation of upward groundwater flow beneath the discharge areas and the impact of the debris flows on this discharge. This figure is scaled to be typical of Yass River catchments. A maximum depth of flow of approximately 100 m is assumed, based upon the results of drilling in the catchment. A hydraulic head of 10 m, typical of current conditions, was used for the preparation of the figure. A homogeneous hydraulic-conductivity distribution was assumed. This condition is a gross simplification of the hydraulic-conductivity distribution in a fractured bedrock aquifer, but it serves as a practical starting point for the development of a conceptual model. Insufficient hydraulic-head information is available to prepare a detailed section.

In the complete absence of recharge, as possibly may have occurred in the Pleistocene Epoch, groundwater levels in the Yass River catchment would decay to the regional discharge point (the Yass River), leaving a horizontal water table in the fractured bedrock throughout the catchment. Under these conditions, local flow systems would not operate. However, during wetter episodes, recharge on hilltops would activate the local flow system, with groundwater discharge occurring unimpeded on the valley floor as stream baseflow, as indicated on the right side of *Figure 5*.

Impact of Debris Flows on the Local Groundwater System

As described above, the debris flows contain a high proportion of clay- and silt-size material. These deposits have a lower hydraulic conductivity than fracture zones in the underlying bedrock, and where they overlie a discharge zone, they can be expected to substantially modify the pre-existing flow system.

Changes to Groundwater Flow

The effect of a unit with low hydraulic conductivity underlying the valley floor is shown on the left side of *Figure 5*. In a local flow system with significant recharge, groundwater discharge tends to be concentrated along the valley margins at the top edge of clay units with low hydraulic conductivity, in effect subdividing the flow system. A shallow component to the flow system is recharged at the top of the slopes and discharges rapidly at the upper contact with the clay. This water then flows over the top of the clay deposits as ephemeral streamflow.

A deeper component to the flow system is recharged on the hilltops and discharges slowly upward through the clay. The presence of the clay has the effect of displacing the flow lines from this part of the system, with the result that discharge through the valley floor is much reduced. Possibly, valley-floor discharge is completely eliminated, with a new constant-head discharge boundary created at the top edge of the clay on the valley side. However, lines of weakness in the Mugga and Gundaroo units are seen in outcrop, indicating discharge pathways through the clay. Old tree roots can also be seen penetrating these zones. These observations suggest that some upward leakage through these units has always occurred at these sites.

Prior to clearing, the flux of groundwater through this system would have been small, perhaps reduced to episodic recharge events on the exposed hilltops, where the soil cover is thin. The water level beneath the recharge zone would have been reduced to perhaps an elevation of only a few meters above the discharge zone, but the water level in the discharge zone would always have been coincident with the valley floor, assuming that some recharge occurred.

Changes to Groundwater Chemistry

A characteristic of a local flow system is that the water quality is fresh, because the groundwater has only a short residence time in the aquifer. Groundwater discharge in the valley floors of an open local flow system is not associated with salinity, because a continuous flux of water occurs through the system, leaving the system by streamflow. The concentration of dissolved salts by evaporative concentration can only occur in a closed system and even here, the balance between inflow (rainfall) and outflow (evaporation) is often such that a fresh-water lake is created, as occurs in Lake George at the present time.

