AGGREGATE BREAKDOWN AND SOIL SURFACE SEALING UNDER RAINFALL

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I certify that this thesis is my own original work
and all sources have been acknowledged.

Guy William Geeves

This work is dedicated to my parents, Elaine and Don Geeves, who have given me unconditional love and support throughout my life.

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Abstract

Aggregate breakdown is an important process controlling the availability of fine soil material necessary for structural sealing of soil surfaces under rainfall. It may be caused by slaking resulting from rapid soil wetting and by physical dispersion resulting from direct and indirect energetic raindrop impacts. Relationships have been proposed by others predicting steady infiltration rate and saturated hydraulic conductivity from final aggregate size following high energy rainfall on initially dry, uncovered soil surfaces. Under these extreme conditions, both rapid wetting and energetic raindrop impact result in maximum aggregate breakdown and surface sealing. Knowledge of the relative importance of these two agents under less severe conditions and knowledge of how increased aggregate stability due to conservative soil management may ameliorate them should improve prediction and management of aggregate breakdown and surface sealing.

This study has isolated and quantified effects of rapid soil wetting and energetic raindrop impact on aggregate breakdown and surface sealing. Simulated rainfall was applied to re-packed soils from differing tillage treatments on light textured soils from near Cowra and Condobolin in New South Wales, Australia. Aggregate breakdown was assessed using aggregate size distribution, determined by wet sieving and summarised by a range of statistics. The degree of breakdown was assessed after 66 mm of simulated rainfall whilst the rate of change in aggregate size distribution was assessed by sampling after 5, 10, 15, 30 and 60 mm. The degree of surface sealing was assessed using final surface hydraulic conductivity after 66 mm rainfall calculated from inferred infiltration and measured sub-seal soil water potential. The rate of surface sealing was assessed prior to ponding using cumulative rainfall volume at ponding and throughout the post-ponding phase by decline in surface hydraulic conductivity as a function of cumulative rainfall kinetic energy. Two levels of raindrop kinetic energy flux and three wetting treatments were used to isolate effects of these agents of aggregate breakdown and surface sealing.

Significant surface aggregate breakdown was observed when either rapid soil wetting or highly energetic raindrop impact were allowed to occur. The majority of the data suggest a negative interaction between the two agents. When soil was initially dry rapid soil wetting was the dominant agent causing rapid aggregate breakdown, generally within the first 5 mm of rainfall. When rapid soil wetting was prevented by tension pre-wetting, energetic raindrop impact was the dominant agent and was able to cause aggregate breakdown of an almost equivalent degree. This breakdown occurred over a period lasting for up to 30 mm of rainfall. In contrast, the rate and degree of surface sealing were influenced primarily by raindrop kinetic energy with highly energetic impact leading to significant surface sealing, irrespective of soil wetting. For the soils studied, it was concluded that structural sealing of surface soil, could be significantly reduced by protecting the soil surface from energetic raindrop impact but that prevention of surface aggregate breakdown required amelioration of both processes.

In addition to the negative interaction referred to above, a positive interaction was observed whereby energetic raindrop impact occurring concurrently with rapid soil wetting caused a greater degree of aggregate breakdown and a greater degree of surface sealing than energetic raindrop impact occurring subsequent to rapid soil wetting. The effect on surface sealing may be explained by the effect of lower sub-seal water potential that necessarily results from initially dry soil condition required for concurrent rapid wetting. However, the effect on aggregate breakdown remains unexplained.

Notwithstanding the above, permeability was reduced under high kinetic energy rainfall even when soil wetting was reduced to very slow rates by tension pre-wetting. Likewise, surface sealing did occur under low kinetic energy rainfall for the least stable soil following rapid soil wetting. It was concluded that threshold soil wetting rates and threshold rainfall energy levels, proposed by others, are either not applicable to these soils or are negligible.

The rate and degree of aggregate breakdown was also dependent on the soil with the Cowra soil being more stable than the Condobolin soil. Greater aggregate stability brought about by conservative tillage treatments at both soil locations retarded and reduced surface sealing. Unvalidated simulation modelling was used to illustrate possible effects for the soil water balance. In contrast to the conclusions of Loch (1994b), that were based on soils throughout eastern Queensland, the soil water balance simulations predicted that the residual benefits in ameliorating surface sealing resulting from improved aggregate stability could significantly reduce point runoff under the lower intensity winter rainfalls experienced in southern New South Wales.

Limited testing with Condobolin soil following tension pre-wetting showed that rainfall intensity, varying over the range from 16.5 to 66 mm h^{-1}, had little effect on the decline in surface hydraulic conductivity as a function of cumulative rainfall kinetic energy. This contrasts with greater seal permeability under higher rainfall intensities observed by Romkens *et al.* (1985) and others. It is proposed that an alternative explanation exists for the observations of Romkens *et al.* based on reduction in seal permeability due to lower sub-seal water potential under lower intensity rainfall.

Post-ponding reduction in K_{sat} under high kinetic energy rainfall exhibited exponential decline as a function of cumulative raindrop kinetic energy as proposed by Moore (1981b). However, inferred rates of decline prior to ponding were more rapid than measured post-ponding rates suggesting that infiltration models using only a single exponential rate of surface K_{sat} decline based on post-ponding measurements may be in error. Potential for error is greatest at early times for loose soil that is highly susceptible to sealing.

Pre-ponding decline in surface aggregation was also relatively more rapid than post-ponding decline. This discrepancy was evident irrespective of soil pre-wetting. From this it was concluded that the more rapid initial aggregate breakdown and surface sealing was due, at least in part, to processes other than aggregate slaking due to rapid soil wetting. An explanation has been proposed as follows. Raindrops initially fall on aggregates that have not

been subjected to rainfall and therefore each drop has the capacity to cause greater aggregate breakdown than subsequent raindrops that fall on aggregates or soil fragments that have been strong enough to survive preceding rainfall impacts. Such a mechanism could provide an alternative explanation of the findings of Baumhardt *et al*. (1991) who found that less cumulative raindrop kinetic energy was necessary to achieve a given reduction in surface conductance when the cumulative energy was supplied through lower energy drops.

Relationships predicting rates of surface sealing using aggregate breakdown under rainfall and aggregate stability were evaluated. Post-ponding infiltration rate and surface K_{sat} were related to aggregate size by exponential functions. The proportion of surface aggregates less than 0.125 mm in diameter provided slightly more consistent relationships. Parameters of fitted relationships differed among wetting pre-treatments suggesting that the influence of sub-seal water potential on surface K_{sat} must be considered whenever such relationships are developed or applied. Aggregate stability determined by wet sieving was related to rainfall volume required for ponding, final K_{sat} and final aggregate size but only for initially dry soil suggesting that such relationships may be unique to the rainfall, soils and flow conditions used to develop them.

This study has established the relative importance of rapid soil wetting and energetic raindrop impact in both aggregate breakdown and surface sealing over a range of antecedent soil water and rainfall conditions. It has quantified the effectiveness of culturally induced aggregate stability in ameliorating effects of these two important agents and illustrated the potentially significant consequences for the soil water balance. It has quantified temporal patterns of surface sealing and aggregate breakdown and proposed an alternative mechanism explaining more rapid aggregate breakdown during the initial stages of rainfall. It has identified possible explanations for effects of rainfall intensity on surface sealing observed in other studies. It has also partially evaluated a mechanism proposed to explain important effects of subseal water potential on seal permeability found in this and other studies. These significant findings have been used with the findings of other studies to amend the conceptual model proposed by Le Bissonnias (1990). The amended model gives a more complete description of the relationships between parameters and processes determining aggregate breakdown and structural surface sealing under rainfall.

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Chapter 1

INTRODUCTION AND OBJECTIVES

This chapter outlines the significance of managing aggregate breakdown and surface sealing under rainfall, presents the rationale, lists the objectives of the study and outlines the structure of the thesis.

1.1 THE SIGNIFICANCE OF AGGREGATE BREAKDOWN AND SURFACE SEALING UNDER RAINFALL

Two interrelated effects commonly observed when rain falls on loose, bare soil are a reduction in surface aggregate size and a reduction in hydraulic conductivity of the surface few millimetres, known as rainfall-induced surface sealing, (eg., Duley, 1939; McIntyre, 1958a).

The reduction in surface hydraulic conductivity potentially limits infiltration in agricultural and other areas (eg., Burch *et al.*, 1986). It may consequently increase surface runoff, reduce soil water available for subsequent crop and pasture growth and alter rates of nutrient leaching, acidification and recharge to shallow ground water tables. Depending on other hydrological processes, surface sealing may influence the hydrological response of catchments, altering the size and shape of flood hydrographs.

While effects of surface sealing on interrill erosion rates are not fully understood (Moore and Singer, 1990) it is clear that increases in surface runoff or the rate of overland flow, referred to above can significantly increase the potential for interrill erosion. The other surface changes associated with rain impacting on loose, bare soil may also influence interrill erosion rates to a lesser degree. Increased surface shear strength commonly observed during surface sealing can increase the threshold of raindrop energy or stream power required to re-detach or re-entrain soil into overland flow hence reducing interrill erosion rates (eg., Bradford *et al.*, 1987a). Reduction in surface aggregate size distribution may also reduce the thresholds of raindrop energy or stream power required to re-detach or re-entrain soil and, in addition, can alter the settling velocities of entrained soil material. Reductions in depressional storage and hydraulic roughness associated with surface smoothing during surface seal development may lead to increased overland flow transport capacity and to higher erosion rates (Hairsine, *et al.*, 1992). Of these effects, only the increase in runoff during surface sealing is specifically considered in this thesis.

1.2 RATIONALE UNDERLYING THE STUDY

Important advances have recently been made in understanding processes leading to formation of surface seals on lighter textured soils (eg., Moss, 1991a; Le Bissonnais *et al.*, 1989; Valentin and Bresson, 1992). Processes associated with two separate agents have been identified as major contributors to surface sealing and the breakdown of surface aggregation when rain falls on bare, dry soil. They are processes associated with rapid wetting of the dry soil (eg., slaking and differential swelling) and processes associated with energetic raindrop impacts (Romkens *et al.*, 1990a).

The degree to which the two agents of aggregate breakdown and surface sealing act will be dependent on, among other things, the degree of soil surface protection and the initial water content of the soil. Surface sealing has commonly been studied under extreme conditions by observing the effects of intense rain falling on unprotected, loose, dry soil. Such conditions maximise the potential for rapid wetting and energetic raindrop impact to cause aggregate breakdown and surface sealing. In practice, less extreme conditions may prevail. For instance, surface soil may be wet or moist prior to a rainfall event as a result of antecedent rainfall, dew, condensation in protected micro-environments or capillary rise of subsoil moisture. It may also be partially or completely protected from energetic raindrop impacts by living plants, plant residue or other material (eg., rocks or inorganic surface mulch)

In order to broaden understanding of surface sealing effects on infiltration, this study aims to isolate and quantify the relative effects of these two agents. In doing so, it aims to isolate the effect of differences in wetting rate from the effect of differences in initial soil water potential. It also seeks to quantify the effects that changes in aggregate stability, brought about by different tillage management systems, may have on aggregate breakdown and surface sealing under rainfall. The magnitude of these effects relative to the effects of variation in soil wetting rate and the energy of raindrop impacts is a prime focus of this study.

The relative significance of processes driven by rapid wetting and by raindrop impact in the breakdown of surface aggregates and the formation of surface seals has implications for land management in cropping areas. Management decisions may influence levels of the factors controlling rates of these processes in several ways. In the short term, decisions that influence the type, amount and arrangement of surface cover can influence the two groups of processes associated with wetting of soil under rainfall. The amount and geometry of surface cover can alter the amount and distribution of interception storage that prevents or delays rainfall from wetting the underlying soil surface. The amount and geometry of this surface cover will also determine the degree of soil protection from high kinetic energy raindrop impacts. Land management can also, in the long term, modify aggregate stability through crop and pasture rotation, tillage and herbicide management and stubble retention, incorporation or burning. It is likely that optimal soil and crop management will involve compromise between minimisation of

surface sealing and other constraints (eg., minimisation of crop disease carry-over, elimination of herbicide resistant weeds and capability to sow crop seed through high levels of surface cover).

