SEEPAGE SCALD:

A CASE STUDY IN SOUTHEASTERN NEW SOUTH WALES

BY

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DECLARATION

Except where otherwise indicated in the text, this thesis is my own work.

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ABSTRACT

Dryland salinity in Australia is usually subdivided into two categories, scald and saline seepage, however, the use of these terms has not been consistent. The existence of a groundwater discharge condition should form the basis for distinguishing different areas of dryland salinity, but areas both with and without this condition have been labelled as 'scalds'. It is suggested that 'seepage scald' and 'dry scald' be used to distinguish scalds with a groundwater discharge condition from those scalds without while retaining the descriptive qualities of the term 'scald'. Further, it is suggested that soils labelled as saline seepages fall into the seepage scald category.

This study addresses the problem of seepage scald in southeastern New South Wales. There is very little information concerning the soil and hydrological properties of these areas and a case study of the Yarralaw seepage scald was undertaken to answer questions concerning the scald's location, the threat of scald expansion, possible offsite effects and the scald's origin. The results of this study have application to a number of similar sites in southeastern New South Wales.

The following characteristics were determined from the Yarralaw study. Scald formation did not occur as a result of any particular soil property inherent to the scalded area. Grassland and scald profiles were similar with the major difference being the surface horizon. The grassland surface was relatively permeable with good tilth. The bare scald surface was sodic, highly dispersive and compacted. As a result, it had lower permeability than the grassland. Soil salt loads were high only in the surface horizons of the scald.

The water table in the lower catchment, even at it lowest level, was within 2 m of the ground surface. Upward capillary water movement is causing the salinity but the salinity is confined to the scald because downward leaching in the grassland keeps the surface of these areas relatively salt-free. The infiltration rate on the scald is too low to keep the soluble salts leached below the root zone.

The Yarralaw seepage scald has been quite stable in terms of total affected area since 1962. This is not to say that heavy runoff conditions in the future will not cause further scald expansion and it is important that reasonable measures be taken to prevent this. However, the perception that the scald is slowly but steadily consuming the grassland in the lower catchment is simply not correct. Scald growth appears to be catastrophic in nature with the majority of the damage occurring in a relatively short period of time. On the scald surface itself, the degradation is steady and ongoing. The rills in the surface are being eroded into miniature gullies that grow steadily until they reach a new equilibrium of size and depth. Thus, the degradation of the scald is progressive but the expansion of the scald area appears to be catastrophic.

There were significant loads of suspended sediment and dissolved solids exported from Yarralaw over the course of the study. If the 1.4 t ha^{-1} y^{-1} suspended sediment loss rate is applied to the severely sheet and gully-eroded areas of the Shoalhaven catchment, one arrives at a figure of 1,750 m^3 y^{-1} suspended sediment put into the Shoalhaven River assuming only 10% of the total sediment actually reaches the river system. Likewise, the 1.6 t ha^{-1} y^{-1} soluble salt loss from the Yarralaw scalded area translates into 2400 t y^{-1} soluble salts dumped into the Shoalhaven River just from the salt-affected soils of the Nerrimunga Creek catchment. This mass is sufficient to increase the salt load in the proposed 2.7 million Ml Welcome Reef reservoir by 1 ppm per year. With a ready supply of suspendable material on the scald surface and at least a 150 year supply of soluble salts in the groundwater, the offsite effects could persist for some time.

The cause of the Yarralaw seepage scald cannot be determined for certain. It is suggested that tree-clearing and possibly overgrazing may have weakened the vegetation and upset the hydrological balance of the catchment. Reduced transpiration would leave an excess of water that could either percolate below the root zone or runoff the surface. In the former case, the resultant high water table would cause salinity and in the latter case, the runoff would cause erosion. Although both processes are now affecting the scald, it is not possible to determine which one was originally responsible for scald formation. The hydrological balance is intrinsic to the catchment but it is suggested that an extrinsic factor, the higher than normal rainfall and the extreme fluctuations between dry and wet periods, actually triggered the formation of the seepage scald during the 1950's.

Estimates of the temporal soil loss pattern at the site indicated that most of the damage occurred very early in the lifetime of the scald. This catastrophic-type of formation has important implications for seepage scald management. It emphasizes the need for seepage scald prevention. However, there is a lack of basic information for predicting probable areas of scald formation. It is suggested that the Soil Conservation Service of New South Wales should undertake the installation of an extensive network of water table wells and monitor the water levels on a longterm basis. This information along with a database of subsurface soluble salt loads (which also needs to be collected) could be used as a basis for predicting likely areas of seepage scald occurrence where preventative measures should be introduced before a problem develops.

Reclamation of established scalds such as Yarralaw is a difficult undertaking. The recommendations, following this study, include fencing the main scald to exclude stock as well as the woodlands at the south end of the catchment to encourage the natural revegetation that is occurring. The main scald must be broken up and treated with gypsum to alleviate the compacted structure problem and vegetation such as salt-tolerant grasses must be established. Groundwater monitoring should continue as a means for assessing the success of any reclamation strategy that is implemented.

The 'economics' of seepage scald are such that reclamation is usually not cost effective based solely on onsite values. Offsite effects must also be considered before reclamation becomes economical and before one can justify the expenditure of public funds for this purpose.

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CHAPTER 1
INTRODUCTION

1.1 The Australian Salinity Problem in Perspective

Soils adversely affected by excess soluble salt have been reported in Europe (Miljkovic, 1964; Szabolcs, 1978), Asia (Orlovskij, 1964; Raychaudhuri, 1964) and North America (Vander Pluym, 1978). However, few locations in the world have salinity problems with the extent of that found in Australia. Northcote and Skene (1972) have reported that at least 5% of the surface area of Australia has saline soils and another 25-30% has sodic soils (Figure 1.1, Table 1.1). The total area represents nearly one third of the entire Australian continent.

Table 1.1 Salt-affected soils in Australia (Northcote and Skene, 1972)

Salt-affected soil category	Area (,000,000 ha)
Saline soils	38.6
Alkaline strongly sodic to sodic clay soils with uniform texture	66.6
Alkaline strongly sodic to sodic coarse- and medium-textured soils with uniform and gradational texture profiles	60.1
Alkaline strongly sodic to sodic duplex soils	45.4
Non-alkaline sodic and strongly sodic neutral duplex soils	13.5
Non-alkaline sodic acid duplex soils	14.1
	238.3

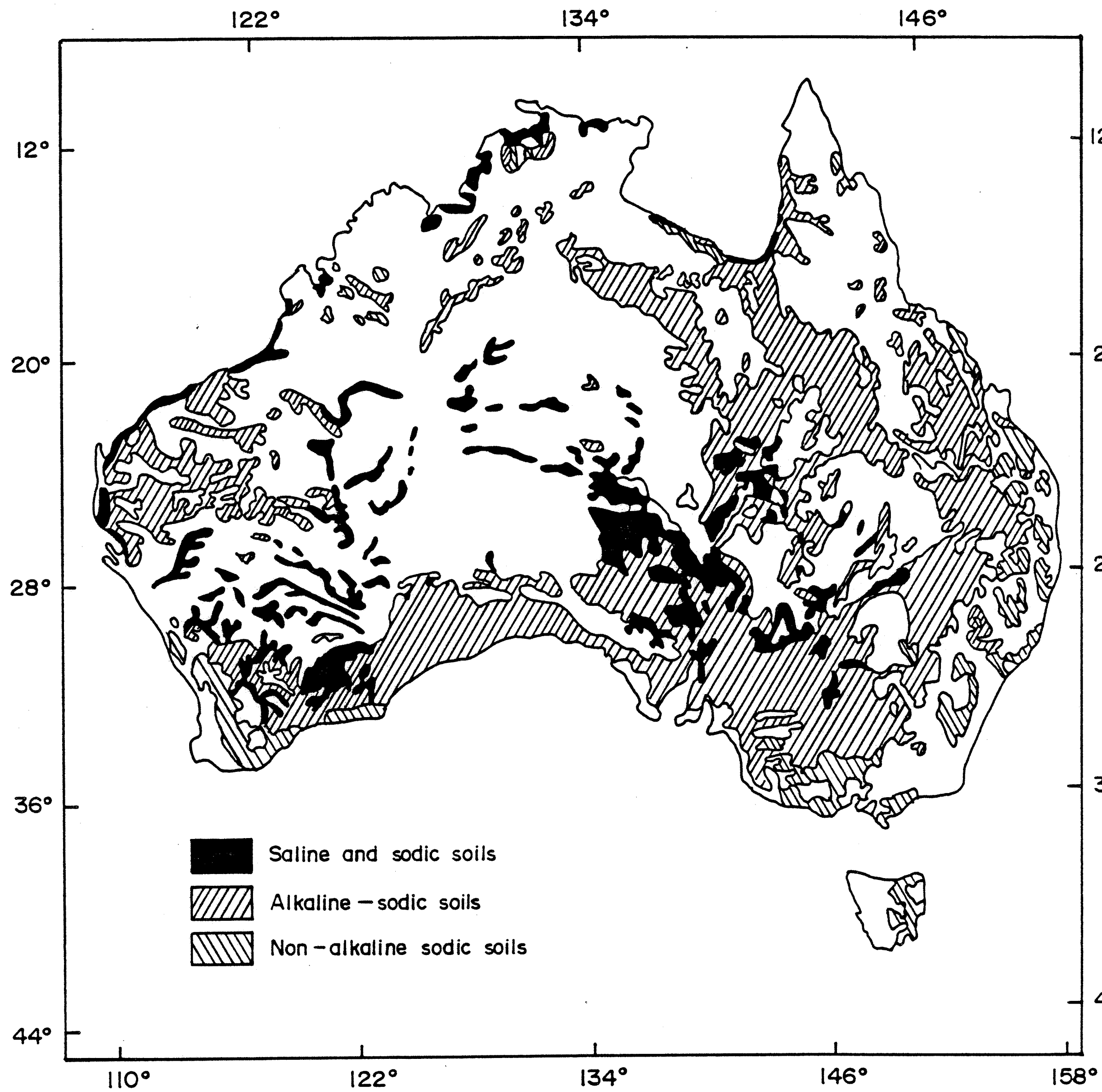


Figure 1.1 Salt-affected soils in Australia (based on Northcote and Skene, 1972).

It should be noted that Northcote and Skene (1972) defined saline soils as having more than 0.1% NaCl in surface sands and loams, more than 0.2% NaCl in surface clay loams and clays or more than 0.3% NaCl in the B horizon. Sodic soils were defined as having an exchangeable sodium percentage (ESP) of more than 6 within the top metre and strongly sodic soils as having an ESP greater than 15 within the top metre. These criteria differ from guidelines established in other areas of the world and have been adopted because of the high proportion of sodium chloride found in the soluble salts of Australia. In North America, saline soils are defined as having an EC greater than 4 dS m^{-1} and sodic soils are defined as having an ESP greater than 15 (Richards, 1954). Szabolcs (1978) distinguished solonetz soils as having greater than 0.2 percent soluble salt in the surface soil layer. Thus, the Australian standards for saline soils are low and the areas of salt-affected land on different continents are not directly comparable. However, arguments over the type of guidelines used to define salt-affected land cannot change the fact that a very significant proportion of Australia's land surface is adversely affected by excess soluble salt levels.

One of the main reasons for the widespread occurrence of salinity is the continent's climatic characteristics, which include an average annual precipitation of 420 mm of which 87% is lost to the atmosphere by evaporation and transpiration (Australian Water Resources Council, 1975). Since it is evaporation that drives the salinization process, there is a high potential for salinization to occur. Most of the saline area shown in Figure 1.1 is primary salinity, which has developed naturally and is not attributable to human activity.

More concern has arisen over secondary salinization and the anthropogenic spread of salinity since European settlement took place. In Table 1.2 it can be seen that the proportion of man-induced salinity in Australia is approximately 13% of the total area of ~~secondary~~ salinization. It has been observed that the ~~secondary~~ salinity problem has increased after European settlement beyond that which could be expected to occur under natural conditions. This implies that land management practices have been detrimental to the environment, and in the case of ~~secondary~~ salinity, those

Table 1.2. Areas of ~~secondary salinization~~ saline soil in Australia. (SCAV, 1982)

	Area (.000,000 ha)
Salt-affected sufficiently to affect primary production	32.4
Natural salt, occurred before European settlement	28.2
Induced salt, result of European settlement	4.2
Scalding (90% of all induced salting)	3.78
Seepage salt (non-irrigated)	0.43
Irrigation salting	0.18

practices which increase the amount of soil water available for evaporation or that strip the fragile vegetative cover from the soil surface and leave it unprotected are especially to blame.

Soil is a valuable resource, which for management policy formulation may be considered non-renewable. Thus, it is in the nation's best interests to protect the land and prevent further spread of salinization. To achieve this goal, there is a need for thorough understanding about the environmental mechanisms involved in the formation of saline soils. This understanding makes possible the identification of management strategies that will help prevent salinization or perhaps stabilize or even reclaim areas that have already been affected. Ultimately, it will be the cost of management compared to the potential economic returns that will determine the feasibility of different management schemes. But unless the environmental system is fully understood and the potential side-effects of land management have been identified, economic assessments can be misleading because they may neglect important, unidentified components of the natural world.

1.2 Literature Review

1.2.1 The Cause of Salt Accumulation

The cause of salt accumulation has been a matter of interest for a very long time. Hilgard (1877) has been credited with producing the first publication dealing with salinity in the United States. Although the mechanism of salt accumulation was not fully understood at that time, Hilgard suggested the most obvious remedy for the problem was to leach the salts by flooding, accompanied, if possible, by underdrains. To date, this remains the only mechanism by which soluble salts can be removed from a saline soil.

It was recognized early in this century that salinity problems were associated with areas that were wet or had high water tables (Harris, 1920; Wood, 1924). Kelley (1951) stated "Water then is the chief agent by which salts are moved, and its evaporation gives rise to the accumulation of salts in the soil". Thus, salt-affected land has been recognized for many years as being a water problem rather than a soil problem.

Once the link between high water tables and saline soil was established, research began to focus on the unsaturated movement of water that resulted from evaporation at the soil surface. The final process involved in the salinization of any landscape is the evaporation of water at the ground surface. At this point water vapor is separated from its load of soluble material which is left behind and accumulates. Since evaporation dries the soil, the final water movement takes place as unsaturated flow but the flow rate depends upon the matric suction gradient in the soil which is a function of the distance between the free water surface (water table) and the evaporating surface.

The equation describing steady upward flow is (Hillel, 1980)

$$q = K(¥)\,(d¥/dz - 1) \qquad (1.1)$$

where
q = evaporative flux (steady-state conditions)
K = hydraulic conductivity
¥ = suction head and
z = height above the water table.

Equation 1.1 can be rewritten as

$$q/K(¥) + 1 = d¥/dz \tag{1.2}$$

which can be integrated to give the relationship between depth and suction:

$$z = \int d¥/(1 + q/K(¥)) \tag{1.3}$$

To do the integration in equation 1.3, a relationship must be established between K and ¥ such as that suggested by Gardner (1958) below.

$$K = a/(¥^n + b) \tag{1.4}$$

where a,b and n = constants.

Talsma (1963) used the above relationship to solve equation 1.3 and produced plots of the suction distribution over a water table in different soils for various steady-state upward flux rates. It is apparent from the example in Figure 1.2 that as the depth to the water table increases, the upward flux rate that can be maintained is reduced. The form of the suction distribution varies between different soils since water moves upward by capillary action from greater depths in fine-textured soils than in coarse-textured soils. But regardless of the differences between soils, the upward flow of water to an evaporating surface is restricted by the depth of soil through which the water must be drawn from a free water surface. This depth is usually referred to as the 'critical depth' to the water table (Talsma, 1963; Peck 1978a).

The depth at which groundwater presents a salinity hazard depends on more than simply the matric suction distribution of the soil. The concentration of salt in the groundwater as well as climatic factors such as temperature (evaporation potential) and precipitation amount and frequency also influence the risk of salinity. The upward movement of water from a water table is only one factor determining net water movement, the other factor being the volume of water infiltrating into the soil. These processes work against each other in terms of soluble salt movement and there will be either a net downward or upward movement of soluble salts depending on which process is dominant. Jackson et al. (1956) found that the net water movement at Tintinarra, South Australia, fluctuated with seasonal climatic changes such that there was a net upward movement of salt during

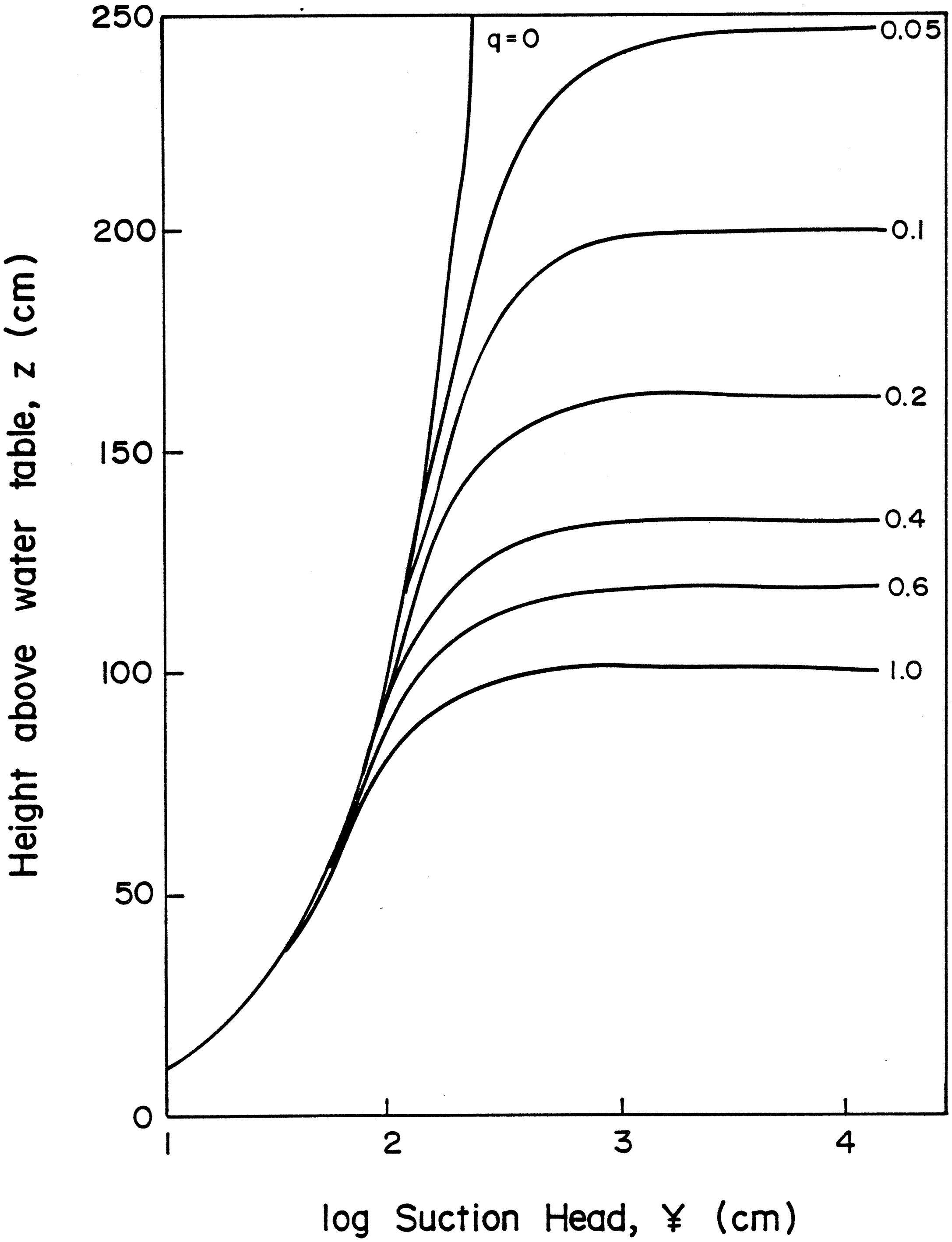


Figure 1.2 Relationship between upward water flux and water table depth for a Yandera loam soil (from Talsma, 1963).

the dry season and a net downward salt movement in the wet season. Benz et al. (1964) found that runoff water that collected in microdepressions was sufficient to desalinize the soil and groundwater beneath the depressions while the microridges remained saline. Thus, net vertical water movement through a soil can be finely-balanced and a small increase in infiltration could possibly desalinize a saline soil or a slight rise in the water table could cause a sufficient increase in upward water flux to salinize a non-saline soil. It is, therefore, not surprising that man can cause considerable salinity damage through land management practices that disrupt the natural hydrological cycle.

Although upward water movement from shallow unconfined groundwater has received a great deal of attention in salinity research, regional aquifer systems can also cause salinity. Benz et al. (1961) documented a saline area in Grand Forks County, North Dakota which was underlain by Dakota sandstone. The piezometric surface of the sandstone was above the ground surface as evidenced by several flowing wells and piezometers. Where the piezometric surface was high in relation to the ground surface, soil salinity levels were also high. Since the water chemistry of the Dakota sandstone was similar to that of the shallow groundwater, it was assumed that the sandstone was contributing to the shallow groundwater which was later verified with piezometer readings. In Saskatchewan, Canada several saline areas were found to be a result of artesian discharge from confined glacial and bedrock aquifers and this mechanism is considered to be the main reason for most of the salinity problems in that province (Henry et al., 1985). Similar aquifer systems have been documented in Australia such as the 'valley salinity' described by Bettenay et al. (1964) in the Belka Valley of Western Australia and the 'Type A' salinity described by Van Dijk (1969) in southeastern New South Wales.

The characteristics for this type of salinity are illustrated in Figure 1.3. The data was taken from a saline area in southwestern Saskatchewan where the piezometric surface of a shallow bedrock aquifer was approximately 1 m below the ground surface. The soil salinity values decreased with soil depth which is typical of sites where groundwater is evaporating at the soil

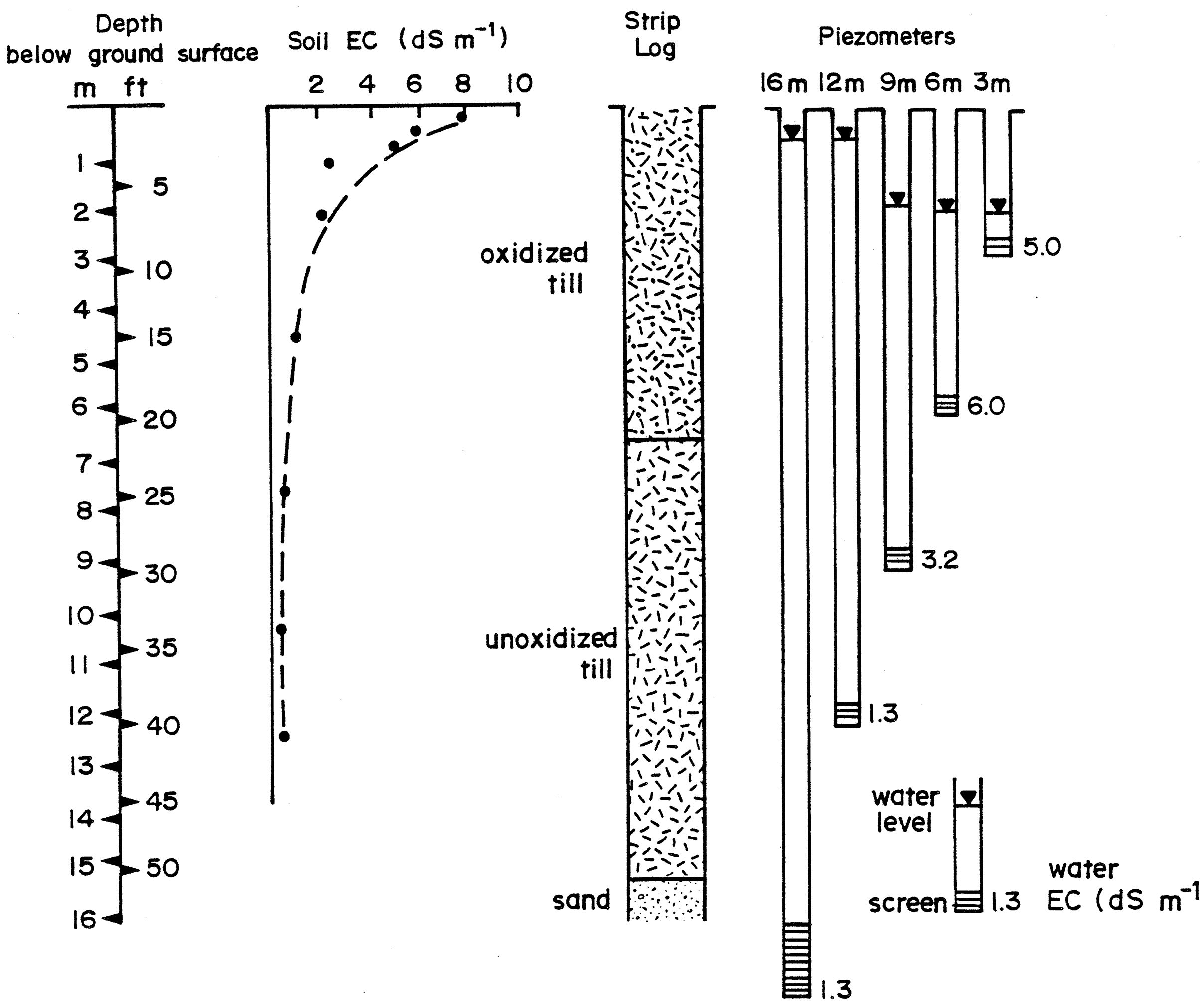


Figure 1.3 Characteristic soil electrical conductivity and piezometric potentials in glacial overburden above a bedrock aquifer under artesian pressure (from Bullock, 1985).

surface. Piezometers revealed that the aquifer was confined by the overlying glacial till and that an upward hydraulic gradient existed. The piezometer water EC levels illustrated how the salt content of the groundwater increased as it moved upward from the aquifer and into the glacial till, especially the oxidized till. On a topographic map, saline soils coincided closely with areas where the piezometric surface of the aquifer approached or was above the ground surface.

This type of salinity must be treated much differently than local saline seepages. In order to cure the salinity problem, the piezometric surface on the aquifer must be lowered and this can involve some difficult solutions. The aquifer causing the salinity problem described in Figure 1.3 was also the source of water for the local town. The area of land affected by salinity did not warrant losing the town water supply besides which the engineering considerations for dewatering an extensive bedrock aquifer would be difficult, if not impossible. Therefore, if an aquifer is the groundwater source for a saline area, it is essential that it be identified if meaningful decisions are to be made concerning management of the salinity problem.

1.2.2 Types of Salinity in Australia

A great deal of the literature concerning dryland salinity in Australia originates from research conducted in Western Australia. For this state, a recent estimate has put the area of previously productive land rendered useless for agriculture due to high salt concentrations at 263,752 ha (Conacher et al., 1983a), which represents an increase of 255% from the time the first salt land survey was carried out by the Western Australian Department of Agriculture (Burvill, 1956). Although the land area represents only 2% of cleared wheatland soils in Western Australia, the salinity is not uniformly distributed throughout the region and it is the rate of increase which is causing alarm. Further, the salinization of freshwater supplies may be even more serious than the salt-affected land. All the major streams and rivers in southwestern Australia have been polluted by soluble salts and their waters are now unfit for human consumption (Conacher et al., 1983a).

The secondary salinity problems in this state have been attributed unanimously to the clearing of native vegetation for the purpose of cropping or growing exotic pasture species (Bettenay et al., 1964; Smith, 1966; Peck, 1978b; Williamson and Bettenay, 1979; Nulsen and Henschke, 1981; Conacher et al., 1983a; Nulsen, 1986). Native vegetation extracts larger quantities of water from greater depths for longer periods of time than introduced crops or pastures (Greenwood et al., 1985). Thus, land clearing has upset the hydrological balance since a lower quantity of water is transpired. The effects of clearing vegetation do not manifest themselves for a period of years after ~~the~~ the clearing takes place. This 'lag time' is somewhat difficult to assess due to lack of information concerning the time of clearing but estimates usually put it somewhere between 5 and 40 years with a mean of approximately 20 years (Conacher et al., 1983a).

Williamson and Bettenay (1979) say that the excess water has caused an increase in stream flow, groundwater recharge and development of water-logged soils . One school of thought from Western Australia adheres to the theory that the rise of groundwater levels has resulted from increased deep percolation of soil moisture below the root zone. The resultant higher water table causes increased seepage of saline groundwater to the soil surface. Bettenay et al. (1964) referred to this as 'valley salinity', Williamson and Bettenay (1979) used the term 'saline seepage' and Nulsen and Henschke (1981) called such discharge areas 'scalds'. Conacher et al. (1983b) argued that rising groundwater levels are a result of reduced uptake by deeper-rooted plants rather than increased infiltration and that the excess water resulting from clearing native vegetation has increased throughflow along shallow perched aquifers. Conacher and Murray (1973), Conacher (1975, 1982) and Conacher et al. (1983a, 1983b) have stated that increased throughflow has caused waterlogging and mobilization of stored salt in the soil profile resulting in the formation of saline areas referred to as 'salt scalds'. As evidence, they cite several examples of 'salt scalds' in southwestern Australia that occur in areas where there has been no recorded increase in groundwater levels. However, reclamation of salt-affected land using throughflow interceptors has been only partially successful which indicates that some other salinization mechanism is also operating in the areas that were studied (Conacher et al., 1983a, 1983b). The distinction between water table salinity and throughflow salinity is an important one because these are two very different hydrological processes which require different management practices if they are to be controlled (Conacher, 1982).

In Victoria and South Australia, the estimated occurrence of secondary salinity is 1.4 M ha for both states, the majority of the area (1.25 M ha) being erosion-induced scalds (SCAV, 1982). These scalds are similar to those found in central New South Wales and Queensland, which will be discussed subsequently. The greatest concern over salinity in Victoria and South Australia has arisen over saline seepage resulting from higher groundwater levels. This type accounts for the remainder of the secondary salt-affected area in these states and appears to be on the increase (Mitchell et al., 1978; Jenkin, 1981).

The cause of the secondary salinization has again been attributed to increased deep percolation of soil water because of reduced transpiration as a result of replacing native forests with pasture and crop (Mitchell et al., 1978; Greig and Devonshire, 1981; George, 1984). Dyson (1983) provided evidence of the ability of native vegetation to reduce groundwater recharge compared to shallow-rooted grasses. In a paired catchment study of forest and cleared land near Bendigo, Victoria the piezometric heads in all the cleared catchments increased by 0.50-0.75 m, while heads under the forested catchments remained unchanged. The increased groundwater recharge following clearing and the subsequent development of groundwater discharge has created a flow system that is effectively leaching ions toward the discharge sites. The resulting salinity manifests itself in a variety of forms because of the variable geomorphology in southern Australia.

There are extensive areas through valleys and basins that have become saline as a result of a regional rise in water table levels (Macumber, 1969; Jenkin, 1981). This form of salinity is potentially very serious since any rise in the water table sufficient to cause surface salinization has an immediate effect over large areas (Jenkin, 1981). There are also localized seepages which occur in a variety of forms depending upon the local geomophology and stratigraphy. George (1984) described a saline area near Boho, Victoria which had remained stable over the past 50 years. A hydrological investigation revealed that the salinity was a result of a shallow water table maintained by lateral groundwater flow along an unconfined surface aquifer. It should be noted that upslope from the saline area, a non-saline discharge area existed that was sustained by a strong upward hydraulic gradient. It was non-saline because of the lower salt content in the groundwater at this point. George (1984) noted that the Boho catchment differed from Kamarooka (Dyson and Jenkin, 1981) because in the latter catchment, salinity resulted from strong vertical hydraulic gradients that existed below the seepage area. No vertical gradients were detected in the saline area at Boho.

It is considered essential to be aware of the preferred paths of water movement in each terrain type if effective remedial strategies are to be developed (Jenkin, 1981). For instance, Jenkin (1979) noted the fundamental difference between valley floor salinity (which he called salt pan) and true hillside seepage (which, although uncommon, is also found in Victoria). With seepages, the salinization appears first on the valley side and may eventually affect the adjacent valley floor. Salt pans appear first on the valley floor and often migrate laterally upslope and up-valley. This is an important distinction because effective control measures are different in each case.

There has also been concern expressed over increasing salinity levels in stream, dam and bore waters in Victoria. Greig and Devonshire (1981) related catchment streamflow salinity (S, mg l^{-1}) to the percentage catchment area occupied by forest (T), the percentage catchment area lying on sedimentary bedrock (R) and mean annual precipitation (P, mm) using the empirical formula

$$\log S = 1.9624 + 0.0092\ (100-T) + 0.0045\ (R) - 0.008\ (P) \qquad (1.5)$$

$$r^2 = 0.71, \quad n = 56$$

Equation 1.5 was developed using information from 56 catchments located throughout Victoria. Although the relationship between salinity and these factors is empirical, it provides a rough guideline to higher risk areas where stream salinity is likely to develop. The forest cover or tree-clearing factor is of particular interest since it can be controlled through land management. In Victoria, there has been a great deal of consideration given to management of trees for salinity prevention and control (Mitchell et al., 1978; Greig and Devonshire, 1981; Morris and Thomson, 1983) but there has been no indication about the success of this strategy.

In the arid interior regions of New South Wales and Queensland, the most common form of secondary salinization is 'scalding' with the total scald area for both states estimated at 1.5 M ha (SCAV, 1982). The accepted definition of scald for this region was given originally by Beadle (1948a) as 'a bare area produced by the removal of the surface soil by the wind, with the consequent exposure of the subsoil which is or becomes relatively impermeable to water.' This definition has been generally accepted (Condon and Stannard, 1957; Jones, 1966; Cunningham, 1974) although Warren (1965) postulated that water erosion may also be an important agent for stripping topsoil from the soil surface in this region. Peck et al. (1983) did not consider scalds to be very important in the overall salinity problem in Australia because they occur mainly on low productivity land and they knew of no evidence to suggest that scalds caused detrimental offsite effects. However, scalding accounts for 90% of the secondary salinity in Australia and occurs in every state on the continent (SCAV, 1982). In addition, Adamson (1976) and Alchin (1983) have both shown that runoff and soil loss from scalds is significantly greater than that from non-scalded areas in the same region.

Scalds are distinguished from other features of the landscape such as dry lake beds, which are referred to as 'claypans' (Beadle, 1948a; James, 1956). Hazelton (1980) also distinguished scalds from non-scald bare areas of the landscape using the criteria that scalds were bare areas that failed to revegetate following heavy rainfall. Beadle (1948a) also recognized 'pseudo-scalds' as areas that become compacted with a surface clay film and thus have a similar appearance to scalds but have not been eroded.

Scalds vary in area from a few square meters to vast stretches of land several square kilometers in size (Beadle, 1948a). They appear as saucer-shaped depressions in the landscape where the topsoil has been removed and are usually devoid of vegetation with a smooth and often shiny surface that is commonly strewn with coarse sand grains, gravel and pebbles. Most commonly, they occur on texture-contrast soils where a light, erodible topsoil overlies a heavier subsoil, since it is the exposure of the subsoil which gives scalded areas their characterisitic appeareance (Condon and Stannard, 1957; Shaw et al., 1987). Although the general appearance of scalds is similar in different areas, the scald surface is more variable. Beadle (1948a) classified scalds according to the nature of the surface into three categories: 1) hard, 2) soft and 3) limestone scalds. Hard scalds have hard, compact surfaces with an absence of cracks. They may be either compacted clays or cemented sands. Soft scalds have a soft, spongy surface with surface cracks present. The softness results from the 'nutty structrure' of the soil which, when dry, shrinks to form small aggregates. Limestone scalds develop only on soils in which limestone nodules occur close to the surface. When the surface is removed the nodules lie embedded in a clay matrix. After prolonged exposure, water movement redistributes the lime as a film over the scald making it hard and relatively impervious.

James (1956) and Condon and Stannard (1957) restrict the definition of scald to those eroded areas where a swelling clay subsoil has been exposed and define the process where a non-swelling subsoil is exposed as 'windsheeting'. Most investigations of scald in Central New South Wales make reference to the swelling nature of the surface and how rapidly it seals upon wetting presumably as a result of high sodicity (Knowles, 1954; James, 1956; Condon and Stannard, 1957; Jones, 1966; Cunningham, 1974). There is very limited soil chemical analysis to substantiate the sodium levels but Hazelton (1980) did find that high sodicity, especially in the shallow subsoil, was common in the soils around Fowler's Gap. Although a slaked and sealed surface is common to most scalds in Central New South Wales, the salinity level is variable. Beadle (1948b) found very low soluble salt contents in scald soils of the 'Four-mile' experimental reserve near Condobolin, New South Wales. Conversely, Jones (1966) found high soluble salt concentrations in the Paradise Experimental Area near Hay, New South Wales. The profiles analysed by Hazelton (1980) varied from non-saline to extremely saline according to Northcote and Skene's (1972) criteria.