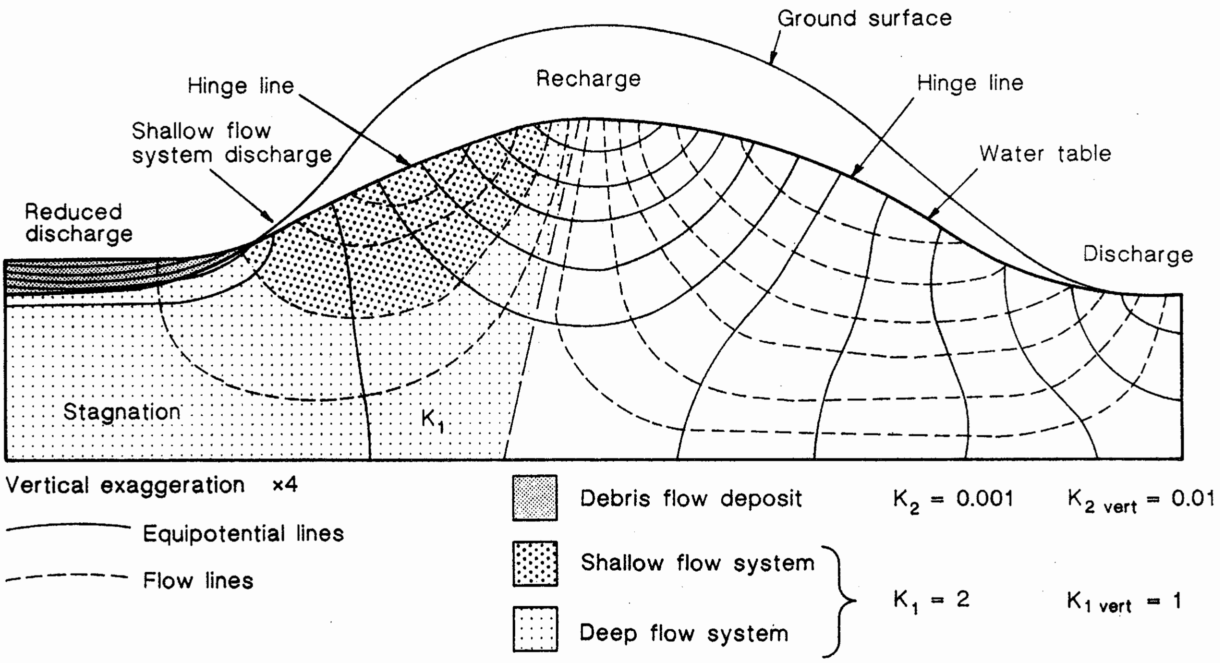

Figure 5. Conceptual model of groundwater flow where low-conductivity debris-flow deposits underlie a discharge area.

The presence of a debris flow underlying the valley floor significantly impacts water quality in the flow system by creating a zone of stagnation (low flow) beneath the valley floor, as shown in *Figure 5*. By contrast, clay on the valley sides has little impact. Erosion of valley-floor clay, which leads to the creation of a window in the clay cover, allows groundwater discharge to recommence.

Water that is recharged on the valley sides and discharges above the break in slope is fresh and is unaffected by the debris flows. The presence of the clay actually increases the flux through the upper flow system, due to the new concentration of flow lines in this zone. Waterlogging may be a problem where excess discharge from the shallow flow system occurs, caused by clearing higher in the catchment.

The major change to groundwater chemistry occurs in the discharge zone of the deeper flow system. The longer residence time of water in the deeper zone and the passage through clays in the debris flows lead to various chemical reactions.

Evidence from the Yass River Catchment Salinity Abatement Monitoring Program

Some aspects of the above hypothesis will remain speculative due to the difficulty of proving beyond doubt all components. However, it is now possible to relate the observed piezometer data in the Yass River catchments to this conceptual model and to test various aspects of the model.

Two components are postulated to be essential for the development of dryland salinity in this area: 1) the presence of a clay-rich and salt-rich debris flow; and 2) the presence of a deep groundwater system discharging through the debris-flow deposits. If either component is missing then the occurrence of one or the other should not cause dryland salinity. Therefore, the model can be tested using existing field data.

Groundwater Discharge in the Absence of Clay

Groundwater-elevation records from monitoring bores on hilltops show no net rise in water levels in the catchment in the past six years (1988-94), although groundwater levels could have risen before this time. Levels respond to winter recharge and rise to a level determined by the quantity of that recharge. During the summer months, they decline toward a local catchment base level. An extract of the record for Bore 36794-1 is shown in *Figure 6*, where daily rainfall is plotted against hourly water levels. The water level is 17-22 m below ground level at this location. The bore is completed at a depth of 50 m, and bedrock crops out at the surface. This data set demonstrates the current rapidity of recharge in these hilltop locations. A longer record from an adjacent deeper borehole (70 m) at the same location (Bore 36794-2) is shown in *Figure 7*.