In order to optimise management of the soil surface, it is necessary to have quantitative knowledge of the effects of the groups of processes associated with rapid soil wetting and highly energetic raindrop impacts and of the effects of increased aggregate stability. It is also desirable to know how the relative magnitudes of these effects may vary with inherent soil properties.

As the agents referred to above are considered to be significant in both the breakdown of aggregates and the reduction in surface hydraulic conductivity, it is feasible that the relative significance of their effects, under any given set of conditions, may influence relationships between aggregation and surface hydraulic conductivity. Research has already been conducted on Australian soils investigating aggregate breakdown and surface sealing under rainfall with the aim of providing measures of aggregate breakdown that can be used to predict the effect of surface sealing on infiltration (eg., Glanville and Smith, 1988; Loch and Foley, 1994). Relationships have been proposed predicting both steady infiltration rate and final saturated hydraulic conductivity of the surface layer using the size of surface aggregates following high kinetic energy rainfall on bare, dry soils. If such predictive relationships can be extended to predict declining surface hydraulic conductivity as well as final conductivity and extended to a wider range of conditions where the relative importance of the two groups of processes may vary, then they can improve management of surface sealing under rainfall. To this end, the current study aims to further evaluate measures of aggregate stability and aggregate breakdown that may predict the effects of surface sealing on infiltration under rainfall.

1.3 OBJECTIVES OF THE STUDY

Specific objectives of the study are as follows -

1. To review published literature relating to aggregate breakdown and surface sealing of weakly aggregated soils.

2. To quantify the importance of rapid soil wetting and energetic raindrop impact as agents of aggregate breakdown and surface sealing under rainfall on light textured soils and determine how this importance varies with soils, tillage treatments and rainfall intensity.

3. To identify and explain any interactions between rapid soil wetting and energetic raindrop impact as agents of aggregate breakdown and surface sealing.

4. To evaluate, relationships between surface soil aggregate breakdown and the effects of surface sealing on infiltration under rainfall, and to evaluate aggregate stability measurements as predictors of surface aggregate breakdown and effects of surface sealing on infiltration under rainfall.

5. To discuss implications of the findings for soil and crop management.

1.4 THE STRUCTURE OF THE THESIS

The objectives of the thesis listed above are addressed within the following framework -

Chapter 2 reviews published literature. Deficiencies identified in current understanding suggest the need for studies quantifying the relative importance of the potential determinants of aggregate breakdown and surface sealing under rainfall.

Chapter 3 describes an experimental study devised to achieve these aims.

Chapter 4 presents data quantifying the rate and degree of decline in surface permeability and resulting soil hydraulic behaviour. These data are used to isolate the important determinants of surface sealing under rainfall and interactions between them. Soil water balance simulations are used to illustrate the potential influence of surface sealing on hydrologic behaviour of soil under differing tillage treatments. A limited investigation of the effect of rainfall intensity on surface sealing is presented.

Chapter 5 presents data quantifying the rate and degree of decline in surface aggregate size distribution under simulated rainfall. These data are used to isolate the important determinants of aggregate breakdown under rainfall. Aggregate stability data are also presented.
Chapter 6 utilises data presented in the previous two chapters in evaluating relationships predicting effects of surface sealing from aggregate breakdown and aggregate stability.

Chapter 7 summarises the main findings of the thesis and incorporates these findings within an improved conceptual model of surface sealing. Opportunities for further research are also described.

Chapter 2

LITERATURE REVIEW

In this chapter, literature relating to aggregate breakdown and surface sealing under rainfall is reviewed in four sections. The first section examines the definition and measurement of surface sealing under rainfall, processes involved in seal formation and factors controlling the rate and degree of surface sealing. The second section discusses the effects of surface sealing on infiltration and the quantitative description of these effects. The third section considers soil aggregates and aggregate breakdown as well as aggregate stability measurement and its interpretation. The fourth section highlights the roles that aggregate breakdown plays in surface sealing processes, examines methods for measuring aggregate stability that are relevant to aggregate breakdown under rainfall and examines relationships predicting the effects of surface sealing on infiltration from aggregate breakdown or aggregate stability.

2.1 SURFACE SEALING UNDER RAINFALL

Surface sealing under rainfall refers to the transformation by raindrops of the uppermost layer of a structured soil into a layer of low porosity, high bulk density and low hydraulic conductivity (Moore, 1981a). The term "seal" is commonly used to refer this layer while it remains in a wet state and the term "crust" is commonly used to refer to the layer when dry. Surface sealing under rainfall results in part from the breakdown of surface aggregates and is driven mainly by the force of impacting raindrops and by stresses in the soil induced by rapid wetting of surface soil. Additional processes of chemical dispersion, elluviation and sedimentation may lead to reductions in surface soil hydraulic conductivity under specific conditions.

This section reviews research relating to the processes of surface seal formation and the rate controlling factors for these processes. These processes and factors have been reviewed previously by others (eg., Romkens *et al.,* 1990a; Mualem *et al.* 1990a).

2.1.1 Morphology and Classification of Rainfall Induced Surface Seals

In agricultural situations, where frequent tillage or other surface soil disturbance tends to homogenise soil structure, it is often possible to identify causal relationships between seal morphology, both macroscopic and microscopic, and the processes involved in seal genesis. This has lead to classification schemes for surface seals that are based on both seal morphology and the processes responsible for seal formation. The system described by Valentin and Bresson (1992) recognises four types of structural seal (ie., seals formed by *in*

situ rearrangement of soil material) namely, slaking, in-filling, coalescing and sieving seals (the authors actually used the term crusts rather than seals). This system recognises two types of deposition seal, namely runoff deposition seals formed by material that has been moved laterally and deposited by flowing water and still deposition seals formed where surface flow has been impeded and material settles from turbid standing surface water. Erosional crusts and biological crusts are also recognised.

The work of Valentin and Bresson (1992), Moss (1991a) and others relating seal morphology to seal genesis has done much to clarify confusion that arose from inconsistencies among micro-morphological descriptions of surface seals found in earlier literature. The conditions under which surface seals form (ie., the soil surface preparation, the antecedent soil water conditions, the boundary conditions and the characteristics of applied rainfall) affect the relative importance of alternative processes of formation and hence the morphology of the seal formed (Moss, 1991a).

An example of inconsistency between morphological descriptions of surface seals is that between the studies of McIntyre (1958a) and Moss (1991a). Surface seals in the former study have been described as consisting of two thin horizontal layers. The upper layer, about 0.1 mm thick, referred to as the "skin seal", consists of tightly packed clay particles. Formation of this layer has been attributed to the action of raindrop impact. The lower layer, about 2.0 mm thick, referred to as the "washed in layer", consists of tightly packed soil aggregates, but contains numerous spherical vesicles filled with air or soil gasses especially in the upper part. McIntyre concluded that downward translocation of clay particles to fill voids played a major role in seal formation. Others have concluded that post-rainfall settling of clay suspended in ponded surface water resulted in formation of this "skin" seal. In contrast, Moss (1991a) described surface seals formed on an aqualf that consist of a thin layer of silt sized particles (0.002 to 0.05 mm diameter primary particles) overlying a compacted soil layer. This compacted layer, up to 7 mm in thickness, contains tightly packed soil aggregates and spherical gas filled vesicles and may be equivalent to McIntyre's "washed-in" layer. A third areally discontinuous layer, overlying both layers, consists of semi-transient arrangements of air-splashed coarse particles, usually sand.

2.1.2 Processes of Formation

A range of processes can lead to formation of a surface layer of reduced permeability when rain falls on bare soils (Moss, 1991a), and the nature of surface seals formed will depend on the processes dominating in each situation. Micro-topographical factors such as soil area, soil slope, surface roughness, surface topography, initial aggregate size and aggregate stability may lead to the formation of a spatially heterogeneous sealed surface consisting of contrasting seals types with varying permeability on the same plot under the same rainfall (eg., Levy *et al.*, 1988). Formative processes may be classified initially as physico-chemical or mechanical (Romkens *et al.*, 1990a).

Physico-chemical dispersion of soil aggregates and consequent reduction of permeability can be caused by swelling of clay particles resulting from clay hydration. The effectiveness of this process will depend upon the surface area of the clay and its initial degree of hydration. Physico-chemical dispersion may also result from absorption of water between interacting diffuse electric double layers associated with clay platelets. The effectiveness of this process will depend upon the charge characteristics of the clay, the exchangeable sodium percentage and the electrolyte concentration of infiltrating water (Romkens *et al.*, 1990a).

Mechanical processes associated with the impact of falling raindrops leading to aggregate deformation and disruption and soil compaction are associated with initial vertical deformation caused by the downward impact of the raindrop and the radial outflow jet formed later. For the idealised soil medium considered by Romkens *et al.* (1990a), the depth of compaction by raindrops on rigid soil is related to the average pressure under the raindrop impact, initial soil density, initial strain, strain at the limit of elastic behaviour and the amount of significant void compaction. In the analysis of Nearing (1987), effective stress caused by raindrop impacts was shown to be dependent on soil water content, reaching a maximum at approximately 85% of soil saturation.

In addition to physical and chemical processes, sealing may result from deposition of fine material from ponded and infiltrating water. Suspended material may settle on the soil surface to form a still depositional seal (Valentin and Bresson, 1992) or may migrate through the soil surface and be trapped in smaller soil voids in a process of filtration or elluviation.

Processes of seal formation may interact in reducing soil surface permeability. It has been recognised that under field conditions, and in some laboratory experiments that are allowed to continue well beyond ponding, soil surfaces can follow a progression from structural sealing to erosional and depositional sealing (eg., Le Bissonnais *et al.*, 1989; Valentin and Bresson, 1992). This progression through surface sealing stages may vary spatially over the surface of interest depending on micro-topography, plot area and plot slope as well as rainfall characteristics and soil characteristics. This progression lead Bresson and Boiffin (1990) to define different surface seal facies for describing the evolution of spatially heterogeneous sealed surfaces.

2.1.3 Factors Controlling Rates of Seal Formation

Rates of seal formation can be measured or assessed using various seal properties in one, two or three spatial dimensions depending on the purpose of the study and the nature of the seal forming conditions. Measurement or assessment of the rate of increase in aerial extent of surface seals (eg., Farres, 1978) may be most appropriate to the early stage of surface sealing and to situations where spatial heterogeneity is significant. Vertical extension of sealing depth (eg., Farres, 1978) and rate of change in spatially averaged parameters such as permeability (eg., McIntyre, 1958a; Bradford *et al.*, 1987a) is generally most appropriate for experimental situations that have a higher degree of spatially uniformity (normally small, level, re-packed soil

plots or columns) and for the later stages of sealing when surface seals may be areally complete. Spatial averaging of vertical extent or other measured properties of highly heterogeneous surface seals may lead to unrealistic conclusions and to significant dependence of measured rates of sealing on the soil plot area used.

Factors potentially controlling rates of seal formation relate to the incident rainfall, soil cover, soil properties or soil condition (Mualem *et al.*, 1990a).

Various characteristics of incident rainfall have been proposed as controls over rates of surface seal development, including cumulative rainfall volume, rainfall intensity, raindrop size, raindrop kinetic energy and other factors derived from these. Generally, the effects of rainfall characteristics on rates of surface sealing have been investigated using simulated rainfall in order to isolate effects of rainfall characteristics that can be inter-related under natural rainfall (eg., drop size and rainfall intensity). In studies using simulated rainfall of a single intensity or single drop size distribution (eg., Farres, 1978) the resulting cumulative raindrop kinetic energy, cumulative raindrop momentum and cumulative rainfall volume are completely correlated. In studies using a constant rainfall intensity, the time or rainfall duration will also be completely correlated with cumulative rainfall volume and cumulative raindrop kinetic energy.