Groundwater discharge does not appear to be a factor in the development of scalds in Central New South Wales and Queensland since there is no mention of seepages or springs. ~~The main consideration for reclaiming these areas is the establishment of vegetation.~~ Once the vegetation is stripped from the soil surface, it becomes very susceptible to erosion and forms a hostile environment for plants to re-establish. Drought and overgrazing are blamed for causing these scalds to develop, although some are known to have existed before the land was settled (Sturt, 1833 in Hazelton, 1980).

In contrast to the erosion-induced scalds of central New South Wales, the saline soils on the Slopes and Tablelands of eastern New South Wales result almost entirely from shallow water tables (Hamilton and Lang, 1978). These saline seepages are usually classified according to landscape position with the valley-floor and hillside seepage types described by Hamilton and Lang (1978) being roughly equivalent to the Type 'A' and Type 'C' salting documented by Van Dijk (1969).

A recent report by Wagner (1987) highlighted the spatial and temporal extent of saline seepage in the southeast region of New South Wales. The information for the report was obtained from field inspection during 1986, examination of available aerial photography from 1941 to 1985 and discussion with landholders, especially older landowners, who had relevant personal knowledge about the areas concerned. Originally there were 100 sites selected for the study but substantial information was available for only 92 of the sites and these were included in the report (Figure 1.4). For southeastern New South Wales, seepage scald occurs exclusively in the northern half of the region (Wagner, pers. comm). There are only insignificant patches on the higher elevations in the south and rare occurrences in the higher rainfall areas to the east. The bulk of the sites are

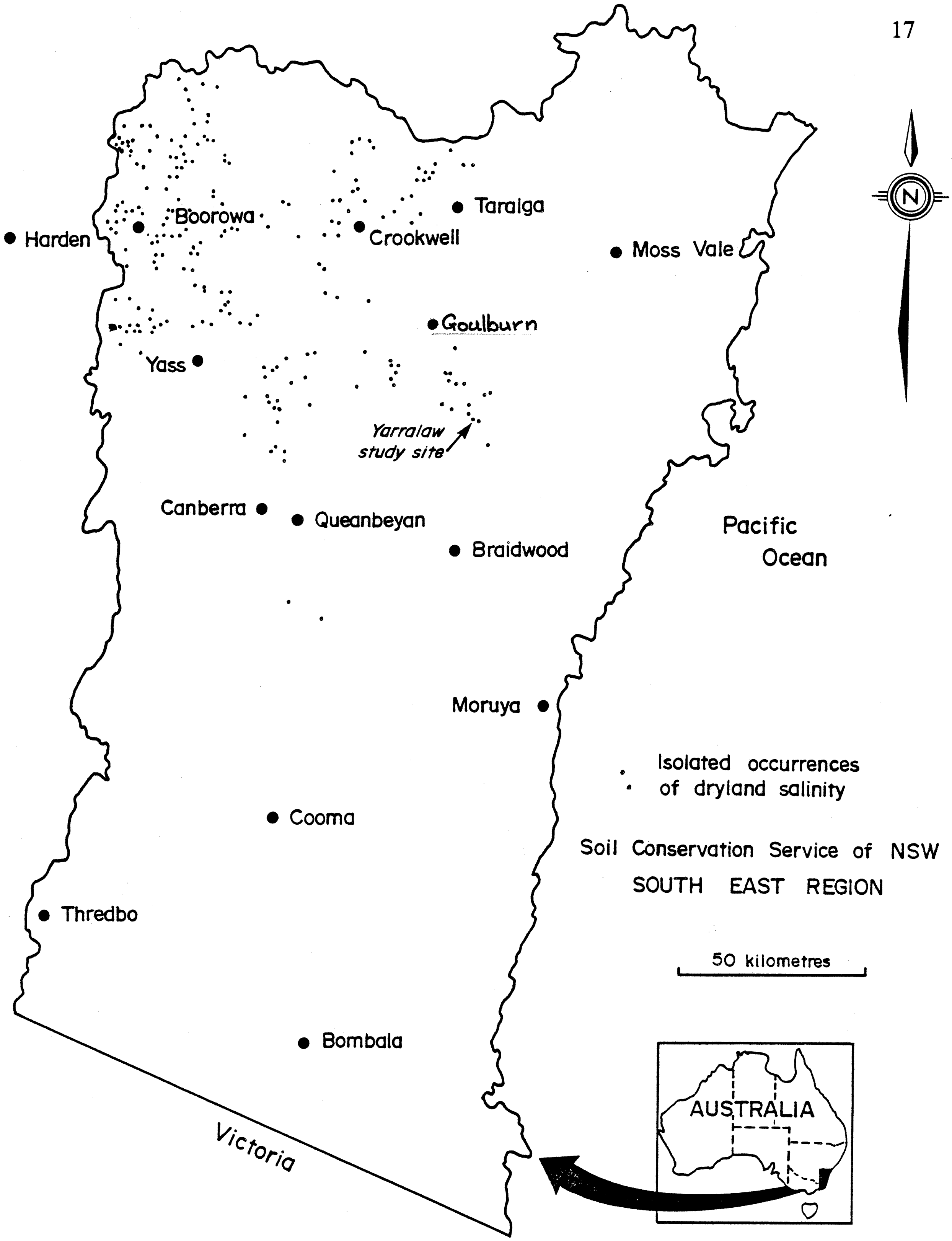


Figure 1.4 Map of southeastern New South Wales showing the location of seepage scalds studied by Wagner (1987).

situated the northwestern part of the region, with significant occurrences also found in the eastern part, principally in the Upper Shoalhaven catchment. Of the 92 sites studied, 72 occurred in regions with mean annual precipitation less than 700 mm, 68 sites occurred or bordered on Ordivician sediments consisting of greywhacke, shale, chert and siltstone deposited in a deep marine basin (Gunn, 1985), 83 sites occupied footslopes or drainage depressions and 90 sites had been completely or extensively cleared of native vegetation. There is a noticeable similarity between these factors and those used in the empirical equation for streamflow salinity (equation 1.5) developed by Greig and Devonshire (1981). For each seepage scald site in his report, Wagner (1987) documented the changes in salinity since 1941 or as available on aerial photography (Table 1.3).

From his study, Wagner (1987) concluded that the salinity problem in the region had increased significantly over the period from 1940-1985. The most significant increase in salinity occurred in the period between 1950 and 1963 when the number of sites with a significant degree of salinity went from 19 to 60 (Table 1.3). During this time there were two instances where a period of two or three wet years were followed by a return to normal or below average rainfall. Wagner stated

Table 1.3. Dryland salinity, southeast region of New South Wales (Wagner, 1987)

	Number of sites in each class (total of 92)						
	Degree of salinity			No Observation Possible	Change since previous obser.		
	None	Minor	Signif.		Degrad.	No Signif. Change	Regen.*
1941-44	34	37	10	11	47**	34**	Nil**
1950-53	19	45	19	9	58	21	4
1960-63	4	24	60	4	71	12	5
1970-73	2	31	56	3	51	25	13
1982-85	7	37	48	3	42	22	25***
1986	7	39	46	-	46	17	29***

*Regeneration is relative and can be much more marked on some sites than on others.
** Initial observations.
*** Includes 7 sites showing no salinity where full regeneration has taken place.

that this was possibly the reason for the salinity increase but he did not indicate the process by which this would occur. Van Dijk (1969) observed that outbreaks of salinity during the summer of 1958-59 in the Yass Valley, north of Canberra, repeatedly occurred immediately following short periods of intense, soaking rainfall that interruped extended periods of warm, dry weather. His explanation was that relict salts contained in the ancient sediments of the valley were being redistributed by rainwater that infiltrated the soil and carried the soluble salts to discharge points.

As is the case for most of Australia, the increase in secondary salinity in southeastern New South Wales has been attributed to clearing native vegetation and overstocking pastures which causes a reduction in transpired water, a rise in the water table and increased groundwater movement to the soil surface (Wagner, 1957; Hamilton and Lang, 1978; Cumming et al., 1984; Gunn, 1985). Reclamation techniques have focused on establishment of vegetation (Hamilton and Lang, 1978) or on mechanical works to control the erosion hazard on the bare areas (Wagner, 1957). Efforts to improve salinized land in this area have had only limited success (Wagner, 1987) which is understandable because of the variability in geology, landscapes and climate found in this region (Higginson, 1970; Gunn, 1985).

1.2.3 Difficulties with Australian Terminology for Salt-affected Land

Comparisons of dryland soil salinity in different regions of Australia are hampered by the differences in terminology contained in the literature. Salinity investigations have been conducted on a regional basis and the terminology has evolved in a similar fashion. It is apparent that the term 'scald' has been used in a different context by different authors which makes it impossible to formulate a precise definition of scald based on the existing literature. For this reason, the terminology for salt-affected soils in Australia was evaluated as a first step towards eliminating the ambiguous usage of some terms.

Salt-affected land is generally divided into two categories; 'primary salinity' is that which has occurred under natural conditions and 'secondary salinity' which has resulted from man's activities. Secondary salinity is further subdivided into 'wetland salinity' which occurs under irrigation and 'dryland salinity' which occurs under non-irrigated conditions. Areas of dryland salinity in Australia are usually categorized either as 'scalds' or 'seepage salinity', but the distinction between these terms is not always clear. The term 'scald' is used to describe different types of dryland salinity in different areas as illustrated by the following examples.

> 'A scald is defined as a bare area produced by the removal of the surface soil by the wind, with the consequent exposure of the subsoil which is or becomes relatively impermeable to water' (Beadle, 1948a).
>
> 'Scalds have been formed where overgrazing and other forms of land disturbance have resulted in the loss of surface cover and then the erosion of the lighter topsoil to reveal the originally saline or sodic subsoil' (SCAV, 1982).
>
> 'Scalded areas are caused when wind or water erosion removes topsoil from texture contrast soils with sodic clay subsoils. This usually occurs as a result of denudation of vegetation by overgrazing, drought, or fire. When vegetation is removed, wind and water can remove the topsoil and a crust forms at the topsoil-subsoil boundary' (Shaw et al., 1987).
>
> 'Salt scalding is a term which should be reserved for the form of dryland salinity which is not associated with groundwater discharge' (Peck, 1980).
>
> 'The occurrences of dryland salinity in Queensland can be divided into two types.
> (i) Salinity associated with shallow water tables (wet areas).
> (ii) Scalded areas are not associated with water tables, but associated with saline and/or sodic soils (dry areas)' (Hughes, 1980).
>
> 'Several criteria can be used to describe and define salt scalds:
> 1. Salt scalds may have bare soil surfaces, be covered by dead trees, or be colonized by salt-tolerant plants.
> 2. Anaerobic conditions are common. Most salt scalds have perched water tables within a few centimetres of the surface, and surface seepages occur frequently on scald margins, especially in winter' (Conacher, 1982).

The first three definitions emphasize the erosional status of scald soils but do not mention the groundwater status. The next two definitions exclude groundwater discharge from the scald process. The last definition specifically includes the presence of shallow groundwater in the scald description. Obviously, there is considerable disparity concerning the meaning of this term.

All scalds, no matter how they are defined, are the result of surface soil degradation following the removal of vegetative cover. For this reason, the term 'scald' is a very good descriptor since it brings to mind the degraded condition which is common to all these areas. Conacher and Murray (1973) first used the term 'salt scald' to refer to the bare saline areas of Western Australia. They recognized that a similar term was used to describe a wind and water erosion process in the arid interior of Australia but said simply that the salinity problems in both locations had much in common. However, there are very major differences in the physical processes at work in different scalds according to the definitions above even though the end result may be similar.

Scalds may form in the absence of groundwater discharge. This process has been described for the arid regions of New South Wales and Queensland (Beadle, 1948a; Hazelton, 1980; Hughes, 1980). In these areas, active erosion is the problem that must be addressed and various management techniques have been evaluated for this purpose (Cunningham, 1974; Shaw et al., 1987). Scalds may also form as a result of groundwater discharge. Conacher (1975, 1982) described such areas in Western Australia. Similarly, Van Dijk (1969) described 'scalded areas' in southeastern New South Wales that are associated with groundwater discharge. For these areas, active salinization is the problem that must be addressed and different management techniques are required (Conacher et al., 1983b; Bullock, 1986).

Scalds that are formed as a result of erosion could be defined as 'erosional scalds'. However, erosion is common to most scalds and is not a practical means for distinguishing between them. The main difference in scalds is the presence or absence of a groundwater discharge condition and this author suggests that it be incorporated into the terminology in the following manner. 'Dry scalds' are not affected by groundwater discharge and are formed by the erosion of the topsoil and exposure of a previously sodic or saline/sodic subsoil. 'Seepage scalds' are formed by salinization associated with groundwater discharge. With these simple adjectives, two entirely different physical processes that cause dryland salinity can be clearly distinguished despite the similar appearance of the landscape they affect.

Dry scalds can be further subdivided by recognizing differences in salt status. Several authors have classified dry scalds as being either non-saline or saline (SCAV, 1982; Shaw et al., 1987), which is a useful distinction for making suitable management recommendations for each type.

The other term used to describe salinity problems resulting from groundwater discharge is 'seepage salting' or 'salt seep' (Hughes, 1980; Peck, 1980; Jenkins, 1981; SCAV, 1982). Saline seepages have an outward physical appearance very similar to scalds as indicated by the following descriptions (SCAV, 1982):

Scald - bared erosion pavement in undulating to flat land

Saline seepage - bare, scalded surfaces at positions near the break of slope

A clear distinction in these descriptions is lacking and it is suggested that 'saline seepage' could be referred to as 'seepage scald' without any misinterpretation about either the appearance or the cause of the salinity. This effectively groups all saline areas that are a result of groundwater discharge into one category.

It is tempting to suggest that the term 'scald' be reserved for saline areas not affected by groundwater discharge as suggested by Peck (1980). The difficulty is that saline areas are frequently labelled as 'scalds' or described as being in a 'scalded condition' based only on their outward appearance. Often, the groundwater status of scalds is not known and it is misleading to assume that all areas described as having a 'scalded appearance' are not affected by groundwater discharge.

The classification system in Figure 1.5 is presented as a summary of the above discussion. The system is based on the differences in process at each level. Since it is the physical processes that are critical to an understanding of salinity, the system should provide a useful basis for management recommendations. The terms are not new or unfamiliar, they are simply re-arranged to clear away the ambiguity surrounding their use.

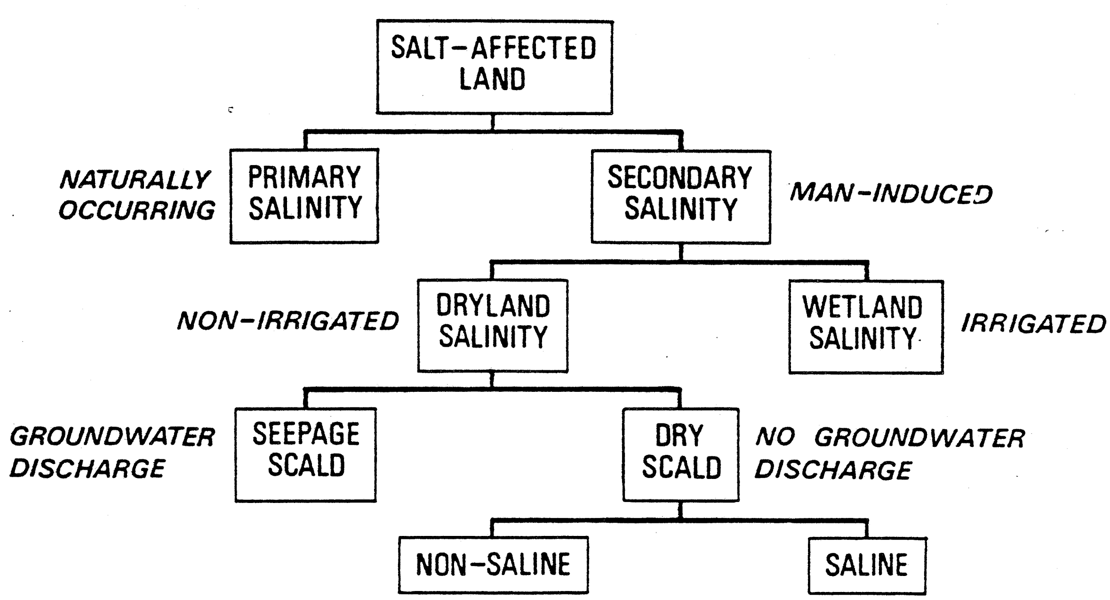


Figure 1.5 Proposed classification system for salt-affected land in Australia.

1.3 Thesis Aims and Objectives

The purpose of this study was to quantify the processess at work in a salt-affected catchment in the southeast region of New South Wales. Generally, the salinity problem in southeastern New South Wales had been attributed to groundwater discharge as a result of poor land management practices causing the level of the water table to rise (Wagner, 1957; SCAV, 1982; Peck et al., 1983). However specific site studies in the region were relatively rare and there was very little information concerning groundwater levels. There was also concern about the contribution of these scattered saline areas to stream salinity and contamination of water supplies (Cumming et al., 1984). In addition, the distribution of the salt-affected sites in the region is puzzling since it is not known why they occur where they do and it is possible that the salt-affected area could expand. Although Wagner (1987) identified some common characteristics of these seepage scalds, there appeared to be cases where similar catchments were not similarly salt-affected. It was hoped that a detailed investigation into the soil and hydrological characteristics of a saline area and its neighbouring unaffected area would isolate diagnostic properties unique to salt-affected sites that could be used to pinpoint other sites which may be prone to salinity in the future. The thesis objectives below were formulated to address the concerns outlined above.

To distinguish the Yarralaw seepage scald from the surrounding non-scalded area on the basis of the soil and hydrological properties.

To assess the threat of scald expansion in the Yarralaw catchment.

To assess the contribution of the Yarralaw seepage scald towards offsite stream salinity and siltation of potential water supplies.

To determine the cause of the Yarralaw seepage scald.

The objectives above required detailed information to provide credible answers. It was the opinion of the author and supervisory committee that a study to provide this information for one salt-affected site could be completed within the lifetime of a PhD project.

CHAPTER 2
MATERIALS AND METHODS

2.1 Site Description

Yarralaw, a salt-affected catchment situated approximately 25 km southeast of Goulburn (Figure 1.4), latitude 34° 16' S, longitude 149° 53' E, was selected as a suitable site for a detailed investigation. It is a 37.8 ha subcatchment of Jacqua Creek, which drains into Nerrimunga Creek and eventually the Shoalhaven River (Figure 2.1). It had been identified as a particularly severe seepage scald by other investigators (Cumming et al., 1984; Gunn, 1985). The Yarralaw salinity resembled that found at many other locations throughout the southeast region of New South Wales (Wagner,1987) and had undergone similar management. Thus, it was felt that the results of the investigation would be relevant to several salt-affected areas in southeastern New South Wales. The small size (37.8 ha) and the close proximity of the site to the research facilities at Canberra were favorable points for the detailed investigation that was intended. The saline area was quite large (4.5 ha) in proportion to the total catchment and it was thought that the salinity would exert a measurable effect on the catchment hydrology. The questions concerning offsite effects such as stream salinity and siltation were particularly relevant since Yarralaw lies with the Shoalhaven River catchment (Figure 2.1), a system that is slated for development into one of Sydney's future water supplies (Costin et al., 1984).

The elevation at Yarralaw is approximately 620 m, with rolling topography and 30 m of relief. (Figure 2.2). The local bedrock is composed of porphyritic monzonite intruded through Ordovician sediments which have a widespread occurrence in that region (Gunn, 1985). Yarralaw contains alluvial valley fill, most probably derived from the surrounding Ordovician layers and deposited on the monzonite (Figure 2.3).

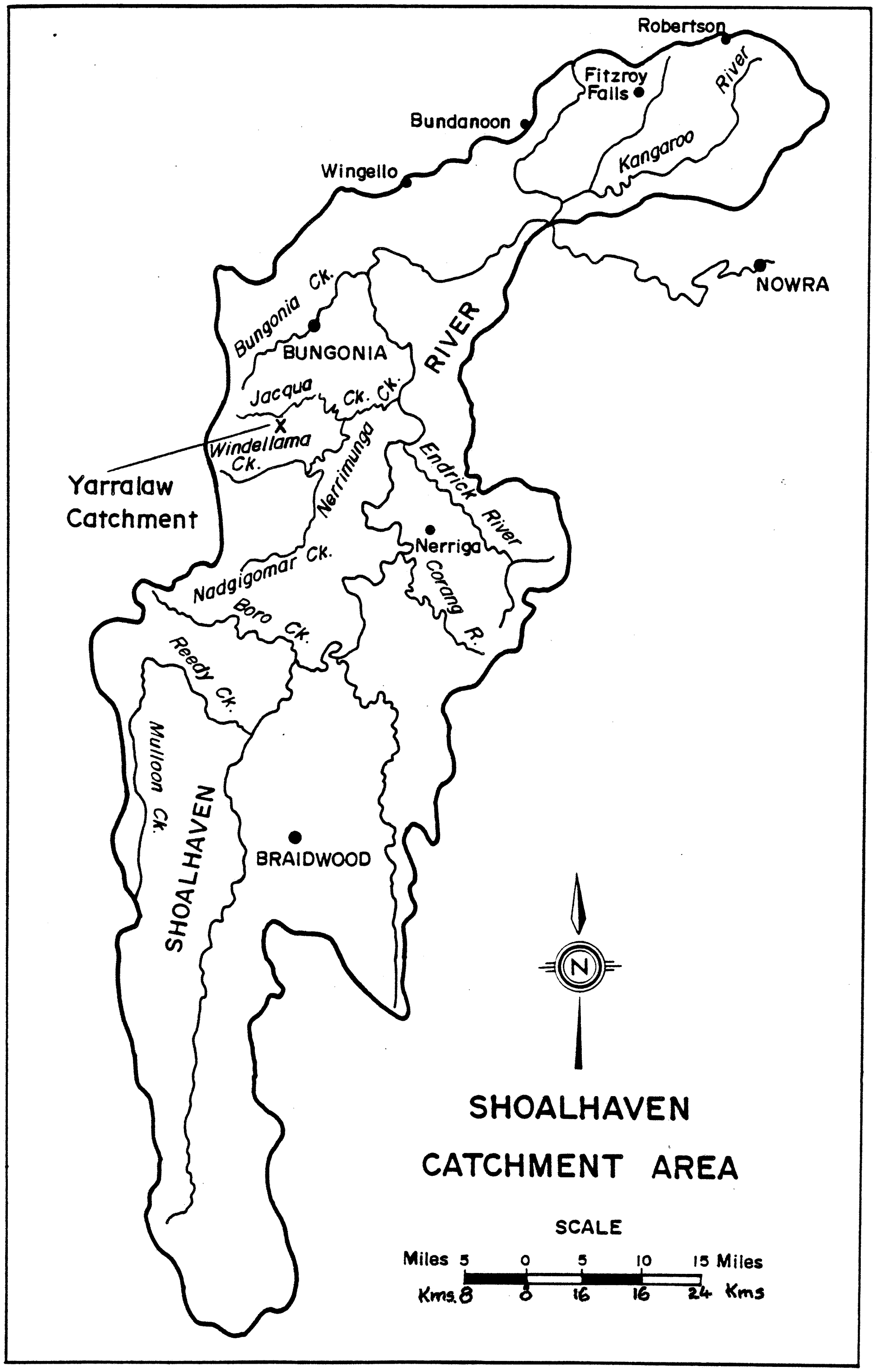


Figure 2.1 Drainage system of the Shoalhaven River showing the position of the Yarralaw site in the network (based on Higginson, 1970).

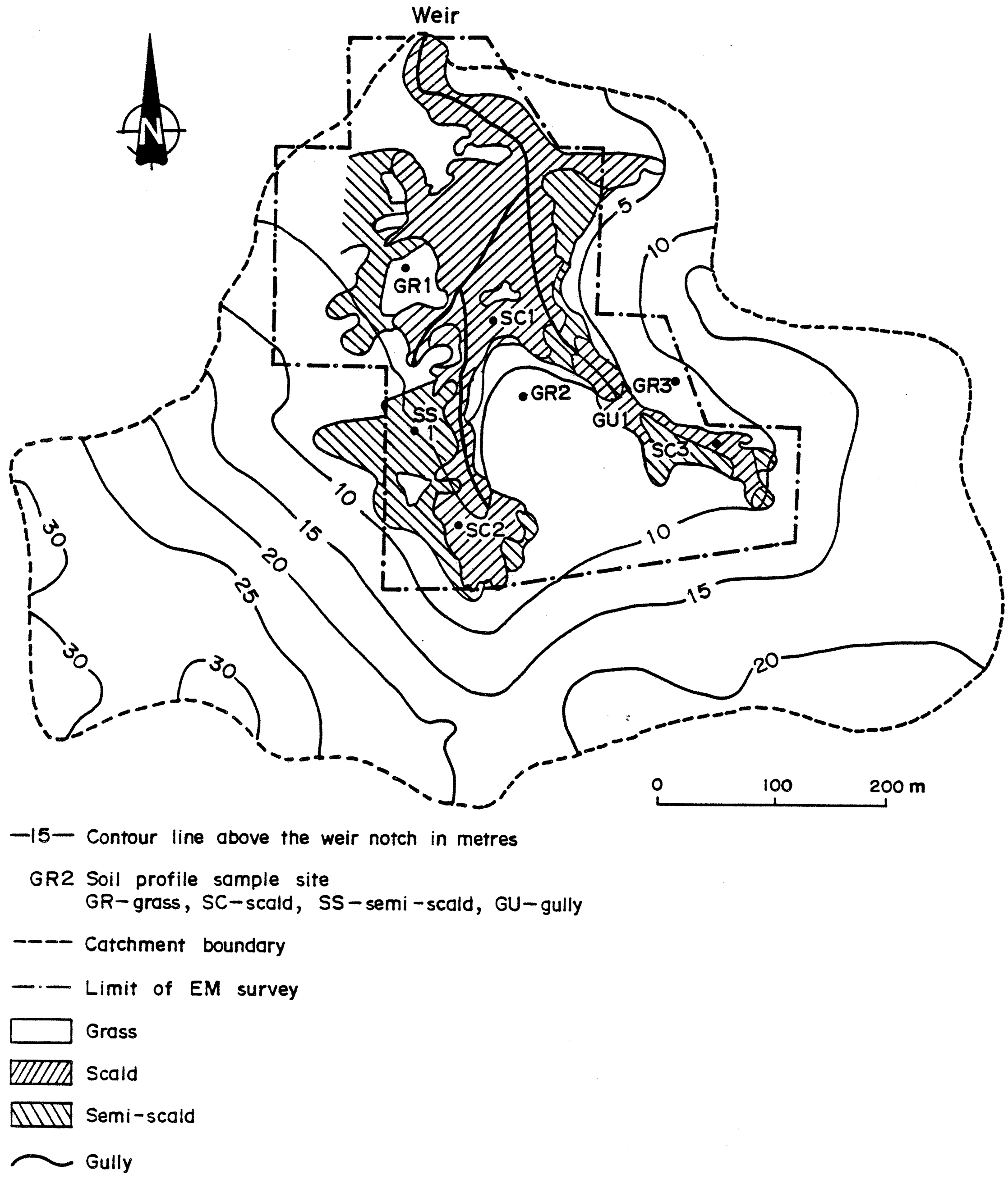


Figure 2.2 Topographic map of the Yarralaw catchment showing the location of the main gully, scald, semi-scald and grassland areas, the soil profile sites and the boundary of the electromagnetic survey for Figures 3.4 and 3.5.
Note: The location of the catchment is shown in Figures 1.4, 2.1 and 2.3.

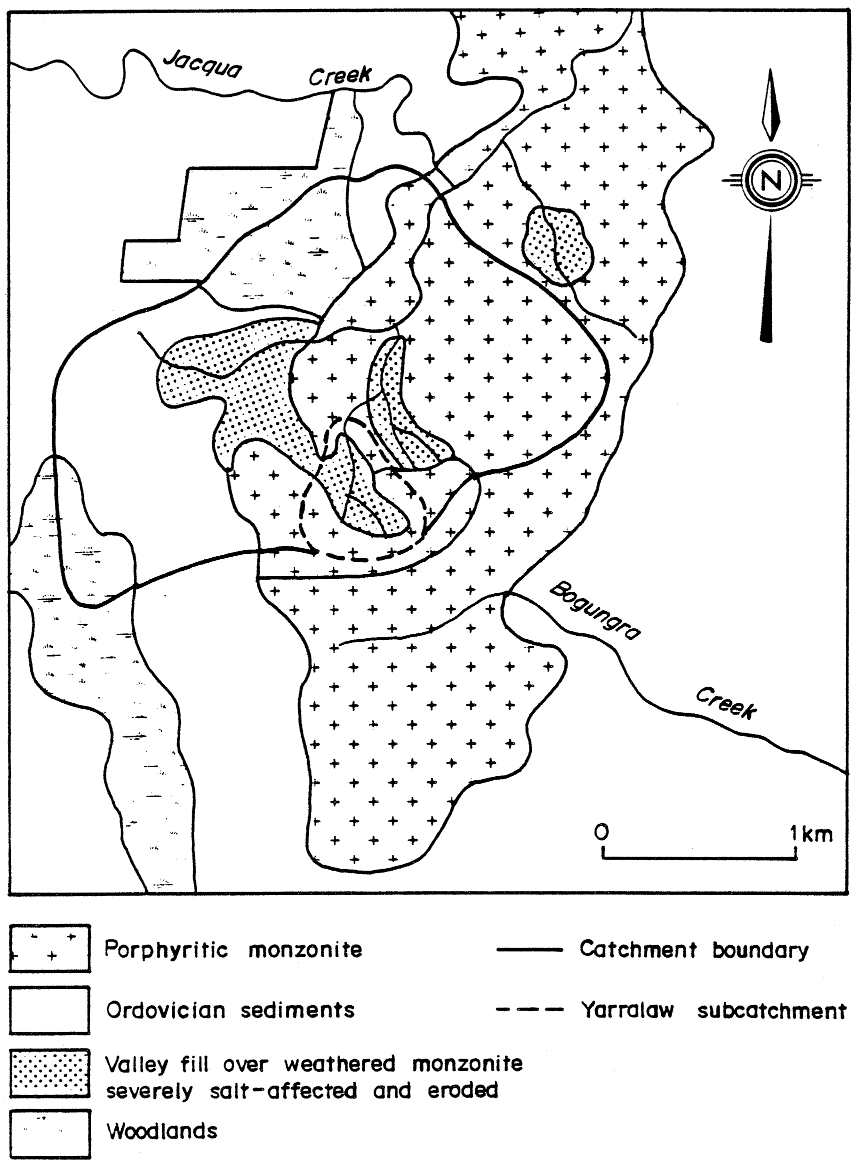


Figure 2.3 Geology of the region surrounding the Yarralaw site (from Gunn, unpublished data).

MacAlpine and Yapp (1969) described the climate of the local region. The average annual precipitation at Goulburn (closest meteorological station) is approximately 670 mm with an even distribution throughout the year. The mean monthly temperature ranges from 20.4°C in January to 6.7°C in July. The average annual potential evaporation is 1240 mm. The climatic properties from the Goulburn weather records are summarized in Table 2.1, along with Yarralaw rainfall measurements for comparision.

Table 2.1. Goulburn climate characteristics (MacAlpine and Yapp, 1969) and measured rainfall at Yarralaw

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Temp.[1]	20	20	18	14	10	7	7	8	11	14	17	19	14
Evap.[2]	188	145	114	58	56	43	48	61	79	114	147	183	1237
Rain[3]	63	57	58	49	51	58	52	52	47	64	54	65	671
Measured Yarralaw rainfall (mm)													
1985						46	6	50	82	103	125	49	
1986	71	1	0	68	38	4	56	96	26				

1 - Mean Temperature (°C), 30 years of record
2 - Mean Evaporation (mm), derived from mean monthly maximum and minimum temperatures, vapor pressure and day length (Fitzpatrick, 1963)
3 - Mean Rainfall (mm), 1901-65

The woodlands in the local vicinity (Figure 2.3) are dry sclerophyll forest-type with Eucalyptus rossii, E. macrorhyncha and E. melliodora being commonly found. The main grass species is Themeda australis, but Hordeum marianum and Cynoden dactylon are found in the saline areas. Landuse is unimproved pasture for sheep grazing.

Seepage scald occurs along the bottom slope positions of the catchment. The scald has been severely eroded with gullies up to 1.5 m deep along the main watercourses and sheet erosion of the topsoil in adjacent areas. There are patches of poorer grass growth adjacent to the scalded area referred to as 'semi-scald' because they are quite distinct from the better growth on the grassland.

Over most of the site, the boundaries between scald, semi-scald and grassland are very distinct and can be mapped quite easily (Figure 2.2).

From the aerial photographs of the site, it is evident that most of the trees in the area area were ring-barked prior to 1941. This practice of peeling a strip of bark from the girth of the tree is done to kill the tree and promote pasture growth. At present, the catchment is grazed periodically with sheep pastured only from February to September, 1986 during the monitoring period. Because of the light grazing pressure, the eucalypts have started to recolonize the non-scald areas, however, there has been no such revegetation on the scald.

The lack of vegetation within the seepage scald is a reflection of the hostile nature of this area for plant growth. Most of the scald surface is made up of ferro-magnesium nodules and coarse sand cemented together within a matrix of finer material which, under dry conditions, is extremely hard. At one point, a D8 caterpillar was moved across the catchment and in some parts of the scald, the treads left no mark on the surface. However, the impact of sheep hooves had a much different effect. After only a week of grazing (during which time the sheep spent most days in the scald gullies, presumably to lick salt and stay cool) the scald surface was completely powdered and covered almost entirely in a 1 cm layer of dust. The surface remained in this condition from mid-February until winter rainfall began in mid-April, 1986 during which time wind erosion was frequently observed. Immediately following the first major rainfall in mid-April, the scald surface was smeared and compacted through the action of raindrop impact. Upon drying, the surface returned to its usual hard-packed condition and since the sheep no longer congregated in the scald (presumably since the weather was cooler), the powdered condition of the scald was not observed again during the monitoring period. Normally, when the scald (in its usual hard-packed condition) was wetted by rainfall, a thin layer formed on the surface that was smeared and slippery. This occurred even with limited amounts of rainfall (1 mm) but it would dry and bake very quickly even after heavy showers. There was never evidence of shrinking or swelling of the surface.

There were isolated patches on the scald surface, usually 1 or 2 m^2, that were extremely tough and did not powder under the impact of sheep traffic. As evidence of the resilient nature of these patches, a geopick would 'ring' when struck against the surface. Microscopic examination from one of these patches revealed a thin (2-3 mm) coating of silica precipitate on the surface (Colin Chartres, pers. comm.). This could explain the extremely resistant nature of the surface in these patches.

In addition to the unfavorable conditions mentioned above, the microclimate of the scald was a further deterrent to plant growth. The silica precipitate described above was coated on top with a layer of NaCl crystals, an indication of intense evaporation occurring at the soil surface. Results from other scalds such as those reported by Beadle (1948b) for central New South Wales have also shown that there is potential for much greater rates of evaporation on scald surfaces as compared with adjacent grasslands. Thus, the high heat and the evaporative buildup of soluble salts would provide further disincentive for plant establishment and growth.

2.2 Soil Analysis

2.2.1 Introduction

The soil investigations were conducted from November 1985 to May 1986, with the laboratory analysis carried out between June and September 1986. Eight soil profiles within the catchment were examined in detail and used for taking soil samples (Figure 2.2). Three profiles each from the scalded and grassland areas of the catchment were sampled to provide a basis for comparing these areas. There was also one profile taken from the wall of the main gully and from an area of semi-scald since these areas were different from either the scald or the grassland. In each profile, 4 to 6 horizons were sampled using the differences in visual horizon characteristics as boundaries for sampling depth intervals. A bulk sample (2-3 kg) from each horizon was collected and several natural soil aggregates or clods were taken and wrapped in aluminum foil for protection. The bulk samples were dried at 35°C, then a portion was ground for laboratory analysis.