The annual recession of groundwater levels implies surface discharge by springs and seeps. The recession often shows two components. The early steeper component reflects discharge by seepages, which can be observed in the field for several days after heavy rain. The later component reflects deeper flow paths and discharge from more permanent springs. The chemical quality of these hillslope discharges and springs is very good, as shown in *Table 1*, analyses 1 and 2. Seepages provide the base flow in streams. Where they occur above stream level they support hydrophyllic vegetation, such as reeds, and they may form small wetlands.

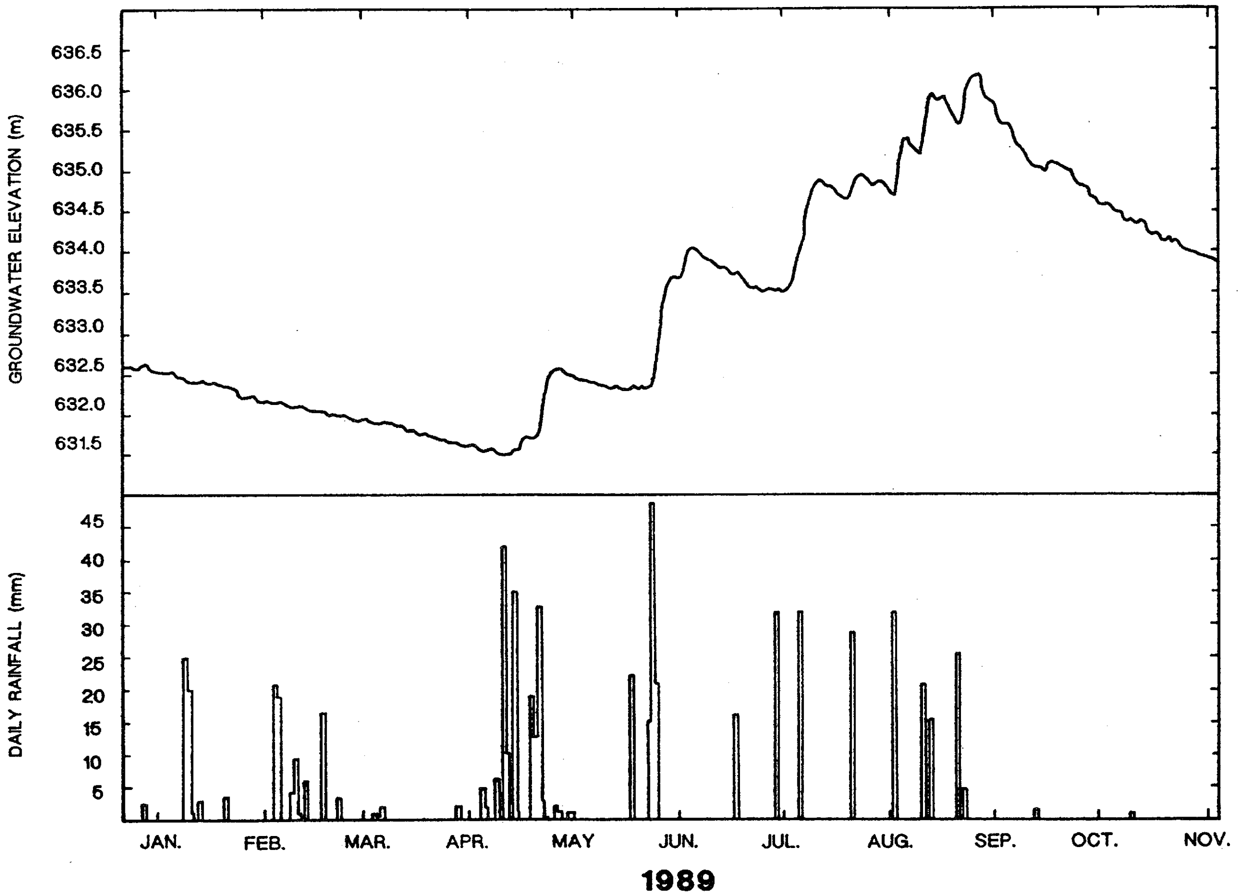

Figure 6. Groundwater-level fluctuations in borehole 36794-1 and rainfall distribution, 1989.