2.1.3.1 Raindrop Kinetic Energy and Surface Cover

Cumulative raindrop kinetic energy has commonly been proposed as the most useful rainfall characteristic describing the effectiveness of rainfall in sealing soil surfaces (eg., Eigel and Moore, 1983a; Bosch and Onstad, 1988). It is calculated as the sum of half the products of drop mass and drop velocity squared and hence its calculated value is most responsive to changes in drop velocity. Drop velocity is in turn controlled by height of fall, drop size, vertical air currents and any initial velocity imparted to the drops by the drop forming mechanism. Raindrop kinetic energy flux in natural rain has been shown to be related to rainfall intensity at lower intensities but to tend towards constant values of approximately 25 to 29 J m^{-2} mm^{-1} when rainfall intensity exceeds 40 mm h^{-1} (Kinnell, 1987).

Surface cover provided by growing plants or plant residue can drastically reduce the kinetic energy of raindrops impacting on the soil surface and significantly affect rates of sealing. The effect of surface cover has often been simulated in experimental studies of sealing by reducing raindrop kinetic energy by protecting soil with mesh screens that have apertures smaller than the diameter of impacting raindrops (eg., Glanville and Smith 1988; Baumhardt *et al.*, 1991; Loch and Foley, 1994).

2.1.3.2 Cumulative Rainfall Volume

Under natural rainfall, drop sizes, and hence terminal drop velocities, may vary between different types of rainfall event. Thus cumulative rainfall volume and cumulative raindrop kinetic energy are often less than perfectly correlated. Practical difficulties generally preclude the continuous measurement of raindrop kinetic energy in field based experiments and workers

have generally either relied on empirical relationships to estimate raindrop kinetic energy from measured rainfall intensity (eg., Wischmeier and Smith, 1958) or related the effects of surface sealing directly to cumulative rainfall volume. Freebairn and Gupta (1990) concluded that the volume or depth of rainfall since the previous tillage combined with soil surface characteristics, such as surface roughness and surface cover level, could be used to predict infiltration rate as affected by surface sealing in field situations where soils experience alternating rainfall and drying cycles.

2.1.3.3 Rainfall Intensity

Initially, the intensity of rain falling on dry soil may influence the rate and degree of surface aggregate breakdown and surface sealing through its control over the rate of soil wetting. It may also exert control in the post-ponding phase through its effect on the amount of rainfall excess available for surface ponding and surface runoff.

The initial intensity of rain falling on dry soil will strongly control soil wetting rate and hence control the degree of aggregate breakdown due to slaking caused by rapid wetting. Quirk and Panabokke (1962) proposed a threshold intensity of approximately 50 mm hr^{-1} for a red brown earth (Xeralf, Soil Survey Staff, 1992) from South Australia. They concluded that below this intensity, the rate of soil wetting was insufficient to cause slaking resulting from entrapment of air inside aggregates or the de-stabilising effects of rapid differential clay swelling. Threshold intensities are most likely to be specific to the particular soils studied or at least the broad types of soil studied (Quirk and Panabokke, 1962; Loch, 1982).

After surface ponding, rainfall intensity will significantly influence the amount of rainfall excess available for surface ponding and surface runoff. This may affect rate and degree of surface sealing through cushioning of raindrop impacts by significant depths of water ponded on the surface and through interrill erosion of surface material. Romkens *et al*. (1985) concluded that the second of these processes was most likely to have caused the positive relationship that they observed between rainfall intensity and final surface hydraulic conductance for a repacked Typic Paleudalf. Interactions between cumulative rainfall kinetic energy and rainfall intensity have important implications for the prediction of surface sealing under field conditions and the findings of Romkens *et al*. are further examined in Section 4.9 in relation to results of the present experimental study.

Various soil properties have been investigated as potential factors controlling the rate of development of surface sealing, including initial aggregate size, aggregate stability, soil texture, surface roughness and surface micro-topography.

2.1.3.4 Initial Aggregate Size

Larger initial aggregate size leads to a delay in soil surface sealing, a delay in the onset of ponding and runoff and to higher infiltration rates in the early stages of rainfall (Moldenhauer and Kemper, 1969; Farres, 1978; Braunack and Dexter, 1988; Freebairn, 1989). These

higher infiltration rates may persist for up to one quarter of the growing season cumulative rainfall kinetic energy (eg., Moldenhauer and Kemper, 1969) and may be reflected in higher final or "steady" infiltration rates in some cases, but not in others (eg., Moldenhauer and Kemper, 1969; Freebairn, 1989).

Slower rates of surface sealing associated with larger initial aggregate size have been attributed to the entrapment of fine soil material. Freebairn (1989) concluded that large surface clods do not act as an inert cover but are a source of fine material that promotes sealing when detached. However, alternative explanations for the effect cannot be excluded. For instance, larger packing pores, that may be expected to occur between larger aggregates, may result in greater infiltrability during the early stages of rainfall. This could potentially delay surface ponding and any process of surface aggregate breakdown that was dependent on a high degree of surface saturation.

Final, or steady-state, seal thickness has also been shown to be positively related to initial aggregate diameter (Farres, 1978).

Experimental studies investigating effects of initial aggregate size have generally used rainfall simulation on surfaces consisting of aggregates from different size classes sieved from original bulk samples of soils. It has been shown that larger aggregates tend to have lower stability (Kemper and Rosenau, 1986) and it is not clear that studies using such methods have actually isolated effects of initial aggregate size from effects of aggregate stability (eg., Farres, 1978).

2.1.3.5 Soil Texture

Relationships between soil texture and rates of surface sealing can be confounded by the effects of soil structure and other soil properties. It has been concluded that the presence of silt and fine sand sized particles is important in processes of surface sealing in weakly aggregated soil (Moss, 1991a) and it has been shown that medium textured soils are more susceptible to surface sealing (Bradford *et al.*, 1987b). However, universal, or even widely applicable, quantitative relationships between texture and rates of surface sealing have yet to be found. In contrast, degree of surface sealing as measured by infiltration rate after a considerable amount of energetic rainfall impact has been related to soil texture for limited ranges of soils. Moldenhauer and Kemper (1969) found a negative correlation between clay content and final infiltration rate for aggregates of various sizes from some soils. Roth (1995) also found a relationship between infiltration rate after simulated rainfall with cumulative raindrop kinetic energy of 1000 J m^{-2} and a texturally based index proposed by Bloemen (1980). Roth was careful to specify that the relationship applied to weakly aggregated loess and glacial till soils from Germany with an initially dry surface and soil water potential between -8 and -10 kPa at 100 to 300 mm depth.

2.1.3.6 Aggregate Stability

The roles of aggregate stability in controlling the process of surface sealing are discussed more fully in section 2.4 but its role as a potential controlling factor is discussed here for the sake of completeness.

Experimental studies quantifying relationships between aggregate stability and surface sealing are uncommon. While difference in aggregate stability have been proposed as a explanations for differences in surface sealing behaviour between soils (eg., Sharma *et al.*, 1981), quantitative studies have been limited to evaluation of relationships between aggregate stability and degree of sealing as measured by final or steady surface seal properties. Such studies have not found consistent relationships between aggregate stability determined by wet sieving and final infiltration rate (eg., Moldenhauer and Kemper, 1969; Loch and Foley, 1994). Moldenhauer and Kemper stated that they had previously assumed that greater aggregate stability would result in higher infiltration rates. They concluded that increasing clay content could simultaneously increase the level of measured aggregate stability and decrease final infiltration rate.

There has been a lack of quantitative investigations evaluating relationships between aggregate stability and the *rate* of surface seal development independently of the *degree* of seal development.

2.1.3.7 Tillage and Crop Management

Conservative tillage and crop management has been shown to induce increases in soil macro-aggregation and aggregate stability (eg., Hamblin, 1980) and small but statistically significant reductions in the degree of surface sealing (eg., Sharma *et al.*, 1981; Loch, 1994b). Loch concluded that increases in steady infiltration associated with conservative tillage systems were small relative to increases brought about by the maintenance of soil surface cover. He concluded that surface cover provided the major benefit of conservative tillage systems in relation to surface sealing. This conclusion contrasts with that of Packer *et al*. (1992). Packer *et al*. (1992) suggested that reductions in runoff brought about by conservative tillage systems on two Xeralfs (Soil Survey Staff, 1992) were chiefly due to biologically created macro-pores and that effects of cover and aggregate stability were secondary. A further study by Packer *et al*. (1995), involving surface cover and crop species comparisons (wheat v canola), indicated a significant effect of crop species and a significant and equally large effect of surface cover on runoff. They suggested that increased water storage in better structured surface soil (50 to 80 mm depth) brought about by fine canola roots was the most likely explanation for observed differences. Soil similar to the Cowra soil investigated in the present study was used as a part of each of the studies by Loch (1989), Packer *et al*. (1992) and Packer *et al*. (1995) and hence their findings are of particular interest. The conclusions of these three studies are discussed in more detail in relation to the findings of the present study in section 4.7. Sharma *et al*. (1981) found that cultural factors were significant in explaining differences in seal hydraulic conductivity formed under 30 minutes of simulated rain. Virgin soils were found to

have higher seal hydraulic conductivity than cultivated soils. Soils under grass were also found to have higher seal hydraulic conductivity than continuously cropped soils. Sharma *et al*. did not present aggregate stability data but did conclude that lower aggregate stability in the cultivated soils had resulted in lower seal hydraulic conductivity.

2.1.3.8 Soil Micro-relief and Surface Roughness

Surface roughness, in the form of artificially created ridge-furrow micro-relief, has been shown to affect the spatial distribution of infiltration during the early part of a rain-storm but not total infiltration volume (Freebairn, 1989). Freebairn concluded that the level of surface cover and antecedent soil moisture content provided the best prediction of effects of surface sealing on infiltration and that quantification of surface roughness improved predictions by a small but significant amount. He found that a range of indices of surface roughness were equally efficient in describing the effects of surface roughness on infiltration.

2.1.3.9 Plot Slope

Studies of the effects of plot slope on surface sealing have been confined to effects on fully developed or steady seals. Both positive and negative associations between slope and degree of surface sealing have been reported. For example, Moss (1991b) found that the compacted layer of seals on a granite derived aqualf were better developed as slope increased, whereas, Poesen (1986) found a negative association between surface slope and surface sealing as defined by decreased permeability and increased tor-vane resistance. While the study of Poesen reported data only for two loose sediments sieved to less than 0.5 mm diameter, unpublished work was cited that used laboratory rainfall simulation to confirm a similar relationship for aggregated soils.

2.1.3.10 Stone Cover

While partial stone cover has been found to decrease the rate and final degree of surface sealing, the nature of the effects are not fully understood. Poesen (1986) found a decrease in surface sealing of trays of loose sediment as defined by permeability and tor-vane resistance when surfaces were protected by simulated stone cover (16.6 mm diameter spherical glass marbles). This effect was found to be reduced when marbles were half buried in the sediment. Poesen concluded that, in the latter case, water running off marble surfaces could not come into contact with the unsealed surface soil beneath the buried marbles and that their effectiveness was thus reduced.

2.1.3.11 Initial soil water content

Differences in initial soil water content have been proposed as a cause of differences in susceptibility to sealing, with initially pre-wet soils generally being found to seal more slowly than initially dry soils. While aggregate strength and resistance to deformation or disruption by

raindrop impacts may be reduced by greater initial water content, reduction in potential for slaking because of higher water content and lower intra-aggregate air and soil gas content is the explanation most commonly proposed (eg., Le Bissonnais and Singer, 1992). This explanation may be valid under some conditions, but where the rate of pre-wetting differs from the rainfall intensity simulated, the effects of differences in wetting rate are not effectively isolated from the effects of differences in initial water content. In such cases, differences in susceptibility to surface sealing may result from varying degrees of "incipient failure" (Panabokke and Quirk, 1957) or "micro-cracking" (Le Bissonnais, 1990) resulting from differences in the rate of wetting rather than differences in initial water content.