Another set of soil samples was taken using a 7.6 cm hand auger to provide data on the salinity levels throughout the catchment. A bulk sample of the A horizon and the B horizon was taken at 38 different sampling locations (19 chosen at random in the scald, 19 chosen at random in the neighbouring grassland). The samples were dried, ground and analyzed for electrical conductivity.

2.2.2 Bulk Density

Bulk density was determined using the clods collected from the profile pits (Brasher et al., 1966). Three clods from each horizon were coated with 2 coats of Dow Saran Resin F-220 (Dow Chemical Company, Midland, Michigan). If any clods still bubbled upon immersion in water, they were given an additional coat. The clods were then oven-dried and weighed. After drying, they were dipped in an overflow container and the weight of water displaced was used to determine the clod volume. Bulk density was determined as

$$\text{B.D.} = \text{oven-dry weight/clod volume.} \qquad (2.1)$$

Since the resin formed an extremely thin coat and had a bulk density of 1.3, no correction was necessary for the coating.

2.2.3 Particle Size Analysis

The pipette method was used for particle size analysis of the mineral fraction of the soil smaples (Day, 1965). A 62.5 g air-dry sample from each horizon was weighed and the weight corrected to obtain the oven-dry equivalent weight. Pretreatment of samples was carried out following the methods described by McIntyre and Loveday (1974). Tap water was added to all samples and they were boiled for 10 minutes. For saline samples, the natant was decanted and the sample was washed with tap water and decanted again. The topsoil samples were treated with hydrogen peroxide and heated to destroy the organic matter. Water was added and the mixture was boiled for 10 minutes. HCl was added to flocculate the clay and the supernatant was removed by successive centrifugation and decantation.

Silt and clay fractions were determined by sedimentation. Sodium hydroxide and 10% Calgon were added to the samples before they were dispersed in stirrers. The samples were transferred to 1250 ml graduated cylinders and made up to volume. The samples were stirred for 1 minute, then sampled by pipette to determine the fraction less than 20 μm and less than 2 μm.

Separation of the sand fractions was done following the method of McIntyre and Loveday (1974). Samples were transferred to beakers and successively filled and decanted to remove the silt and clay fractions. The remaining sample was then dried and sieved to separate the fine and coarse sand fractions.

Results were reported as a percentage of the total oven-dry equivalent weight of the sample.

2.2.4 Dispersion Index

The stability of soil aggregates was determined with a modification of the procedure described by Blackmore (1956). Air-dry soil was sieved and aggregates in the 0.5 - 2.0 mm size fraction were collected. A 62.5 g subsample was placed in a 1250 ml cylinder and made up to volume with tap water by running the water at high speed down the cylinder side. The samples were left to stand overnight and were then stirred with a plunger for 1 minute. The cylinders were sampled with a pipette for the fraction less than 20 μm (silt + clay) and for the fraction less than 2 μm (clay). This treatment does not fully disperse the aggregates unless they are quite unstable. The percentages in each fraction from this treatment were compared with the percentages obtained in the particle size analysis where the samples had been fully dispersed. Results were expressed as dispersion indices,

$$DI(si+c) = \%(\text{silt + clay}) \text{ undispersed}/\%(\text{silt + clay}) \text{ dispersed}, \qquad (2.2)$$

$$DI(cl) = \% \text{ clay undispersed}/\% \text{ clay dispersed}. \qquad (2.3)$$

An index of 1 indicates a sample that dispersed completely as a result of the above treatment. Lower values indicate aggregates that are more stable and do not competely disperse from the above treatment.

2.2.5 Electrical Conductivity (EC) and pH

A 5 g soil sample from each horizon was mixed with 20 ml of water and shaken for 1 hour. The EC and pH of the suspensions were measured on laboratory EC and pH meters, ~~and~~ EC is reported in dS m^{-1}.

2.2.6 Soluble Ions

The soluble ions in the samples were extracted using a 70% ethanol - 30% water extractant, or Tucker's (1985b) reagent "E". A 25 ml volume of extractant was added to a 5 g sample, shaken for 30 minutes, centrifuged and the supernatant decanted and saved. This extraction was done twice on each sample.

A 5 ml aliquot of natant was titrated with 0.0108 M HCl to determine the CO_3^{-2} and HCO_3^- content. Tucker's (1985b) pH endpoint values were used.

The Na^+, Ca^{++}, Mg^{++} and K^+ ion levels were determined using atomic absorption spectrophotometry.

Unfortunately, the soluble Cl^- levels could not be determined due to difficulties with the laboratory facilities. Accordingly, the soil EC levels were converted to %NaCl using the relationship given by Richards (1954) to facilitate the characterization of the soil profiles using the criteria given by Northcote and Skene (1972).

2.2.7 Exchangeable Cations

Exchangeable bases were extracted with choline chloride or reagent XE, as recommended by Tucker (1985a). Soluble ions were first removed as described in section 2.2.6 and then the open centrifuge tube was stood upside down on absorbent paper to complete drainage of the wash liquid. After draining the sample tube, 20 ml of extract was added. The sample was dispersed and mixed for 30 minutes. After centrifuging, the extract was decanted into a container. The extraction was repeated three times.

The Na^{+}, Ca^{++}, Mg^{++} and K^{+} ion levels in the extract were determined using atomic absorption spectrophotometry.

The exchangeable acidity was determined using the barium chloride - triethanolamine method described by Thomas (1982). A 25 ml volume of buffer was added to 5 g of soil and left for 1 hour. The suspension was then filtered and washed 3 times with 25 ml of buffer. A 100 ml volume of replacement solution was washed through the sample. The filtrate was then titrated to pH 5.1 as recommended by Peech (1965).

Cation exchange capacity (CEC) was calculated from the total of the exchangeable bases and the exchangeable acidity in meq kg^{-1} soil. The ESP was calculated as

$$ESP = (\text{Exchangeable sodium} \times 100)/CEC. \qquad (2.4)$$

2.3 Hydrological Methods of Investigation

2.3.1 Introduction

The hydrological monitoring devices were installed between May and October, 1985 and monitoring was carried out until October 1986. Both surface and groundwater hydrological properties were investigated. Piezometers and water table wells were used to assess the groundwater flow pattern, water table levels and to measure hydraulic conductivity. The infiltration properties were measured to determine the permeability of different areas of the catchment. These properties all have significance with regards to the development of soil salinity as described earlier in Section 1.2.1. Total runoff, soluble salt and suspended sediment loss were also monitored to assess offsite effects and catchment erosion.

2.3.2 Runoff Gauging

A concrete, Crump, sloping-line weir (Bonham, 1972) was constructed along a linear portion of the gully which drained the Yarralaw catchment. The specifications are listed in Appendix A. The water level above the weir notch was monitored in a 1 m diameter stilling well by a Hewlett-Packard data logger system, which recorded the level every 6 minutes.

The weir was calibrated by bailing water from a cutoff trench and recording the time for the flow over the weir to refill it. This measurement was used to calculate the flow rate and was plotted against the corresponding data logger reading to produce a calibration curve.

For each runoff event the stilling well levels were converted to discharge rates which were plotted against time to produce hydrographs. The area under the hydrographs was planimetered to determine the total volume of runoff for each event. The peak instantaneous discharge rate for each event was taken as the highest discharge rate recorded.

2.3.3 Infiltration

The infiltration characteristics of the catchment were investigated using a disc permeameter, similar to the one described by Clothier and White (1981). The hypodermic syringe was replaced with a burette which regulated the suction on the water in the permeameter. Readings were taken on the soil surface and on the surface of the B horizon, both at saturation and under a slight (5 mm) suction. A thin layer of fine sand was used to make a base for the permeameter to ensure good contact with the soil. For the pressure readings, a plastic ring was placed around the sand base and sealed to the soil surface with a thick bentonite slurry. The ring ponded the water in the sand base so that infiltration took place under a slight (2-3 mm) pressure.

Cumulative infiltration was plotted against both time and the square root of time. The sorptivity (S) was determined from the slope of cumulative infiltration versus the square root of time at the early stages of infiltration when the effects of gravity were still small. The hydraulic conductivity (k) was calculated by taking the steady-state slope of infiltration versus time relationship and correcting for sorptivity (Clothier and White, 1981).

$$k = k_o - (2S^2/\Pi(\varnothing s-\varnothing n)r) \quad (2.5)$$

where k_o = slope of infiltration versus time,
S = sorptivity
$\varnothing n$, $\varnothing s$ = volumetric moisture content before and after infiltration measurement, respectively and
r = the radius of the water intake area.

2.3.4 Piezometers

Fifty-eight piezometers were installed at thirty different locations within and adjacent to the catchment. Piezometer installations were completed between March and November 1985. Two special sets of water table wells (piezometer sites 22-30) were installed in April 1986 to monitor groundwater fluctuations close to the gully (Figure 2.4). Specifications for each piezometer and well are listed in Appendix A. All holes were drilled using either a Gemcodril with 14 cm solid stem augers or a hand auger the same diameter. When the holes were completed, PVC pipe (100 mm diameter) was installed after the bottom 0.5 m of pipe was slotted with a hacksaw. The bottom was packed with sand then a powdered bentonite seal was poured down the anulus. The remainder of the anulus was backfilled with auger cuttings and topsoil. Water table wells were constructed by hand augering a hole and installing PVC pipe (100 mm diameter) slotted along its entire length. The anulus was backfilled with auger cuttings.

The exposed top of each piezometer and well was fitted with a PVC end cap. A small hole was also drilled in the side of each piezometer pipe, near the top, to prevent pressure differentials between the inside and outside of the pipe.

Most piezometer levels were measured once a week by lowering a metal tape measure down the pipe until it contacted the water surface and reading the distance to the top of the piezometer pipe.

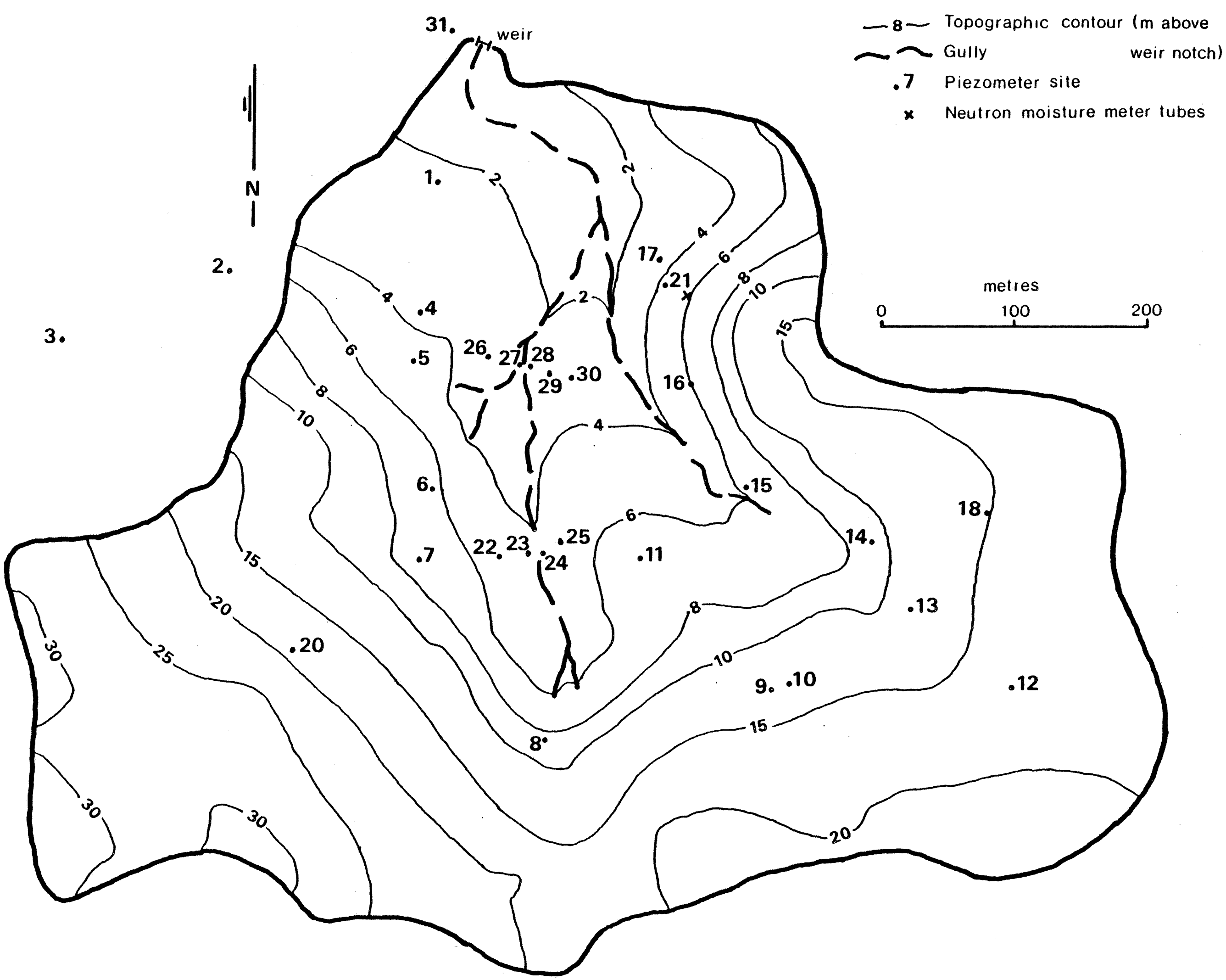


Figure 2.4 Topographic map of the Yarralaw catchment showing the location of the piezometer sites and the neutron moisture meter tubes.

Nine of the piezometers (4-6, 4-3, 8-7, 8-3, 11-7, 11-3, 21-5, 21-3, 21-1) were equipped for recording the water level once every six minutes on the data logger system.

For each measurement date, the hydraulic potential for each piezometer was plotted on a cross-sectional diagram of the catchment. These measurements were used as a guide for constructing equipotential lines. Once the lines had been roughed in, the approximate flow lines in the saturated zone could be inferred following the flow diagram construction technique by Freeze and Cherry (1979). The piezometers located on the higher elevations near the catchment boundaries were not drilled to a sufficient depth to intersect the saturated zone even though the moisture level of the drill cuttings indicated otherwise. These piezometers were usually dry or contained water for only short periods of time during wet conditions. This meant that the groundwater flow regime near the catchment boundaries could not be determined directly, however, the dry piezometers did indicate that saturated conditions could not exist above the depth of the hole. The flow pattern could usually be inferred from the cross-sections through the lower catchment.

The piezometers were periodically bailed out and sampled. This provided a means for assessing whether the piezometers were functioning properly and assured that representative water samples were taken. The EC of the water samples was measured using a standard laboratory conductivity meter. The recovery rate was monitored in some piezometers as a means for assessing the saturated hydraulic conductivity using the piezometer test described by Boersma (1965) and the augerhole test described by Van Bavel and Kirkham (1948).

2.3.5 Interflow

Piezometer site 21 was installed to monitor the piezometric potential in an area where interflow was suspected to be occurring. The water levels in the three piezometers at that location were monitored at 6 minute intervals using the data logger.

2.3.6 Soil Moisture

A series of 5 neutron probe access tubes were installed about 20 m upslope from Site 21. Neutron moisture readings were taken on a weekly basis to determine the moisture profiles down to 1.6 m. The neutron probe had been previously calibrated in several soil profiles with different texture by plotting the ratio of count/standard count to volumetric soil moisture in the same profile. The calibration curve for sandy loam was applied to the neutron counts from the upper part of the profile and the curve for clay loam was applied to the subsoil counts. Standard counts were taken at each tube.

2.4 Investigation Methods for Erosion

2.4.1 Introduction

The Yarralaw catchment was severely damaged by erosion and there was concern that the eroded area was expanding. For this reason, a series of photo stations were established at different locations around the scald to determine the rate of scald expansion into the adjacent grassland. Each station consisted of a star picket, driven into the ground to a depth such that a camera could be set conveniently on the top. While the camera was focused on a section of the scald, two white pegs were pushed into the ground such that they were positioned in the uppermost corners of the picture. By this technique, the same section of the scald could be photographed from precisely the same camera angle at different times. Twenty sites were established and color print photos were taken periodically during the monitoring period.

The offsite effects of the erosion were of particular importance since Yarralaw was part of the Shoalhaven catchment (Figure 2.1) which has been slated for development as one of Sydney's future water supplies (Costin et al., 1984). For this reason, the total sediment load (both suspended and dissolved) exiting the catchment was also measured.

2.4.2 Sediment Load

A Manning sampler was installed next to the weir for the purpose of taking discharge samples during runoff events. The sampler was modified to hold 500 ml whirlpacks and the intake for the sampling hose was located at the weir notch. The sampler was triggered by a switch connected to the data logger. During a runoff event, samples were taken initially at hourly or half-hourly intervals. The triggering system was later modified to take samples on a flow proportional basis.

The discharge samples taken by the sampler were analyzed to determine the suspended sediment (SS) and total dissolved solid (TDS) concentrations. The water samples were left in the whirlpacks and transported to the laboratory. After settling overnight, the electrical conductivity (EC) of the natant was measured using a standard electrical conductivity meter and cell. The samples were then shaken and transferred to 600 ml beakers where they were agitated with a magnetic stirrer. All samples were analyzed in duplicate. A pipetted subsample was filtered through a preweighed 0.45 μm filter paper. The suspended sediment was trapped on the filter paper and the soluble salts were washed through with the filtrate. The filter papers were then dried and reweighed to determine the weight of suspended sediment per ml of subsample.

For the first 200 samples, a 25 ml subsample of the filtrate was pipetted and evaporated to determine the TDS concentration. A linear regression between TDS and EC revealed that

$$TDS = -4.4 + 0.57\,EC, \quad r^2 = 0.987 \qquad (2.6)$$

where TDS = total dissolved solid concentration (ug g^{-1}) and
EC = electrical conductivity of the natant, dS m^{-1} x 1000.

For the remaining analysis, TDS was estimated using EC values and equation 2.6.

Once the analysis was completed, the SS and TDS concentration (mg l^{-1}) was known for certain times during the runoff event. The sediment values were multiplied by the runoff rate (l s^{-1}) and plotted against time to produce a sediment graph. The area under the graph was planimetered to determine the total weight of suspended sediment and total dissolved solids lost from the catchment during each runoff event.

2.4.3 Bedload

Approximately 10 m downstream from the weir, a concrete cutoff trench was installed perpendicular to the direction of discharge flow. The trench was located such that all the discharge from the weir had to flow over the trench. This trapped the bedload during runoff events. After an event the water was pumped out and the bedload material was levelled out and measured to determine its volume. A sample of material was taken and used to determine the density of the bedload material in the trench. The remainder of the bedload was shovelled out of the trench in readiness for the next event. The bedload for each event was determined by multiplying the bulk density of the material by the volume of the material measured in the trench.

Measurement of bedload discharge is difficult and no single method or formula has been found that is completely adequate for its determination (Gregory and Walling, 1973). The cutoff trench is a form of pit sampler with low but unknown efficiency (Goudie, 1981). However, it was felt that some data was better than none. The cutoff trench was suitable for this study because of its simplicity and low maintenance requirement, the small catchment size, the ephemeral nature of the runoff and the low flow velocity at the weir.

The dimensions for the cutoff trench are listed in Appendix A.

2.4.4 Diachronic Erosion

Aerial photographs of the Yarralaw catchment were available for 1941, 1952, 1962, 1967, 1976 and 1978. These provided a photographic history of the catchment from the period before the seepage scald formed. This information and historical rainfall records (Adomeit et al., 1987) were used to approximate the date of scald formation.

A comparison was then made between soil loss levels from the catchment determined in this study and the total soil loss over the life of the seepage scald. The latter was done in 1986 by Mr. Dave Neil, who was at that time working with the CSIRO, Division of Water and Land Resources in Canberra. The following is a description of the method he employed to determine the total soil loss from the catchment.

A topographic survey of the Yarralaw catchment was conducted along 27 cross-sections of the scalded area at 25 m intervals. The contemporary land surface was surveyed as well as a series of soil pedestals, which are 'mesas' or relicts of the original land surface located in the scalded area of the catchment. The original and contemporary land surfaces were plotted in cross-section and the area (as volume m^3/m) between the surfaces was determined with a Planix digital planimeter. The volume measured for each transect was then multiplied by 25 and these values were summed to give the volumetric soil loss from the scalded area. The total soil volume lost was subdivided into the loss per soil horizon by using the thickness of the A_1 and A_2 horizons at 19 sites and total depth to B horizon at a further 16 sites in the catchment. Contour maps of A_1 horizon thickness and depth to B horizon were prepared using a computer contouring program called SPLIN2H (Hutchinson, 1981). The product of area and thickness for each thickness increment was summed to yield a total volume (pre-scald) of both A_1 and A_2 horizons. A cross-section of the contour plot for each horizon was then obtained for each of the 27 transects, plotted on the survey cross-sections of the original and contemporary surfaces and the cross-sectional area of loss (m^3/m) for each horizon was then determined.

This author then used the volume of soil lost from each horizon and the bulk densities determined in the soil investigations to determine the total weight of soil lost from the catchment.

2.5 Electromagnetic Induction Survey

Electromagnetic induction (EM) techniques have been used successfully as a rapid means for assessing the electrical conductivity of the soil (DeJong et al., 1979) and for mapping shallow geological features (Zalasiewicz et al., 1985). The principle involves generating an EM wave in a loop transmitter at the soil surface. This creates secondary electrical currents within the soil profile which induce a secondary EM wave that is received by a surface detector. The greater the electrical conductivity of the soil profile, the greater is the signal strength. The technique has been described in detail by Williams and Baker (1982). The information is extremely useful for mapping areas of high and low salinity that may not be obvious from surface features. Two EM non-contacting terrain conductivity meters were used in this study for the purpose of characterizing the distribution of salinity in the Yarralaw catchment.

The EM34/3 consists of separate receiver and transmitter coils which can be spaced 10, 20 or 40 m apart. For this study, a 10 m spacing with vertical coil orientation was used which provided a measure of apparent electrical conductivity (ECa) to a depth of approximately 7.5 m. The EM38 is a smaller instrument which contains both receiver and transmitter coils separated by a fixed distance in a single casing. The EM38 was used in vertical orientation and provided a measure of ECa to 1.2 m depth.

A series of readings was taken with both instruments at points along a predetermined 10 x 20 m grid. The readings from each instrument were entered into separate computer files and used as input to a contouring program package called 'MAPROJ' (Hutchinson, 1981). The output was used to produce contour maps of the ECa readings in the Yarralaw catchment.

2.6 Meteorological Monitoring

Air temperature, relative humidity, rainfall and wind speed were monitored on a continuous basis at the catchment. Temperature and humidity were recorded on a Lambrecht thermohygrograph. Wind speed and direction were recorded on a wind recorder.

Rainfall was measured using a standard tipping bucket raingauge (.2 mm per tip), with the HP monitoring system recording the number of tips for each 6 minute interval. Maximum hourly rainfall intensities were calculated by taking a running mean of the 6 minute rainfall over progressive 1 hour periods. For short rainfall events, the maximum 6 minute intensity was reported. There was also a standard rain gauge at the site that was checked weekly and used for verification of the tipping bucket readings.

CHAPTER 3
RESULTS AND DISCUSSION

3.1 Soil Properties

3.1.1 Soil Physical Properties

The physical soil properties of the soil profiles sampled in the catchment (Figure 2.2) are tabulated in Table 3.1. The particle-size distribution in each horizon was similar for all the profiles in the catchment with either a loamy sand or silt loam A horizon underlain by a clay loam to clay B horizon with a lighter-textured C horizon beneath. The sharp discontinuity in texture between the A and B horizon is referred to as 'duplex' and is a common occurrence in Australian soils (Northcote, 1971). For the hand auger samples, the measured thickness of the A horizon varied between 8 and 58 cm with a mean of 32.5 cm and a standard deviation of 11.3 cm.

Generally, the proportion of sand, especially fine sand, decreased with depth. Since wind action affects soil particles mainly in the fine sand fraction (Thompson et al., 1986), the high proportion of fine sand near the soil surface may be an indication that aeolian sorting has taken place. Horizon SC1-4 was noticeably coarser in texture than the horizon above or below and this was the only instance where such a layer occurred in the B horizon. Other coarse-textured horizons were associated with gravelly layers overlying the B horizon (i.e. GU1-2, SS1-2). There were no major differences in soil texture between the scalded and grassland profiles.

The bulk densities were also quite similar for all the profiles (Table 3.1). The highest bulk densities were in the B horizon with values as high as 1.85 g cm^{-3}. The surface horizons were much less dense ranging from 1.26 to 1.50 g cm^{-3}. The C horizons usually had a similar or slightly lower bulk density than the B horizon.

There were significant differences in dispersion index between profiles and horizons (Table 3.1). Both the DI(si+c) and the DI(c) were higher for the scald profiles than for the others,

Table 3.1. Physical properties of Yarralaw soils.

Sample[1]	Depth (cm)	Hor.	B.D.	DI_1	DI_2	Gr	CS	FS	Si	C	Texture
						% oven-dry weight					
GR1-1[2]	0-15	A	1.31	.50	.00	4	23	53	15	5	ls
GR1-2	15-30	B	1.63	.26	.08		3	25	9	63	c
GR1-3	30-60	B	1.79	.42	.16		1	25	14	60	c
GR1-4	60-85	B	1.76	.43	.15		7	27	19	47	c
GR1-5	85-120	C	1.56	.44	.17		3	36	30	31	sicl
GR2-1	0-10	A1	1.26	.36	.00		15	59	21	5	ls
GR2-2	10-20	A2	1.38	.48	.14		19	56	18	7	ls
GR2-3	20-45	B	1.62	.38	.13		3	32	17	48	c
GR2-4	45-70	B	1.61	.42	.16		9	32	26	33	sicl
GR2-5	70-120	C	1.53	.45	.18		25	25	33	17	sil
GR3-1	0-10	A1	1.36	.21	.00		32	44	18	6	ls
GR3-2	10-20	A2	1.38	.27	.12		38	39	14	8	ls
GR3-3	20-40	B	1.53	.35	.14		17	28	19	36	c
GR3-4	40-120	C	1.57	.49	.18		12	34	25	29	cl-sicl
SC1-1	0-12	A1	1.36	.75	.74		8	66	22	4	ls
SC1-2	12-40	A2	1.75	.47	.14		9	54	15	22	l
SC1-3	40-70	B	1.85	.39	.08		3	47	12	38	c
SC1-4	70-110	B	1.76	.48	.12	3	23	38	11	25	cl
SC1-5	110-120	B	1.74	.61	.16		5	36	9	50	c
SC2-1	0-8	A	1.29	1.11	.40		5	68	22	5	ls
SC2-2	8-40	B	1.74	.92	.66		3	45	16	36	c
SC2-3	40-65	B	1.65	.92	.58		3	44	21	32	cl
SC2-4	65-80	B	1.73	.73	.47		22	34	20	24	l
SC2-5	80-120	B	1.67	.93	.69		1	30	22	47	c
SC2-6	120-130	C	1.62	.84	.70		1	36	30	34	sicl
SC3-1	0-10	A1	1.50	.90	.29		3	59	30	7	sil
SC3-2	10-18	A2	1.66	.88	.44		18	44	24	14	l
SC3-3	18-55	B	1.72	.68	.18		17	24	18	41	c
SC3-4	55-130	C	1.71	.47	.36		45	20	24	11	l
SS1-1	0-12	A1	1.41	.59	.16		9	62	23	6	ls
SS1-2	12-28	A2	1.60	.48	.40	4	27	47	16	5	ls
SS1-3	28-40	B	1.75	.80	.39		11	42	10	37	c
SS1-4	40-70	C	1.63	.51	.19		8	38	11	43	c
SS1-5	70-120	C	1.61	.75	.53		12	28	27	33	sicl
GU1-1	0-15	A1	1.26	.46	.24		5	62	25	8	ls-sil
GU1-2	15-40	A2	1.51	.27	.33	11	36	31	16	6	ls
GU1-3	40-80	B	1.76	.40	.11		2	46	13	39	c
GU1-4	80-120	B	1.68	.51	.13		2	37	22	38	c

1 - Site locations are shown in Figure 2.2 2 GR - grassland, SC - scald, SS - semi-scald, GU - gully.
B.D. - Bulk density (g cm^{-3}) DI_1 - Dispersion Index (si+c) DI_2 - Dispersion Index (c)
Gr - gravel Cs - coarse sand Fs - fine sand Si - silt C - clay.

especially in the surface horizons. The value of 1.11 for DI(si+c) in SC2-1 is theoretically not possible and is a result of measurement error in either the particle-size analysis, the dispersion analysis or both. The high dispersion indices are indicative of the poor structural stability in the scald profiles, especially the surface and highlights the main difference between the scald and non-scald soils. Raindrop impact will break down the surface structure on the scald more readily than the grassland surface which means that the scald is more prone to smearing and crusting as a result of physical disturbances such as raindrop impact.

All the profiles have a strong blocky or prismatic structure in the B horzion and a massive C horizon except for SS1-3 where the B horizon has a very dense columnar structure. Below this the soil was dry with virtually no root penetration. Thus, the poor grass growth on the semi-scald is most likely a result of the shallow rooting depth.

There are very few differences in physical characteristics between profiles. All the soil profiles at Yarralaw are classified as duplex according to Northcote (1971) and red brown earths or non-calcic brown soils according to Stace et al. (1968). Thus, these soil classification systems do not distinguish between the scald and the non-scald soils. The main difference between these soils is in the nature of the surface. The grassland surface has a permeable structure and good tilth whereas the scald surface is either smeared under wet conditions or hard-packed under dry conditions. This is reflected in the infiltration characteristics of the profiles (discussed in Section 3.2.2).

3.1.2 Soil Chemical Properties

The chemical properties of the soil profiles are listed in Table 3.2. Only horizons SC1-1, SC1-2 and SC2-1 are saline according to Northcote and Skene's (1972) classification. The soluble ion content in most of the horizons was very low and has not been reported. Soluble Ca^{++}, K^{+} and HCO_3^- levels were less than 1 meq kg^{-1} except for horizons SC1-1 to SC 1-3 where the Ca^{++} level was 9.2, 1.5 and 1.3 meq kg^{-1} respectively. In all profiles, Na^{+} was the dominant soluble

Table 3.2. Chemical properties of Yarralaw soils

Sample	EC ($dS\ m^{-1}$)	pH	NaCl[1] %	Na^+	Ca^{++}	Mg^{++}	K^+	H^+	CEC	ESP %
				Exchangeable Cations (meq kg-1)						
GR1-1	0.02	6.3			5.5	0.5	0.4		6.4	
GR1-2	0.06	6.2		7.1	28.0	84.8	0.3	73.9	194.1	3.7
GR1-3	0.26	7.6	0.04	14.5	32.0	123.6			170.1	8.5
GR1-4	0.52	8.9	0.07	16.2	27.2	92.8			136.2	11.9
GR1-5	0.59	8.9	0.12	20.0	19.5	88.7	0.1		128.3	15.6
GR2-1	0.04	6.4	0.01	1.3	13.0	16.3	2.0	28.4	61.0	2.1
GR2-2	0.02	6.2		0.7	3.6	9.9	0.5	7.3	22.0	3.2
GR2-3	0.13	6.0	0.02	8.5	7.1	100.6	0.2		116.4	7.3
GR2-4	0.45	6.8	0.09	14.6	5.2	112.8	0.1		132.7	11.0
GR2-5	0.80	8.2	0.16	22.4	3.7	128.7	0.1		154.9	14.5
GR3-1	0.03	6.3			11.2	11.2	1.3	51.9	75.6	
GR3-2	0.02	6.3			5.7	14.2	0.6	38.5	59.0	
GR3-3	0.03	6.6		4.1	1.9	86.8	0.4		93.2	4.4
GR3-4	0.05	7.3	0.01	11.0	2.5	128.6	0.1	16.5	158.7	6.9
SC1-1	4.20	6.0	0.79	2.5	10.4	13.0	0.2		26.1	9.6
SC1-2	0.97	7.9	0.22	11.6	7.4	36.9	0.1	1.1	57.1	20.3
SC1-3	1.03	7.9	0.22	21.8	17.8	78.1	0.1	7.5	125.3	17.4
SC1-4	0.80	8.1	0.17	16.5	12.6	55.9	0.1	1.3	86.4	19.1
SC1-5	0.47	9.0	0.10	32.3	20.0	90.5	0.3		143.1	22.6
SC2-1	2.86	8.5	0.72	8.0	0.1	3.9	0.1		12.1	66.1
SC2-2	1.26	8.6	0.27	43.6	9.7	53.3	0.2	4.4	111.2	39.2
SC2-3	0.47	9.0	0.09	35.8	14.6	69.5		4.8	124.7	28.7
SC2-4	0.48	9.1	0.09	32.8	9.9	50.3			93.0	35.3
SC2-5	0.44	9.3	0.06	33.1	15.9	39.4	0.1		88.5	37.4
SC2-6	0.34	9.2	0.06	26.9	13.1	55.9	0.1		96.0	28.0
SC3-1	0.32	6.7	0.06	3.5	1.2	12.7		27.9	45.3	7.7
SC3-2	0.22	6.6	0.04	6.7	2.8	19.4	0.1	26.8	45.8	14.6
SC3-3	0.37	8.0	0.07	31.5	22.2	138.4	0.1		192.2	16.4
SC3-4	0.13	9.4	0.03	36.9	31.4	132.8	0.1	16.5	217.7	16.9
SS1-1	0.03	7.4		1.6	5.4	4.5	0.9	37.8	50.2	3.2
SS1-2	0.04	7.6	0.01	1.3	3.0	2.0			6.3	20.6
SS1-3	0.12	7.4	0.01	10.6	16.0	63.1	0.1	5.3	95.1	11.1
SS1-4	0.17	7.4	0.03	16.2	14.3	95.5	0.1	9.5	135.6	11.9
SS1-5	0.19	8.0	0.03	18.3	9.9	83.8	0.2		112.2	16.3
GU1-1	0.02	5.9		0.7	7.1	6.3	0.5	26.8	41.4	1.7
GU1-2	0.05	7.2	0.01	1.4	4.6	10.7	0.1	33.4	50.2	2.8
GU1-3	0.51	6.9	0.10	13.1	10.2	85.2	0.1		108.6	12.1
GU1-4	0.56	8.1	0.11	22.9	12.6	115.0	0.2		150.7	15.2

1 - converted from EC, Richards (1954) Blanks indicate concentration was below detection limits

ion with Mg^{++} being subdominant. The highest level of soluble Na^{+} and Mg^{++} occurred in SC1-1 with 134 and 105 meq kg^{-1} for each ion respectively. All other horizons had soluble Na^{+} and Mg^{++} levels less than 50 meq kg^{-1}.

Generally, the soil pH levels were neutral to slightly acid at the surface and more alkaline at depth. Profile SC2 is an exception since the pH is alkaline for its entire depth. The scald profiles were more alkaline than the others, although GR1 was quite alkaline at depth.

The cation exchange capacity is low in all the A horizons and low to medium in the subsoil. The exchangeable base cations are dominated by Mg^{++} as illustrated in Figure 3.1. The proportion of exchangeable Mg^{++} ranges from 40 to >90%, the exchangeable Na^{+} proportion from 5 to 25% and the exchangeable Ca^{++} proportion from as low as 1% in the subsoils to a high of 50% in GU1-1. The exchangeable H^{+} levels varied considerably between horizons and profiles and did not show a consistent pattern. There was no exchangeable H^{+} detected in horizons GR1-1, GR2-3, GR3-3 or SC1-1 even though the pH of these layers was in the acid range. In the opposite case, exchangeable H^{+} was detected in SC2-2, SC2-3 and SC3-4 when it was not expected because of the alkaline pH level. It is possible that Al^{+++} (which was not measured) dominates the pH reaction of some horizons and is the cause of the acidity in some cases.

Using Northcote and Skene's (1972) guidelines, profiles GR2 and GR3 were sodic and the remainder were strongly sodic, thus there was no distinction between scald and grassland soils with this type of classification. However, the scald soils could be distinguished from the grassland profiles by the ESP of the surface horizon. SC1-1 and SC3-1 were sodic and SC2-1 was extremely sodic, but the surface horizons of the other profiles were non-sodic (Figure 3.2). Thus, the scald surface is characteristically high in exchangeable Na^{+} just as it is also prone to smearing and hard-packing. High sodicity is known to impart adverse physical properties by promoting dispersion and breakdown of soil structure from physical disturbances such as raindrop impact (Emerson, 1984). Thus, one would expect a correlation between ESP and dispersion index. The linear regression (equation 3.1) between these parameters is illustrated in Figure 3.3.