Piezometer SCS-112 at Dicks Creek was installed to monitor conditions in the weathered profile at a location where the debris-flow material was absent and where no surface evidence exists of dryland salinity. The XRD data from the bulk samples (*Fig. 4*) show that samples are dominantly kaolinitic, indicating a weathered in-situ profile. The lack of smectite further confirms this condition (*Fig. 5*). A profile of soil 1:5 extracts, a gamma log, and a bulk-electrical conductivity log (EM-39) are shown in *Figure 8*. These data show that the bulk electrical conductivity is low, further confirming the absence of debris-flow clay at this site. Water-level and rainfall data for a five-year period (*Fig. 7*) indicate active groundwater recharge and discharge. Groundwater chemistry data (*Table 1*, analysis 3) indicate fresh-water conditions.

These data provide evidence that no dryland salinity development exists in the Yass River catchment wherever discharge from the groundwater system is unimpeded by the presence of clay.

Clay Soil Development in the Absence of Groundwater Discharge

Where clay deposits exist higher up on the sides of hillslopes, due perhaps to inadequate development of debris-flow conditions, groundwater passes beneath the clay through the weathered rock and discharges in the valley floor. No long-term saturation of the clay with groundwater is possible under these conditions, and dryland salinity has not been observed there. Indeed, the clays in this position on the landscape often support good vegetation. Elevated levels of salt beneath the root zone (Nicoll and Scown, 1993) may provide some evidence for evapotranspirative concentration of salts at these locations, although the relative significance of this process is yet to be determined.

Piezometers SCS 130 and SCS 104b were installed into the clay to monitor conditions of this type. Elevated levels of bulk electrical conductivity, as measured by the EM-39 and shown in *Figures 9 and 10*, and the presence of smectite in the bulk-sample analyses (*Fig. 4*), both characterise the clay at depth. Broughton (1992), and Calvert and Acworth (1994) also carried out extensive geophysical surveys across the site, the results of which provide further confirmation of the presence of the debris-flow unit. Piezometer SCS-130 is completed in the clay and shows a subdued response to recharge. Piezometer SCS-104b is completed at 12 m in clay. The groundwater response to seasonal rainfall demonstrates a greater response to recharge, which may be the result of a higher elevation in the flow system (*Fig. 7*). Typical chemical analyses for these