There are studies that have concluded that surface sealing of dry soil was delayed relative to initially wet soil (eg., Le Bissonnias and Bruand, 1995; Nishimura *et al*., 1995). However these studies have used observations of surface ponding and runoff to evaluate rates of sealing without allowing for possible effects of differences in subseal soil water potential. These studies are discussed in more depth section 4.6 in relation to the findings of the present study.

2.1.3.12 Soil Chemistry

Exchangeable cations on soil surfaces can affect stability of aggregates through effects on physico-chemical dispersion. Rates of development of surface sealing have been found to be more rapid for sodic soils (eg., Bresson and Boiffin, 1990) and final hydraulic conductivities have been found to be negatively correlated with exchangeable sodium percentage (eg., Painuli and Abrol, 1986).

2.1.3.13 Interactions Between Factors

Factors potentially controlling rates of surface sealing may interact in various combinations.

In experimental studies, such interactions are generally taken into account either statistically or through the use of derived parameters. For example, Mohammed and Kohl (1986) referred to the use of droplet energy flux density (the product of rainfall intensity and raindrop kinetic energy level) to describe interactions between rainfall intensity and raindrop kinetic energy level in a manner analogous to the erosivity index of Wischmeier. They concluded that this derived parameter better explained changes in infiltrability.

In field experiments investigating surface sealing interactions are generally more complex and the relative influence of factors controlling rates of surface sealing may change through a growing season. An example of this kind of study is that of Rawls *et al*. (1995) that investigates the effect of plant residue and plant growth on surface sealing at various times through a growing season.

2.1.4 Re-aggregation and Seal Breakdown

Seals formed under rainfall may be broken or completely destroyed by subsequent tillage or by pedological and biological processes including cracking and re-aggregation caused by clay shrinkage on drying; re-aggregation caused by root growth and pedo-turbation by soil macro-fauna (Kladivko *et al.,* 1986). Freebairn (1989) described re-formation of macro-pores within 5 minutes of rainfall ceasing. He concluded that breakdown of surface seals resulted from surface cracking due to shrinkage on drying and from biological activity but he did not quantify the mechanisms involved.

Rates of seal breakdown could potentially influence soil water balance in cropping soils. There is a need for improved understanding of processes causing seal breakdown and for quantification of the rates of breakdown. It is proposed that investigations addressing these aims need to be carried out under controlled field conditions because of difficulties and complexities involved in experimental manipulation of soil macro-fauna.

2.2 EFFECTS OF SURFACE SEALING ON INFILTRATION

This section reviews the effects of surface sealing on infiltration and attempts that have been made to quantify these effects. Several authors have previously reviewed literature concerning surface sealing effects on infiltration (eg., Romkens *et al.,* 1990a; Moss, 1991a; Loch, 1989).

Laboratory studies of the effects of surface sealing on infiltration have commonly simulated single rainfall events of constant intensity and energy on columns or trays of re-packed soils. Field studies have commonly monitored cumulative infiltration or determined changes in infiltration rate under simulated rainfall events over longer time periods and related this to indices of rainfall kinetic energy such as cumulative rainfall volume. Large reductions in infiltration under rainfall observed in both laboratory and field situations have been attributed to the effects of surface sealing (eg., McIntyre, 1958a; Freebairn, 1989), and these reductions in infiltration have been used as a measure of the rate and degree of surface sealing. Numerous authors have concluded that the hydraulic properties of surface seals control infiltration into bare soil under rainfall, over-riding the effect of hydraulic properties of the bulk soil (eg., Morin and Benyamini, 1977).

Quantitative descriptions of the reduction in infiltration due to surface sealing range from simple comparisons of initial and final soil hydraulic conductivity (eg., "a two thousand fold decrease in permeability" McIntyre, 1958a), to computer based simulations of infiltration and runoff changing in response to surface sealing (eg., Baumhardt *et al.,* 1990).

In terms of soil hydraulic properties, surface sealing involves a significant decline in the permeability of a relatively thin sealing layer to a fraction of its original value (in practice, the original permeability may be unknown and the reference against which changes in surface hydraulic conductivity are assessed may be the hydraulic conductivity of the bulk soil beneath the sealed layer). It is also likely to involve changes to soil water characteristic of the surface layer resulting from destruction of macro-pores. Decline in permeability by definition creates an increased impedance to the flow of infiltrating water and can result directly in reduced infiltration rates in cases where the following conditions are met -

1. infiltration rate is not limited by supply rate,
2. soil profile infiltration is not limited by drainage through a less permeable sub-surface soil layer,
3. and surface sealing is areally complete or three dimensional flow of water underneath the seal is negligible.

The effects of surface sealing on infiltration in two cases have received most attention in previous literature. The first case is that where the above three conditions hold and a fully developed steady seal of constant permeability exists. The second and more complicated case is where the above three conditions apply and a sealed layer develops as a function of time, or a correlated parameter, over the duration of a rainfall event or events. Reduction in infiltration for these two cases has generally been quantified either for practical purposes of describing and predicting infiltration under field conditions or as a measure of the rate and degree of surface sealing. Expressing the rate of surface sealing in terms of the parameters used in methods for describing infiltration provides a quantification of surface sealing with convenient practical relevance.

2.2.1 Models of Infiltration Through a Surface Seal

Following the theory of Darcy the flux of water through a surface layer of soil (q) will be determined by the hydraulic conductivity of the layer (K) and the potential gradient driving the flow of infiltrating water ($d\Psi / d\theta$).

$$q = -K \quad d\Psi / d\theta \qquad \text{[Eqn. 2.1]}$$

The potential gradient is itself strongly influenced over time by cumulative infiltration volume. For example, infiltration rate into an initially dry soil may remain relatively high for some time, despite very low and declining surface hydraulic conductivity, simply because of the sorptive effects of dry soil underlying the surface seal. Infiltration rate may decline as the subseal layer becomes progressively wetter and the water potential gradient is reduced. Description of infiltration is most effectively achieved using models that account for the effects

of both low or declining surface hydraulic conductivity and changing soil water potential gradient.

Mathematical models describing infiltration may be categorised as follows -

1) empirically based models, such as the equations of Kostiakov (1932) and Horton (1940) and the SCS curve number method as described by McCuen (1982),
2) models based on general physical relationships for flow through porous media, such as the Richards' equation (Marshall and Holmes, 1979),
3) equations based on approximations of 2), such as the equations of Green and Ampt (1911) and Philip (1957).

Models in the first category, being empirically based, may be capable of incorporating the effects of surface sealing without modification, but generally do so implicitly through empirically determined parameters that have little or no physical meaning. For example, Morin and Benyamini (1977) found that Horton type equations of the form

$$I_t = (I_i - I_f) * e^{-Yit} + I_f \qquad \text{[Eqn. 2.2]}$$

and

$$I_t = (I_i - I_f) * e^{-nat} + I_f \qquad \text{[Eqn. 2.3]}$$

where I_t = infiltration rate at time t
I_i = initial infiltration rate
I_f = final infiltration rate
Y = number of median size drops per unit time per unit area
i = rainfall intensity
t = rainfall duration
n = fitted soil parameter
a = area sealed to $I = I_f$ by a median drop

described instantaneous infiltration rate on a Hamra soil under a range of rainfall intensities. However, their analysis could not explicitly consider effects of declining soil water potential gradient. If such effects existed, they would be implicitly incorporated into the fitted parameter n in Equation 2.3, along with surface sealing effects on surface hydraulic conductivity. Morin and Benyamini concluded that the lack of ponding and runoff on identical soils that were protected from high kinetic energy raindrop impacts indicated that declining hydraulic gradients would have had relatively insignificant effects on infiltration into their soils. However, reductions in potential infiltration due to hydraulic potential gradient effects may have occurred but not to a degree sufficient to produce runoff on protected soils under the rainfall intensity used.

Infiltration models in categories 2) and 3) above have generally been derived using conceptual soil profiles that have uniform constant hydraulic properties. As such, they commonly require modification to account for either the existence of a thin less permeable sealed surface layer or for dynamic changes in soil hydraulic properties of the surface layer caused by surface seal formation during an infiltration event. Such modifications for i.) the steady surface seal case and ii.) the developing surface seal case, are commonly based on one of the following three specifications -

1. Specification of a uniform seal layer of finite but small thickness that is completely saturated during rainfall and has -

for i.) low hydraulic conductivity or conductance,

for ii.) declining hydraulic conductivity or conductance.

Soil water retention properties within such a layer are irrelevant to infiltration rate providing saturation is maintained throughout the duration of rainfall.

2. Specification of an infinitely thin seal layer that has -

for i.) constant low hydraulic conductance

for ii.) declining hydraulic conductance (eg., Ross, 1990a,b).

3. Specification of a seal layer of finite but small thickness that has -

for i.) low non-uniform hydraulic conductivity or conductance varying with depth and non-uniform soil water retention characteristic varying with depth.

(eg., Mualem and Assouline, 1989)

for ii.) declining non-uniform hydraulic conductivity or conductance varying with depth and dynamic non-uniform soil water retention characteristic varying with depth that may be unsaturated or partially unsaturated during rainfall events.

Models incorporating modifications based on 1. or 2. above require parameterisation of seal hydraulic conductivity or seal conductance only. They do not require knowledge of soil water retention properties or change in these properties.

The most commonly used functional descriptions of declining surface hydraulic conductivity or conductance involve exponential decline from an initial value towards a final or steady limit as typified by the following equation proposed by Moore and Larson (1980).

$$K_t = (K_i - K_c)\, e^{-at} + K_c \qquad \text{[Eqn. 2.4]}$$

where K_t = saturated hydraulic conductivity at time t

K_i = initial saturated hydraulic conductivity

K_c = final saturated hydraulic conductivity

t = rainfall duration

a = a constant.

An equation analogous to Equation 2.4 was proposed by Brakensiek and Rawls (1983) relating declining hydraulic conductivity to cumulative rainfall kinetic energy rather than duration of rainfall.

$$K_t = K_c + (K_i - K_c)\, e^{-SE} \qquad \text{[Eqn. 2.5]}$$

where K_t = saturated hydraulic conductivity at time t

K_i = initial saturated hydraulic conductivity

K_c = final saturated hydraulic conductivity

E = cumulative rainfall kinetic energy

S = a constant referred to as the Soil Stability Factor

The parameters of Equation 2.5 may used to describe the extent and rate of surface sealing. The term (K_i - K_c) quantifies the maximum degree of the reduction in surface hydraulic conductivity caused by surface sealing, while the constant S in the exponent (ie., the Soil Stability Factor) quantifies the rate at which this reduction occurs.

Equations similar to Equation 2.3 and 2.4 above have been used in two-layer Green and Ampt models to derive an effective hydraulic conductivity behind the wetting front, calculated as the harmonic mean of hydraulic conductivities of the sealed layer and unmodified bulk soil (eg., Moore, 1981b). Such equations have also been used to update surface hydraulic conductivity in models based on numerical solution of the Richards' equation (eg., Moore, 1981a).

Hydraulic conductance and its reciprocal, hydraulic impedance, are both measurable parameters that integrate the effects of seal thickness and seal conductivity without requiring separate determination of the two variables. Hydraulic conductance of a seal layer can be expressed as the ratio of the hydraulic potential difference across the seal layer (in terms of pressure head) over the infiltration flux through the seal, as follows.

$$B = q / (h_0 - h_u) \qquad \text{[Eqn. 2.6]}$$

where B = hydraulic conductance

h_0 = total water potential at surface

h_u = total water potential under seal

q = flux through seal

For a relatively thin surface seal, the difference in hydraulic potential associated with gravity across the seal can be ignored. Where no differences in solute potential exist, the difference in total potential is directly determined by the difference in matric potential across

the seal. When the seal is saturated and the depth of water ponded above the surface is negligible, the matric potential at the surface can be considered to be equal to zero. The matric potential immediately below the seal, that can be measured with a tensiometer or other methods, approximates $h_0 - h_u$. Providing q can be measured or estimated, hydraulic conductance can be evaluated through a rainfall event for times following surface ponding.