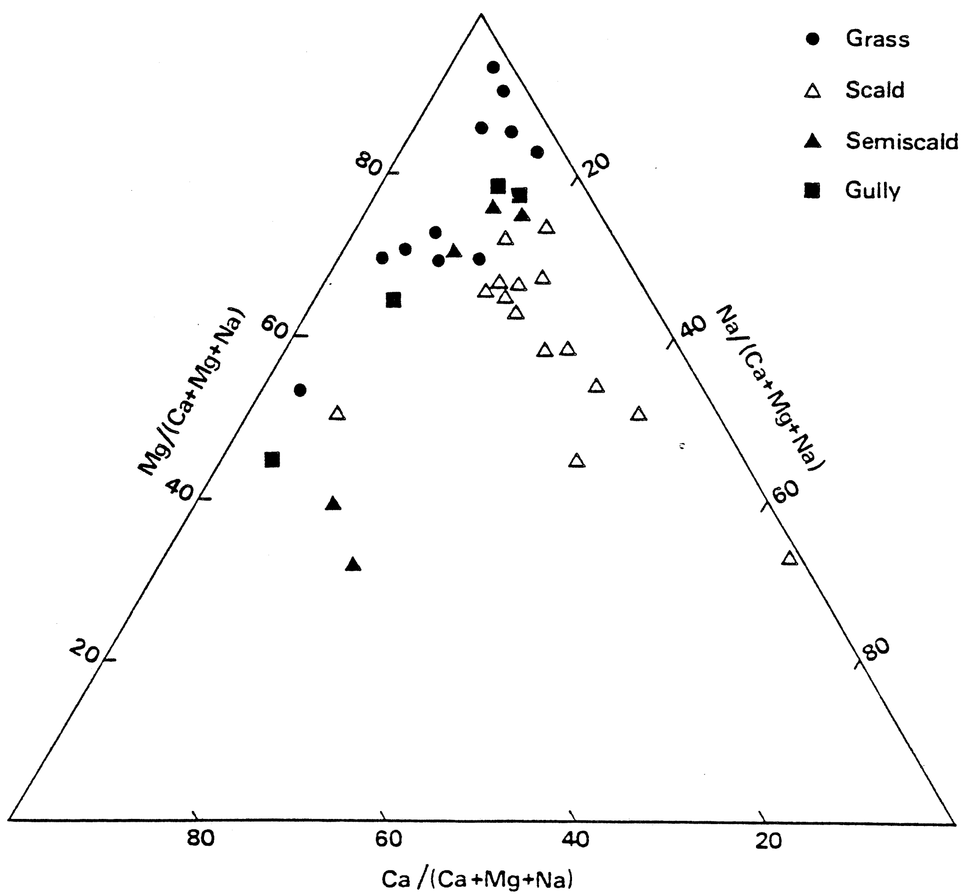


Figure 3.1 Relative proportions of exchangeable Na^{+}, Mg^{++} and Ca^{++} in the Yarralaw soils.

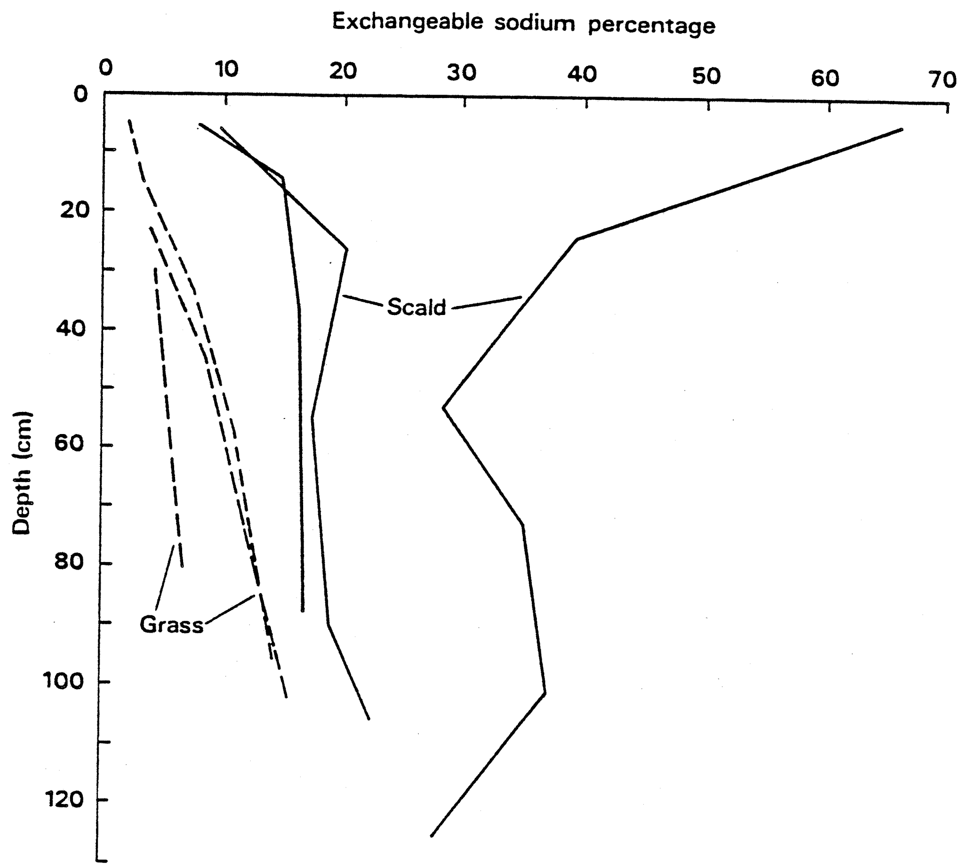


Figure 3.2 Exchangeable sodium percentage versus depth for the Yarralaw scald and grassland profiles.

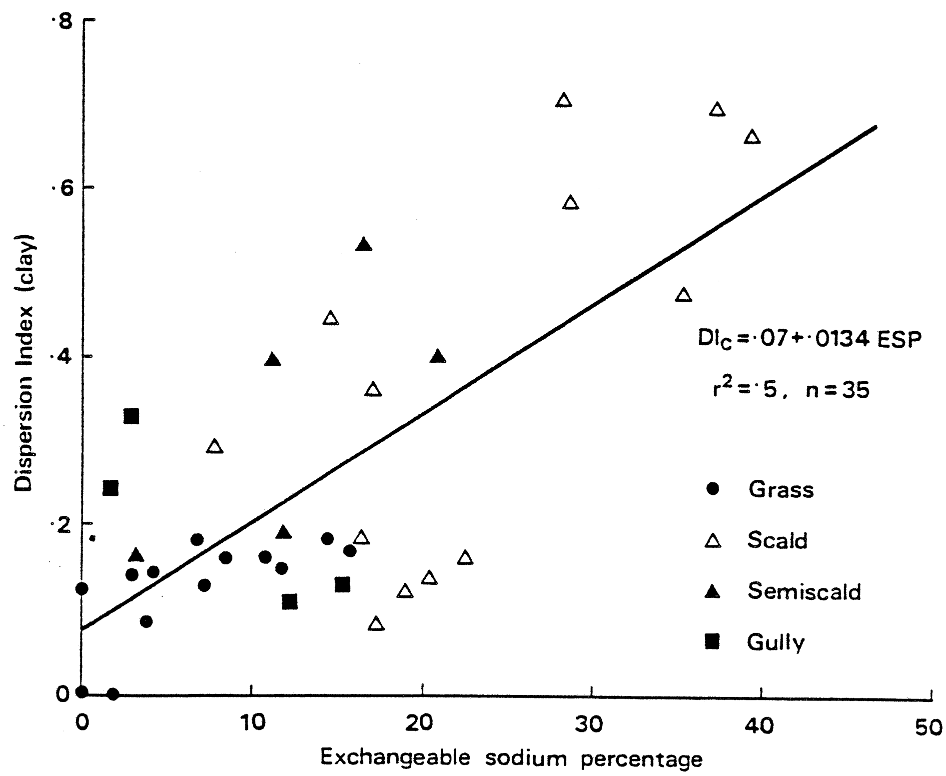


Figure 3.3 Relationship between exchangeable sodium percentage and dispersion index(clay) for the Yarralaw profile samples.

$$DI(clay) = 0.07 + 0.0134\ (ESP) \quad (3.1)$$
$$(r^2 = 0.50,\ n = 35)$$

Although there is considerably more scatter in this relationship than that shown by Emerson (1984) for clay surface soils, the detrimental effect of exchangeable Na^+ on soil structure is apparent. The strength of the effect appears to vary between different profiles but there were insufficient data points to analyze each profile separately.

It has been suggested that the dominance of exchangeable Mg^{++} may compound the tendency for dispersion caused by exchangeable Na^+ (Emerson, 1984; Keren, 1984). In the case of the Yarralaw soils the combined effect of exchangeable Na^+ and Mg^{++} is

$$DI(clay) = 20.2 + 1.39\ (ESP) - 0.242\ (EMP) \quad (3.2)$$
$$(r^2 = 0.58,\ n = 37)$$

where EMP is the exchangeable magnesium percentage. This would suggest that Mg^{++} does not contribute to dispersion but rather offsets the effect of sodium by imparting some stability to the soil aggregates. However, the exchangeable Mg^{++} levels did not exhibit any noticeable trends between profiles.

Magnesium does have other effects on the soil which may contribute to scald formation. For example, Carter et al. (1979) have demonstrated that calcium deficiency in barley is induced in nutrient culture when the Mg/Ca ratio exceeds 1.0 or when Ca/Total Cations < 0.15, regardless of salinity levels. Both of these conditions are common in the Yarralaw soils. Mg/Ca ratios of the grassland surface soils are generally about 1 to 3 compared with 5 to 10 for the scalded soils. The high ratio may be a further deterrent to vegetative growth on the scald.

3.1.3 Spatial Distribution of Salinity

The EC levels reported in Table 3.2 were lower than what would be expected for a saline catchment. The profile samples indicated excessive soluble salt levels only in the surface of the scalded area and only profiles SC1 and SC2 would be classified as saline according to Northcote and Skene (1972). It appears that excess sodicity is more characteristic of the scald than salinity, a condition which is also characterisitc for several seepage scalds in the York-Mawson area of Western Australia (Conacher, 1975).

The salinity pattern in the hand auger samples was similar to the pattern revealed by the EM (Figure 3.4). Only the 100 mS m^{-1} ECa boundary is illustrated to simplify the figure. Soil samples from zones where the EM38 ECa was greater than 100 mS m^{-1} averaged 1.85 and 0.63 dS m^{-1} for the A and B horizons respectively. The corresponding values in the areas with an ECa less than 100 mS m^{-1} were 0.21 and 0.17 dS m^{-1}. The high ECa areas located by the EM meters, especially the EM38 were located mainly within the scalded portion of the catchment. Thus, the salinity problem appears to be concentrated within the bare scald area and not in the adjacent semi-scald or grassland. An extended EM survey of upper Jacqua Creek has shown a similar pattern for other scalds in this area (Cumming et al., 1984). Malcolm (1983) reported that the work of Teakle and Burvill (1938) also demonstrated a pattern of high salinity in bare areas and not in the adjacent grassland near Welbunging and Yilgarn, Western Australia. Even though the soluble salt levels at Yarralaw may not be high as might be expected, the combination of sodicity and salinity is sufficient to prevent plant growth on the bare scald as evidenced by the lack of vegetation in this location.

Table 3.3. Vertical distribution of soil salinity at Yarralaw.

	Grassland		Scald	
$EC_A > EC_B$*	6 of 19 profiles		17 of 19 profiles	
	A Horizon	B Horizon	A Horizon	B Horizon
E.C. (dS m^{-1})				
- mean	0.060	0 .106	1.313	0.486
- range	0.015 - 0.608	0.023 - 0.460	0.186 - 5.900	0.175 - 1.710
- stan. dev	0.134	0.109	1.519	0.387

* - Number of profiles where EC of the A horizon is greater than the EC of the B horizon.

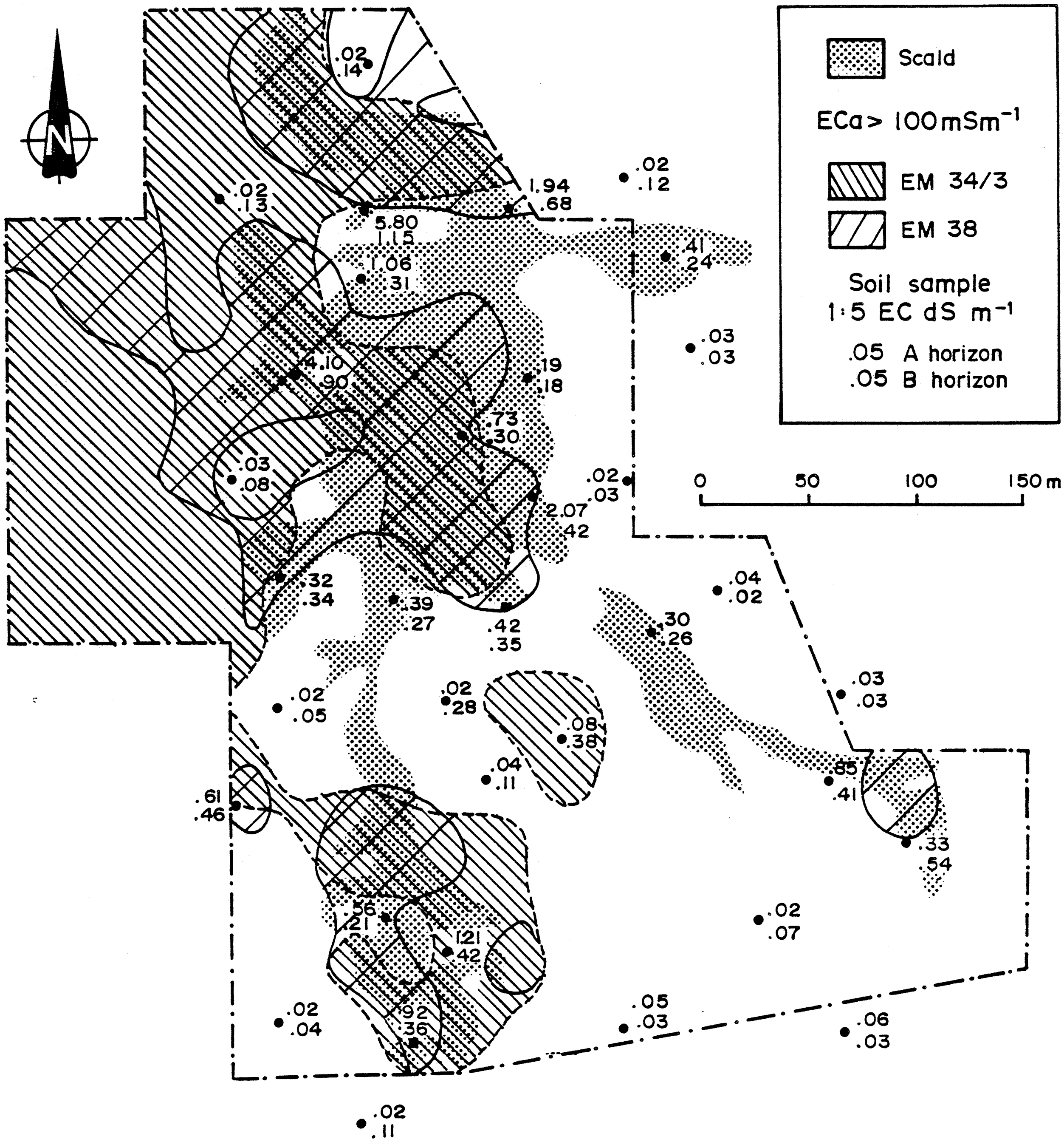


Figure 3.4 The location of the high apparent electrical conductivity areas for the EM 38 and the EM 34/3 in relation to the electrical conductivity of the hand auger samples and the location of the scald. Note: the boundary for the EM survey is shown in Figure 2.2.

The vertical salt distribution (Table 3.3) is indicative of the direction of salt movement occurring within the catchment. On average, the soil EC increases with depth in the non-scalded profiles with the pattern reversed for the scald profiles (Table 3.3). This matches the general vertical salt distribution pattern described by Conacher (1982) for seepage scalds in Western Australia. As discussed in Section 1.2.1, active groundwater salinization occurs when groundwater moves upward by capillary movement to an evaporating surface where the soluble salt load is left behind. Thus, salt levels are expected to be higher near the surface than at depth in an area that is undergoing active salinization. Where upward movement is not occurring (or occurring at a very slow rate), infiltration of rainwater tends to leach soluble salts down from the surface into the subsoil. The infiltration measurements in the catchment (discussed in Section 3.2.2) indicate that infiltration exceeds upward water movement in the grassland but not in the scald. The vertical salt distribution above supports this assessment (Table 3.3).

Areas with an ECa < 60 mS m^{-1} were highlighted on a detailed ECa contour map of EM38 readings as a rough guideline for delineating non-saline areas (Figure 3.5). Most of this occurred in the higher slope positions of the grassland, however, there were exceptions where a 'finger' of low salinity extended well into the scalded area. One such 'finger' extended into the scald downslope from piezometer site 21 (Figure 3.5). The stratigraphy at site 21 was 50 cm loamy sand overlying a 50 cm sandy-gravelly layer overlying a clay subsoil. The reason for the low ECa is the coarse textured layer just below the soil surface. The upslope extent of this layer was difficult to ascertain because of the low ECa readings on the hills but the downslope extent was quite apparent on the ECa contour map. Physically, these layers resemble the throughflow 'percolines' described by Conacher (1975) to which much of the salinity in Western Australia has been attributed (see Section 1.2.2). These layers (discussed in Section 3.2.4) are mentioned at this point only because the EM survey highlights their position along the edge of the scald.

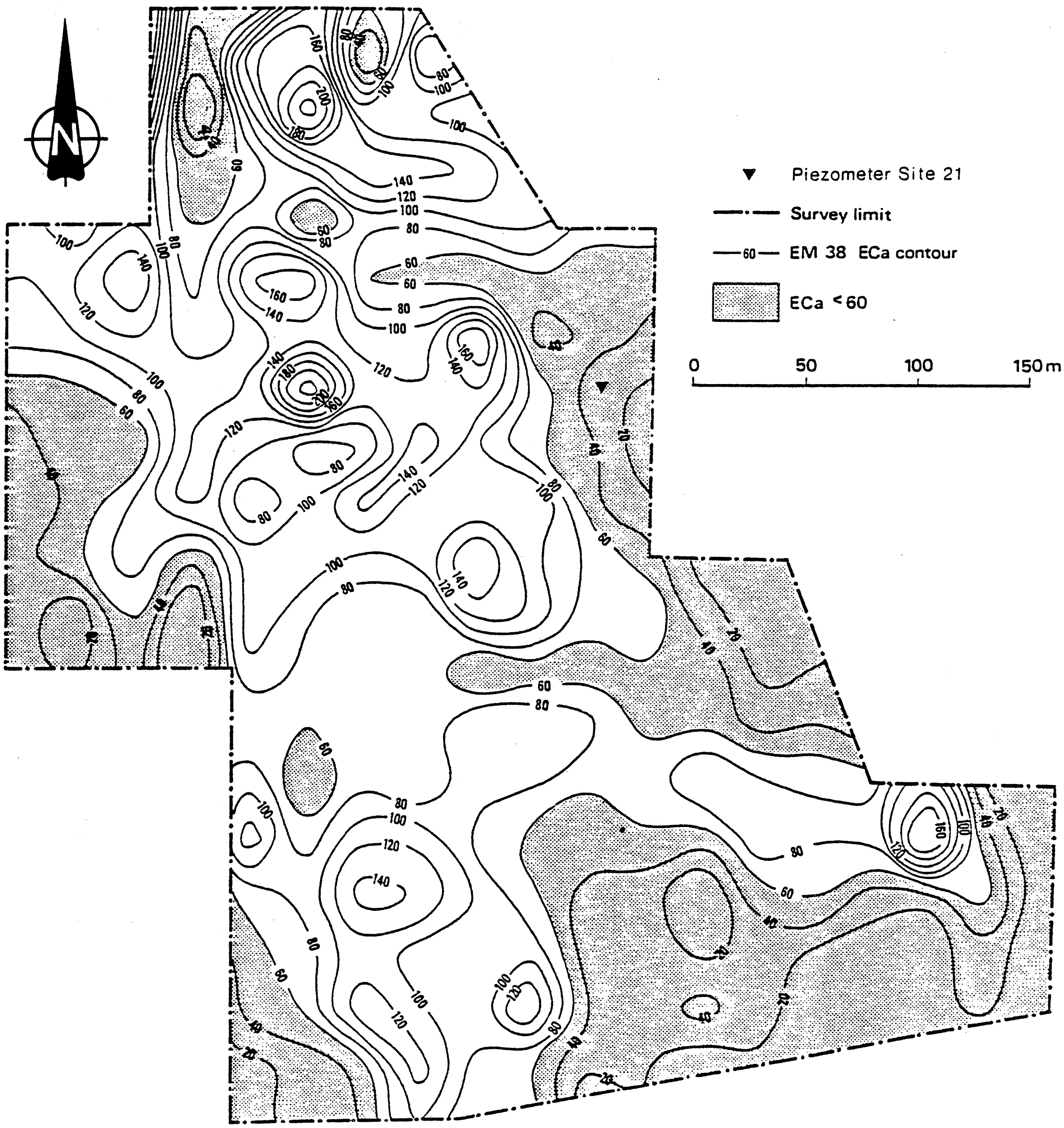


Figure 3.5. The location of the low apparent electrical conductivity areas for the EM 38 and piezometer site 21. Note: The boundary for the EM survey is shown in Figure 2.2

3.2 Hydrological Characteristics

3.2.1 Groundwater

The groundwater monitoring provided a good continuous record of groundwater levels except for some of the piezometers at higher elevations in the catchment which were too shallow to intersect the water table (sites 3, 10, 12, 18 and 20). All the piezometers displayed a similar temporal water level pattern, which is illustrated (Figure 3.6) for sites 5, 16 and 21. The entire set of piezometer water levels is listed in Appendix B. The highest water levels were recorded in October, 1985 with declining potentials commencing at the start of December, 1985. The water levels declined steadily until August, 1986 when a sharp rise in potential occurred following the heavy rainfall at the start of that month. The piezometer water levels generally reflected the rainfall pattern observed during the monitoring period (Table 2.1). During September, October and November, 1985, the highest water levels were recorded and groundwater potentials responded rapidly to the higher than average rainfall (Table 2.1). During December, 1985 and January, 1986, the water levels started to decline and displayed limited or no response to rainfall events. The water levels declined steadily through July, 1986 even though there was above normal precipitation in April, 1986. Most likely, the water storage capacity of the catchment was high at this time because of the extremely dry conditions during February and March, 1986 and this buffered the groundwater response. All the piezometers displayed a rapid increase in water level during the same large rainfall event in early August, 1986. This indicates that the catchment water storage was filled at this time and excess soil moisture percolated into the groundwater. Gunn (1985) observed a similar water level pattern during 1983 in a single piezometer he had installed near piezometer site 8. He also noted the rapid response of groundwater levels to rainfall during winter months and the dampened response during the summer. Thus, this fluctuating water pattern recorded in the numerous piezometers at Yarralaw appears to be a fairly representative phenomenom.

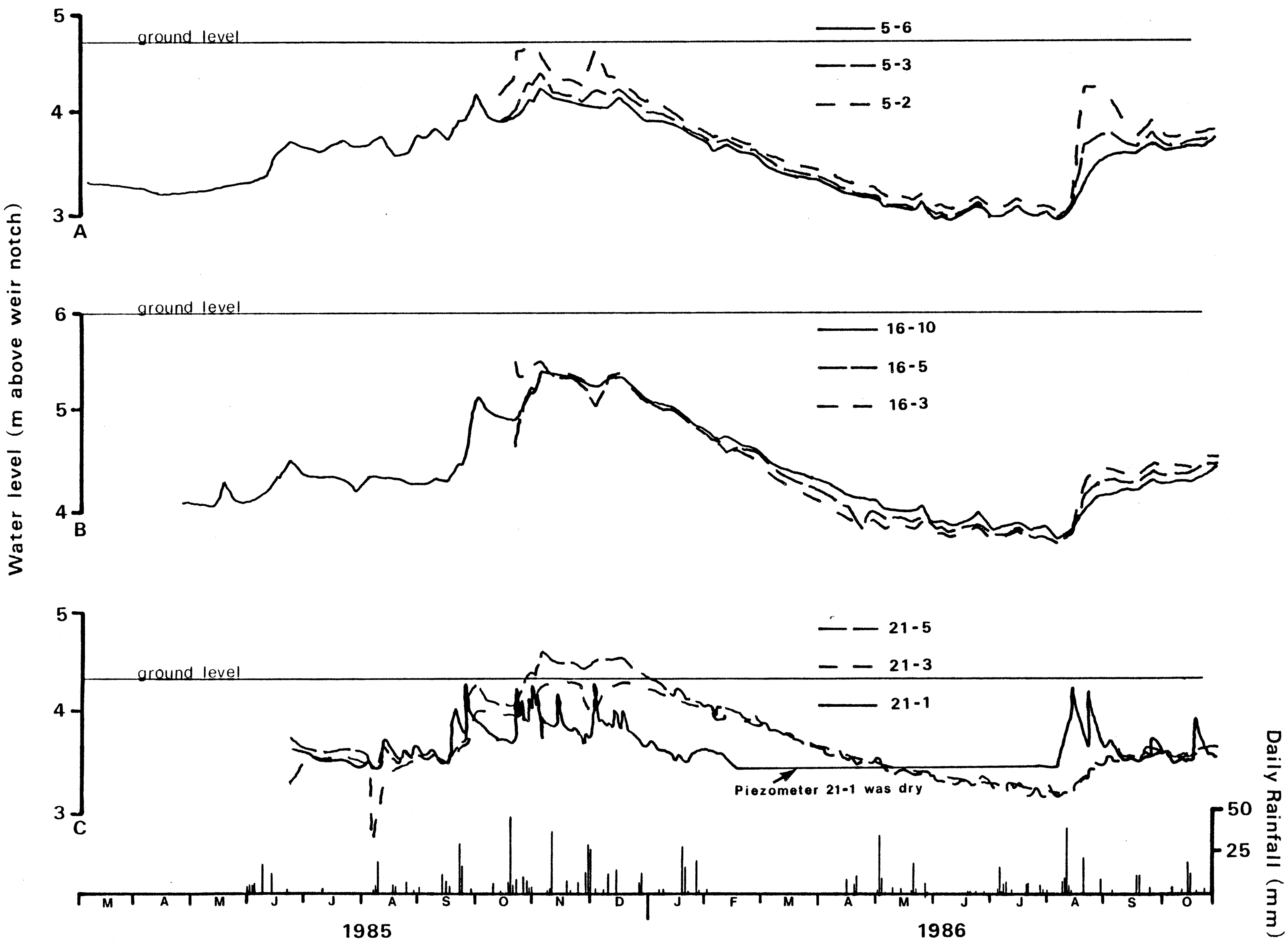


Figure 3.6 The entire record of piezometer water levels versus rainfall for (a) piezometer site 5, (b) piezometer site 16 and (c) piezometer site 21. The location of the piezometers is shown in Figure 2.4.

Measurements of subsurface saturated hydraulic conductivity varied between 1.8 x 10^{-7} and 8.0 x 10^{-6} m s^{-1} (Table 3.4) with an arithmetic mean of 1.5 x 10^{-6} m sec^{-1}. The values were best approximated with a log normal distribution with a mean of 8.8 x 10^{-7} m sec^{-1}. A value of 1.0 x 10^{-6} m s^{-1} was taken as the representative value for the catchment subsoils as other work has indicated that bulk hydraulic conductivity lies between the geometric and arithmetic means of the measured values (Peck and Watson, 1979).

Table 3.4. Saturated hydraulic conductivity measurements

	Piezometer Site	Depth m	Ksat m s^{-1}
Piezometer Test	1	16	4.0 x 10^{-6}
		4	1.5 x 10^{-6}
	5	6	3.6 x 10^{-6}
	6	5	1.2 x 10^{-6}
	7	14	2.3 x 10^{-6}
	14	5	5.0 x 10^{-7}
	15	10	8.0 x 10^{-6}
Augerhole Test	1	2	1.8 x 10^{-7}
	4	2	4.0 x 10^{-7}
	5	2	4.9 x 10^{-7}
	14	3	2.6 x 10^{-7}
	15	2	5.3 x 10^{-7}
	16	3	4.2 x 10^{-7}
	22	2	5.2 x 10^{-7}
	30	2	1.8 x 10^{-6}
	31	2	1.1 x 10^{-6}
Disc Permeameter		.3	1.1 x 10^{-6}
		.3	1.8 x 10^{-7}
		.3	1.3 x 10^{-6}
		.3	3.8 x 10^{-7}
Mean (m s^{-1})		Arithmetic	1.5 x 10^{-6}
		Geometric	8.8 x 10^{-7}

A cross-section illustrating hydraulic potentials for December 5, 1985 is shown in Figure 3.7. The equipotential pattern did not vary significantly over the monitoring period and the cross-sections all displayed groundwater flow lines from the higher slopes of the catchment towards the gullies and lower slopes. Field evidence for this pattern was observed during the dry period from February to April, 1986 when the gully bottoms remained moist. This condition could only be sustained by groundwater but the rate of discharge was insufficient to maintain any baseflow. The unsaturated hydraulic conductivity of the catchment soils was even slower than the saturated rate (see Section 3.2.2), therefore, it is understandable that the unsaturated groundwater flux was insufficient to maintain baseflow in the gullies.

The vertical hydraulic gradients in Figure 3.7 ranged from 0.075 m m^{-1} downwards between piezometers 11-3 and 11-7 to 0.138 m m^{-1} upwards between piezometers 21-5 and 21-3, although most gradients were much less extreme (Table 3.5). The vertical hydraulic gradients did not

Table 3.5. Vertical hydraulic gradients measured in the Yarralaw catchment, December 5, 1985.

Between	Gradient[1]	Between	Gradient
1-2 and 1-4	0.0	11-2 and 11-3	+0.011
1-4 and 1-16	+0.003	11-3 and 11-7	+0.075
4-2 and 4-3	0.0	14-3 and 14-5	+0.005
4-3 and 4-6	-0.019	14-5 and 14-11	+0.013
5-2 and 5-3	+0.052	15-2 and 15-3	-0.014
5-3 and 5-6	+0.034	15-3 and 15-5	+0.009
		15-5 and 15-10	-0.041
6-2 and 6-3	-0.002		
6-3 and 6-5	+0.010	16-3 and 16-5	+0.005
		16-5 and 16-10	-0.002
7-2 and 7-3	-0.072		
7-3 and 7-7	-0.013	21-1 and 21-3	-0.071
7-7 and 7-14	-0.012	21-3 and 21-5	-0.138
8-2 and 8-3	+0.014		
8-3 and 8-7	-0.025		

1 - Gradient in m m^{-1}. Positive - downwards, negative - upwards

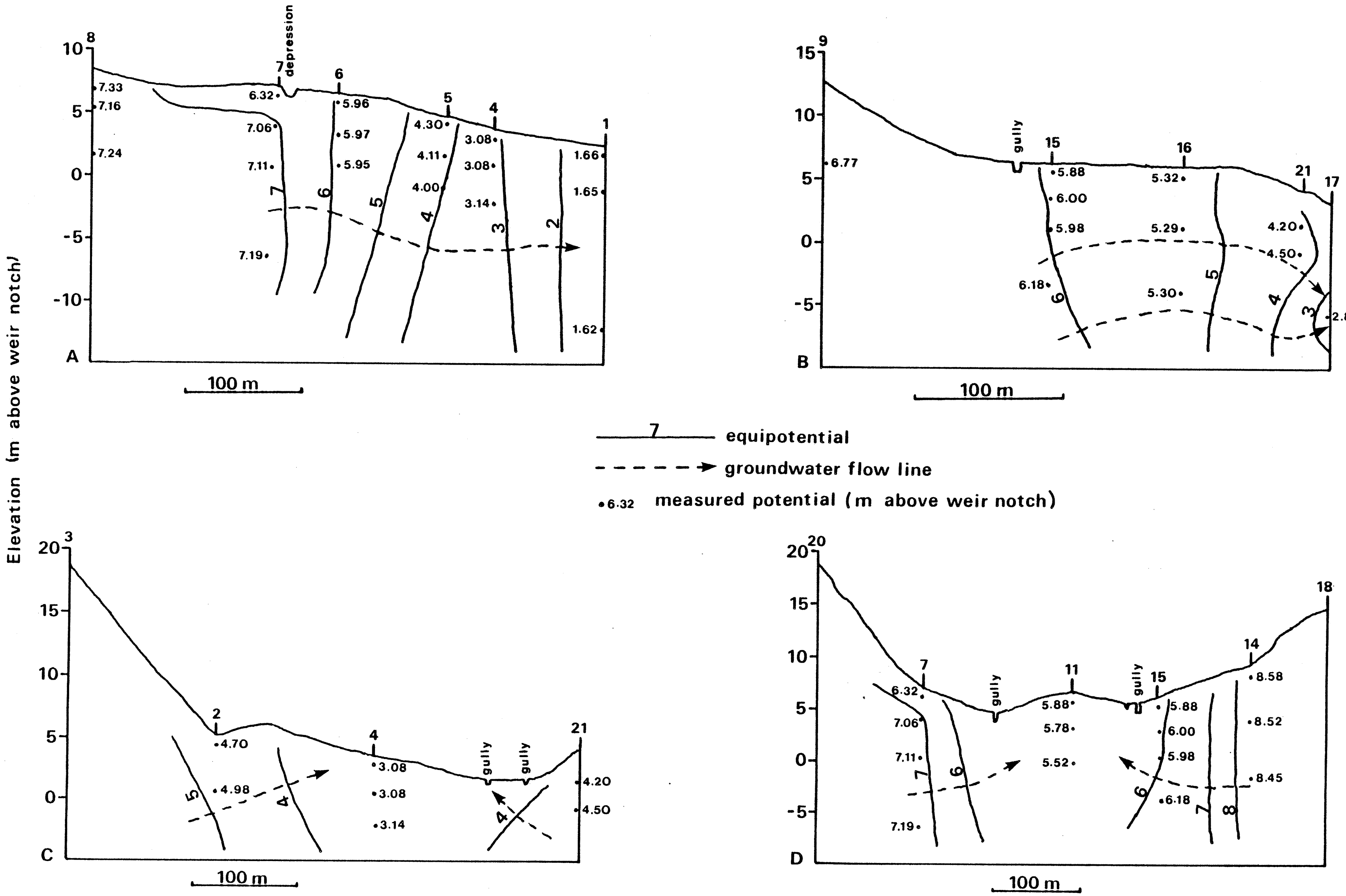


Figure 3.7 Groundwater equipotential cross-sections for December 5, 1985. The location of the piezometers is shown in Figure 2.4.

exhibit a consistent pattern throughout the catchment and did not indicate that the salinity was a result of upward water movement from a deeper aquifer system.

The highest and lowest water table levels in the lower catchment are illustrated on the isopach maps in Figure 3.8. The water table contours roughly corresponded to the ground surface but with a subdued gradient that did not vary substantially over the course of the monitoring period. The slope of the water table was measured at three different locations between each of the water table contours shown in Figures 3.8a and 3.8b. The gradient of the water table surface varied from 0.014 m m^{-1} to 0.047 m m^{-1} with a mean of 0.024 m m^{-1}. The direction of flow was convergent from the higher elevations of the catchment towards the gullies and the catchment outlet, which was in agreement with the pattern shown by the equipotential cross-sections (Figure 3.7). In the lower catchment, the water table remained within 2 m of the ground surface even at the lowest groundwater levels recorded during the monitoring period. Groundwater at this depth is well within the critical range to cause soil salinity according to several authors (Peck, 1978a, Conacher, 1982). Upward capillary movement from the water table, although slow, is persistent enough to cause salinity as shown by the soil analysis (Section 3.2). Therefore, the high water table model of soil salinity that has been suggested for southeastern New South Wales appears to be correct for the Yarralaw catchment. Gunn (1985) observed similar groundwater levels in several other catchments in the local area and it is probable that these areas are also afflicted by salinity resulting from a high water table.

In Section 3.2, it was shown that the soluble salt levels in the soil were quite low except for the surface of the scalded area. In contrast to this, the soluble salt level in the groundwater was quite substantial. The soluble salt levels measured in individual piezometers varied widely between locations and between depths at the same site (Table 3.6). The salinity levels in each piezometer did not vary significantly over time even though they were bailed out occasionally and sampled in both wet and dry periods. Gunn (1985) observed a similar pattern in the single piezometer he had installed at Yarralaw during 1983 and in the other piezometers throughout the local area.