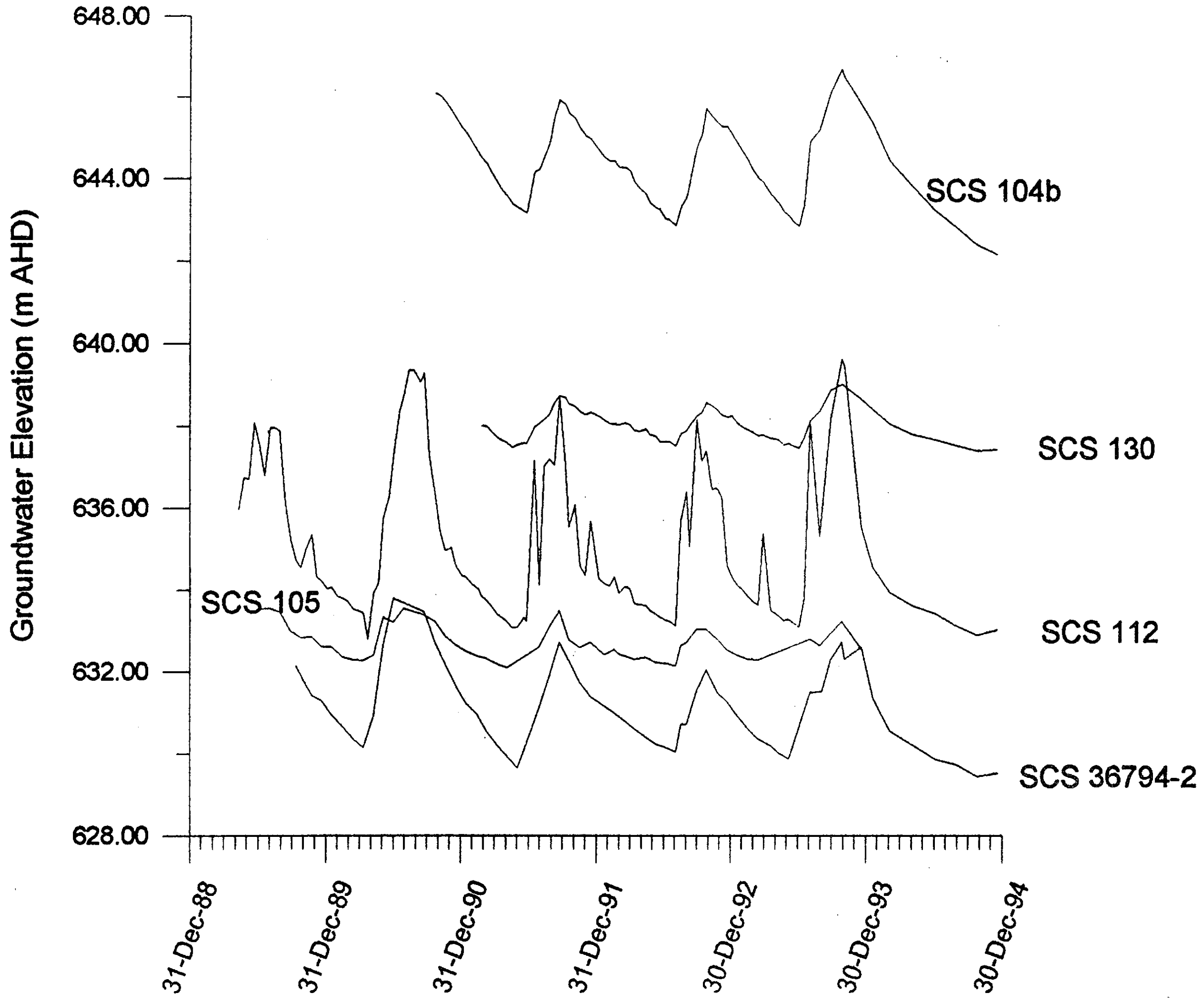

Figure 7. Groundwater-level fluctuations, 1988-94.

Table 1. Hydrochemical analyses of hillslope springs and seeps and groundwater from piezometers.

Anal. no.	Location	T (°C)	EC (mS/m)	pH	Eh (mV)	Dissolved constituents (mg/L)									
						TDS	CO_2	Na	K	Ca	Mg	Fe	HCO_3	Cl	SO_4
1	Hillslope	6.8	2.7	5.7	18.0	26.2	3.1	5.0	0.6	0.1	0.7	0.1	9.2	4.9	2.1
2	Hillslope	10.4	4.9	6.8	5.0	35.4	4.4	6.5	1.0	0.1	1.9	0.0	6.7	9.2	5.8
3	SCS-112	15.3	51.0	5.2	59.5	308	23.8	56.0	1.0	0.5	22.7	0.0	21.4	56.0	125
4	SCS-130	14.8	92.8	5.7	40.0	609	107.4	76.2	1.1	7.4	61.3	0.0	188	145	81.6
5	SCS-104b	12.6	211	6.6	-7.0	1,638	57.2	138	2.0	10.8	217	0.0	409	126	704
6	SCS-105	12.6	512	8.4	-54.3	3,903	0.0	882	1.2	1.2	186	0.0	1,585	672	556
7	SCS-111	10.0	479	7.3	-11.0	2,987	30.2	736	1.2	5.0	175	nd	598	1,034	41.0

nd, not detected

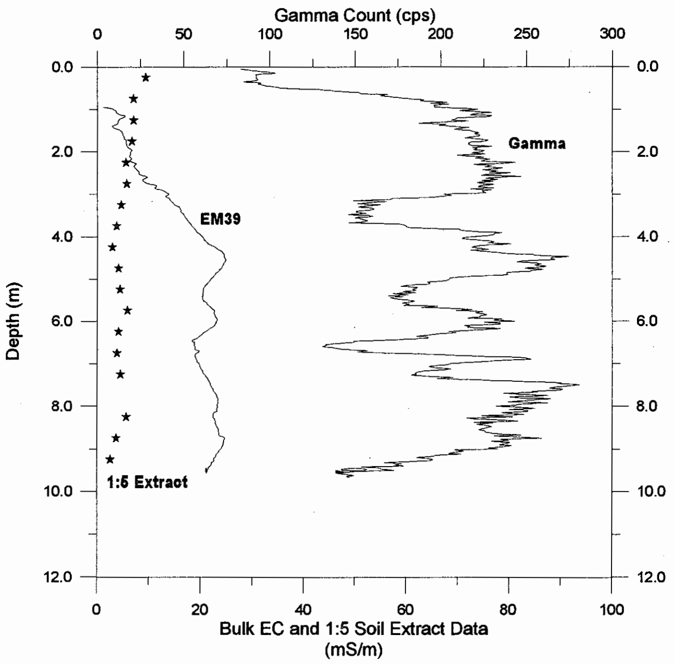

Figure 8. Geophysical and soil-extract data, piezometer 112.