The use of seal hydraulic conductance simplifies modeling of soil hydrological behaviour as it allows for the surface seal to be represented as an infinitely thin layer with no vertical dimension. Two advantages arise from this. Firstly, since the layer is infinitely thin, it can be considered to be saturated immediately after rainfall begins and the soil water retention properties of the layer need not be considered. Secondly, it is not necessary to adjust the depths of the sealing layer and the layer below to account for vertical extension of the developing seal.

Exponential decline of surface hydraulic conductance, analogous to the exponential decline of surface hydraulic conductivity described by Eqn. 2.4, has been used to model effects of surface sealing on infiltration (eg., Ross 1990a,b)

Alternative functional forms for describing decline in surface conductance have been proposed. For example, in using a numerical solution of the Richards' equation to explain infiltration under simulated rainfall of varying intensity and kinetic energy into columns of Atwood silty clay loam, Baumhardt *et al.* (1990) proposed a single three stage relationship to update seal hydraulic conductance. During the first stage of rainfall, up to 146 J m^{-2} of cumulative raindrop kinetic energy, surface hydraulic conductance was fixed at a constant value derived from ponded measurements of saturated hydraulic conductivity in a separate core. During the second stage, surface hydraulic conductance was assumed to declined rapidly according to the function:

$$B_f = (a_1/E_t) - a_2 \qquad \text{[Eqn. 2.7]}$$

where B_f = hydraulic conductance of forming seal

a_1, a_2 = fitted soil dependent parameters

E_t = cumulative kinetic energy at time t

This decline in seal hydraulic conductance was limited to a constant equilibrium minimum value assumed for the third stage and given by:

$$B_t = ((RI - a_3)a_4 + a_5)/100 \qquad \text{[Eqn. 2.8]}$$

where B_t = final equilibrium hydraulic conductance

a_3, a_4, a_5 = empirical soil dependent parameters

Assumed seals or sealing layers that are infinitely thin and constantly saturated are convenient for modeling but physically unrealistic, especially in the early stages of rainfall. Soil water retention properties of sealing layers and changes in these properties cannot be conveniently measured directly because of the small soil volumes involved and potential damage to the seal structure during sampling. However, changes in soil water retention have been represented in some models of infiltration through surface seals. For example, Baumhardt *et al*. (1990) represented changes in the soil water retention of a sealing layer in their studies on Atwood silty clay loam. Soil water retention in the sealing layer was updated using water entry values derived from measured saturated hydraulic conductivities of the seal and subseal layers combined with Poiseuille's equation and a relationship between pore size and water entry value.

Representation of changes in soil water retention in the sealing layer increases the complexity of infiltration models and their solutions. It has been shown that simulated surface sealing effects on hydraulic conductivity have a tenfold greater effect on time to ponding than do considerable simulated changes in initial soil water content (Moore, 1981a). On the basis of this finding, it can be concluded that, for the purposes of describing or predicting infiltration into tilled soils, changes in soil water retention properties of surface seals is generally of secondary importance relative to changes in soil permeability. This conclusion does not preclude the potential importance of quantifying changes soil water retention properties in studies investigating the nature of processes involved in surface sealing.

Increases in hydraulic impedance or decreases in hydraulic conductivity of a seal are unlikely to be constant throughout the depth of a sealed zone (Mualem and Assouline, 1989) and the depth of a sealed zone is unlikely to be constant throughout a rain event (unless it has reached a steady equilibrium depth prior to rainfall). Modeling of soil seals as non-uniform layers allows for specification of hydraulic conductivity and soil water retention properties that vary with depth. Mualem and Assouline (1989) represented the effects of surface sealing as change in bulk density from the initial value of the undisturbed soil to a sealed value. The degree of the change in bulk density was considered to decline exponentially with depth from a maximum alteration at the soil surface. Changes in both hydraulic conductivity and soil water retention were described by depth functions related to the predicted change in bulk density.

Modifications have been made to some infiltration models to account for the effects of a surface seal without the specification of distinct sealing layer. For example, Rawls *et al*. (1990) stated that numerically solved multi-layer models of infiltration into surface sealed soils have not been used in catchment hydrology models because of excessive computational requirements. They consequently proposed a single layer Green and Ampt infiltration model in which the effect of a surface seal was incorporated into an effective K for the profile through the use of a crust factor.

The crust factor CF (always less than 1) is given by

$$CF = K_e/K_S = SC/(1+\Psi_i/L) \quad \text{[Eqn. 2.9]}$$

where K_e = effective conductivity of the two layer system

K_S = saturated sub-seal conductivity

Ψ_i = steady state capillary potential at the interface

SC = correction factor for partial sub-crust saturation

L = wetted depth.

Using data from 53 soils at 24 locations they showed that SC and Ψ_i are related to soil texture and may be predicted using percentage of sand. Using these relationships to obtain values for SC and Ψ_i, the crust factor becomes a function of wetted depth and as the wetted depth increases CF approaches SC.

Approaches similar to that of Rawls *et al.* (1990) are unable to dynamically describe soil water content profiles throughout infiltration events but may be of practical value when only rainfall volume at ponding, infiltration rate or total infiltration volume are of interest.

2.2.2 Development of Negative Matric Potential in the Sub-seal Layer

An important consequence of decline in surface hydraulic conductivity relative to hydraulic conductivity of underlying undisturbed soil is the development of a significant sub-seal matric suction. The negative sub-seal matric potential that develops maintains a balance between the reduced saturated hydraulic conductivity of the sealed zone and the corresponding unsaturated conductivity of the unsealed bulk soil beneath (Hillel, 1980).

Sharma *et al.* (1981) described the measurement of matric potential under saturated and ponded soil surface seals. They measured steady sub-seal matric potential in a variety of soils and found a range from -0.64 to -1.42 kPa. These sub-seal matric potentials remained relatively constant throughout the depth of soil that was monitored with tensiometers (placed in the depth range 10 to 200 mm). These findings have been used to justify the use of a single tensiometer to measure matric potential for the soil below the sealing layer.

2.2.3 Differences between Infiltration under Experimental and Field Conditions

Three-dimensional water movement under broken or areally discontinuous surface seals can significantly increase spatially averaged infiltration rate (McIntyre, 1958a; Freebairn, 1989; Moss and Watson, 1991). Moss and Watson found that as the area of an experimentally sealed surface that was flawed or ineffective was experimentally increased from 0% to 10%, the spatially averaged infiltration rate increased. When 10% of the area was flawed, spatially averaged plot infiltration rate was equivalent to that of an unsealed surface.

Seals formed under field conditions may have considerably greater potential for seal flaws caused by miscellaneous surface protection and seal breakdown (eg., stone cover, weathering and soil macro-faunal activity) than experimentally formed seals on re-packed soils. Rainfall simulation on re-packed soils may therefore lead to under-estimation of field

infiltration or over-estimation of the effectiveness of surface sealing, especially when field infiltration is considered over a longer, biologically active time period such as a cereal crop growing season.

A further potential cause of discrepancies between experimentally determined infiltration into re-packed soil columns and field infiltration is the entrapment of air. Experimental columns are commonly vented to the atmosphere in order to prevent a reduction in infiltration rate caused by the build-up of positive air pressures in soil pores ahead of an advancing wetting front (eg., Eigel and Moore, 1983a). In field situations, soil pore networks may be inadequate or unconnected to the atmosphere and the escape of entrapped air may be prevented. Rainfall simulation on adequately vented experimental columns may therefore over-estimate field infiltration. The net effect of any such discrepancies will be specific to the particular field and experimental conditions considered.

2.3 AGGREGATION, AGGREGATE STABILITY AND AGGREGATE BREAKDOWN

This section presents a review of soil aggregates, aggregation, aggregate breakdown, and the measurement of aggregate stability. The roles of aggregate breakdown and the importance of aggregate stability relating specifically to surface sealing under rainfall are discussed in the following section.

2.3.1 Definition of Aggregates

Aggregates may be defined conceptually as groups of organic and inorganic primary particles that cohere more strongly to each other than to the rest of the soil (Kemper and Rosenau, 1986). However, aggregates will always be operationally defined by the process used to measure them and any definition should state that aggregates have greater strength than the strength of forces applied by their environment (Farres, 1980) or by the methods used to isolate and measure them.

The size and arrangement of soil aggregates can affect the size and arrangement of soil matrix pores or packing pores. Soil aggregates may be classified on the basis of size as macro-aggregates (> 0.25 mm) and micro-aggregates (< 0.25 mm). Their stability, along with stability of inter-aggregate contacts, largely determines the stability of packing pores and may influence the stability of other biologically created macro-pores. Aggregate breakdown can be an important process in soil structural change and aggregate stability, along with factors controlling rates of aggregate formation, may act as controlling factors for various soil processes including infiltration under rainfall, wind and water erosion, soil aeration, root growth and soil response to tillage.

2.3.2 Models of Aggregation

Kemper and Rosenau (1986) review the forces involved in aggregation. Surface tension of the air water interface and cohesive tension in the liquid phase are identified as the main forces of aggregation in moist soils. As moist soils dry, these forces tend to pull soil particles together and soil water retreats to inter-particle contact points. Soluble compounds such as silica, carbonates and organic matter are concentrated at inter-particle contact points. Chemical cementation, hydrogen bonding and other types of inter-molecular, inter-ionic and crystalline bonding are thus promoted.

A more detailed conceptual model of aggregation was proposed by Emerson (1959) who used it to predicted that the major effect of organic matter or soil conditioners was to strengthen bonds existing between quartz particles and clay domains. The model incorporated organic matter bonding between two quartz particles, organic matter bonding between two clay domains (face to face, face to edge and edge to edge bonds) and for bonding between clay domains (edge to face bonds).

Models of aggregation incorporating different aggregation mechanisms and controlling factors for a hierarchy of aggregate size classes have been proposed by Coughlan *et al.* (1973) and Tisdall and Oades (1982). Both of these two models are specific to their particular soil types, which are classified as a krasnozem and a red-brown earth (Xeralf) respectively according to Stace *et al.* (1968).

In the model proposed by Tisdall and Oades, for aggregation in a red-brown earth, aggregates larger than 2 mm in diameter are formed from aggregates in the size range 0.25 to 0.02 mm in diameter and are stabilised mainly by plant roots and fungal hyphae. Plant roots and fungal hyphae are considered as transient agents of aggregation and their density and rate of growth (and hence the degree and stability of aggregation in this size class) are influenced in the short term by agricultural management. Aggregates in the size range 0.02 to 0.25 mm are stabilised by more persistent organic materials, crystalline oxides and disordered aluminosilicates. Aggregates in the size range 0.002 to 0.02 mm are stabilised by persistent organic bonds that may be associated with current or previous bacterial activity and products of fungal hyphae. Aggregates less than 0.002 mm in diameter are generally clay flocules held together by forces derived from the interaction of clay particles. The frequency and stability of aggregates in the smaller size classes, that is up to 0.02 mm, are unaffected by agricultural management.

2.3.3 Processes Resulting in Aggregate Breakdown

Aggregates may break down under a wide variety of forces and environmental conditions but, under field conditions, a small number of basic processes have been identified (eg., Le Bissonnais, 1990). Three important categories of processes are discussed below, namely, mechanical disruption or erosion, slaking and chemical dispersion.

2.3.3.1 Mechanical Disruption or Erosion

Aggregates may be broken down by the application of a mechanical stress sufficient to overcome the net strength of intra-aggregate bonding mechanisms. The nature of the fracturing (and hence the size of products) will be dependent on the magnitude and distribution of the applied forces, the size of the aggregate, and the spatial variation in strength of intra-aggregate bonding. Such fracturing may be catastrophic, resulting in breakdown to a number of much smaller aggregates or primary particles, or incremental, resulting in liberation of a small aggregate or primary particle from a parent aggregate that remains relatively intact.