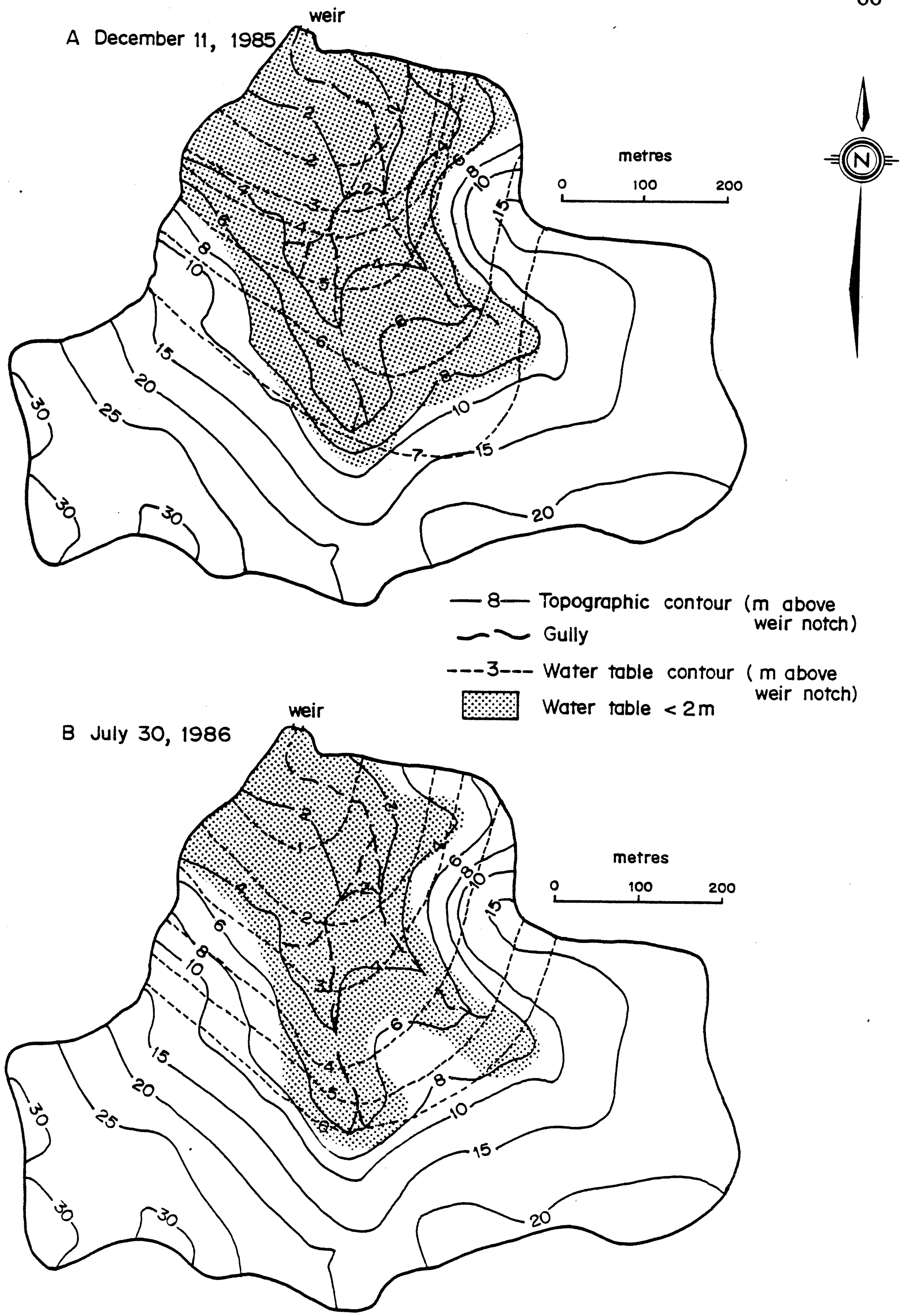


Figure 3.8 Water table isopach maps for (a) the highest water table level (December 11, 1985) and (b) the lowest water table level (July 30, 1986).

Table 3.6. Electrical conductivity of Yarralaw piezometer water

Piezometer Site	Piezometer Depth (m)	Sampling Date 26/7/85	Sampling Date 21/11/85	Sampling Date 29/1/86	Mean
1	2		2.9[1]	5.3	4.1
	4		7.7	8.1	7.9
	7		10.0	10.9	10.4
	16	2.2	2.2	2.3	2.2
2	2		2.9	3.7	3.3
	4	2.7	3.1	3.0	2.9
4	2	10.8	8.5	10.0	9.8
	3	13.7	13.1	13.1	13.3
	6		11.4	11.5	11.4
5	2		3.5	3.7	3.6
	3		6.3	6.0	6.1
	6	9.5	8.4	8.8	8.9
6	2		3.5	6.0	4.8
	3		12.2	12.5	12.3
	5	13.3	13.4	13.8	13.5
7	2		4.3		4.3
	3		2.7	2.6	2.7
	7		2.3	2.3	2.3
	14	0.8	1.5	1.7	1.4
8	2		1.2	2.2	1.7
	3	7.8	7.6	7.6	7.7
	7	4.4	6.6	6.8	5.9
11	2		2.8	2.9	2.9
	3		14.4	14.2	14.3
	7		2.0	2.1	2.0
13	7	0.5	1.0	2.4	1.3
14	3		0.8	0.9	0.9
	5		10.1	8.7	9.4
	11		2.3	2.7	2.5
15	2		7.4	7.6	7.5
	3		7.4	7.3	7.3
	5		5.7	5.5	5.6
	10	2.5	2.4	2.5	2.5
16	3		1.3	1.8	1.6
	5		7.8	6.5	7.1
	10	4.3	3.9	5.5	4.6
17	8	1.7	1.0	0.9	1.2
21	1		2.8	1.1	2.0
	3	1.0	0.9	0.9	0.9
	5	0.8	0.7	0.8	0.8

1 - (dS m^{-1})

In order to analyze the distribution of soluble salt in the groundwater, a simple mean water EC at depth below the water table was calculated from the mean values in Table 3.6. This yielded an average soluble salt profile for the groundwater (Table 3.7) down to the depth of the groundwater investigation (approximately 15 m). On average, the soluble salt levels increased from the water table surface to a depth of 6 m below the water table at which point the groundwater EC declined. Similar salt bulge profiles have been described by Johnston (1981) in the Darling Range of Western Australia and by Batini et al. (1976) in the Helena catchment east of Perth. It is interesting to note that the salt bulge pattern described by the above authors occurs in unsaturated material, whereas the profile shown in Table 3.7 occurs in the groundwater.

The total salt content of the upper 15 m of the groundwater within the area represented by the piezometers was estimated using the following assumptions. The percentage salt concentration

Table 3.7. Mean salt profile for the groundwater beneath the lower Yarralaw catchment.

Depth below mean water table (m)[1]	Number of samples	EC (dS m^{-1})	Percent Salt[2]	Salt Content of the layer (t)
0-1	4	4.7	0.24	154
1-2	9	6.3	0.33	211
2-3	5	7.5	0.40	256
3-4	1	7.1	0.38	243
4-5	5	7.3	0.39	250
5-6	4	8.3	0.44	282
6-7	*	4.8	0.25	160
7-8	1	1.2	0.06	38
8-9	1	4.6	0.24	154
9-10	2	2.5	0.13	83
10-11	*	2.2	0.11	70
11-12	*	1.8	0.09	58
12-13	1	1.4	0.07	45
13-14	*	1.8	0.09	58
14-15	1	2.2	0.11	70
				2132

1 - Mean of the highest and lowest water table levels, 11 December 1985 and 30 July 1986, respectively.
2 - Converted from the relationship given by Richards (1954) for NaCl.
* - Indicates that the EC was interpolated from the values in the layers above and below.

was estimated from the EC for each layer with the NaCl relationship given by Richards (1954). The total water content was estimated by assuming a bulk density of 1.6 g cm^3 or 40% pore space in the deeper subsoil (all water-filled) and a 16 ha portion of the lower catchment represented by the piezometers. From this, the volume of water and, therefore, the weight of water for each layer was multiplied by the percentage salt concentration to estimate the total weight of salt in each layer. As shown in Table 3.7, there is more than 2100 t of salt in the groundwater within the upper 15 m of the lower catchment. This figure is simply a rough estimate of the mean salt content in the groundwater during the monitoring period.

3.2.2 Infiltration

As discussed in Section 3.1.1, the main physical difference between the grassland and the scald soil is the nature of the surface. The grassland soils are permeable with good tilth while the scald is either dry and hard-packed, or wet and smeared. These qualitative observations translate into quantitative differences in the infiltration characteristics for each area.

The infiltration measurements taken at Yarralaw are summarized in Table 3.8. Under unsaturated conditions the infiltration characteristics between profiles are quite similar. Under saturated conditons, however, the A horizon of the grassland is much more permeable than the scald . The final steady-state infiltration rate and hydraulic conductivity is nearly an order of magnitude higher for the grassland and semi-scald areas as compared to the scald. This is a very important difference, since infiltration acts in opposition to the upward movement of saline groundwater by capillary action.

Soluble salt buildup in soils is determined by the net balance between upward capillary flux and infiltration flux. Earlier (Section 3.1.3) it was shown that excessive soluble salt levels occur mainly within the scalded portion of the Yarralaw catchment and not in the grassland. If the salinity distribution was considered only in relation to the water table level (and, hence, the upward capillary flux), there would be a problem explaining the location of the saline areas because the

Table 3.8 Infiltration, sorptivity and hydraulic conductivity of Yarralaw soils.

	A Horizon					
	Unsaturated[1]			Saturated[2]		
	f	S	k	f	S	k
Grassland	$2.5x10^{-5}$	$1.5x10^{-4}$	$1.1x10^{-6}$	$3.0x10^{-5}$	$7.9x10^{-4}$	$1.6x10^{-5}$
Scald	$3.9x10^{-5}$	$1.7x10^{-4}$	$2.4x10^{-6}$	$3.1x10^{-6}$	$1.2x10^{-4}$	$2.4x10^{-6}$
Semi-scald	$4.2x10^{-5}$	$1.3x10^{-4}$	$2.5x10^{-6}$	$2.7x10^{-5}$	$6.6x10^{-4}$	$8.0x10^{-6}$
	B Horizon					
	Unsaturated			Saturated		
	f	S	k	f	S	k
Grassland	$2.4x10^{-7}$	$3.9x10^{-5}$	*	$6.7x10^{-7}$	$9.0x10^{-6}$	$6.5x10^{-7}$
Scald	$5.0x10^{-7}$	$4.4x10^{-4}$	*	$8.3x10^{-7}$	$6.5x10^{-5}$	$6.4x10^{-7}$
Semi-scald	*	$1.9x10^{-5}$	*	$1.9x10^{-7}$	*	$1.9x10^{-7}$

1 - Unsaturated measurements were carried out at suctions between 5 and 6 cm.
2 - Saturated measurements were done with a positive head of about 0.5 cm.
f - Final steady-state infiltration rate ($m s^{-1}$)
S - Sorptivity ($m s^{-0.5}$)
k - Hydraulic conductivity ($m s^{-1}$)
* - Value was too small to be measured.
Note: The figures reported are the mean value of 2 measurements at 2 different sites.

non-saline grasslands in the lower catchment are just as close to water table as the adjacent scald. However, if the infiltration flux is considered sufficient to prevent a buildup of salts near the soil surface of the grassland but not in the scald, it becomes more apparent why the salinity occurs as shown in Figures 3.4 and 3.5.

3.2.3 Runoff

From May 1985 through October 1986, 29 individual storms at Yarralaw were monitored for both rainfall and runoff. One event in June 1985 and three smaller events at the end of 1985 were missed through difficulties with the weir. The rainfall for a small runoff event in September 1986 was not measured because of a problem with the tipping bucket rain gauge. These were only minor gaps and the data collected represent a nearly continuous monitoring period. The entire rainfall and runoff data set is listed in Appendix B.

Hydrological data for individual storm events are given in Table 3.9. Runoff at Yarralaw consists of a series of distinct events separated by periods with no flow, thus no baseflow

Table 3.9. Characteristics of individual storm events at Yarralaw

Date	Rainfall	Runoff	Max. 60-min inten.	Peak Instan. runoff	Suspended Sediment	Total Dissolved Solids	Bedload
	---------- mm ----------		---- mm h^{-1} ----		------------ tonnes ------------		
1985							
May 31	4.4	.15 (3.4)*	3.2	.21			
June 1-2	11.0	.68 (6.2)	2.6	.21			
June 12-13	12.2	.82 (6.8)	7.2	.42			
June 20	3.0	.08 (2.5)	3.0	.11			
Aug 15-16	9.0	.14 (1.6)	3.2	.13			
Aug 22-23	7.0	.13 (1.9)	2.4	.05			
Sept 10-11	12.6	.30 (2.4)	4.6	.12			
Sept 12-15	17.2	1.98(11.5)	2.0	.11			
Sept 19-22	45.8	8.94(19.5)	6.2	.48	8.78	1.68	
Sept 25-26	3.8	.08 (2.0)	2.8	.13	.06	.06	
Oct 15	5.6	.09 (1.6)	3.0	.06	.13	.08	
Oct 16-20	59.2	4.17 (7.0)	18.6	.68	6.52	1.12	
Oct 23-29	28.6	5.16(18.0)	2.8	.18	1.63	2.35	
Nov 7-10	36.0	2.32 (6.5)	21.4	.15***	1.27	.84	
1986							
Jan 16	2.4	.16 (6.7)	22.0**	.67	2.45	.05	
Jan 22	17.8	.20 (1.1)	12.2	.56	3.19	.07	
Apr 17	6.8	.04 (0.6)	3.4	.09	.11	.01	
Apr 17	5.2	.09 (1.7)	4.2	.17	.21	.03	
Apr 28-May 2	44.2	1.35 (3.1)	5.4	.29	4.75	.32	}.90
May 17-18	20.2	.62 (3.1)	9.8	.70	9.16	.24	}
July 4-5	5.8	.09 (1.5)	2.0	.03			.01
July 5-6	6.0	.20 (3.3)	3.4	.10	.37	.08	.01
July 25	1.8	.02 (1.2)	6.0**	.02	.02	.01	<.01
Aug 4-9	62.0	4.06 (6.5)	7.4	.48	19.58	.72	1.09
Aug 15-17	21.0	1.64 (7.8)	6.4	.18			.83
Aug 24	8.4	.20 (2.4)	2.0	.05	.11	.07	.01
Sept 12-15	21.2	.39 (1.9)	4.2	.07	1.41	.12	.12
Sept 19-20	3.4	.05 (1.6)	1.6	.03	<.01		
Oct 9-10	30.6	.92 (3.0)	3.8	.08	2.06	.30	.44
Total	476.2****	35.07 (6.9)			61.81	8.15	3.42

* - Runoff conversion as % of rainfall
** - Peak instantaneous intensity, event less than 1 hour in duration
*** - May not be accurate because of siltation in the stilling well inlet.
**** - Only rainfall associated with runoff events has been reported.

separation was necessary in the runoff analysis.

Runoff originates from basically three different mechanisms: overland flow, interflow and groundwater discharge (Smith and Hebbert, 1983). Baseflow is normally sustained by groundwater discharge and since there was no baseflow between runoff events, it was assumed that runoff water originated from surface and near-surface storages rather than groundwater. Interflow tends to lag the catchment response to rainfall since the rainwater must first pass through a shallow surface storage and move laterally downslope before it re-emerges at the surface to become runoff. This process and its importance in the Yarralaw catchment are discussed more fully in the next section. The discussion in this section will deal with overland flow.

Overland flow can occur through two different mechanisms. Hortonian overland flow occurs whenever the intensity of rainfall exceeds the infiltration capacity of the soil (Horton, 1933). Saturation overland flow occurs when vertical infiltration into a soil profile is restricted above a shallow flow-restricting layer over which a saturated zone develops which eventually rises to the surface to form a wet area that contributes to runoff (Dunne and Black, 1970). These mechanisms are fundamentally different because Hortonian overland flow can occur when the soil is not saturated and saturation overland flow requires a saturated soil profile. Depending on antecendent moisture conditions, soil properties and rainfall intensity, a given catchment can exhibit a combination of both processes during any given event (Smith and Hebbert, 1983).

A typical hydrograph and sediment load record for Yarralaw is shown in Figure 3.9. The sediment discharge will be discussed in Section 3.3 but it is shown in Figure 3.9 for the sake of temporal comparisons that will be made later. The rapid response of the catchment to rainfall is evident in the steep rising limb of the hydrograph (Figure 3.9a). Frequently during the study, it was observed that rainfall was shed quickly from the scald surface, sometimes with only limited amounts of precipitation. This indicates that runoff from the scald is dominated by Hortonian overland flow. A linear regression between the maximum storm intensities and the peak runoff

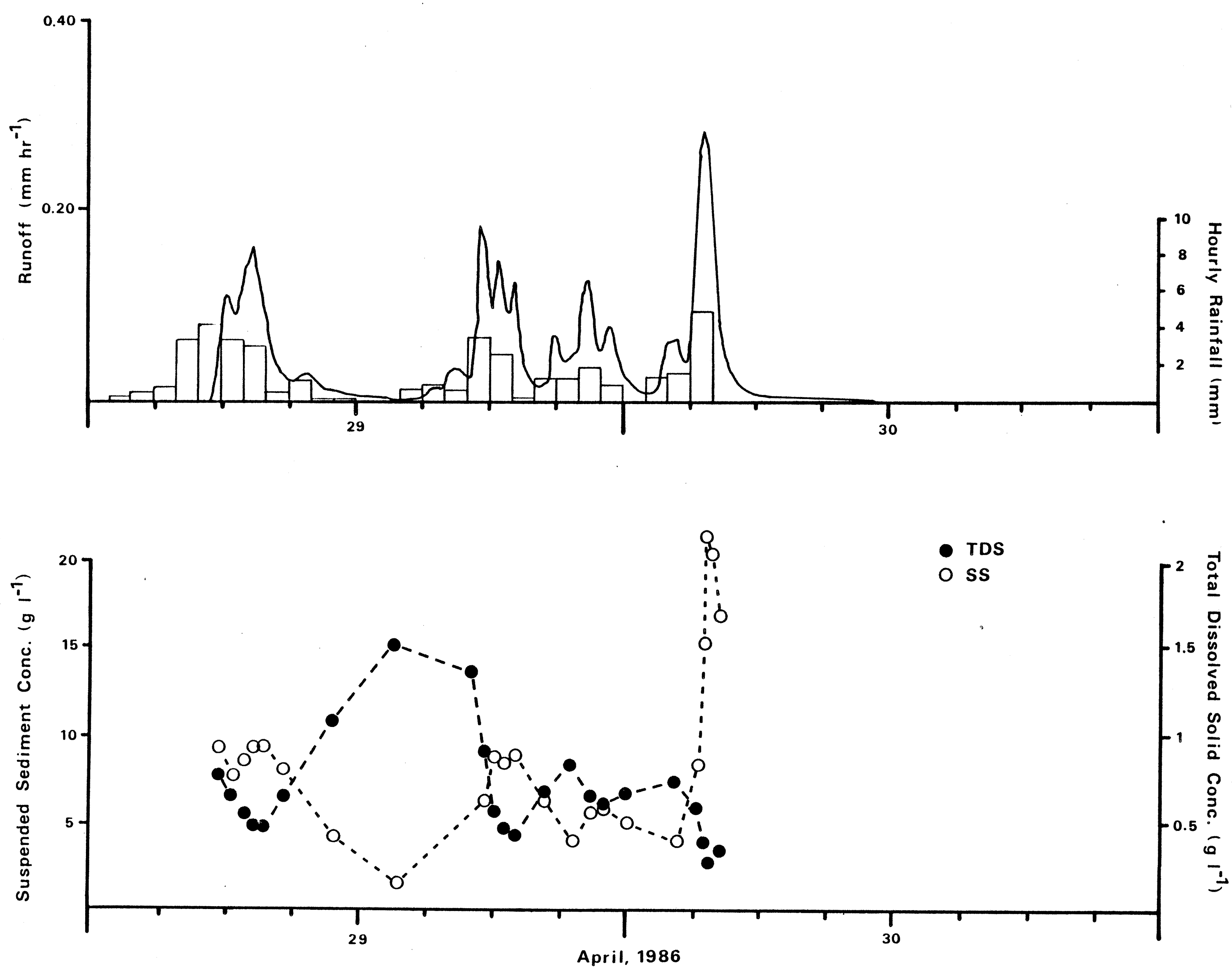


Figure 3.9 (a) Rainfall and runoff hydrograph and (b) suspended sediment and total dissolved solid concentration for the April 29-30, 1986 runoff event.

rates (Figure 3.10) demonstrated that the runoff response was closely related to rainfall intensity, further evidence of the Hortonian runoff mechanism.

However, as shown in Table 3.9, the maximum 60-minute rainfall intensities seldom exceeded the saturated infiltration rate measured on the scald surface (10.8 mm h^{-1}) and never exceeded the rate for grassland (107 mm h^{-1}). Taken at face value, these measurments would indicate that Hortonian runoff occurs only very rarely. Possibly the best explanation for this inconsistency is the effect of raindrop impact smearing the soil surface, something which would not occur when using the disc permeameter to measure infiltration rates. The disc permeameter measures the infiltration rate of the scald surface in an undisturbed state rather than in the smeared condition exhibited during rainfall events. Presumably, the scald surface would be less permeable in the latter condition which would promote Hortonian runoff generation.

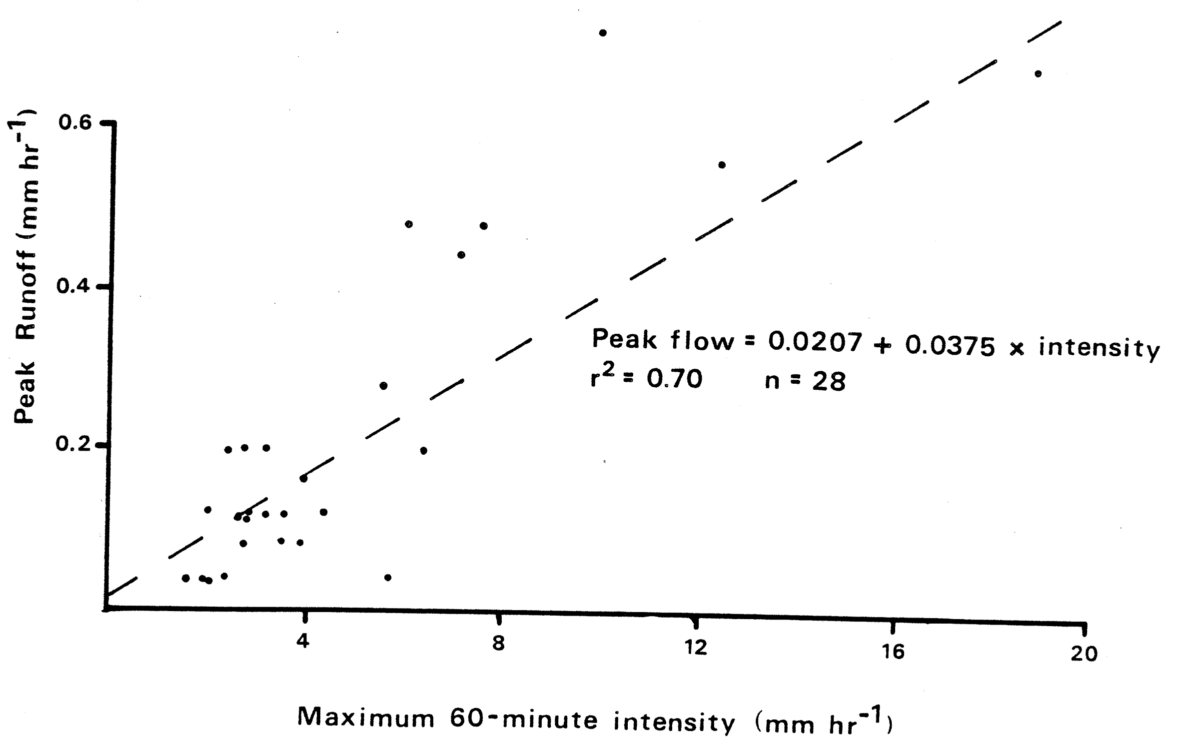


Figure 3.10 Relationship between peak runoff rate and maximum 60-minute rainfall intensity for the Yarralaw runoff events.

Direct observations of runoff on the grassland were hampered by the vegetation cover, but overland flow did occur. It was observed running over the edge of the grassland-scald boundary and at various locations further upslope but it was not possible to determine if this was a result of rainwater being shed from the surface or from saturation runoff. It was also possible that some of this overland flow originated from interflow that had resurfaced. The duplex nature of the Yarralaw soils and the permeable nature of the grassland are both characteristics that favor runoff generation by saturation overland flow.

The largest percentage of rainfall lost as runoff was less than 20% in any event, within the range reported in other Australian studies (Aston and Dunin, 1980; Moore et al., 1986). The percentage increased during prolonged wet spells (see, for example, Sept 10-11, Sept 12-15, Sept 19-22, 1985 in Table 3.9). This indicated that as antecedent soil moisture increased, there was a smaller volume of soil storage to fill and a greater percentage of the rainfall could run off on the surface. This tendency is a sign that saturation overland flow is a factor in runoff generation from the catchment. It is possible that the source of runoff at Yarralaw is segregated to some extent between the scald and the grassland with the former area being responsible for the rapid catchment response to rainfall through Hortonian runoff and the latter area affecting the trailing limb of the hydrographs through saturation runoff. The most important point to be made about the runoff mechanism at Yarralaw is that overland flow was observed running off the scald and into the gullies. As will be shown in Section 3.4, this process is critical not only to the degradation of the catchment itself, but also to the offsite effects of the Yarralaw seepage scald.

3.2.4 Interflow

Interflow is water that infiltrates into the ground surface and moves laterally through the upper horizons of the soil until it re-emerges at the surface and contributes to runoff. Conditions which promote interflow are a porous and permeable surface layer underlain by a relatively impervious subsoil (Gray and Wigham, 1970a). Both conditions occur in the grassland soils at Yarralaw and interflow would seem a process likely to occur.

The piezometer nest at Site 21 (Figures 2.4 and 3.5) was located upslope from the low ECa zone discussed in Section 3.1.3. This particular area was considered likely to produce interflow because of a permeable gravelly layer overlying the less permeable clay. Layers similar to this have been described by Conacher (1975, 1982) around several seepage scalds in the York-Mawson district of Western Australia. Observations in these scalds revealed that shallow interflow along these 'percolines' delivered water and soluble salt to the lower parts of the catchments causing salinity. The piezometer nest at Site 21 measured the hydraulic potentials associated with one such layer, referred to as the 'interflow layer', in the Yarralaw catchment. The interflow volume was not measured, since this is a very difficult measurement to make in a catchment the size of Yarralaw.

The water levels in piezometers 21-5 and 21-3 (below the interflow layer) moved in phase with the regional groundwater system (Figure 3.6c). Piezometer 21-1 (within the interflow layer), however, responded quickly to rainfall during wet periods indicating that infiltrating surface water accumulated rapidly in the layer. Following wet periods, the water levels declined and followed a pattern similar to piezometers 21-5 and 21-3. Since piezometer 21-1 was very shallow, it dried out during prolonged periods with no rainfall.

A more detailed description of the water levels at site 21 for a 30 day period is shown in Figure 3.11. Following the dry period prior to September 14, piezometer 21-1 did not respond immediately to rainfall but when the precipitation continued, the water level suddenly increased and was very sensitive to further events. This type of response is typical when the soil is dry and the soil moisture storage must be filled before excess water can begin to influence other storages in the catchment (Gray and Wigham, 1970b).

Prior to the water level rise on September 15, 1985, an upward hydraulic gradient existed between piezometer 21-5 and 21-1. This indicates that groundwater was potentially moving upwards into the interflow layer at this time. This condition occurred again after September 27 and commonly throughout the monitoring period (Figure 3.6c). In fact, the water levels in piezometer 21-5 were above the ground surface for six weeks near the end of 1985 (Figure 3.6c) indicating that the upward gradient was very strong during some periods. However, the area around the piezometer nest was not saline most likely because the interflow layer intercepted any water that was moving upwards from depth.

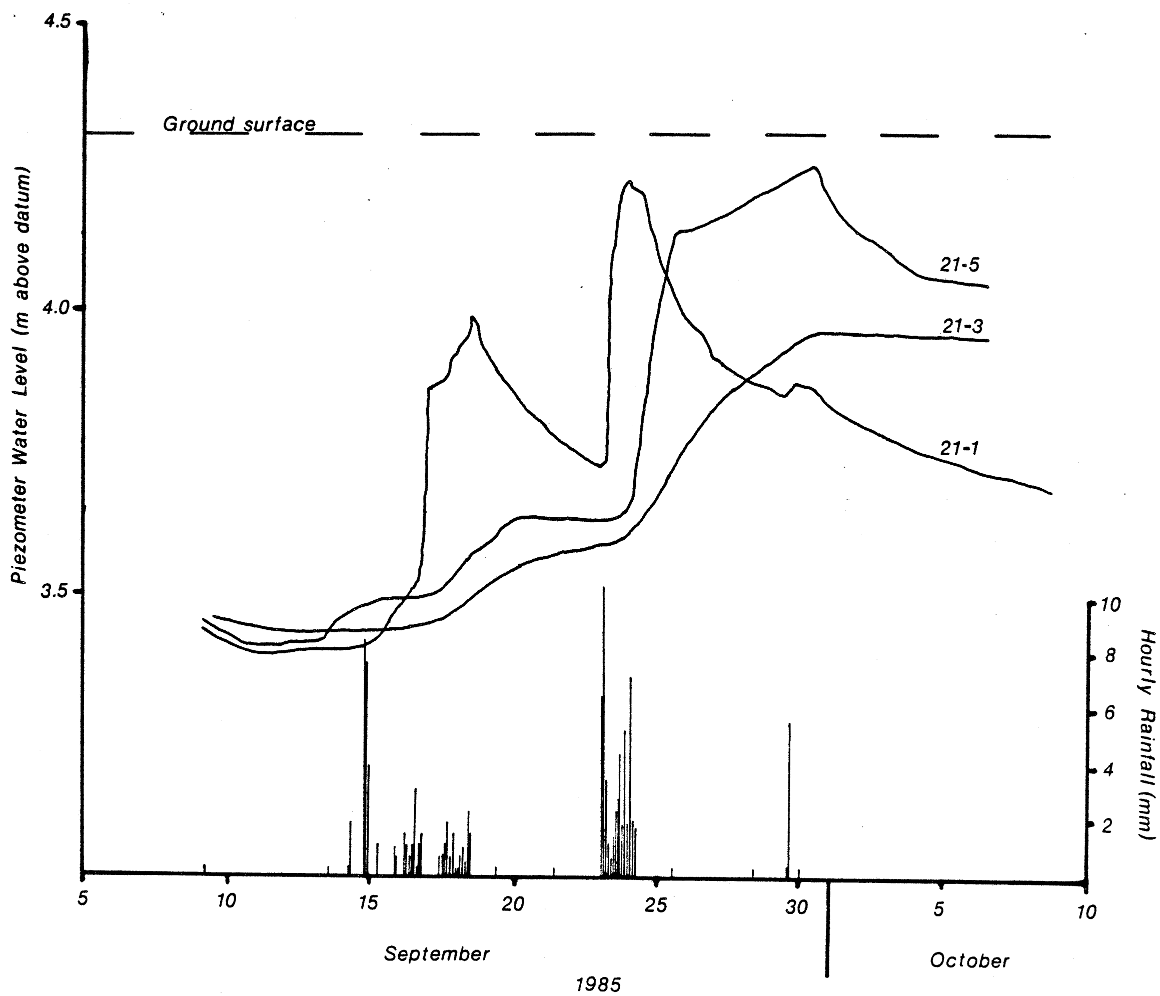


Figure 3.11 Detailed water levels at piezometer site 21 over a 30-day period from September to October, 1985.

During the rainy period between September 15 and 25, the interflow layer behaved like a leaky perched aquifer. The potentials indicate that there was a flux of water from the interflow layer to a point 3 m below ground surface at the same time that there was an upward flux from the 5 m to 3 m depth. This flow pattern of 'both ends towards the middle' may be part of the explanation for the higher concentration of soluble salts in the groundwater at intermediate depths (Section 3.2.1).

The recession limb for the piezometer 21-1 water levels (Figure 3.11) indicated that water was depleted from the interflow layer more rapidly than at depth. It seems likely that a portion of the water in the interflow layer moved laterally downslope and was discharged into the gullies. This was verified in a qualitative manner by field observatons. At the point where the interflow layer intersected the soil surface about 40 m downslope of site 21, slow seepage from the layer kept the shallow subsoil saturated over periods of several weeks following heavy rainfall. It is believed that this prolonged seepage was produced initially by interflow of percolating rainfall and subsequently by interflow resulting from upward groundwater movement into the layer.

The interflow component was not quantified directly nor was it possible to distinguish clearly between interflow and surface runoff on the hydrographs. Since the interflow passes through a shallow storage it is delayed en route to the catchment outflow and it would be expected to influence mainly the trailing limb of the hydrographs. Several hydrographs exhibited exceptionally long trailing limbs, especially following heavy rainfall during wet periods such as the September 19-22, 1985 storm (Figure 3.12). The trailing limb from the April 29-30, 1986 (Figure 3.9a) storm is also marked on Figure 3.12 to demonstrate the differences that can occur with similar sized rainfall events (44 to 46 mm over 3 to 4 days) with different antecedent moisture conditions. The April event occurred following two very dry months and the trailing limb on the hydrograph showed that runoff ceased less than 6 hours after rainfall finished. In contrast, it was very wet during September 1985 and the hydrograph showed that runoff continued for approximately 56 hours after rainfall ceased. Figure 3.6c shows that piezometer 21-1 was dry during April 1986 and that the interflow layer could not contribute to runoff, whereas during the September 1985

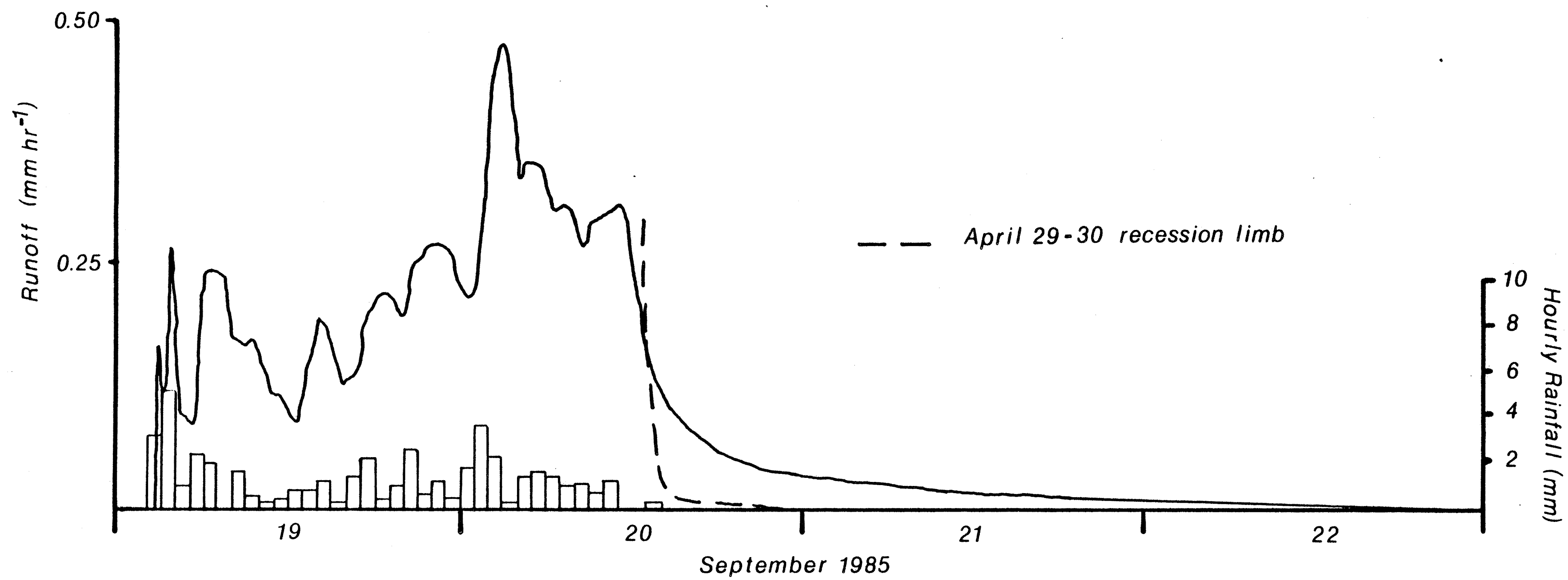


Figure 3.12 Rainfall and runoff hydrograph for the September 19-22, 1985 event. The trailing limb from the April 29-30 event (Figure 3.9a) is also shown for comparison.

event, piezometer 21-1 responded rapidly to the rainfall (Figure 3.11). With the wet antecedent moisture conditions during September 1985, other storages in the catchment may have contributed to the long trailing limb of the September 19-22 event but this cannot be distinguished on the hydrograph.