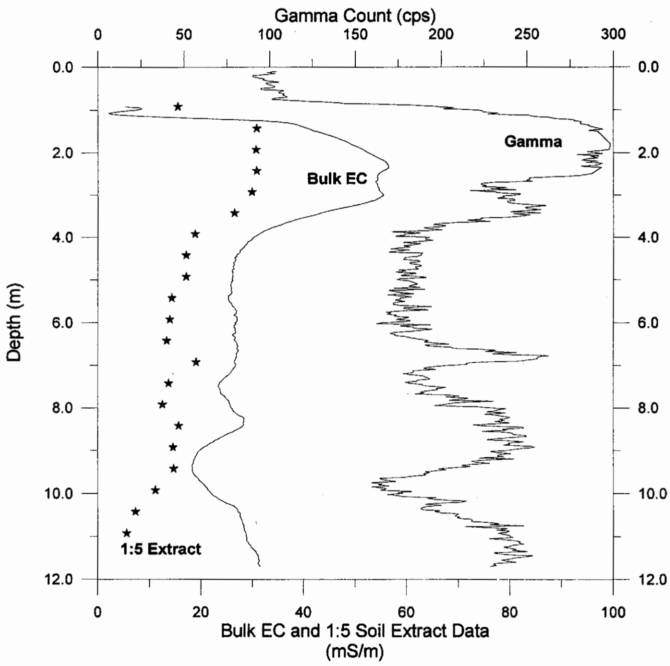

Figure 10. Geophysical and soil-extract data, piezometer 104b.

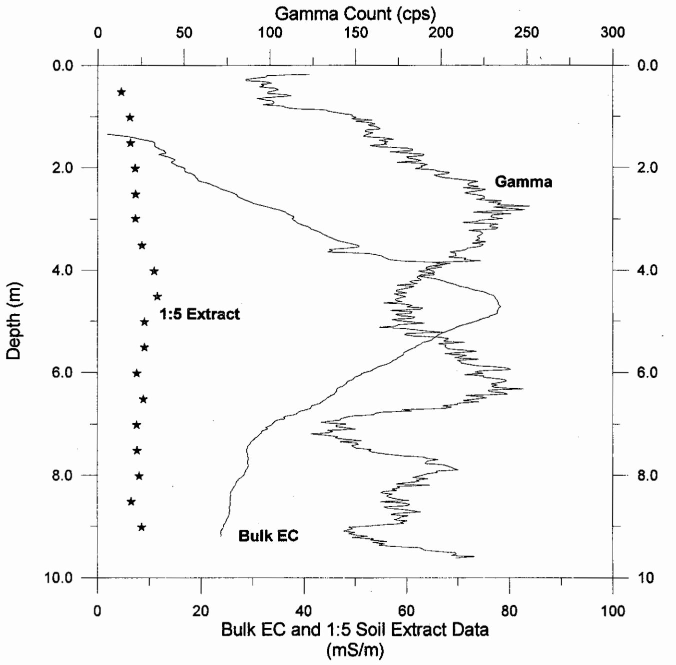

Figure 9. Geophysical and soil-extract data, piezometer 130.

piezometers (*Table 1*, analyses 4 and 5) demonstrate the higher conductivity of waters held in the clay.

Geophysical methods can be used to identify the presence of the clays but cannot be used to predict areas at risk of dryland salinity without the additional use of hydrogeological data, because the presence of the clay without groundwater discharge is insufficient to cause dryland salinity.