2.3.3.2 Slaking

Slaking refers to the breakdown of aggregates on rapid wetting. Two mechanisms of slaking have been proposed. Firstly, aggregates may be disrupted by the build-up, to explosive pressures, of air and soil gases trapped in intra-aggregate pores by wetting fronts, enhanced by surface tension, advancing from all surfaces toward the centre of an aggregate. Secondly, they may be disrupted by differential rates of swelling resulting from hydration of clays within the aggregate (Emerson and Grundy, 1954). The effects of slaking on an aggregate may take the form of total breakdown, where the aggregate is physically dispersed by the wetting process, or they may take the form of incipient failure (Quirk and Panabokke, 1962) or micro-cracking (Le Bissonnais, 1990). In the later form, stresses induced by rapid wetting result in micro-fractures within the aggregate. Aggregates remain apparently intact in the absence of mechanical energy, but disperse completely under the impact of a small mechanical force.

2.3.3.3 Chemical Dispersion

Chemical dispersion refers to the chemically based de-stabilisation of soil aggregates in free water. It results from the repulsive forces caused by interaction of diffuse double layers associated with nearby clay particles (Romkens *et al.*, 1990a).

2.3.4 The Measurement of Aggregate Stability

When a soil aggregate is subjected to a force it may remain intact or separate into smaller primary particles and or aggregates, depending on whether the strength of the force acting on the aggregate is greater than its internal strength. A soil in its natural condition generally contains aggregates with a range of sizes and a range of internal strengths, and the cohesive forces will vary spatially within these aggregates. Any method of measuring the size of aggregates must impose some force on the aggregates, and will likely cause some aggregates to break into smaller aggregates or particles. The resulting size distribution of aggregates is only relevant to the particular type and degree of disruptive force applied. Therefore, any aggregate size measurement technique, in effect, integrates measurement of aggregate size and

stability at that size. Kemper and Rosenau (1986) reviewed methods for measuring aggregate breakdown or aggregate stability.

Methods for aggregate size/stability measurement can be described in terms of the forces applied to the aggregates during both pre-measurement and measurement stages.

2.3.4.1 Pre-measurement

Methods for measuring aggregate stability commonly involve some pre-measurement treatment that consists of physical preparation of the soil followed by some form of wetting and optionally some form of mechanical force. Physical preparation varies between studies but generally involves collection, drying and sieving to obtain a particular size fraction. This size fraction is commonly < 10 mm, < 2 mm or 1 to 2 mm. Reasons for using pre-measurement sieving include -

1. Simplification of method and calculations by limiting the sample to one size fraction and
2. Removal of fines that may clog apertures in sieving based methods. (De Boodt *et al.*, 1961)

Pre-measurement wetting can affect the extent of wetting that occurs during treatment and hence may affect measured aggregate breakdown due to slaking considerably. Kemper and Rosenau (1986) propose that pre-measurement wetting should be chosen to simulate the processes under investigation. Immersion wetting or shock wetting involves rapid immersion of aggregates in water. Such immersion creates a potential for slaking forces within the aggregate that depends strongly on the soil water content prior to immersion and the physico-chemical status of the aggregate. The effects of these factors are discussed below. Immersion wetting of air dry aggregates results in maximum potential disruptive slaking forces and may simulate the effects of flood irrigation on air dried surface soils. Immersion wetting of tension pre-wet aggregates may simulate flood irrigation of already moist soils, while immersion wetting of rain wetted aggregates may simulate wetting occurring at ponding or under overland flow under rainfall. The two latter immersions generally result in less breakdown due to the higher water content prior to immersion. This higher water content reduces the amount of air or soil gas that can potentially be trapped within the aggregate, reduces the hydraulic potential gradient driving water into the aggregate, and reduces the potential for further intra-aggregate stresses resulting from swelling of clay on further hydration.

Tension wetting involves bringing aggregates into contact with a supply of water at negative potential (eg., a tension plate). Suction or negative potential applied to the water source reduces the water potential gradient from the water supply to the relatively dry aggregates. Water is drawn more slowly into the aggregates by the hydraulic gradient that persists until the matric potential throughout the aggregates is equal to the suction on the water supply. The slower rate of wetting allows for air and soil gas to be displaced from intra-

aggregate pores without the build-up of explosive pressures and this results in a reduction of slaking. Tension wetting may simulate the wetting of a layer of air dried topsoil aggregates from subsoil water storage. As stated previously, Kemper and Rosenau (1986) concluded that slaking potential is eliminated by application of a small suction to the water supply used for wetting. They found aggregate stability unaffected by changes in the potential used for aggregate wetting from -0.05 to -1.5 kPa.

Kemper and Rosenau (1986) discussed variability in aggregate size measurements following vacuum wetting of aggregates. In this method, aggregates are wet after adsorbed O_2 and N_2 and intra-aggregate air have been removed under vacuum, hence reducing the potential for entrapment of air and soil gasses. They concluded that variation among results using this method was due to inadequately established vacuum conditions. Whilst vacuum wetting does not realistically simulate any naturally occurring field condition, it can potentially isolate slaking effects in studies investigating mechanisms of aggregate breakdown. Unfortunately, this method is not easily adapted for studies using real or simulated rainfall.

Wetting aggregates by subjecting them to a flow of water vapour is an alternative and relatively rapid method for minimising slaking effects while wetting aggregates in preparation for water based size measurements.

2.3.4.2 Measurement

Measurement techniques to separate aggregates on the basis of size are generally based on sieving or sedimentation (Kemper and Rosenau, 1986).

Aggregates may be sieved in a dry state, either manually using flat sieves or with mechanical rotary sieves. Samples are sieved twice through a range of sieves to determine size distribution. The difference in the two consecutive size distributions measures the aggregate breakdown resulting from the second sieving. Such sieving applies abrasive mechanical forces that may simulate, the abrasive forces operating in wind erosion processes in the field. The difference in size distribution may be used to back-correct the first size distribution to account for breakdown due to abrasion in the first sieving and hence estimate the original aggregate size distribution.

Wet sieving methods involve the use of a nest of sieves or a single sieve oscillated vertically through a standard distance in water at a standard frequency for a standard time period. Aggregates remaining on each of the nested sieves are removed and weighed to determine a size range distribution. In the case of the single sieve method, the amounts of material passing through the sieve during the initial sieving and during a subsequent sieving that follows chemical and mechanical dispersion are weighed. The water-stable fraction is given by the weight of material passing the second sieving divided by the sum of weights passing both sievings. The first sieving applies forces that may simulate the forces applied by flowing water under in field conditions, while the second quantifies the primary particles in the size fraction greater than the sieve aperture.

Sedimentation methods for sizing aggregates are based on the application of Stokes' Law, which states that the settling velocity of small spherical particles through viscous liquid is proportional to the square of their radii. Sedimentation techniques for aggregate size measurement are essentially those commonly used for particle size determination (Kemper and Rosenau, 1986) but without additional chemical and physical dispersion.

Aggregate settling velocity methods (eg., Lovell and Rose, 1988) also utilise the dependence of settling velocity on aggregate or particle size. A sample of soil is introduced into a long, liquid filled column and aggregates settling to the bottom of the column during particular time intervals are collected, dried and weighed. Settling velocity can be calculated from the length of the column and the average time taken for aggregates to settle. Deviations from the conditions required for application of Stokes' Law are likely for larger aggregates. Hence, aggregate size cannot be accurately inferred from settling velocity. These methods have generally been used to measure settling velocity distribution for use in erosion and sediment transport modeling.

Sedimentation methods for sizing aggregates generally apply only minor mechanical forces additional to the disruptive forces involved in the method used to bring the aggregates to the necessary saturated state. Sample handling and the hydrostatic forces in a long settling tube are potential sources of minor additional mechanical force.

Kemper and Rosenau (1986) also describe the now uncommonly used elutriation methods in which a flow of water is passed upward through a column containing an aggregate sample. Aggregates and particles of a particular size range with a settling velocity equal to the velocity of the upward water flow should remain stationary in the column. They conclude that difficulties in creating, controlling and standardising the upward flow velocity throughout the tube, combined with the likely presence of turbulent flow have discouraged use of such methods.

Commonly, no distinction is made in either sedimentation or sieving techniques between aggregates and primary particles but both methods may incorporate subsequent particle size determination to allow the effect of initial particle size on aggregate size to be determined (eg., Mbagwu and Bazzoffi, 1988).

Five other approaches for assessing aggregate stability that were not described by Kemper and Rosenau are discussed below.

Firstly, a range of methods have been proposed (eg., Childs, 1940; Williams, 1963) to quantify aggregate breakdown indirectly by measuring changes in inter-aggregate pore volume resulting from differing wetting treatments or wetting and mechanical deformation treatments. These methods are based on the assumptions that the degree of breakdown of aggregates within a bed caused by various treatments will result in decreases in inter-aggregate pore volume and that these changes in inter-aggregate pore volume will be reflected in the soil water retention function near saturation. Change in aggregation can be quantified for desired ranges of resulting pore sizes by measuring soil water content at two or more matric potentials

close to saturation. These methods generally involve immersion, tension or raindrop wetting treatments (with or without mechanical compaction) of a bed of aggregates placed on a tension table. Particular soil matric potentials are then imposed on the soil and the measured outflow from the tension table indicates the pore volume between the two matric potentials. This volume can be used directly as an index of stability, or contrasted with the volume resulting from a different treatment, again in the form of an index (eg., Greive, 1979). The same principle forms the basis of measures such as the improved High Energy Moisture Characteristic method (Pierson and Mulla, 1989).

Secondly, Emerson (1967) proposed a scheme for classifying aggregates on the basis of slaking and dispersion as determined by visual assessment. The method provides a qualitative assessments of the degree of aggregate slaking and the degree of clay dispersion. Aggregate classifications using this scheme and schemes derived from it (eg., Loveday and Pyle, 1973) have been related to various physical behaviours of field soils.

Thirdly, Hignett (1991) proposed a method for measuring aggregate breakdown by the turbidity of runoff from beds of aggregates subject to simulated rainfall. The turbidity of the water sample is measured with an optical turbidity meter. The result may be expressed either directly in NTU or as the ratio of the measured turbidity divided by the turbidity of the sample following ultrasonic dispersion. Water samples were taken from beakers in which soil aggregates had been immersed and from runoff collected during simulated rainfall on 75 mm diameter columns. Hignett (1991) concludes that "the turbidity of the runoff water during the rainfall simulator tests provides a good measure of the instantaneous stability of surface aggregates during the test". It is likely that results from such methods reflect the size ranges of breakdown products more than the stability of the original aggregates.

Fourthly, micro-morphological measurements made under microscopes on thin sections of resin impregnated soils or soil aggregates have been used to semi-quantitatively assess aggregate sizes before and after certain treatments (eg., McIntyre, 1958a; Chen *et al.*, 1980; Moss, 1991a). Such measurements are generally restricted to a small number of aggregate samples and are not suitable as a routine method. Important stereological considerations that must be taken into account to correctly measure aggregates observed in essentially planar sections have been stressed by Ringrose-Voase (1991).

Fifthly, North (1976) proposed an absolute method of soil structural stability based on the amount of ultrasonic energy required to completely disperse an aggregated sample. He concluded that such a measure would be useful in predicting a particular soil's behaviour without reference to values for other soils.

2.3.5 Factors Influencing Aggregate Stability

Factors proposed as agents of aggregation in the models described in section 2.3.2 may potentially affect measured aggregate stability but, as explained in section 2.3.4, measured aggregate stability is relevant only to the forces applied to isolate and size the aggregates.

Hence, aggregate stability may be influenced by soil factors, factors related to the method of measurement and interactions between these. The factors considered important are discussed below.