The runoff hydrograph in Figure 3.12 can be compared to those shown by Burt and Butcher (1985) for a South Devon catchment where the runoff response was dominated by interflow. Approximately 99% of the total South Devon catchment outflow occurred as subsurface runoff or interflow during delayed secondary discharge peaks which developed about two days after rainfall. These double peak hydrographs occurred only when conditions were favorable for interflow. By comparison, the trailing limbs of the Yarralaw hydrographs comprised only a small percentage of the runoff for all the storms that were monitored and it is likely that interflow was only a small part of the total catchment runoff.

Interflow may have qualitative effects on the condition of the catchment. As previously mentioned, slow seepage from the layer downslope of piezometer site 21 kept the soil moist and soft for several weeks following heavy rainfall. In this condition, the soil is especially prone to water erosion from subsequent runoff events. This is possibly the reason for the distinct 'scour line' along the east side of the grassland-scald boundary where stones occur frequently between the A and B horizon as verified with hand augering, visual observation and the EM38 readings (Figure 3.5). Discharge from this interflow layer may have kept the grassland downslope of the discharge area moist and susceptible to erosion while the grassland upslope would presumably remain more resistant to erosion. Overland flow from the higher slopes would erode the susceptible areas which would become part of the scald and leave a sharp boundary between the grassland and scald.

Although the interflow component of the Yarralaw hydrology was not measured directly, it is not believed to have had a large effect in terms of the formation of the scald, although it may have been responsible for the erosion pattern that developed in some locations. It is highly unlikely that interflow could have caused all the degradation now evident at Yarralaw. This is in contrast to the reports by Conacher (1975, 1982) which have suggested that interflow is the main reason for much of the seepage scalding in the York-Mawson district of Western Australia. However, it should be noted that reclamation strategies designed to reduce the amount of interflow into seepage scalds in Western Australia have had only limited success (Conacher, 1983a, 1983b) suggesting that other factors may be involved in the formation of these areas.

3.2.5 The Catchment Water Balance

The water balance concept states that in a given catchment, the difference between the amount of water added and the amount of water withdrawn over a certain time period is equal to the change in catchment water storage during the same time period. This simple relationship was used as a means for assessing the measurement accuracy for each component of the water balance in the Yarralaw study.

For an unirrigated catchment the water balance can be expressed as

$$S = P - Et - Q - GWO \qquad (3.3)$$

where S = change in catchment water storage (mm)
P = total precipitation (mm)
Et = total evapotranspiration (mm)
Q = total runoff (mm)
GWO = groundwater outflow at depth (mm).

This equation was evaluated for the period October 1, 1985 to September 30, 1986 using the data that has been described in the previous sections.

The P and Q components were measured directly and totalled for the above period. (Note, that in Table 3.9, only the rainfall associated with runoff events is reported.)

The S component is the lumped sum of several stores including groundwater, canopy, surface detention and channel storages. Since moisture conditions at the beginning and end of the evaluation period were similar, it was assumed that changes in the latter three storages were negligible, leaving groundwater as the main indicator of S. The water levels in the piezometers were all lower at the end of the period than at the beginning with the differences ranging from -0.052 to -0.753 m with a mean of -0.413 m. To convert water table levels to mm of water, a series of soil moisture profiles were sampled at different times and different points in the catchment by hand augering down to and past the water table. The total soil moisture in each profile was compared to the water table level below the ground surface. These values indicated that there was approximately 100 mm of water storage per 1 m water table rise. Thus, it was assumed that the mean change in groundwater level (-0.413 m) corresponds to approximately 41 mm of water lost from catchment storage.

The GWO component was calculated from the groundwater information presented in Figure 3.8. At each water table contour, the flux of water ($m^3 s^{-1}$) perpendicular to the contour was calculated by multiplying the mean subsurface saturated hydraulic conductivity (1×10^{-6} $m s^{-1}$) by the mean gradient in the water table at the contour ($m m^{-1}$) and the cross-sectional area of the upper 15 m of groundwater at the contour. The 15 m depth was used because it represented the depth of groundwater exploration at the site. The mean flux across all the water table contours in both Figures 3.8a and 3.8b was 20 mm y^{-1}. This was used as the GWO component of the water balance.

Soil moisture levels were determined from the readings in five neutron moisture meter (NMM) tubes located 20 m upslope from piezometer site 21 (Figure 2.4). Soil moisture profiles for the wet and dry extremes of the monitoring period are shown in Figure 3.13. Spring and autumn volumetric water contents varied by approximately 0.1 $mm^3 mm^{-3}$ at any one depth with the entire profile change being 150 mm of water. The marked difference between the A and B horizons

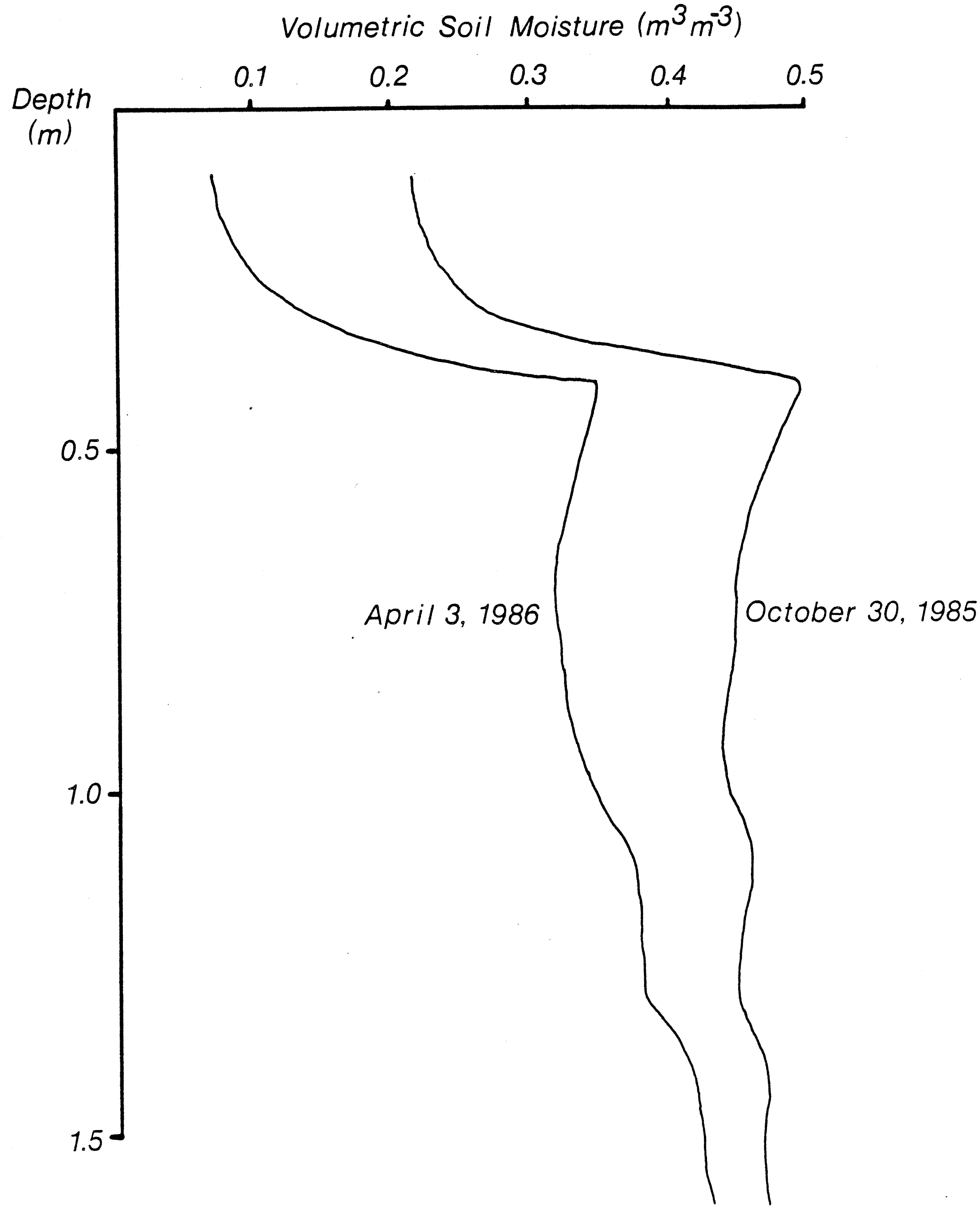


Figure 3.13 The wettest and driest soil moisture profiles measured in the Yarralaw neutron moisture tubes between June 1985 and October 1986. Location of the neutron moisture tubes is shown in Figure 2.4

reflects their textural differences and the concentration of grass roots in the upper portion of the profile.

The volumetric water contents up to 0.45 m^3 m^{-3} in the April profile are greater than the volume of pore space. The bulk density of the Yarralaw subsoil is approximately 1.6 g cm^{-3}, which corresponds to a pore volume of only 0.40 m^3 m^{-3}. This difference may be a result of mineral absorption or bound water effects (Greacen, 1981) or variability of subsurface bulk density. However, these factors would apply to both the dry and wet profiles in Figure 3.13, so the differences in moisture content measured with the NMM are real and the relative gain and loss of soil water is still valid.

The Et component was calculated by converting Goulburn pan evaporation (Ep) with a pan coefficient function dependent on soil moisture levels (Costin et al., 1984). The function has the form shown in Figure 3.14a and has been used successfully in other modelling applications (Aston et al., 1980). It neglects short period and seasonal variations, therefore, during wet periods (i.e. Rainfall > Ep), Et was set equal to Ep. It also combines the evaporation of water intercepted by leaves with that from the soil surface as well as that transpired from the root zone. This means that the calculated Et will likely overestimate the loss of water from soil storage. The function is also shown to be linear when it is likely curvilinear. However, this will tend to reduce the Et estimate and offset the overestimation above.

The pan function was tested with a simple soil moisture model. Inputs to the model were weekly Yarralaw rainfall and weekly Goulburn Ep values since this was the closest meteorological station where Ep values were available. For each week the model calculated Et from Ep using the function (Figure 3.14a), then summed the rainfall input and Et output to calculate a net gain or loss from soil storage. The soil moisture storage was defined as the A horizon because most of the vegetation at Yarralaw consists of grasses with little root penetration into the B horizon. The thickness of the layer was set at 300 mm, the average depth of A horizon in the catchment. The observed soil moisture levels from the NMM readings were used to calibrate the model. Over the

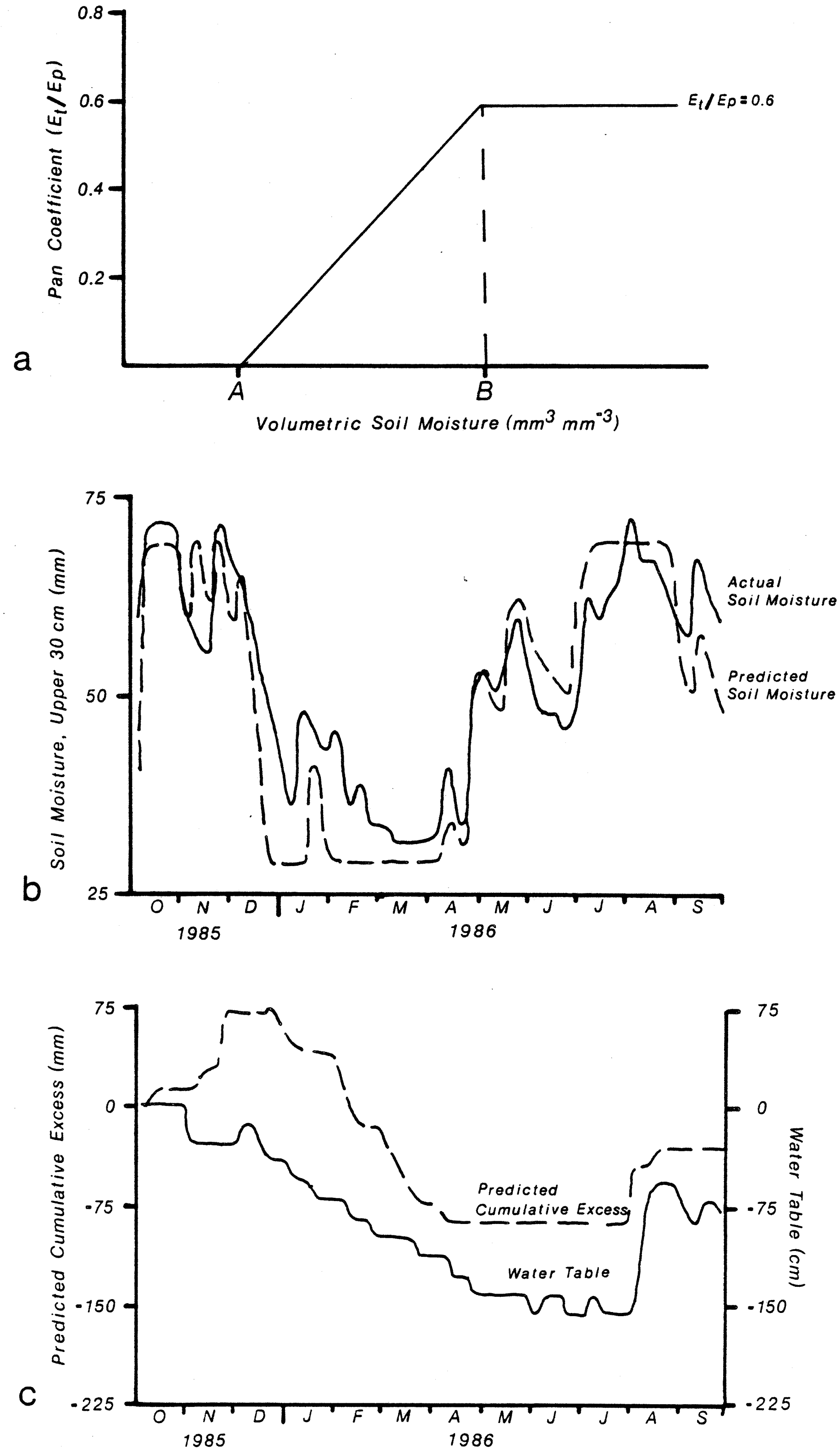


Figure 3.14 The soil moisture model (a) pan evaporation function, (b) predicted versus actual soil moisture levels in the upper 30 cm of soil and (c) predicted cumulative excess moisture versus water table levels.

course of the monitoring period, the maximum water storage observed in the upper 300 mm of soil was 70 mm and the minimum storage was 30 mm, therefore, the model was confined within these limits (Figure 3.14b).

The best match between predicted soil storage and actual soil storage ($r^2 = 0.72$) was achieved with soil moisture values of .05 and .13 for the A and B coefficients respectively (Figure 3.14b). These values are very close to those found for a similar region of southeastern New South Wales (Costin et al., 1984). The predicted response tends to dry out or wet the profile more rapidly than the observed moisture changes. However, this is understandable considering that the observed moisture levels were taken from NMM tubes in only one location in the catchment.

As mentioned above, the model was confined to soil moisture values between a maximum of 70 mm and a minimum of 30 mm. Once the storage is filled to the maximum level, further water input must runoff and/or percolate below the root zone. When the storage reaches the minimum level, the soil moisture is maintained by upward groundwater movement from the water table. If for a given week, P - Et exceeded the maximum soil storage, the model saved the amount above the maximum as a positive excess. If the P - Et tried to dry the soil below the minimum soil storage, the model saved the amount below the minimum as a negative excess. The cumulative excess moisture values saved by the model are plotted in Figure 3.14c along with the change in the water table during the same period. Although not exact, the excess moisture pattern follows the water table levels quite closely. Particularly significant is the fact that both curves turn sharply upward at the same point in August 1986. A comparison of Figures 3.14b and 3.14c shows that once the soil moisture storage is filled, excess moisture recharges the water table (August to September, 1986). It also shows that when the soil moisture storage is at a minimum during periods of high evaporative demand, there is an upward flux of water from the water table to the surface soil because the moisture level of this layer stays at the minimum level while the water table drops (January to April, 1986).

These results add further support to the Et predictions made with the soil moisture model. Not only does the model do a reasonable job of predicting the observed soil moisture levels but also the observed groundwater levels. Therefore, the weekly Et values predicted from the soil moisture model were considered to be acceptably accurate and were then summed to provide a measure of Et for the water balance.

The values determined for each component of the water balance are as follows with all totals in mm.

$$S = 637 - 669 - 23 - 20 = -75 \qquad (3.3a)$$

The calculated loss from the store was -41 mm and the 34 mm discrepancy is only 5.3% of the total rainfall input. Despite the errors inherent in the various measurements and assumptions, the water balance indicates that the values calculated for each component are reasonable.

3.3 Erosion Characteristics

3.3.1 Forms of Erosion at Yarralaw

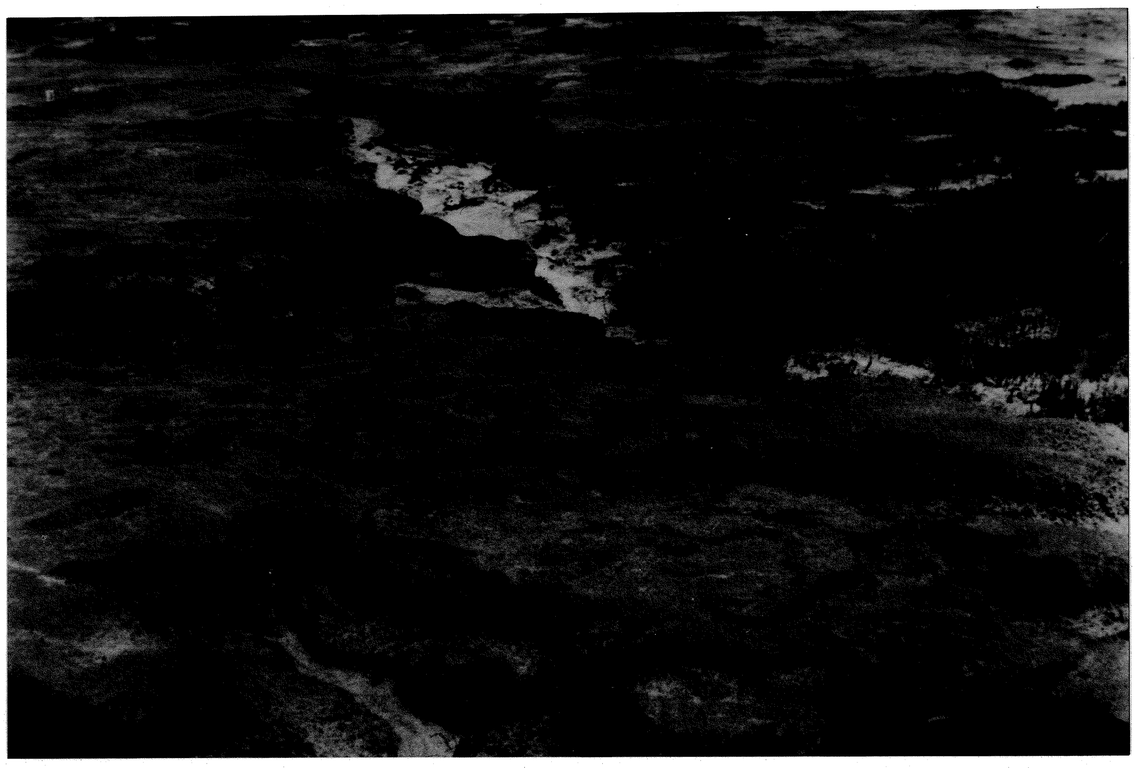
Yarralaw has been severely damaged by both gully and sheet erosion. There are two major gullies ranging from 0.5 to 1.5 m in depth with several smaller tributaries. Sheet erosion has stripped the upper 10 to 30 cm of soil from the area adjacent to the gullies. Overland flow from the grassland runs over the scald-grass boundary and erodes the unprotected soil from around the grass roots until a 'scallop' or hollow pocket forms under the grassland edge. The overlying soil eventually collapses into the hollow either from sheep traffic or under its own weight. This mechanism of erosion, a result of runoff from the grassland soils, is a means by which the scald can expand into the grassland area. However, a series of photographs taken from ten different locations along the headcut edge of the scald and nine locations along the sides of the scald, revealed that this mechanism was occurring only very slowly during the monitoring period. There was evidence that this sort of slumping had occurred in other isolated locations and it is possible that the photograph stations were poorly selected. However, it would be expected that more evidence would have been detected if this mechanism was indeed very active.

The flat surfaces of the scald which have been stripped by sheet erosion are undergoing further degradation by gully erosion. Tiny rills in the scald surface grow quickly into miniature gullies as a result of overland flow. As the minature gullies deepen, the walls eventually collapse, either from sheep traffic or by natural slumping, making the gullies wider. In contrast to the scald edges, the miniature gullies are forming and growing very rapidly. With only two photo locations on the scald surface, it was possible to document the obvious changes that occurred on one of the miniature gullies (Figure 3.15). Thus, the scald itself appears to be degrading rapidly which supports observations of the quick runoff response from this area of the catchment (Section 3.2.3).

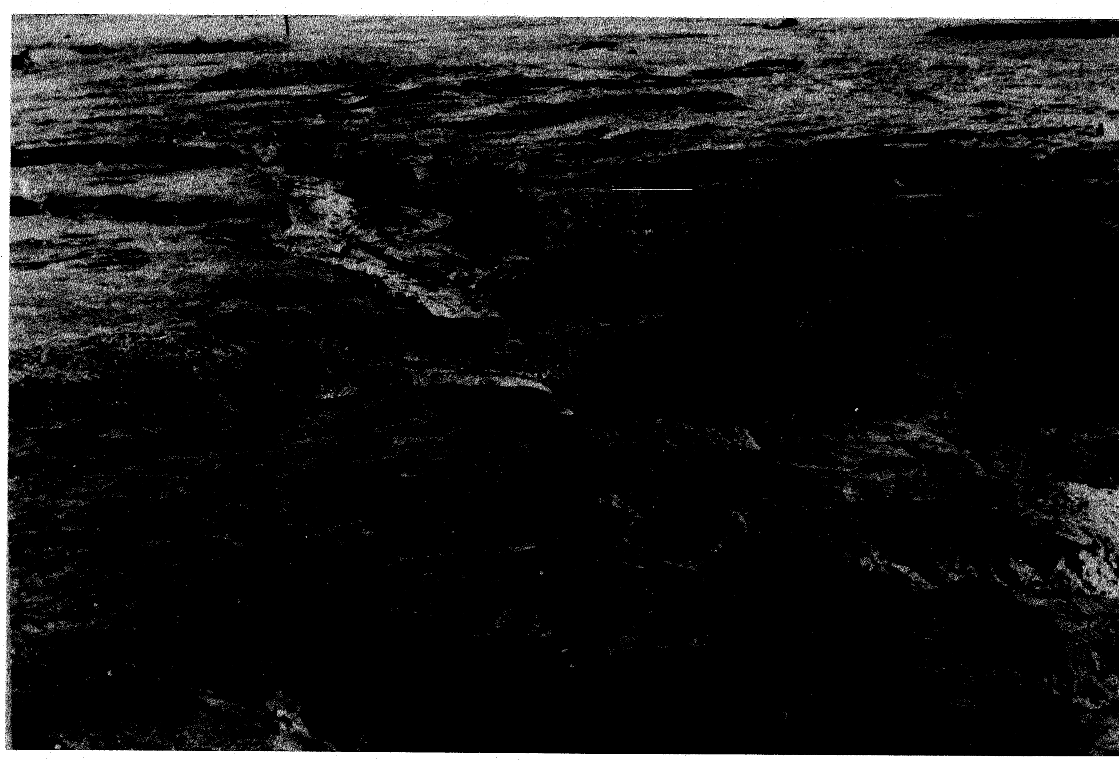
Wind erosion is also active in the scald under certain conditions. In Section 2.1, a description was given of the powdered condition on the scald surface as a result of sheep traffic. The soil loss due to wind erosion was not measured, but dust was observed blowing off the scald and out of the catchment. There was also a great deal of soil redistribution since miniature dunes of drifted soil built up in the protected portions of gullies and dead tree stumps on the scald.

3.3.2 Suspended Sediment Loss

Sediment monitoring commenced in September 1985 and continued through October 1986. The events for which suspended sediment (SS) load was measured are listed in Table 3.9 and the individual sample measurements are listed in Appendix B. The SS concentration in the runoff varied widely between and during events, ranging from as high as 50 g l^{-1} down to 0.01 g l^{-1}. The SS concentration of the discrete samples was usually higher when the runoff rates were high and decreased when the runoff rate decreased (Figure 3.9b). Continuous measurements may have revealed more complex SS concentration patterns such as those illustrated by Olive and Reiger



a)



b)

Figure 3.15 Two photographs of a miniature gully on the scald taken (a) November 20, 1985 and (b) May 22, 1986. Notice how much the gully has grown between these dates.

(1985). Complex discharge-concentration patterns can occur when SS concentration is limited by the availability of suspendable material such as clay, silt and fine organic particles (Freebairn and Wockner, 1986b). The large bare scald surface at Yarralaw may provide a virtually unlimited supply of suspendable material especially considering the poor structural stability in this area (Section 3.1.2)

The capacity of rainstorms to erode soil has been shown to be closely correlated to a rainfall erosion index (EI) calculated as the product of storm energy and maximum storm intensity (Wischmeier and Smith, 1978). The energy of a rainfall event is a function of the amount of rain and all the component intensities for the event (Foster et al., 1981).

$$e_j = 0.119 + 0.0873 \log_{10} i_j, \quad i_j \leq 76 \text{ mm h}^{-1} \tag{3.4}$$

or

$$e_j = 0.283, \quad i_j \geq 76 \text{ mm h}^{-1} \tag{3.5}$$

where e_j is kinetic energy in megajoules per hectare per millimeter of rainfall (MJ ha^{-1} mm^{-1}) for time interval j, and i_j is intensity in millimeters per hour (mm h^{-1}) for time increment j. The energy for a rainfall event (E) is calculated as

$$E = \Sigma e_j \, p_j \tag{3.6}$$

where E is in MJ ha^{-1} and p_j is rainfall (mm) for time interval j. For this study, an erosion index (EI) was calculated for the major storms which had been monitored for suspended sediment loss using the following formula.

$$EI = E \times I_{60} \tag{3.7}$$

where I_{60} is the maximum 60 minute storm intensity in mm h^{-1} and El is in MJ mm ha^{-1} h^{-1}. The EI values are listed in Table 3.10 and plotted in Figure 3.16 against the suspended sediment loss measured for the same storm. Note that the storm of November 7-10, 1985 was not included because of possible problems with the runoff measurements. The storm of October 16-20, 1985 was also excluded from Figure 3.16 because equation 3.7 yielded an unreasonably high EI, most probably because this was a long, complex rainfall event and the maximum 60 minute intensity did not apply equally to each portion. The close relationship between EI and SS load (Figure 3.16) indicates that the limiting factor for producing SS is probably the energy in individual rainfall events, rather than the supply of erodible material. This is consistent with the observations of rapid runoff response on the scald (Section 3.2.3), the poor structure stability of the scald surface (Section 3.1.2) and the rapid gully growth in this area (Section 3.3.1).

Table 3.10. Erosion indices for Yarralaw storms monitored for suspended sediment loss.

Storm	Erosion Index[1]
1985	
Sep 19-22	40.2
Sep 25-26	1.4
Oct 15	2.4
Oct 16-20	193.9
Oct 23-29	9.1
1986	
Jan 16	12.1
Jan 22	41.4
Apr 17	3.2
Apr 17	3.4
Apr 28 - May 2	35.6
May 17-18	32.0
Jul 5-6	2.9
Aug 4-9	63.8
Aug 24	2.2
Sep 12-15	12.9
Oct 9-10	16.0

1 - MJ mm ha^{-1} h^{-1}

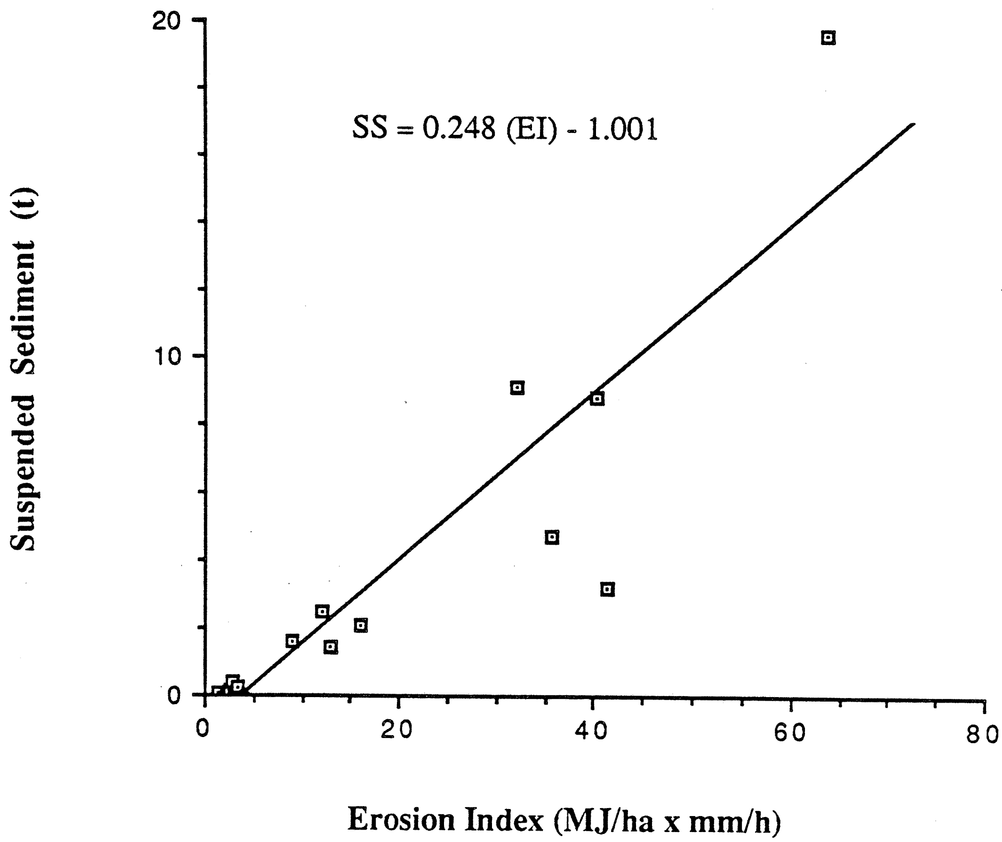


Figure 3.16 Relationship between suspended sediment loss and erosion index for Yarralaw storms. The storms of October 16-20 and November 7-10, 1985 are not included.

A SS rating curve was constructed by graphing SS concentration versus runoff rate (Figure 3.17a). The variation in runoff rate accounted for only 39% of the variation in SS concentration and log values did not improve the correlation. The data set was divided into 2 subsets, based on the time-proportional sampling period and the flow-proportional sampling period. The 251 samples taken on a time-proportional basis had a rating curve with an r^2 of only 0.10, but the 100 flow-proportional samples had a rating curve with an r^2 of 0.68 (Figures 3.17b,c). This is most likely a result of the sampling distribution with each system. For a small catchment such as Yarralaw, peak runoff rates may last only a few minutes and a time-proportional sampling scheme can easily miss the peak flows. With a flow-proportional sampling scheme, samples are taken at higher frequency during peak flows which gives a more representative sample distribution. However, use of the rating curve in Figure 3.17c to predict SS loss incurs a substantial amount of error as shown in Table 3.11. The difference between predicted and actual SS loss is large considering that the events listed are the same ones from which the rating curve in Figure 3.17c was derived. This is in agreement with other research that has shown a high level of error when SS loads are estimated from rating curves (Geary, 1981; Olive and Reiger, 1985; Walling, 1978). Rating curves assume that SS concentration is solely a function of discharge rate. For Yarralaw, it

Table 3.11. Comparison of measured and estimated suspended sediment loss

Date	Measured	Estimated[1]	Difference
	----------- tonnes	----------	%
1986			
Apr 17	.11	.09	-18.8
Apr 17	.21	.25	+19.0
Apr28-May2	4.75	3.99	-16.0
May 17-18	9.16	4.42	-51.7
July 4-5	.37	.38	+2.7
July 25	.02	.03	+50.0
Aug 4-9	19.58	14.86	-24.1
Sep 12-15	1.41	.79	-44.0
Oct 9-10	2.06	1.70	-17.5

1 - Using equation from Figure 3.17c

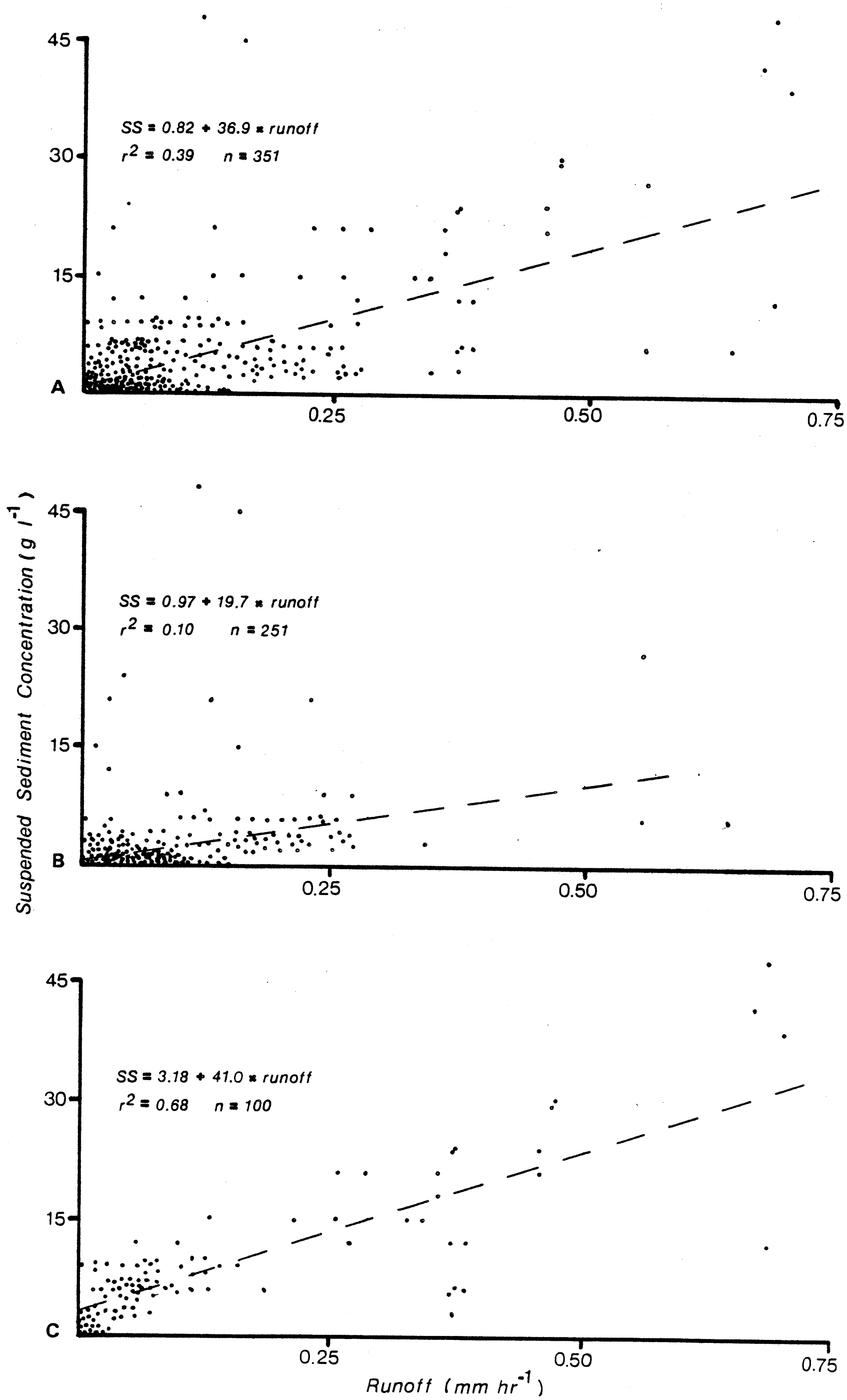


Figure 3.17 Relationship between suspended sediment concentration and runoff rate for (a) all samples, (b) samples taken time-proportionally, (c) samples taken flow-proportionally.

has been demonstrated that SS load is more closely related to rainfall characteristics which determine the amount of energy available for erosion (Figure 3.16). For this reason, SS rating curves are not considered to be a suitable predictive tool for use in seepage scalds.