Conjunction of Debris-Flow Deposits and Groundwater Discharge

The surface conditions developed where groundwater discharges from the fractured bedrock aquifer and where the clay in the debris-flow deposit is permanently saturated are those commonly described as dryland salinity. As reviewed above for the Yass area, dryland salinity develops where groundwater discharges from the fractured-bedrock aquifer and where the clay in the debris-flow deposit is permanently saturated. The location of groundwater discharge may be controlled by bedrock ridges; by a narrowing of the catchment; or by the presence of faulting. Similarly, the debris-flow depth is determined by the surface morphology prior to the flow. Greater depths of clay may prevent early outbreaks of salinity.

The conceptual model suggests that dryland salinity first occurs where the clay deposit is the thinnest. This situation has been observed at many sites where bedrock crops out in gullies.

Piezometers installed in these zones generally have pressure surfaces at or above the ground surface for much of the year and, therefore, show little response to recharge events. This lack of response is due to the low hydraulic conductivity of the silty clay, which also limits the volume of poor-quality water that discharges from these sites.

The fluid electrical conductivity in piezometers installed in these locations is brackish (>400 mS/m), as shown by analyses 6 and 7 of *Table 1* for piezometers SCS-105 and SCS-111. The

1:5 extract analyses from these piezometers is also high (Nicoll and Scown, 1993). A groundwater hydrograph for the 1.5-m-deep piezometer SCS-105 (*Fig. 7*) shows a subdued response to recharge, which is possibly complicated by surface runoff. Piezometers in similar locations at other sites show practically no response to recharge.

Land-Management Implications

The conceptual model proposed herein states that dryland-salinity development in the Yass River catchment is expected to be a problem only on the clays that underlie groundwater discharge locations, and mapping by Nicoll and Scown (1993) provides further evidence for this.

Revegetation of the upper slopes and slopes just above salinity occurrences does not materially impact the salinity in the valley floors, because the conditions are related to discharge of groundwater through the deep flow path, as indicated in *Figure 5*. Recharge reduction by tree planting on the upper slopes reduces groundwater discharge through the shallow flow system above the clays and leads to an improvement in waterlogging where this is a problem. Revegetation of the hilltops to reduce the groundwater flux beneath the clays is very difficult due to the poor soil conditions at these locations.

A solution to the problem is either to dewater the valley-floor clays at the locations where groundwater from deep flow paths is discharging, or to allow the deep groundwater to bypass the clays. The first option would involve, where possible, re-establishing high-water-use vegetation on the clays at groundwater-discharge locations, although this approach is not always advised (Jolly et al., 1993). In many instances, it is too late for this option, because the clays are saturated and have commenced dispersion, creating conditions under which plant growth is slow and inefficient and, in the worst cases, impossible. A second option would be to make use of the flowing artesian pressures that exist in the fractured bedrock and allow the water to drain through boreholes cased through the clay. Shallow inclined bores may be sufficient to achieve this objective in many areas.

A criticism is that no increase in poor-quality water should be allowed to discharge into the existing streams and thus into the River Murray. However, the reworking of the debris-flow deposits occurred in all probability several times during the Pleistocene Epoch, with the products returned westward. A state of meta-stable equilibrium had been reached before clearing of vegetation began, and this state has been disrupted by the effects of clearing. Reactivation of processes that have been mostly dormant for probably 5,000 years is now being witnessed. Failure to prevent the steady destabilisation of the clays by contact with the fractured bedrock groundwater would cause much greater salt loads to enter the streams as the clay disperses in the future.

Land management involving clays that occur on the valley sides or where the clay is sufficiently thick to prevent groundwater discharge should take account of the danger of exposing the clays to dispersion, resulting in the release of salt. Mapping of the clay occurrences in the landscape of the Yass River catchment would provide land managers with some of the necessary information to address the salinity problem.

Conclusions

A conceptual model is developed that provides an explanation for the occurrence of dryland salinity in the Yass River catchment. Although the model is based upon studies in a single catchment, the processes that have been established must have had a wide impact, because they are related to widespread dust accessions. Thus, components of this model probably have validity throughout the Tablelands, from Victoria to Southern Queensland. Many variations exist on the theme; however, recognition of the parts that aeolian accessions and climatic variability have played in the salinity problem, both in Australia and in other parts of the world, are expected to provide essential information for management of the problem.

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