2.3.5.1 Initial Soil Water Content and Wetting Rate

Initial soil water content of aggregates has been shown to affect aggregate stability (eg., McCalla, 1944; Cernuda *et al.*, 1954; Panabokke and Quirk, 1957; Francis and Cruise, 1983) and micro-aggregate stability (eg., Mbagwu and Bazzoffi, 1988). It is generally recommended, at least for comparative studies, that aggregate stability measurements be made on aggregates at similar water content (eg., McCalla, 1944).

Variation in initial water content may have a number of potentially opposing effects on the measured stability of aggregates. It has been proposed that higher antecedent water content may partially dissolved inter-particle chemical cementing agents thus weakening aggregates stability (Cernuda *et al.*, 1954). It has also been proposed that for aggregates that are initially drier than pF 5.5, stability may increase because of air preventing some colloidal interfaces from wetting at all, hence increasing measured stability (Panabokke and Quirk, 1957). However, the net effect on aggregate stability of variation in initial water content is dominated, at least for most soils, by the increased aggregate breakdown due to slaking caused by greater degree of wetting of initially drier soil aggregates. In effect, the inherent stability of aggregates may be little changed by changing initial water content but the forces that result during methods of measurement that involve immersion in water, such as wet sieving or settling velocity, are much greater for initially drier aggregates. Mechanisms of breakdown that have been proposed include the development of explosive pressures in air trapped ahead of advancing wetting fronts in lighter textured soils and differential swelling in clay soils. In accordance with these proposed mechanisms, measured aggregate stabilities have generally been found to increase as initial water content increases.

This relationship between initial water content and measured stability can be reversed as initial water content approaches saturation. Francis and Cruise (1983) found that small decreases in matric potential from saturation to matric potentials of -0.5 kPa increased aggregate stability. They proposed that the increase in stability could be significant if management practices could produce drainage sufficient to give this small moisture suction during heavy rainfall. It has been concluded that the weakening of aggregates as initial matric potential approaches 0 kPa is due to a loss of cohesion and the introduction of swelling forces (Truman *et al.*, 1990).

The effects of initial water content on measured aggregate stability may not be independent of the wetting rate that brought about the given initial water content. Aggregates that have been rapidly pre-wet to an initial water content close to saturation may have similar measured stability to initially dry aggregates if the wetting rate during measurement equals the pre-measurement wetting rate. In general, aggregate stability will be greater when aggregates

are brought to higher initial water contents at slow rates using tension wetting. Kemper and Rosenau (1986) cited work of Kemper and Koch showing that aggregate stability as measured by wet sieving was not significantly different for aggregates wet under tensions of -0.05 Pa and -1.5 kPa. Kemper and Rosenau concluded that aggregate breakdown due to slaking would be prevented using wetting rates corresponding to tension wetting at relatively low suction.

2.3.5.2 Wetting and Drying History

Measured aggregate stability may be influenced by the wetting and drying history of soil aggregates. Mbagwu and Bazzoffi (1988) found that dis-aggregation measured by wet sieving decreased to a minimum after soils were subjected to three artificial wetting and drying cycles but that dis-aggregation increased with further cycles for all three soils used. These results can be explained by transient thixotropic hardening of clay particles causing an increase in aggregation up to the third wetting cycle and by formation of planes of weakness caused by subsequent cycles (Utomo and Dexter, 1982).

2.3.5.3 Soil Organic Matter Content

Differences in aggregate stability have been shown to be positively correlated with differences in soil organic matter content and organic carbon content brought about by differing agricultural management in many soils (eg., Hamblin, 1980) or by direct application of organic matter (eg., in the form of carbohydrate, McCalla, 1944; or in the form of manure, Mbagwu and Bazzoffi, 1988). The response of aggregate stability has been shown to interact with clay content and antecedent moisture (Mbagwu and Bazzoffi, 1988).

2.3.5.4 Aggregate Size and Shape

The quantitative models of aggregation described by Coughlan *et al.* (1973) and Tisdall and Oades (1982) in section 2.3.2 both contain a hierarchical system of aggregation. These models imply that smaller aggregates are generally more stable under an applied force than larger aggregates (otherwise the larger aggregates would break down to directly to primary particles). Inverse relationships between aggregate size and aggregate stability have been demonstrated experimentally, but have been found to be soil specific (eg., McCalla, 1944).

Aggregate shape has rarely been considered in the measurement of stability because of the difficulty in quantifying shape and the considerable effort required to do so for a representative sample of aggregates. Aggregate samples are frequently prepared and pre-selected using sieves that effectively select aggregates only on the basis of their smallest equivalent diameter, irrespective of shape. It has been found that aggregates with a high ratio of horizontal to vertical dimension are more easily disrupted by slaking (Cernuda *et al.*, 1954) but no physical explanation for the phenomenon has been proposed. These authors compared

surface and sub-soil samples and it is possible that aggregate shape within the soil used is correlated with sodicity, or some other factor, that may be causally related to the mechanisms of aggregate breakdown.

2.3.5.5 Water and Soil Temperature

In most water based methods of determining aggregate stability, a relatively small mass of soil is immersed in a relatively large mass of water that will usually be equilibrated at a standard temperature. Irrespective of the thermal inertia of the soil sample, the initial water temperature will dominate and hence temperature variation during stability determinations is likely to be small. One possible exception to this is the single drop test where relatively small amounts of water contact relatively large amounts of soil. Interestingly, this test was used in one of the rare determinations of water temperature effects by McCalla (1944). In that study, McCalla found that aggregate stability to single drops decreased as temperature increased from 0^{o}C to 60^{o}C.

2.3.6 Methods for Expressing Aggregate Breakdown or Aggregate Stability

A range of methods exist for expressing results of aggregate size/stability measurements (Kemper and Rosenau, 1986). Some methods are listed below.

2.3.6.1 Median Aggregate Diameter (D_{50})

Median weight diameter is that diameter at which 50% of the sample, by weight, is greater and 50% less.

2.3.6.2 Mean Weight Diameter (MWD)

Mean weight diameter is the summation of products of proportions of the treated sample in each size interval and the mean diameter for each interval.

$$MWD = \sum_{i=1}^{n} \bar{x}_i w_i \qquad \text{[Eqn. 2.10]}$$

where w_i = weight of treated sample in size fraction i

$\bar{x}_i$ = mean aggregate diameter in size fraction i (Van Bavel, 1949)

2.3.6.3 Change in Mean Weight Diameter (De Boodt *et al.*, 1961)

Change in mean weight diameter is the difference in MWD for two size distributions determined by dry sieving and by wet sieving after rainfall wetting.

2.3.6.4 Geometric Mean Diameter (Mazurak, 1950)

Geometric mean diameter is given by the following.

$$GMD = \exp\left(\frac{\sum_i^n w_i \log \bar{x}_i}{\sum_i^n w_i}\right) \qquad \text{[Eqn. 2.11]}$$

where w_i = weight of treated sample in size fraction i

$\bar{x}_i$ = mean aggregate diameter in size fraction i

It can be used in conjunction with the log standard deviation of sizes to fully describe the resulting size distribution where this distribution is log normally distributed.

2.3.6.5 The Proportion in a Particular Size Fraction

The proportion in a particular size range can be used to express information about the final distribution (eg. the proportion of the treated sample with diameter less than 0.125 mm, labelled P125 by Loch and Foley, (1994)), or to express the proportion of an original size fraction remaining in another size fraction, (eg. the percentage of 1 to 2 mm aggregates remaining larger than 0.25 mm in diameter after wet sieving). A further example is the use of Aggregated Silt (AS) and Aggregated Silt plus Clay (ASC) (Mbagwu and Bazzoffi, 1988), given by the differences in the amounts of the original sample measured in the silt or silt plus clay particle size range with and without dispersion using size analysis by sedimentation.

2.3.6.6 Other Indices

Some aggregate stability measures, such as those evaluated by Greive (1979), that measure the difference in inter-aggregate pore space at different water potentials, produce results expressed in units that do not relate directly to aggregate size. For these measures, results are often converted to, or used as, a dimensionless index. A further example of a dimensionless index is that used by Farres and Cousen (1985) to express the results of single drop tests is

$$I = (\Sigma\, T_i/T_{crit})*100/n \qquad \text{[Eqn. 2.12]}$$

where I = the dimensionless index

T_i = time to breakdown of the aggregate in seconds

T_{crit} = time of exposure at which an aggregate is defined as rain-stable (240 sec)

n = number of aggregates in sample

2.3.7 Evaluation of Aggregate Stability Methods and Methods for Expressing Results

Several authors have compared aggregate stability tests and indices and concluded that the choice of test is dependent on the purpose of the investigation (eg., Matkin and Smart, 1987; Grieve, 1979). Kemper and Rosenau (1986) also conclude that disruptive forces applied in determining aggregate stability will not necessarily correspond exactly to forces encountered in the field. These authors concluded that methods should be chosen where possible to reflect the

forces considered important in particular investigations but that results often need to be correlated empirically to the field behaviour or processes of interest. It can be concluded that the value of any particular method will depend on the purpose to which it is applied. Evaluations of various aggregate size/stability measures for investigating surface sealing processes and susceptibility to surface sealing are discussed in section 2.4.

2.4 AGGREGATE BREAKDOWN AND THE FORMATION OF STRUCTURAL SURFACE SEALS

When water drops fall on unprotected or partially protected soil, that is drier than saturation point, potential exists for each of the three important categories of aggregate breakdown processes mentioned in section 2.3.3 namely, mechanical disruption or erosion, slaking and chemical dispersion, to occur. This section reviews current understanding on the relative importance of the suite of processes leading to aggregate breakdown under rainfall. It goes on to examine the various roles that aggregate breakdown may play in surface sealing and to evaluate a range of aggregate stability methods relevant to aggregate breakdown under rainfall. It concludes with a discussion of published relationships predicting the effects of surface sealing on infiltration or surface hydraulic behaviour from aggregate breakdown or aggregate stability.

2.4.1 The Relative Importance of Processes Leading to Aggregate Breakdown Under Rainfall

Le Bissonnais *et al.* (1989) reviewed work showing that mechanisms of aggregate breakdown under rainfall for non-dispersive soils were closely related to initial water content and wetting procedure, and that the resulting aggregate size distribution was dependent on the dominant mechanism of breakdown. Later Le Bissonnais (1990) proposed a conceptual model identifying potential relations between parameters that control the relative importance of rapid soil wetting and energetic raindrop impact in causing aggregate breakdown under rainfall. While the model identifies relations it does not attempt to quantify them. The model is examined in more detail and amendments are suggested in Chapter 7.

A number of studies have sought to isolate and quantify the effects of energetic raindrop impact on aggregate breakdown and surface sealing experimentally by repeating rainfall simulations with both high and low kinetic energy raindrops on identically prepared soil surfaces. These studies have generally either varied the drop energy simulated (eg., Eigel and Moore, 1983a) or inserted protective screening above the soil (eg., Glanville and Smith 1988; Loch and Foley, 1994). Other studies have sought to assess the effects of soil wetting rate by comparing behaviour of dry soil under simulated rainfall with either tension pre-wet soil without rainfall (eg., Glanville and Smith, 1988) or soil under simulated rainfall following slow pre-

wetting by either suction devices beneath the soil (eg., Le Bissonnais and Singer, 1992; Nishimura *et al.*, 1995) or mist sprays (eg. Loch, 1989).

A small number of studies have combined techniques and drawn inferences concerning the relative importance of the two sets of processes. Glanville and Smith (1988) compared degree of aggregate breakdown of dry soil under high energy rainfall with breakdown following immersion and tension wetting. They concluded that rapid wetting was the more significant agent of aggregate breakdown for two swelling clay soils and one slaking clay soil but not for a fourth clay soil that was dominated by sesquioxides. Loch and Foley (1994) compared degree of aggregate breakdown under high and low energy rainfall of a single intensity for a wide range of soils from eastern Australia. Whilst they found slightly greater breakdown under high energy rainfall, they interpreted the high degree of correlation between final surface aggregate size under high and low kinetic energy rainfall as evidence that rainfall intensity, and, therefore, soil wetting rate, was the more important determinant of aggregate breakdown for most soils.