The total SS loss (61.8 t in 14 months) is substantial considering the ephemeral runoff pattern in this catchment. The loss is equivalent to 1.4 t ha^{-1} y^{-1} which can be compared to sediment yields for other catchments in Australia (Table 3.12). Geary (1981) stated that the losses he reported for Deep Creek, NSW were probably higher than the long term average for that catchment because of above normal precipitation during the monitoring period. The scald plot at Hay, NSW (Alchin, 1983) had no vegetative cover of any kind. Also, it has been shown that sediment yields measured on small plots are normally much higher than those reported for larger areas (Olive and Walker, 1982). As can be seen in Table 3.11, catchments that are in pasture, improved pasture or forest generally have much lower sediment yields.

It was not possible to quantify the proportion of SS that originated on the grassland versus that which originated on the scald at Yarralaw. Surveys of farm dam sedimentation in the Yass Valley, 60 km west of Yarralaw, showed that average grassland sediment yields of about 13 m^3 km^{-2} y^{-1} are likely in this region (Neil and Galloway, 1988). Assuming a similar yield from the grassland at Yarralaw and a density of 1.0 t m^{-3}, the 33.3 ha of grassland at Yarralaw would yield about 6 t y^{-1}. This would leave a sediment yield of 47 t y^{-1} for the scald or 10.4 t ha^{-1} y^{-1}. During one event, a small sample of runoff was collected at two points where it was flowing off the grassland into the head of the scald. The samples were clear (SS conc < 0.050 g l^{-1}) and virtually non-saline (EC = 0.20 and 0.05 dS m^{-1}). Judging from this and from the widespread gully formation taking place on the scald, it seems quite likely that the bulk of the SS originates from the unprotected soils in the scalded area rather than the grassed portion of the catchment. This is consistent with the results of other studies where it was found that surface cover greatly reduced erosion losses (Costin, 1980; Freebairn and Wockner, 1986a).

The magnitude of the SS discharge can be put in another perspective by considering the offsite

Table 3.12. Sediment yields from some Australian catchments

Location	Catchment Area (ha)	Sediment Yield ($t\ ha^{-1}\ yr^{-1}$)	Length of Record (years)	Catchment Condition
Adamson (1976)				
Wagga, NSW*	7.3	2.02 (0.01-10.14)	23	unimproved and eroded pasture
	7.5	0.03 (0-0.35)	23	improved pasture (contoured)
Alchin (1983)				
Hay, NSW*	1.7×10^{-4}	12.79	1	scald
	4.2×10^{-4}	0.45	1	uneroded area adj. to above
Bello et al. (1978)				
Sandy Ck, NSW		<0.01	1	
Pipeclay Ck, NSW		0.02	1	
Boorolong Ck, NSW		<0.01	1	
Bevan (1970)**				
Dumaresq Ck, NSW	56×10^{2}	0.20		forest and pasture
Costin (1980)				
Ginninderra, ACT*	88	0.18 (<0.01-0.38)	5	pasture
Geary (1981)				
Deep Ck, NSW	25×10^{2}	1.45-2.90	1	pasture and viticulture
Loughran (1976)				
Chandler R, NSW	208×10^{2}	0.03-0.11	0.53	forest and pasture
Loughran (1977)				
Congewai Ck, NSW	86×10^{2}	0.28	2	forest, pasture and farmland
Olive (1973)**				
Brown Ck, Tas	13×10^{2}	0.12		forest
Mountain R, Tas	40×10^{2}	0.11		forest, moorland and pasture
Snug Rivulet, Tas	19×10^{2}	0.12		forest
Yarralaw, NSW*	37.8	1.4	1.17	88% pasture, 12% scald

* - catchments exhibiting ephermeral runoff patterns.
** - as reported by Olive and Walker (1982) and Geary (1981).

effects of this loss. Yarralaw is part of the Shoalhaven catchment, an area slated for development into one of Sydney's future water supplies. Higginson (1970) reported 12,500 ha of severely gullied and severely sheet-eroded soils within the Shoalhaven catchment. If it is assumed that Yarralaw represents a typical example of a severely gullied and sheet-eroded catchment and the suspended sediment loss rate for Yarralaw is extrapolated to the 12,500 ha of land within these classes as given by Higginson (1970), then we arrive at a total suspended sediment loss of 17,500 t y^{-1} for the severely eroded areas of the Shoalhaven catchment. If it is further assumed that only 10% of the suspended sediment actually reaches the Shoalhaven River and that the sediment bulk density is 1 t m^{-3}, then 1,750 m^3 of suspended sediment would flow annually into the Shoalhaven River as a result of gully and sheet erosion. This is a significant volume when considering possible siltation problems in an important river system.

3.3.3 Total Dissolved Solid Loss

The total dissolved solid (TDS) loss from each monitored event is shown in Table 3.9 and the individual sample measurements are listed in Appendix B. The TDS concentrations were not as high as those for SS, varying between 0.15 g l^{-1} and 3.50 g l^{-1}. TDS concentration in runoff water was inversely related to runoff rate, opposite to the pattern for SS concentration (Figure 3.9b). The relationship between TDS and discharge rate is shown in Figure 3.18. The plot in Figure 3.18b is similar to the relationships reported in other studies of solute yields (Geary, 1981; Walling, 1978).

At Yarralaw, the high TDS concentration at the beginning of an event probably represents the removal of surface salt that accumulated on the scald areas. Once this initial salt load was washed away, the TDS concentration decreased substantially since runoff entering the scalded area from the adjacent grassland and that derived from channel precipitation was relatively salt-free. The increase in TDS concentration at the end of each event was probably due to the higher interflow component at this stage. Evidence for this was provided by the similar quality of the water in

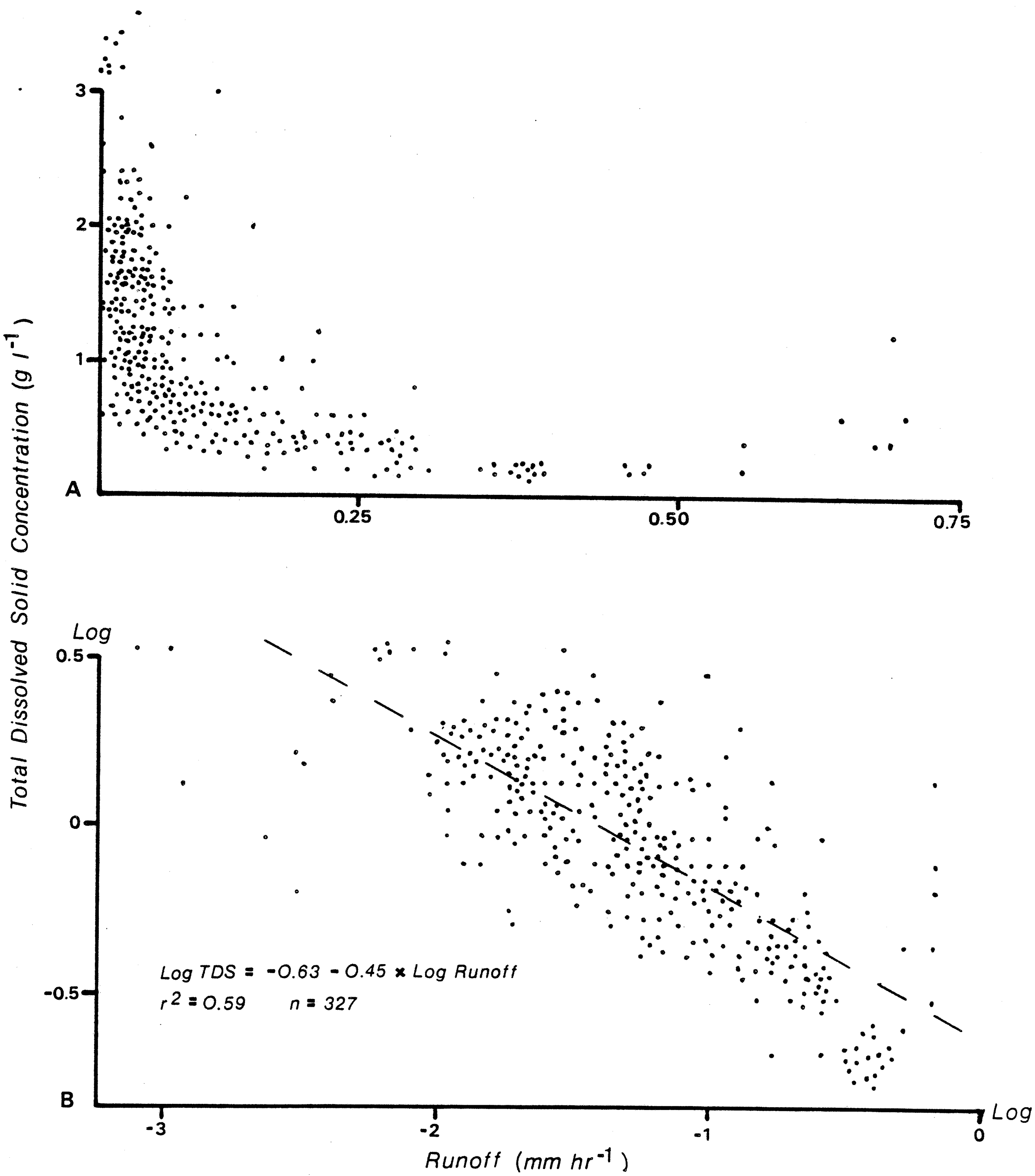


Figure 3.18 Relationship between total dissolved solid concentration and runoff rate (a) normal values and (b) logarithmic values.

piezometer 21-1 (Table 3.6) and the salt level of the runoff on the recession limb shown in Figure 3.9b (early on April 29).

There was a substantial mass of soluble salts (8.2 t in 14 months) exported from the catchment during the monitoring period. The solute yield of 0.18 t ha^{-1} y^{-1} is comparable to that for some continuously flowing streams around Australia (Table 3.13) Considering that runoff occurs during only a small percentage of the time at Yarralaw, the solute yield is remarkably high.

The significance of this level of dissolved sediment loss is better appreciated by considering it on a larger scale. Cumming et al. (1984) estimated the total salt-affected area of Nerrimunga Creek catchment (a subcatchment of the Shoalhaven River which includes Yarralaw and Jacqua Creek) to be 1500 ha. If it is considered that the salt-affected area at Yarralaw is confined to the scald and that the TDS is derived mainly from this area, then the rate of dissolved sediment loss is actually 1.6 t ha^{-1} y^{-1} from the 4.5 ha salt-affected area. Extrapolation of this rate to the total salt-affected area of Nerrimunga Creek yields a figure of 2400 t y^{-1} in dissolved sediments, most of which, would presumably reach the Shoalhaven River. This is a significant amount considering that it originates from a catchment only 90,000 ha in size and is sufficient to raise the TDS level of the proposed 2.7 million megalitre Welcome Reef dam by 1 part per million per year.

One question that comes to mind about the export of salt from Yarralaw concerns the source of the soluble salts and the total supply available. If salt in rainwater is considered to be the only salt input to the system, a very simple calculation concerning the sustainability of the current level of dissolved sediment loss can be made. Salt input from rainfall at Yarralaw was estimated from the equation given by Hingston and Gailitis (1976) for Western Australia. Using a figure of 5 mg Cl^- l^{-1} in rainfall and a mean annual rainfall of 670 mm, the total salt input from this source is approximately 1.3 t y^{-1}. A rough calculation in Section 3.2.1 yielded a salt load of 2100 t in the groundwater of the lower Yarralaw catchment. If 20 mm of groundwater outflow at depth per year (Section 3.2.5) is considered to be an average value, then at a mean salt concentration of 0.22%, there is a salt loss of 7.0 t y^{-1} in the groundwater. Finally, adding the measured dissolved

Table 3.13 Solute yields from some Australian catchments

Location	Catchment Area (km^2)	Solute Yield ($t\ ha^{-1}\ yr^{-1}$)	Length of Record (years)	Catchment Conditon
Bello et al. (1978)				
Sandy Ck, NSW		0.03	1	
Pipeclay Ck, NSW		0.20	1	
Boorolong Ck, NSW		0.10	1	
Geary (1981)				
Deep Ck, NSW	25	0.44-0.52	1	pasture and viticulture
Loughran (1975)**				
Congewai Ck, NSW	86	0.69-1.04	2	forest, pasture and farmland
Olive (1973)**				
Brown Ck, Tas	13	0.39		forest
Mountain R, Tas	40	0.50		forest, moorland and pasture
Snug Rivulet, Tas	19	0.42		forest
Peck and Hurle (1973)				
Julimar, WA	180	0.08	5	forest + 5% cleared
Seldom Seen, WA	7	0.16	5	forest with strip mining
More Seldom Seen, WA	4	0.14	5	forest with strip mining
Waterfall Gully, WA	10	0.18	4	forest, extensively diseased
North Dandalup, WA	150	0.18	32	forest
Davies, WA	67	0.14	17	forest
Yarragil, WA	72	0.13	20	forest
Harris, WA	300	0.13	4	forest + 5% cleared
Wooroloo, WA	430	0.42	13	forest + 30% cleared
Williams, WA	1400	0.65	4	forest + 70% cleared
Collie East, WA	130	0.74	2	forest + 40% cleared
Brunswick, WA	86	0.35	5	forest + 30% cleared
Trotman (1974)				
Carey, WA	147	0.17	10	forest + 3% cleared
Fly, WA	68	0.23	9	forest + 13% cleared
Donnelly, WA	827	0.19	10	forest + 17% cleared
Lefroy, WA	275	0.14	28	forest + 23% cleared
Wilgarup, WA	451	0.31	10	forest + 28% cleared
Perup, WA	655	0.29	10	forest + 16% cleared
Warren, WA	3745	0.29	5	forest + 26% cleared
Tanjannerup, WA	15	0.11	5	forest
Millstream, WA	9	0.15	8	forest
Shannon, WA	329	0.24	7	forest + 2% cleared
Deep, WA	566	0.24	7	forest + <1% cleared
Gardner, WA	348	0.30	5	forest + 15% cleared
Yarralaw, NSW	0.38	0.18	1.17	88% pasture, 12% scald

** - as reported by Olive and Walker (1982) and Geary (1981) sediment loss from the catchment (7.2 t y^{-1}) to the loss in the groundwater and subtracting the salt input yields a net salt loss of 12.9 t y^{-1}. At this rate, it will take over 150 years to exhaust the mean salt storage in the groundwater of the lower catchment. This, of course, is a very simplistic estimate since it considers only the salt store in the lower 16 ha of the catchment and no input of salts from groundwater inflow. Thus, the estimate of 150 years for salt load depletion is probably the minimum amount of time required.

3.3.4 Bedload

Bedload was measured from April to October, 1986. During this period, 3.4 t of bedload was lost from the catchment compared to 37.5 t of SS and 1.9 t of TDS (Table 3.9). This is less than 10% of the SS loss, a result which is similar to those of other studies (Bello et al., 1978; Costin, 1980). However, such a limited monitoring period may not provide a good indication of the temporal bedload patterns. Bello et al., reported that 50% of the bedload they measured was discharged in 0.2% of the monitoring period. A similar pattern could be occurring at Yarralaw.

A large alluvial fan, about 500 m downstream of the weir, has built up since the scald formed in the 1950's. It is likely that the majority of the material in the fan originated from a limited number of large events that shifted most of the bedload. This possibility is discussed in more detail in the following section.

3.4 Possible Origin of the Yarralaw Seepage Scald

3.4.1 Introduction

Reported earlier (Section 1.2.2) were the results of an investigation by Wagner (1987) into the occurrence of seepage scald in southeastern New South Wales (Table 1.3). One of the most notable findings in his investigation was the very large increase in seepage scald occurrence during the period between 1950 and 1960. The obvious question is "Why did such an increase occur at this time?" Yarralaw is one of the many seepage scalds that first appeared during the 1950's and information regarding its origin may well prove useful for answering the question posed above. A definite answer may never be provided but this does not mean that the cause of the Yarralaw scald should not be speculated upon because insights from such an exercise may prove to be useful for present day considerations about seepage scald prevention and reclamation.

3.4.2 Historical Observations and Facts

Aerial photographs of Yarralaw are available for 1941, 1952, 1962, 1967, 1976 and 1978. The photos reveal that in 1952 there was no evidence of salinization but by 1962, a seepage scald over 4 ha in area had formed. There was relatively little change in the lateral extent of the scald between 1962 and 1986.

The rainfall records for southeastern New South Wales revealed that the precipitation pattern in the area during the 1950's (Figure 3.19) was characterized by a wet period (1948-53) followed by a dry period that was most severe in 1954 followed by another wet period that peaked in 1956. Although such fluctuations are normal for the rainfall records in the area, the period from 1948-53 was one of the wettest on record for New South Wales (Pittock, 1983; Cornish, 1977). Thus, even though a cycle of dry and wet periods is normal for this region, the cycle that occurred during the 1950's may not have been typical because the increase in monthly rainfall was greater than normal.

The total soil loss from the eroded area in the Yarralaw subcatchment, as estimated from a survey of the scald (Section 2.3.4), is 14,060 t (Table 3.14). The bulk densities were taken from measured values in three grassland profiles (Table 3.1) since it was assumed that these profiles were most representative of the site prior to seepage scald formation.

Since the scald is known to have appeared between 1952 and 1962, the age of the scald (in 1986) is between 24 and 34 years, which means that the mean rate of soil loss between scald formation and 1986 is between 410 and 590 t y^{-1}. Between 1985 and 1986, the suspended

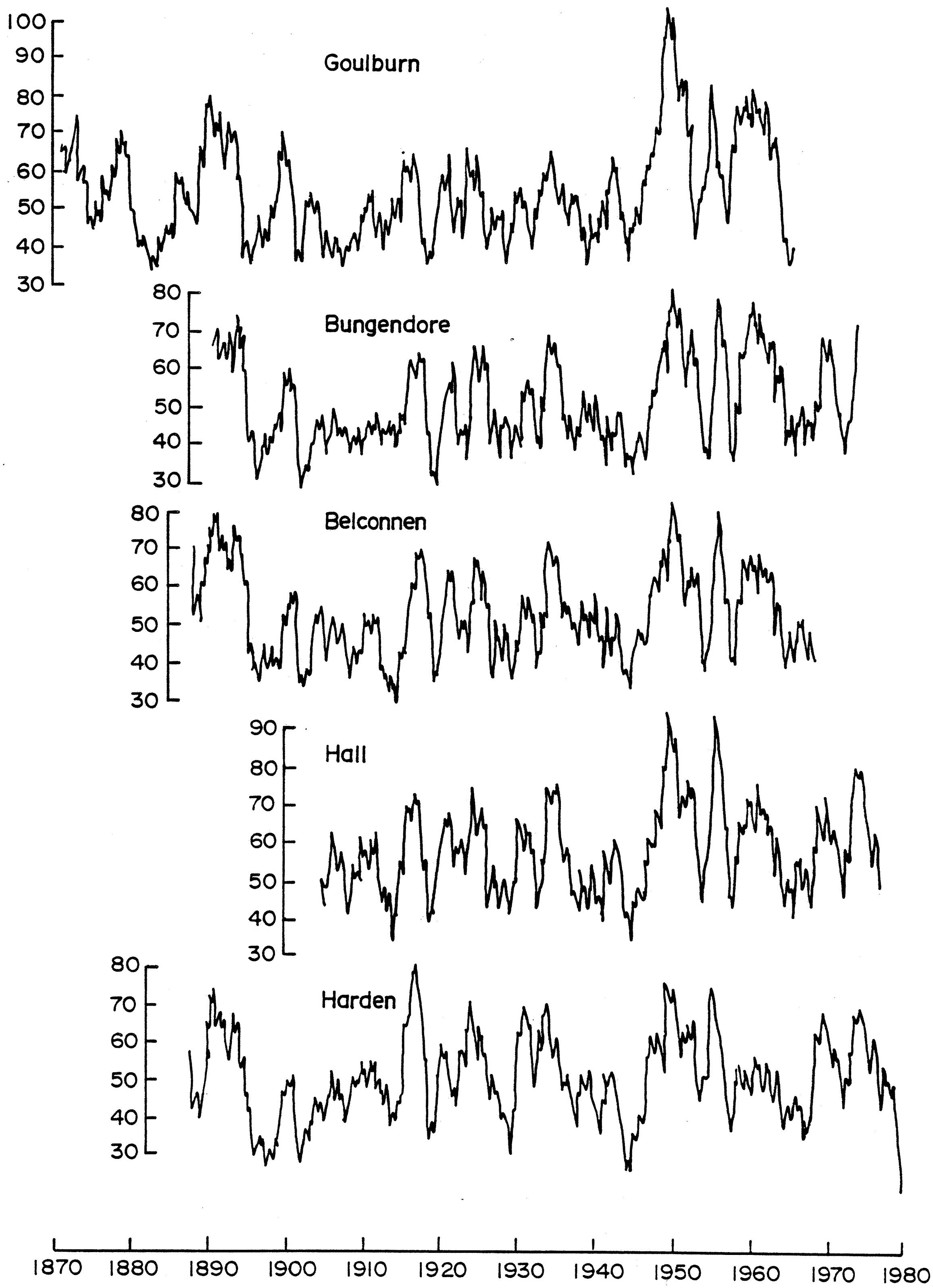


Figure 3.19 Monthly rainfall (24-month running mean) for several stations in southeastern New South Wales (rainfall data from Adomeit et al., 1987).

Table 3.14. Total soil loss from Yarralaw as determined by the survey.

Horizon	Volumetric Soil Loss (m^3)	Bulk Density ($t\ m^{-3}$)	Soil Loss (t)
A_1	3600	1.3	4680
A_2	4300	1.4	6020
B	2100	1.6	3360
			14,060

sediment loss was calculated as 47 $t\ y^{-1}$. If the 7 $t\ y^{-1}$ bedload loss rate (3.5 t in 6 months) is added to the suspended sediment loss rate, then the total soil loss rate between 1985 and 1986 is 54 $t\ y^{-1}$. The rainfall between 1 October 1985 and 30 September 1986 was 637 mm, very close to the longterm mean for this area. If 1985-86 is considered to be an 'average' year in terms of soil loss from Yarralaw, then the present soil loss rate is now only a fraction of the mean soil loss rate over the lifetime of the scald.

3.4.3 Hypothesis

The precipitation pattern in the area during the 1950's was characterized by a wet period (1948-53) followed by a dry year in 1954 followed by another wet period that peaked in 1956. During 1954, drought, salinization and possibly overgrazing would have been detrimental to the grassland vegetation, leaving the catchment susceptible to erosion. The high rainfall in 1956 would have done considerable erosion damage if the catchment did not have an adequate vegetative cover. Frequently in the literature there is mention of a noticeable increase in salinity following a period of wet years (Wagner, 1957; Van Dijk, 1969; Jenkin, 1981). For the remainder of the analysis in this section, it will be assumed that the above scenario is a reasonable reconstruction of the events at Yarrlaw in the 1950's and the starting date for the erosion will be taken as 1956. This assumption does not introduce serious errors into the subsequent arguments since it is known that the scald did form somewhere within a ten-year span straddling this date. It could be argued that the wet period of 1948-53 caused the erosion that initiated the Yarralaw seepage scald. Coupled with the air photo evidence, this would mean that the scald would have formed in 1953 instead of 1956 as postulated. However, even over the short lifespan of the scald, the above difference introduces an error of less than 10% in mean soil loss rate calculations.

The sediment yield from the scalded portion of the Yarralaw subcatchment in 1985-86 was substantially lower than the longterm mean soil loss rate. Clearly, the rate of soil loss at some time after 1952 was much higher than that measured during 1985-86. The 1962 air photo indicates that a great deal of the damage had occurred by this time. It is possible that most of the erosion at Yarralaw occurred in a relatively short period early in the history of the scald, in other words, the scald formation may have been catastrophic rather than progressive. This type of sudden geomorphological change in landscapes which have reached a certain threshold of energy input has been documented for gully and stream formation (Patton and Schumm, 1975; Bradford and Piest, 1980) as well as for more spectacular features such as landslides (Leighton 1980). At Yarralaw, the energy threshold for water erosion may have been exceeded during the heavy rainfall period in the mid 1950's.

Judging from the air photos, at least 50% of the erosion that was evident in 1986 had probably occurred by 1962 since the areal extent of the seepage scald did not change significantly between 1962 and 1986. If this is correct, then the average rate of soil loss for the first 6 years of scald formation (1956-62) would be 1170 t y^{-1} and for the final 24 years (1962-86) it would be 295 t y^{-1}. This yields a soil loss figure during the last 24 years that is still substantially higher than that measured in 1985-86. It is also possible that the heaviest soil losses took place prior to 1962 and that the 1985-86 rate represents the mean rate since that time. With this assumption, the mean rate of soil loss would be 2125 t y^{-1} for the 1956-62 period and 54 t y^{-1} for the 1962-86 period. The actual pattern of soil loss is probably somewhere between these extremes which are shown graphically in Figure 3.20, along with a line representing a 'best guess' estimate of soil loss rate over the life of the seepage scald. If this is indeed, a realistic representation of the temporal soil loss pattern at the catchment, then it supports the hypothesis that the formation of the Yarralaw seepage scald was a catastrophic event.

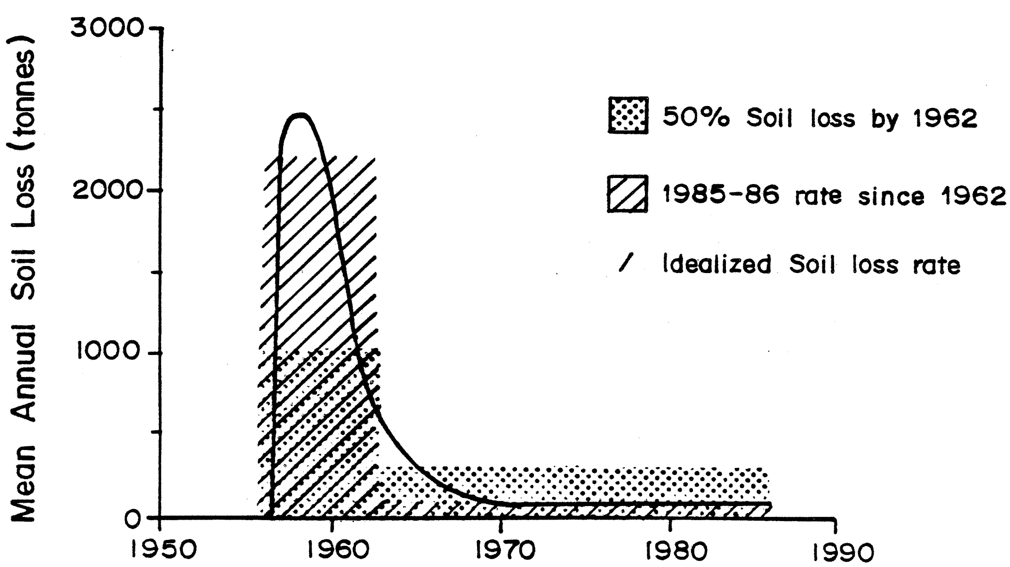


Figure 3.20 Possible pattern of temporal soil loss rates for the Yarralaw seepage scald.

The Australian literature dealing with saline soils is filled with references to a 'lag time' (SCAV 1982, Peck and Hurle 1973; Conacher, 1983a) which refers to the period of time between a detrimental land practise, such as ring-barking to kill trees, and the appearance of saline soils or saline streams in the same area. It is assumed that following detrimental land management, there is reduced transpiration of soil moisture and an increase in deep percolation to the water table. During the 'lag time', the water table presumably rises closer to the ground surface until it reaches a critical point where evaporative accumulation can cause salinity. Certainly a delay must be expected between increased percolation below the root zone and the response of the water table (Peck, 1975) but this concept is limited in that it assumes that the threshold level at which degradation begins is intrinsic or a function only of changes in the landscape itself (Schumm, 1980). The intrinsic features of the landscape were not identical in the multitude of catchments in southeastern New South Wales where seepage scald suddenly appeared between 1950 and 1963 nor is it likely that they were all cleared or overgrazed at the same time. It is more likely that the precipitation pattern during that time period was the main factor for the increase which means that the threshold point for the occurrence of the degradation was exceeded as a result of an extrinsic factor. The concept of 'lag time' with the connotation that seepage scald or stream salinity is inevitable following a certain number of years may be misleading because the unpredictable nature of the climate may also be involved.

If the above is assumed to be correct, one could ask, "Why did a major increase in seepage scald formation take place during the wet-dry cycles of 1950-60 and not in previous cycles?" First of all, the precipitation increase during the 1950's was larger than any other cycle on record. Therefore, the input of rainfall energy may have surpassed a certain critical level required for scald formation. Secondly, land management practices may have affected the pattern of seepage scald formation. Tree-clearing and grazing may have reduced the thriftiness of the vegetation so that catchments were more susceptible to seepage scald damage than they were before the clearing and grazing took place. Healthy vegetation transpires significantly larger quantities of soil water than stressed vegetation or cleared areas (Greenwood et al., 1985) and provide a 'buffer' against periods of above normal precipitation by using the excess moisture rather than letting it runoff or percolate below the root zone. Thus, ring-barking the eucalyptus at Yarralaw may have lowered the threshold level required to initiate seepage scald by allowing the water table to rise and by removal of protective vegetation. Under these conditions, the catchment would be more vulnerable to wet periods of weather when previously it was resistant to these cycles.

3.4.4 Salinity before Erosion or Erosion before Salinity?

There are two different scenarios that could be postulated to explain the exact origin of the Yarralaw seepage scald. The first follows from the most frequently cited cause of dryland salinity in Australia which states that increased percolation of soil moisture into the groundwater following clearing of native vegetation causes the water table to rise close enough to the ground surface to cause salinization. Following the buildup of soluble salts in the soil profile, the grassland vegetation is killed which leaves the soil susceptible to erosion. This scenario requires that the salinity must occur before erosion takes place. The other scenario is just the opposite and states that during a period of high rainfall, the topsoil is eroded leaving the sodic subsoil exposed with its inherent poor structure characteristics. The exposed soil is more impermeable than the previous grassland cover and the reduced infiltration allows a buildup of soluble salts, if a shallow water table exists. This scenario is just the opposite of the first since the erosion is required to strip the topsoil before salinity can result. The difference is an important one, especially for considerations about seepage scald prevention. Are we trying to prevent salinity or are we trying to prevent erosion?

It was shown earlier (Section 3.1.2 and 3.1.3) that the soluble salt levels at Yarralaw are not as high as would be expected for a saline site and the biggest problem is not so much the salinity as the sodicity. Investigations into the soluble salt distribution have shown that the salinity problem is concentrated in the scald soils at Yarralaw (Figure 3.4) and throughout the upper Jacqua Creek catchment (Cumming et al., 1984). The main difference between the saline soils in the scald and the non-saline soils in the grassland immediately adjacent is the permeability of the soil surface (Section 3.2.2), since the groundwater is at the same depth below both locations. This implies that the salinity pattern is a result of the soil characteristics which further implies that the scald, with its poor surface structure, would have to have been formed before the salinity could result.

It is just as possible that the opposite scenario is the correct one. Following the wet years from 1948-53, the groundwater levels would be expected to be high if present day observations are any indication. The dry year in 1954 would provide a strong evaporative demand that may have caused salinization to occur as a result of a shallow water table. If the dry conditions and the salinity weakened the vegetation sufficiently, high runoff in 1956 may have done considerably more damage than usual and stripped the topsoil from the salinized areas. However, if this is the case, the saline area should have expanded because the groundwater levels are close to the ground surface and water table salinity should be spreading in to the grassland surrounding the scald.

It is not possible to provide a definite answer about an event that happened in the past and was not closely monitored. The exact mechanism of scald formation is important but we can also learn from the observations regarding the rapid rate of Yarralaw's formation. Clearly, an important implication of this theory is the need for seepage scald prevention. A policy of treating seepage scald in the early stages of formation is not likely to be successful because most of the damage would have occurred before the treatment could take effect. Also, the cyclical nature of seepage scald formation would make it difficult to keep pace with the sudden appearance of several scalds in a widespread area.

CHAPTER 4
SUMMARY AND CONCLUSIONS

4.1 Summary

The objectives for this thesis are restated below.

To distinguish the Yarralaw seepage scald from the surrounding non-scalded area on the basis of the soil and hydrological properties.

To assess the threat of scald expansion in the Yarralaw catchment.

To assess the contribution of the Yarralaw seepage scald towards offsite stream salinity and siltation of potential water supplies.

To determine the cause of the Yarralaw seepage scald.

The location of the scald does not appear to be related to any inherent soil property. The profiles in both grassland and scald areas are very similar except for the surface. The location is more a function of landscape position which would be expected since the lower slope positions are most susceptible to the processes causing seepage scald, water erosion and salinization from a high water table. The high water table, presently at a shallow depth beneath the lower catchment, is causing the salt accumulation in the scald soils and may have been responsible to some degree for the formation of the scald.

Estimates of the temporal soil loss pattern at Yarralaw suggest that most of the damage to the catchment occurred very suddenly and at an early stage in the scald's development. This has important implications for policies aimed at both seepage scald prevention and treatment of existing seepage scald. The Yarralaw seepage scald has been quite stable in terms of total affected area since 1962. This is not to say that heavy runoff conditions in the future will not cause further scald expansion and it is important that reasonable measures be taken to prevent this. However, the conception that the scald is slowly but steadily consuming the grassland in the lower catchment is simply not correct. Scald growth appears to be catastrophic in nature with the majority of the damage occurring in a relatively short period of time. On the scald surface itself, the degradation is steady and ongoing. The rills in the surface are being eroded into miniature gullies that grow steadily until they reach a new equilibrium of size and depth. Thus, the degradation of the scald is progressive but the expansion of the scald area appears to be catastrophic.

Measurements of the soluble salt and suspended sediment loads being exported from Yarralaw indicate that we cannot afford to ignore the offsite effects of erosion from seepage scalds. The economic factors involved in any benefit/cost analysis of seepage scald rehabilitation extend far beyond the affected area. The results from Yarralaw indicate that seepage scalds in southeastern New South Wales represent a threat to water supplies in terms of salinization and siltation. With a large supply of soluble salt and suspendable material, areas such as Yarralaw will threaten water supplies for a number of years to come.

The policy-makers require a comprehensive assessment of the costs associated with both onsite and offsite effects of seepage scald. This assessment requires estimates of suspended sediment and soluble salt loads from ungauged seepage scalds. A rough estimate from simple extrapolations based on area could be provided if the estimate was based on thorough information about the areal extent of seepage scald and runoff data from more than just one catchment. The calculations in Section 3.3.2 and 3.3.3 are simple examples of how this may be done.

The cause of the Yarralaw seepage scald cannot be determined for certain. The catchment has been eroded and salinized but the relationship between these characteristics and the formation of the seepage scald can only be speculated upon. The catchment may have been salinized and subsequently eroded, eroded and subsequently salinized or the erosion and salinization may have developed concurrently. In all the above cases, tree-clearing and grazing would have contributed to scald formation by making the catchment more susceptible to erosion from higher runoff rates and to ~~salinity~~ salinization as a result of higher groundwater levels. As shown in the water balance (Section 3.2.5), evapotranspiration is the mechanism by which most of the rainfall exits the catchment, even when 12% of the area is bare scald which yields runoff very readily. Using the 1985-86 water balance values for illustration, lowering the Et component by only 1% would increase the excess water component by nearly 7 mm; enough to increase runoff or the groundwater component by 30%. Excess water in the form of runoff and groundwater can damage the catchment by causing erosion and salinity, respectively. Thus, management practices such as tree-clearing and poor pasture management which reduce transpiration capacity can make a catchment more susceptible to seepage scald formation.

It is suggested that the timing of the Yarralaw seepage scald formation was a function of above average precipitation in the period between 1952 and 1962. This is a reasonable assumption considering that it is excess water which does the damage and that there are numerous references stating that outbreaks of seepage scald occur following wet periods. The distinction between extrinsic factors (i.e. rainfall) and intrinsic factors (i.e. catchment characteristics) is important. The concept of 'lag' time, where, for example, salinity will inevitably occur a certain number of years following tree-clearing is, perhaps, misleading because it totally ignores the variability in extrinsic factors which may be involved in seepage scald formation.

4.2 Management strategies for seepage scald prevention and reclamation

4.2.1 Introduction

Landowners and soil conservationists usually have two basic questions concerning seepage scald; 'What can be done to prevent seepage scald from occurring?' and 'What can be done about areas that are already affected?' To answer these questions, it must be recognized that every catchment is different and management practices that work on a neighboring property are not necessarily the proper approach in every case. However, Wagner's (1987) survey showed that many of the seepage scalds in southeastern New South Wales appeared during the same time period, which suggests that the problem has common roots.

4.2.2 Seepage scald prevention

The ~~catastrophic~~ pattern of seepage scald formation suggested for Yarralaw and many other scalds in southeastern New South Wales emphasizes the need for seepage scald prevention. A policy of treating seepage scald in the early stages of formation is not advocated since it appears that there is precious little time before the appearance of a seepage scald leads to extensive damage. In addition, effective treatment of established seepage scalds is very difficult as will be discussed in the following section. For these reasons, a policy of seepage scald prevention is far more appealling than trying to treat the symptoms.

The difficult part about prevention is knowing just where preventative measures are required. The isolated, widely-scattered occurrences of seepage scald make generalizations about scald-prone areas very difficult. Neither does there appear to be any readily measurable soil property which could be used to delineate susceptible areas since the appearance of scald appears to be more a result of hydrological factors (i.e. runoff and groundwater). However, some generalizations have been drawn (Wagner, 1987; Greig and Devonshire, 1981) and some empirical relationships have been suggested between scald occurrence and geology, climate, landscape and management. For the latter two factors, Wagner (1987) found that 83 of 92 seepage scalds occurred in lower slope positions and 90 of 92 seepage scalds had been extensively or completely cleared sometime before their formation. Judging from these observations, the lower slopes of cleared catchments are the areas most susceptible to seepage scald.

Information on the salt status of a catchment is very useful because it can indicate areas with a high subsoil salt load that may be ~~threatened by salinity if the salt is~~ moved upward by capillary action. Assessing salt status is relatively fast and simple using electromagnetic induction techniques. As illustrated in Section 3.1.3, EM devices can delineate areas with high salt load without the need for extensive sampling. The EM 34/3 is especially useful for locating salt loads at depth which may not be obvious from the surface features in the landscape. It is suggested that a series of EM surveys be undertaken extensively throughout southeastern New South Wales. The

CSIRO has developed this technology to the point where it can be usefully deployed for extensive surveying. The Soil Conservation Service has the resources and personnel to carry out such a survey and should begin to build up a database of information on salt levels in the catchments of the southeastern part of the state which may be susceptible to salinization.

The hydrological status of a catchment is the key to seepage scald susceptibility but it is very difficult to determine. One means for judging a catchment's capacity to transpire water (and therefore, its ability to keep runoff and water tables low) is to assess the groundwater levels. The only means for doing this is to measure the water level in a water table well. There is an appalling lack of groundwater information in New South Wales and this particular problem highlights the need for a thorough groundwater monitoring system for the state. To address the needs for seepage scald prevention, a system consisting of at least one well (3 m deep) in the lower slope position in each of an extensive network of cleared catchments in southeastern New South Wales needs to be established. These wells could be installed inexpensively with a small drill and using slotted PVC pipe. The Soil Conservation Service could read water levels and quality periodically and build up a much-needed database of groundwater information. This could be used to pinpoint areas where water tables were on the rise and require attention to prevent seepage scald formation.

If scald-prone catchments can be identified there are a number of strategies that can be implemented to try and prevent a seepage scald from forming.

1) There should be an immediate halt to any further tree-clearing. The emphasis must be shifted towards increasing transpiration in an effort to prevent excess water as either runoff or groundwater from damaging the catchment. George (1984) suggested that increased groundwater recharge of only 20 mm caused by reduction in transpiration following forest-clearing was sufficient to cause a seepage scald. This means that any farm practices which reduce transpiration and increase soil water levels should also be avoided.

2) In catchments that have been extensively cleared, the lower slopes should be replanted with trees. There is a great deal of question concerning how much and where replanting should be

done. Malcolm (1983) suggested that trees should be sited on intake areas for aquifers but these are often difficult to identify. In this case it is suggested that tree-planting should be concentrated along the drainage lines where the catchment is most susceptible to water erosion and salinization. The idea is to establish the trees so that the roots can anchor the soil against erosion and biologically 'pump' water from the area most susceptible to a high water table.

3) The grazing pressure on the catchment should be reduced or eliminated completely depending on how great the risk appears to be. Maintenance of an adequate grass cover is vital because once the ground is bared it becomes very difficult to revegetate.

4) Depending on the landuse in a particular catchment, it may be worthwhile considering establishment of lucerne (Medicago sativa) or another deep-rooted pasture plant. The transpiring capability of these species can be very useful for reducing excess water as either runoff or groundwater.

Just as groundwater levels can serve as an indicator of which catchments may be at risk from seepage scald, they can also be used to assess the success of any preventative measures taken. In any catchment where preventative management is undertaken, the water table should be monitored as a means for judging whether the practices implemented are having a positive effect.

4.2.3 Seepage Scald Reclamation

Once seepage scald becomes established, it is very difficult to reclaim the land for useful purposes. The ultimate objective of seepage scald reclamation is to establish plants on the scald. There are numerous publications which testify to the difficulty of revegetating the hostile environment of a scald surface (Beadle, 1948b; James, 1956; Jones, 1966; Hamilton and Lang, 1978; Wagner, 1987). Scald surfaces tend to persist through a range of conditions (Yarralaw is a good example) and trying to reclaim an area with the multiple problems of salinity, sodicity and poor surface structure can be a very expensive or fruitless undertaking. Wagner (1987) noted that the potential for successful regeneration varies between sites. In areas with more favorable soil conditions, there is a greater chance of successful reclamation and perhaps even some natural revegetation. However, one cannot count on these areas to reclaim themselves on their own. The most successful reclamation of seepage scalds in southeastern New South Wales has occurred where a combination of judicious management and rehabilitation work was applied.

Nulsen (1986) stated that seepage scald management can follow either of two different approaches, offsite strategies aimed at reducing the damaging excess water at the recharge end of the flowpath or onsite strategies aimed at treating the damage in the discharge area (Table 4.1). The offsite strategies in Table 4.1 are designed to reduce runoff and groundwater recharge either through increased biological use of water or by mechanical exclusion. The onsite strategies in Table 4.1 are designed to make the scald surface more hospitable to plant growth. Some concentrate on the salinity problem by reducing surface evaporation or groundwater discharge, while others are aimed at leaching salts from the root zone. Some onsite strategies are designed to deal with the structure problems on the scald either through mechanical disruption or chemical amendments. In general, the offsite strategies are preferred because they involve the relatively

Table 4.1. Rehabilitation strategies for seepage scald.

Offsite strategies
- judicious stocking
- pasture improvement to increase crop use of soil moisture
- maximization of crop growth and water use with tillage and fertilizer
- tree-planting or natural revegetation to increase evapotranspiration
- mechanical tillage, diversion banks or interceptor banks to divert water from the discharge area

Onsite strategies
- exclusion of stock to aid in vegetation establishment
- seeding of salt-tolerant plants and trees
- surface or subsurface drainage to lower groundwater levels
- deep pumping to lower groundwater levels
- tillage, ripping and contouring to increase leaching
- surface mulches to reduce evaporation and improve leaching efficiency
- soil ameliorants to improve soil structure, leaching efficiency and soil fertility

fresh water entering the system and the local environment is much more hospitable to plants than the degraded condition of the discharge area. However, the often diffuse nature of the recharge area can make implementation of management schemes difficult and social conflicts can arise since the discharge salinity on someone's land can be a result of poor management of the recharge area on someone else's property. Each strategy, as well as its merits for the Yarralaw site, is discussed briefly below.

Offsite Strategies

(i) Judicious stocking

This practice is simply management of stock numbers so as not to deplete the pasture vegetation. In some cases, stock may have to be totally excluded for a period of time. Maintenance of good pasture cover can alleviate the salinity hazard through increased water use by pasture plants which, in turn, reduces the groundwater levels. As such, it is a means for addressing the high water table at the recharge end of the problem. The procedure is straightforward but not without cost since it may involve lower stocking rates with a subsequent reduction of farm income.

At Yarralaw, the grazing pressure was moderate during the course of the study. By December of 1985, the grass growth was quite lush but was grazed back between February and September 1986. Even though the stock numbers were not excessive, the grazing period was not well-timed because the sheep did considerable damage during the dry period of February and March 1986. ~~Therefore, there is room for improvement in this aspect.~~

(ii) Pasture improvement

Pasture improvement is the establishment of a healthy, transpiring growth on the recharge area to reduce the excess water. This usually requires a balance of species, including introduced perennials, to maintain high transpiration rates throughout the year.. This reduces the water available for discharge and helps alleviate the salinity. Deep-rooting species such as Medicago sativa (lucerne) can be especially effective for transpiring excess water. Miller et al. (1981) documented a case where use of this species followed by a flexible cropping system in the recharge area was sufficient to reclaim a saline seep but this measure alone is probably insufficient to reclaim a seepage scald. The costs of this approach involves the expenses for seed, fertilizer and establishment of the pasture but if a perennial system is established, the costs can be spread out over several years.

Unfortunately, the stoniness of the subsoil make pasture improvement schemes very difficult at Yarralaw. In the past, an attempt had been made to do some breaking just beyond the southeast gully but it had been abandoned because of stones that were continually brought up to the surface. The site was ill-chosen because the east side of the catchment happens to contain a large quantity of stones between the A and B horizons. It is possible that a pasture improvement scheme along the west side of the catchment would be more practical, although there may be a problem with land tenure.

(iii) Maximization of crop growth

The aim of this method is the same as that for pasture improvement except that crops are used instead of grazing systems to enhance water use in the recharge area. For example, tillage practices can be used to increase crop water use. Hamblin et al. (1982) reported that the water use of wheat was significantly higher with a disc plough - combine seed drilling treatment than either a direct combine drill or triple disc drill treatment. Likewise, adequate nitrogen levels help maintain a high leaf area and thus, maximize the transpiration rate of crops. The benefits of this approach in terms of water use are not as great as for pasture improvement because of the shorter growing season for commercial crops. An advantage of this approach is that it does not involve radical changes in land use and the costs are minimal.

This scheme has no application at Yarralaw because the land is not broken for crop production and breaking is not recommended.

(iv) Tree-planting

Tree-planting has been frequently suggested as a means for reclaiming seepage scalds by increasing transpiration and reducing excess water for runoff and groundwater. In terms of recharge management, this involves transpiring soil water before it percolates below the root zone. The strategy is simple enough but the questions of how many trees to plant and where to plant them have still not been resolved. Morris and Thomson (1983) suggested that an agroforestry approach could be taken in the recharge zones of saline areas since the density of trees for effective control of recharge will usually allow continued agricultural production within the planted area. Tree-planting could also be concentrated along the upslope portion of drainage lines or in the lowest topographic recharge sites where the groundwater is usually closer to the surface and the trees can have a proportionally large effect on the recharge volume. This strategy would be more favorable if tree-growing could provide some economic advantage such as fodder trees, wood production, eucalyptus oil or sawn timber. A better estimate of the costs of this approach is needed as well as data concerning the density of trees required to bring about effective control. Smith (1966) has suggested that 40% of the land area in a catchment may need to be reforested to have a significant effect on the water table. Conacher et al. (1983a) have suggested that 50% of the catchments in Western Australia need to be reforested. These estimates represent substantial acreages in comparison to the area affected by scald and it may be difficult to convince land owners of the merit of reforestation.

At Yarralaw, it may be more practical to encourage the regrowth of the native eucalypts rather than trying to establish new trees. Fencing the woodlands at the south end of the catchment would ease stock pressure on the young trees and would be very beneficial towards their re-establishment.

(v) Mechanical works

Where waterlogging is associated with seepage scald, diversion and interceptor banks can be used to divert excess water from running onto the discharge area. Diversion banks have been successfully applied in some areas of southeastern New South Wales (Wagner, 1957). Conacher et al. (1983a) suggest that there is potential for using interceptor banks as a means of diverting shallow throughflow away from seepage scalds in Western Australia. However, the banks may need to be combined with other measures to control deeper groundwater (Conacher, 1983b). There may also be problems with leakage around and through the interceptors. These techniques are costly both in terms of the installation and the area of land used for the works.

At Yarralaw, the interflow component of runoff is probably small and interceptor banks are not likely to have a significant effect. They are not recommended.

Onsite Strategies

(i) Exclusion of stock

Exclusion of stock gives natural salt-tolerant plants an opportunity to grow without being stressed and eliminates the effect of stock traffic on the scalded area. Natural species such as Cynodon dactylon and Hordeum hystrix are common in saline areas of southeastern New South Wales (Wagner, 1987). These species, though slow-growing, have some usefulness as pioneer plants in saline areas. However, they rarely revegetate a seepage scald completely on their own. Exclusion of stock by itself is not sufficient to reclaim seepage scalds, but it is an essential part of any overall management scheme. The cost of this approach involves the expense of fencing the discharge zone and the value of lost production from the fenced area.

At Yarralaw, fencing the scald to exclude the stock is essential to the success of any reclamation scheme.

(ii) Seeding salt-tolerant vegetation

The establishment of salt-tolerant species influences the pattern of groundwater discharge. When evaporation takes place on a bare area, the salt load is deposited on the surface making it very inhospitable for plants. Plant establishment aids in the biological use of water before it can evaporate at the surface. Further, plants usually improve soil structure and leaching efficiency which also reduces surface salt loads. Introduced species such as Agropyron elongatum and Puccinellia spp. have potential for use in southeastern New South Wales and are usually quite successful where they have been used (Hamilton and Lang, 1978). Midgley et al. (1986) and LeHonerou (1986) have documented a range of salt-tolerant woody species (Eucalyptus spp., Acacia spp., Rhizophora spp., Prosopis spp., Casuarina spp., Melaleuca spp., Tamarix spp., and Atriplex spp.) which may also be useful for establishment of vegetation in seepage scalds. For waterlogged saltland, Malcolm (1983) recommended Halosarcia spp. and Paspalum distichum.

Seeding salt-tolerant vegetation involves the cost of seed or seedlings and the cost of establishment. This method becomes more costly when survival rates are low and species and planting sites must be carefully selected. There are often 'pockets' of non-saline or slightly saline soil within a discharge area, which can be located readily using electromagnetic induction techniques and planting should be concentrated in these zones (Bullock and Williams, 1987). Although salt-tolerance is a vital requirement for vegetation establishment in saline areas, there is the additional problem of frosts in southeastern New South Wales, which is especially important for tree species.

The Yarralaw seepage scald requires some form of vegetation established on the most severely affected areas before reclamation can progress. It is suggested that Agropyron elongatum or Puccinelia spp be established on the bare scald. These plants would improve the permeability of the soil, slow down the evaporation process and add valuable organic matter to the scald surface.

(iii) Drainage

Surface and subsurface drains can be used to lower a high water table and reduce the amount of evaporation at the soil surface. If the water table can be lowered below a critical depth the upward water flux can be reduced sufficiently so that salt is leached from the surface soil faster than it is replenished. This depth is usually considered to be in the range from 1 to 2 m below the ground surface (Talsma, 1963; Malcolm, 1983). Installation of drains to sufficient depth for this purpose can be difficult and costly. Furthermore, a suitable disposal site for the saline water can be a major problem.

Open drains can be used but they may have the problem of siltation or collapsing in areas with active erosion. Mole drains can be created by pulling a special plough and bullet-shaped implement through the soil. Once again, collapsing and siltation can be a problem. Sub-surface tile drainage, such as used in irrigation areas, can also be used for drainage on dryland and it can help prevent the problems of collapse and siltation. With this method, the cost of the tile must be added to the cost of installation.

Drainage can sometimes be justified in special cases, for example where saline groundwater threatens railway water supplies, farm dams or other capital investments. However, the prospects for using drainage in agricultural areas are poor. Malcolm (1983) reports low permeability in the subsoils of Western Australia which means that very close drainage spacing is required for proper water level control. The situation at Yarralaw is similar because the hydraulic conductivity of the subsurface is very low. The high cost of this measure make it inappropriate for Yarralaw where the landuse is unimproved pasture.

(iv) Deep pumping

Groundwater levels can be lowered by installing wells and pumping excess groundwater away from the area. The hydraulic conductivity of the subsoil determines how quickly the water can be pumped and the size of the area affected. Disposal of saline groundwater can be a problem.

Doering and Benz (1972) assessed the merits of this approach in a saline area of North Dakota that was underlain by a regional sandstone aquifer. The pumping costs were very reasonable ($0.84 per ha) but the low permeability of the overburden meant that a great deal of time was required before any effects would be noticed. The results of a 179 day pumping test revealed that a 10 m drawdown in the sandstone aquifer would initiate water table drawdown in about 4 years and it would take 7 years to lower the water table by 1.5 m.

Malcolm (1983) reported that the low permeability of the soils in Western Australia would limit the effectiveness of the method. At Yarralaw, it would not be possible to pump significant quantities of groundwater because the subsurface hydraulic conductivity is too low (the 15 m wells and piezometers could be bailed dry by hand).

(v) Tillage, Ripping and Contouring

Tillage, ripping and ponding water with contour banks are designed to increase the downward water flux and leach the excess salts below the root zone (Cunningham et al., 1974). These techniques are applied widely and with some success on dry scalds in central New South Wales where the water table is not close to the surface. Breaking the hard scald surface aids plant establishment and improves the efficiency of leaching (Malcolm, 1983). In seepage scalds, there can be physical difficulty implementing these works because the scalds are frequently deeply incised with gully erosion (Hamilton and Lang, 1978). If implemented, these techniques may aggravate the problem since they increase recharge and can cause a further rise in water table levels. It has also been shown that the effects of ripping scalds can be very short-lived unless it is accompanied by other measures such as establishment of salt-tolerant vegetation (James, 1956). These techniques are also quite costly.

At Yarralaw, ripping could be done only on the more level sections of the scald and should be accompanied by a chemical ameliorant such as gypsum (see reclamation measure xii) to prevent the sodic surface from resealing. It is also recommended that salt-tolerant grasses be established at the same time. Ponding water would be difficult because of the uneven surface and may be detrimental in terms of causing a rise in the water table.

(vi) Surface mulches

Surface mulches of straw or other organic material or even sand can be spread on the ground surface of scalded areas to hold water and improve leaching while simultaneously reducing the evaporation at the soil surface (Benz et al., 1967). The mulch protects the exposed soil from raindrop impact and provides a better micro-climate for plant growth (Wagner, 1987). It has also been shown that an organic cover significantly reduces soil erosion (Costin, 1980; Singer and Walker, 1983). When used in conjunction with establishment of salt-tolerant species and other works, a surface mulch is a valuable part of the reclamation strategy. Used on its own, the effect is not likely to persist. The cost of this measure will vary depending on the availability of suitable mulch material and the size of area affected.

At Yarralaw, a surface mulch would be beneficial but there may be problems maintaining the cover unless it is anchored. Yarralaw is a very windy site and materials such as loose straw or dry manure would simply blow away.

(vii) Soil Ameliorants

Soil ameliorants such as gypsum or lime can be applied to the soil to improve the conditions for plant growth and leaching (Loveday and Bridge, 1983). Displacing Na^+ ions with Ca^{++} ions helps improve the structure of scald soils since the sodic condition usually causes development of a hard surface with poor permeability. The beneficial effect of gypsum application on infiltration rates has been demonstrated by Kazman et al. (1983). In the field, Milthorpe and Newman (1979) applied gypsum at 2.5 and 10.0 t ha^{-1} to a dry scald near Condobolin, New South Wales. They found measurable improvement in both soil properties and crop yield but the high rate of application was required to sustain the effect beyond five years.

At Yarralaw, a gypsum amendment should help alleviate the hard-packed sodic surface on the scald but it should be combined with plant establishment in order to capitalize fully on the soil improvement. The cost of the amendment would be a major consideration because of the low value of the land.

Applications of phosphate and nitrogen fertilizer can also be useful to help establish vegetation since seepage scalds are usually deficient in these nutrients (Hamilton and Lang, 1978).

4.2.4 A Reclamation Plan for Yarralaw

Currently, the Soil Conservation Service of New South Wales is undertaking reclamation of seepage scalds on a cost-sharing basis with land owners. Their recommendations for Yarralaw include fencing the scald for stock exclusion, ripping the scald and seeding grass species such as Agropyron elongatum. They would possibly apply gypsum in the scalded area.

The following plan is recommended as a reclamation scheme for the Yarralaw catchment based on the knowledge gained from this study. Before anything else, the main part of the scald including the area between the two main gullies should be fenced to exclude stock. The sheep do a great deal of damage to the scald itself and to the vegetation. The scald itself needs to be broken up and treated with gypsum to alleviate the problems with the hard-packed surface. Salt-tolerant grasses such as Agropyron elongatum and Puccinelia cyliata should be established after the surface has been broken up and after some rainfall so that the surface salt loads are somewhat reduced. A surface mulch and gypsum would be beneficial to the scald, however, the use of these amendments will be determined by the 'economics' of the site.

Tree-planting is not recommended because of the low success rate of tree establishment in this area. Rather, the woodlands at the south end of the catchment should be fenced to help establish the young eucalyptus seedlings that have started to grow in this area. This should increase the transpiration capacity of the catchment and leave sufficient grassland for some grazing to continue.

Pasture improvement through establishment of exotic species is not recommended since this usually involves tillage, ~~of some sort.~~ There is a problem with stoniness along the east side of the catchment and this may hamper any seeding operations in this area.

Most of the runoff appears to be generated on the scald itself, therefore, diversion of runoff and interceptor banks are not recommended since they are not likely to have a large impact on the runoff at the site.

The gullies themselves may be left alone since it is possible that they will collapse and revegetate on their own once the runoff level is reduced (Heede and Debano, 1984). If the gullies cause difficulty with equipment access, they could be levelled somewhat with a bulldozer.

It is also suggested that some groundwater monitoring be undertaken during and following the implementation of reclamation measures. The water table levels can be compared to those measured during this study in order to evaluate the success of the management schemes implemented.

4.2.5 The 'Economics' of Seepage Scald Reclamation

The actual implementation of any type of management strategy for seepage scald is dependent on the economics involved for each situation. Do the benefits of reclamation exceed the cost of implementing reclamation works? Determination of the costs involved with saline land is extremely difficult because salinity is the end result of a complex set of biophysical relationships which are difficult to quantify and poorly understood (Oram and Dumsday, 1986). These costs involve not only onsite degradation but also offsite effects from transporting soluble salt pollution to other land owners and water users. Greig and Devonshire (1981) used a cross-sectional regression analysis of 56 Victorian catchments to estimate the increase in stream salinity involved with clearing trees. They then calculated the cost of increased water salinity on the downstream users. From this they could assign a cost, from increased stream salinity, of clearing trees. This was a useful exercise in terms of putting dollar values on management practices but it was not complete. The onsite costs of tree removal were not considered. Also, they categorically did not enter into the reciprocal discussion about whether reafforestation will decrease salinity since there were insufficient data on this matter. This example illustrates the difficulty involved when attempting an economic analysis of the benefits of reclamation.

Dumsday et al. (1983) assessed the economics of farming practices in terms of reducing salinity hazard. They used percolation below the root zone as an indicator of the positive or negative effects of farm practices on salinity. The data from their study revealed that switching from an annual pasture system to annual pasture - lucerne or perennial pasture - lucerne achieved both a reduction in deep percolation and a reduction in marginal production costs. Theoretically, this means that land owners in the study area would require no taxes or other incentives to switch to the land management practices which reduced the hazard of salinity since the reduction of production costs is itself an economic incentive. Any further reductions in percolation required incentive or taxation because the management systems incurred an increase in marginal production costs. The same analysis also revealed that agroforestry and reafforestation were potentially profitable approaches to reducing the salinity hazard in the study area. However, these practices required more drastic changes to the current farming techniques and would probably not be as readily adopted by the land owners (Oram and Dumsday, 1986). This type of analysis is well-placed since it is directed at the benefits of reducing recharge which is the most desirable means for managing excess groundwater. However, until the relationship between recharge and the incidence of salinity is quantified, the analysis can do no more than provide a qualitative estimation of the benefits involved with land use changes.

Without subsidization, most farm operators will not undertake any kind of seepage scald reclamation work. In the area around Yarralaw, the main landuse is unimproved pasture for sheep grazing and the value of this land use simply does not justify the large cost involved with reclaiming the scald. In order to justify this work, consideration must also be given to the offsite effects of seepage scald. Soil erosion within the Shoalhaven River Catchment is a threat to the future Welcome Reef Dam and the quality of water therein. Economic analysis has shown that the value of water from the Shoalhaven Catchment exceeds the value of both sheep and timber production from the same area (Costin et al., 1984). In addition, there are other considerations such as wildlife, recreation and aesthetic values which could be considered. When all these aspects are tallied, the reclamation of seepage scalds is more justifiable in economic terms and a case can be made for subsidization of these works using public funds.

4.3 Future Research

There remains a gap in our knowledge concerning the link between land management and its quantitative effects on the hydrology of individual catchments. Information concerning water table response to different numbers and densities of trees, the quantity of water transpired by different vegetation and the effects of different crop and pasture management on transpiration are examples of gaps in our knowledge. We have established that we can measure the components of the hydrological cycle on a catchment and we are reasonably certain how traditional land management has led to the type of land degradation we see today. Now we must work toward quantifying the effects of land management practices for seepage scald prevention and reclamation on the components of the hydrological cycle so that practical, economic solutions to this problem can be identified.

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Appendix A. Specifications for the piezometers, weir and cutoff trench

Site	Piez/Well	Total length of pipe (m)	Top of Pipe to datum (m)
1	1-16 (p)	16.17	2.62
	1-7 (p)	7.45	2.92
	1-4 (p)	4.45	2.85
	1-2 (w)	2.50	2.71
2	2-4 (p)	4.77	5.55
	2-2 (w)	2.40	5.54
3	3-5 (p)	5.75	19.00
4	4-6 (p)	7.13	4.21
	4-3 (p)	3.71	3.92
	4-2 (w)	2.25	4.11
5	5-6 (p)	6.71	4.83
	5-3 (p)	3.50	4.83
	5-2 (w)	2.45	4.85
6	6-5 (p)	5.60	6.87
	6-3 (p)	3.50	6.86
	6-2 (w)	2.45	6.66
7	7-14 (p)	13.76	7.32
	7-7 (p)	7.15	7.33
	7-3 (p)	3.40	7.38
	7-2 (w)	2.50	7.53

Appendix A continued.

Site	Piez/Well	Total length of pipe (m)	Top of Pipe to datum (m)
8	8-7 (p)	6.80	8.74
	8-3 (p)	3.49	8.69
	8-2 (w)	2.58	8.95
9	9-6 (p)	6.92	13.07
10	10-5 (p)	5.93	13.55
11	11-7 (p)	6.96	7.01
	11-3 (p)	3.53	7.03
	11-2 (w)	2.55	6.96
12	12-5 (p)	5.70	17.39
13	13-7 (p)	7.64	12.94
14	14-11 (p)	11.78	10.00
	14-5 (p)	5.95	9.73
	14-3 (w)	3.45	9.68
15	15-10 (p)	10.65	6.60
	15-5 (p)	5.95	6.72
	15-3 (p)	3.50	6.50
	15-2 (w)	2.45	6.52
16	16-10 (p)	10.88	6.42
	16-5 (p)	5.95	6.49
	16-3 (w)	3.45	6.39

Appendix A continued.

Site	Piez/Well	Total length of pipe (m)	Top of Pipe to datum (m)
17	17-8 (p)	8.72	3.29
18	18-6 (p)	5.87	15.28
20	20-7 (p)	6.80	19.05
21	21-5 (p)	5.32	4.61
	21-3 (p)	3.13	4.60
	21-1 (w)	1.40	4.69
22	22-3 (w)	3.00	5.52
23	23-3 (w)	2.95	4.94
	23-1 (w)	1.50	4.97
24	24-2 (w)	3.00	4.97
25	25-2 (w)	2.90	6.02
26	26-2 (w)	3.00	3.74
27	27-3 (w)	2.96	3.15
28	28-2 (w)	3.00	3.24
29	29-2 (w)	3.00	3.55

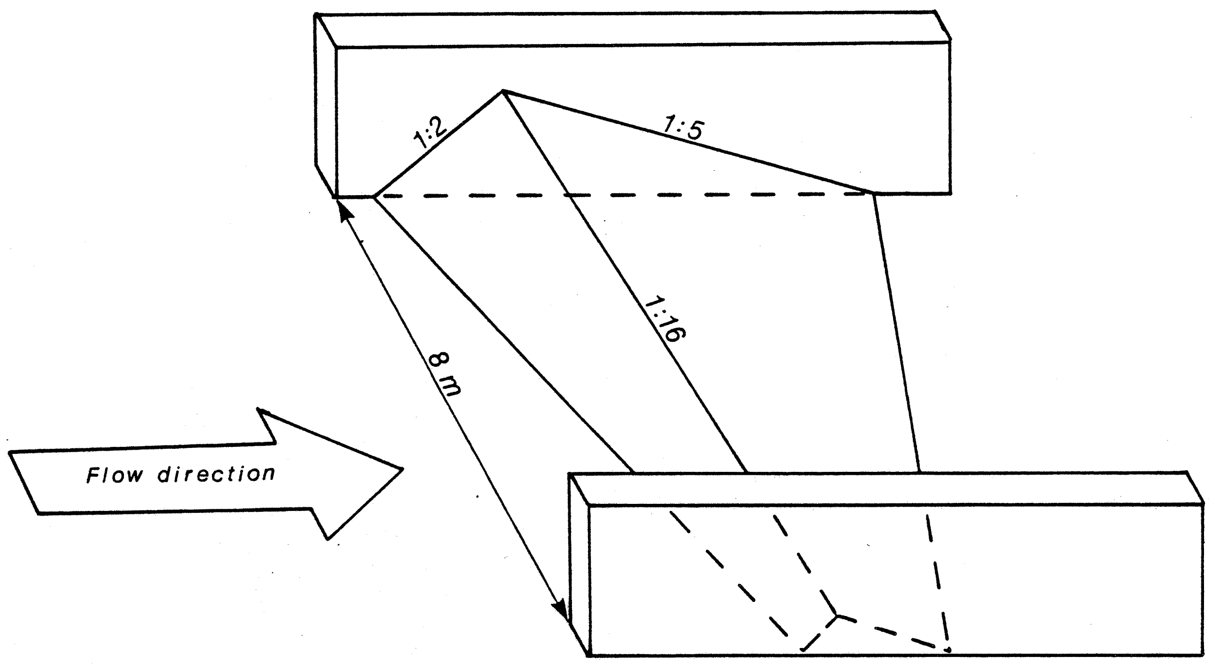
Appendix A continued.

Site	Piez/Well	Total length of pipe (m)	Top of Pipe to datum (m)
30	30-3 (w)	2.95	3.54
31	31-5 (p)	5.22	.39
	31-2 (w)	2.50	.71

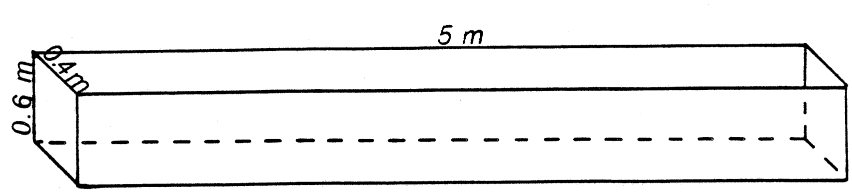
Appendix A continued.

Note: These diagrams are not drawn to scale. Dimensions and slopes are labelled.

WEIR



CUTOFF TRENCH



Appendix B. Runoff-Rainfall-Sediment-Piezometer measurements for the Yarralaw catchment (microfiche).

The microfich files in the pocket of the back cover contain the hydrological measurements that were taken in the Yarralaw catchment between May, 1985 and October, 1986. There are five separate files, a) Runoff, b) Rainfall, c) Suspended sediment, d) Total dissolved solids and e) Piezometer water levels. The first four files are contained on one fiche and the piezometer file is contained on a second fiche. The format for each file is outlined below.

a) Runoff file

This file consists of two-column entries where the first number represents the date and time and the second number represents the instantaneous runoff measurement in mm h^{-1}. The date and time is represented as days and fractions of days since midnight, December 31, 1984. January 1st, 1985 is day number 1 and the decimal represents the portion of the day past midnight. For example, 0100 hours (1:00 a.m.) on January 1st, 1985 would be represented as '1.042'. The time 0100 hours (1:00 a.m.) on January 2nd, 1985 would be represented as '2.042'. The number '91.500' corresponds to 1200 hours (noon) on April 1st, 1985. The numbering continues into 1986 with January 1st, 1986 corresponding to day number 366. A list of day numbers for the first day of each month during the site study is given at the end of the Appendix introduction.

The file is arranged in chronological order and segmented with a label at the beginning of individual runoff events. The third entry in the file is '139.551 0.00078'. The first number corresponds to 1313 hours (1:13 p.m.) on May 19, 1985. The second number indicates that a flow rate of 0.00078 mm h^{-1} was measured at the given time.

b) Rainfall file

Similar to the runoff file, the rainfall file consists of two-column entries with the first number corresponding to date and time as before, and the second number corresponding to hourly rainfall in mm. The file is in chronological order and segmented with a label for each month. The first entry in the file is '149.542 0.8'. The first number corresponds to 1300 hours (1:00 p.m.) on May 29, 1985. The second number indicates that 0.8 mm of rainfall was recorded in the hour starting at 1300 (1:00 p.m.) and finishing at 1400 (2:00 p.m.).

c) Suspended sediment file

The suspended sediment file consists of three-column entries. The first number corresponds to date and time as before, the second number refers to the suspended sediment concentration (mg l^{-1}) of a runoff sample taken at that time and the third number represents the instantaneous rate of sediment loss in t h^{-1}. The final number was calculated by multiplying the suspended sediment concentration by the runoff rate for the same time. The file is arranged in chronological order and segmented with a label for each event. The first entry in the file is '262.117 4842 0.25'. The first number corresponds to 0248 hours (2:48 a.m.) on September 19, 1985. The second number shows that a runoff sample at that time had a suspended sediment concentration of 4842 mg l^{-1}. The third number shows that the instantaneous rate of suspended sediment loss at that time was 0.25 t h^{-1}.

d) Total dissolved solid file

The format for this file is exactly the same as that for the suspended sediment file above. The numbers correspond to the values for total dissolved solids rather than suspended sediment. The first entry in the file is '262.117 1918 0.0973'. The first number corresponds to 0248 hours (2:48 a.m.) on September 19, 1985. The second number shows that a runoff sample at that time had a total dissolved solid concentration of 1918 mg l^{-1}. The third number shows that the instantaneous rate of total dissolved solid loss at that time was 0.0973 t h^{-1}.

e) Piezometer file

The format for this file consists of two-column entries with the first number corresponding to the date and time as before and the second number corresponding to a piezometer water level reading in metres above the weir notch. The file is grouped into separate sections for each piezometer with a label at the start of each section. Note that piezometers 4-3, 4-6, 8-3, 8-7, 11-3, 11-7, 21-1, 21-3 and 21-5 were continuously monitored on the data logger and there are a large number of readings that cover several pages for each piezometer. The readings for each piezometer are in chronological order with the piezometer sections ordered by site number.

The first entry in the file is '289.500 1.67' for piezometer 1-2. The first number corresponds to 1200 hours (noon) on October 16, 1985. The second number indicates that the water level in piezometer 1-2 was 1.67 metres above the weir notch at the indicated time.

Day Numbers for the First Day of each Month for the Study Period

Date	Day Number	Date	Day Number
May 1, 1985	121	January 1, 1986	366
June 1, 1985	152	February 1, 1986	397
July 1, 1985	182	March 1, 1986	425
August 1, 1985	213	April 1, 1986	456
September 1, 1985	244	May 1, 1986	486
October 1, 1985	274	June 1, 1986	517
November 1, 1985	305	July 1, 1986	547
December 1, 1985	335	August 1, 1986	578
		September 1, 1986	609
		October 1, 1986	639