The experimental procedures used to isolate the effects of high kinetic energy and rapid wetting in the above studies appear logical. However, three short-comings should be noted. Firstly, in studies where energetic rainfall on bare dry soil and on protected dry soil have been compared (eg., Glanville and Smith, 1988), effects of energetic raindrop impacts have only been assessed in the presence of concurrent rapid soil wetting. The two sets of processes have not been fully isolated. If any interaction occurs between the energetic impacts and concurrent rapid soil wetting then the assessed relative importance may be affected. Secondly, in many studies the effect of energetic raindrop impacts has only been assessed under dry antecedent soil water conditions that generally lead to a considerable hydraulic gradient through the sealing layer. While such dry antecedent soil water conditions may be comparable to the most commonly experienced field situation of rain falling on dry soil surfaces, other antecedent soil water contents are feasible and deserve consideration. Thirdly, some studies have compared effects of tension wetting without rainfall against effects of rapid wetting under rainfall with negligible kinetic energy to determine the influence of rapid wetting on surface aggregate size distribution measured by wet sieving (eg., Glanville and Smith, 1988). In such cases, any differences in aggregate size resulting from packing, handling and re-sampling the soil for rainfall simulations may be inappropriately attributed to rapid soil wetting.

A sound understanding of the suite of processes leading to aggregate breakdown under rainfall is likely to be a fundamental prerequisite to improved management of surface sealing. It would appear to be a deficiency that the relative importance effects of rapid wetting driven processes and raindrop impact driven processes on aggregate breakdown under rainfall have not been fully isolated in literature published to date.

2.4.2 Quantitative Models of Aggregate Breakdown Under Rainfall

Quantitative models describing the breakdown of aggregates under rainfall have generally been confined to statistical models summarising empirical results of single drop tests. For example, Farres (1980) used Principal Component Analysis to develop a statistical model for the breakdown of individual aggregates under single raindrops as a function of eleven variables relating to drop energy, drop volume and rainfall intensity.

$$Y = 1.58\ C_1 + 1.55\ C_2 + 2.16\ C_3 + 5.77 \quad (R^2 = 0.92) \qquad \text{[Eqn. 2.13]}$$

where Y = time to aggregate breakdown
C_1, C_2, C_3 = components with eigenvalues > 1

Component C_1 was loaded highly with drop energy related variables such as height of fall, velocity of impact, and cumulative kinetic energy. Component C_2 was loaded highly with the volume related variables such as drop volume, drop diameter, and number of drops. Component C_3, which alone explained 53% of variation in time to breakdown, was characterised by only one variable, drop frequency.

The importance of drop frequency lead Farres to propose a conceptual model explaining aggregate breakdown under single drops. In this model, aggregate strength is reduced sharply at each drop impact as the slug of water enters the outer aggregate and -
a) lengthens dipolar water bridges and upsets electro-chemical and electro-kinetic balance hence weakening the aggregate,
b) causes a greater hydraulic gradient into the centre of the aggregate and hence greater potential for slaking stress on the aggregate.

Farres proposed that aggregate strength rises more slowly as a function of the relaxation time between drops as the electro-chemical status of the aggregate adjusts to the new set of conditions and the slaking stress is reduced due to entrapped air migrating outwards. When the strength of the aggregate falls below a threshold level the aggregate is broken down by the next drop. Farres concluded that, for the topsoil aggregates of the calcareous silty loess soil used, slaking was the dominant process of breakdown under rainfall.

A further example of statistical models is that proposed by Wustamidin and Douglas (1985). These authors used multiple regression to develop a model incorporating 15 soil properties that explained 99% of the variation in the number of single drops required to break down single aggregates. No single property by itself could explain aggregate breakdown although percentages of sand and percentage of silt were highly correlated with number of drops required.

A physically based model of clod breakdown was proposed by Elwell (1989). The model describes the breakdown and burial of hemispherical clods in a fersiallitic clay soil and was developed using experimental data for 200 mm diameter hemispherical milled clods. The model is relatively simplistic in that it considers only incremental removal of soil material from

the clod by raindrop impacts and it is unlikely to be applicable to the breakdown of smaller, irregularly shaped aggregates in light textured, weakly aggregated soils susceptible to slaking.

2.4.3 Role of Aggregate Breakdown in Surface Sealing

A smaller number of studies have explicitly considered the role of aggregate breakdown in the process of surface sealing (eg., Le Bissonnais, 1990). Le Bissonnais *et al*. (1989) related an analysis by Boiffin and Monnier (1985) proposing the sequence of seal formation processes on a silty soil. The proposed sequence of processes is -

1. Detachment of particles (that may be aggregates or primary particles),
2. Movement of detached particles to the lowest areas by raindrop splash (no spatial scale for this movement was specified),
3. Compaction by raindrop impact,

and the mechanisms contributing to detachment of particles from larger aggregates are -

1. Slaking,
2. Mechanical breakdown due to raindrop impact,
3. Micro-cracking resulting from swelling and shrinkage due to wetting and drying.

The major role of aggregate breakdown in surface sealing identified in this conceptual model is the liberation of fine particles. Such a role has been identified in other studies (eg., Freebairn, 1989; Loch, 1989; Moss 1991a,b).

In addition to the imprisonment of fine particles, Moss (1991a) proposed a major role of aggregates in retarding the sealing process by increasing the grain size and packing pore size in the soil surface hence increasing hydraulic penetration and inhibiting seal formation. A further roles in retarding sealing proposed by Moss were resisting breakdown, compaction and deformation in the compacted layer of the surface seal and protecting underlying soil surfaces from raindrop impact.

2.4.4 Measures of Aggregate Stability Relevant to Field Behaviour of Aggregates under Rainfall and Their Relative Value

Measures of aggregate stability have been used as indicators of the susceptibility of surface soils to sealing but more commonly as indicators or measures of soil erodibility (Greive, 1979). Measures of aggregate stability that may be appropriate for assessing susceptibility of surface soils to sealing are discussed below.

2.4.4.1 Single Drop Tests

Single drop tests use drop formers to produce single drops that fall a given distance onto a soil sample or selected soil aggregate. Samples or aggregates rest on a sieve or aperture of known diameter. The number of drops, or the time at a constant drop frequency, required to break the sample or aggregate down into fragments small enough to pass through the aperture are used as measures of aggregate stability (eg., McCalla, 1944; Grieve, 1979; Cousen and Farres, 1984; Farres and Cousen, 1985). Drop water chemistry, drop height, drop size, aggregate size and aperture size have been shown to influence stability and it has been concluded that these variables should be standardised for comparative studies (Farres and Cousen, 1985).

2.4.4.2 Simulated Rainfall Followed by Wet Sieving

Simulated rainfall followed by wet sieving has been used to assess the separate effects of aggregate breakdown due to raindrop impact and aggregate breakdown by flowing water in rills (Young, 1984). This method has also been used to determine soil related differences in aggregate breakdown under rainfall (Truman *et al.*, 1990) and relationships between infiltration rate and aggregate breakdown under rainfall (Glanville and Smith, 1988; Loch and Foley, 1994). It has the advantage that the method of soil wetting is analogous to wetting that may occur in a field situation.

2.4.4.3 Simulated Rainfall Followed by Settling Velocity Determination

Loch (1989) compared results of settling velocity determination and wet sieving on the same sediments from rainfall simulations on field plots of a weakly aggregated sandy loam and an aggregated cracking clay (Irving Clay), both from north of Warwick in Queensland, Australia. Settling velocities were required as inputs to a process erosion model (CREAMS), however, Loch converted the settling velocity distribution to an aggregate/particle size distribution and density and used a module of the model to re-create the settling velocity. Loch concluded that aggregate size distributions computed from settling velocity distribution (assuming an aggregate density of 2.66 Mg m^{-3}) and determined by wet sieving would be similar for weakly aggregated soils and could be made similar for aggregated soils by calculating an effective particle density for aggregates and particles greater than 0.1 mm in diameter. He concluded that such an approach would be more convenient and efficient, but did not clarify how an appropriate effective particle density should be determined without prior knowledge of the settling velocity distribution.

2.4.4.4 Relative Usefulness of Measures

Loch and Foley (1994) compared several methods of pre-measurement wetting and several methods for expressing results. They concluded that the wetting of aggregates under tension or by immersion causes aggregate breakdown (and hence final aggregate size distribution) that

is not relevant to rainfall in the field. They concluded that wetting under rainfall should be used and that the results of aggregate breakdown should be expressed as the proportion by weight of particles and aggregates remaining less than 0.125 mm (P125). This work was carried out on beds of aggregates and it is unclear to what degree these conclusions may be extended to wetting in single drop tests.

Farres (1987) and Loch and Foley (1994) concluded that methods for assessing aggregate stability in studies of surface sealing or rain-splash erosion must measure the size of breakdown products because it will be the size of breakdown products that influences rates of these processes.

Assessment of the relative value of aggregate stability methods in surface sealing studies is further confounded by recognition of different surface sealing sub-environments. Moss (1991b) listed three separate surface sealing sub-environments in which the stability of aggregates may influence the process of surface sealing under rainfall -

1. the pre-sealing surface
2. the post-sealing surface
3. the post-sealing sub-surface "compacted zone".

He proposed that the forces acting to break down aggregates and the stability of aggregates to these forces differed significantly between these sub-environments for some soils and he concluded that a single concept of aggregate strength would be inadequate under such circumstances.

It is desirable that aggregate stability tests closely mimic field processes of interest, and that aggregate stability to the appropriate range and mix of forces occurring be defined. This will be particularly important when a mechanistic description of aggregate breakdown is sought.

2.4.5 Quantitative Relationships Between Aggregate Breakdown and Reduced Surface Permeability

Quantitative relationships between aggregation and surface seal conductivity or conductance may potentially be based on -

1. statistical relationships between experimentally determined seal hydraulic properties and aggregate stability determined for an arbitrarily selected soil sample,
2. partially physically based models of the sealing process,
3. complete physically based packing pore models of the sealing layer.

Statistical relationships based on empirical data may take a variety of functional forms limited only by the measurements made in a particular study. An example relationship of this type is that established by Glanville and Smith (1988) between infiltration rate and the interpolated proportion of surface soil aggregates and particles less than 0.12 mm in the surface of the 5 to 9.5 mm size fraction of three clay soils under simulated rainfall. Loch and Foley (1994) extended this approach to establish a relationship between final surface hydraulic

conductivity and the proportion of surface soil aggregates and particles less than 0.125 mm in diameter (P125). However, the relationship of Loch and Foley may be considered to be representative of the second category above as Loch (1989) used packing pore models to establish the significant role of small surface particles and pores in preventing hydraulic penetration and promoting compaction by raindrop impacts. The model developed provides a physically based explanation for the occurrence of surface seals but not a physically based description of the effects on infiltration through pores of the sealing layer.

Physically-based packing pore models are generally based on idealised non-interacting particles (eg., perfect spheres made of an effectively inert material) and are generally applied to uniform mixtures of particles of discrete sizes. The amount of data required to parameterise such models for a dynamically non-uniform layer consisting of particles that are non-ideal in shape and that may be deformed as well as reduced in size, is large and has effectively prevented their use.

2.5 SUMMARY AND CONCLUSIONS FROM THE LITERATURE REVIEW

Published literature relating to aggregate breakdown and surface sealing under rainfall has been reviewed. It is clear from this literature that surface sealing can drastically reduce surface permeability and potentially affect the soil water balance of tilled soils.

Aggregate breakdown has been identified as an important sub-process contributing to surface sealing of aggregated soils. Rapid soil wetting and energetic raindrop impact have been identified as the two major agents of aggregate breakdown and structural surface sealing on light textured cropping soils. The importance of rapid soil wetting has been emphasised in studies focussing on initially dry soils. The influence of energetic raindrop impact has not been adequately isolated from the effects rapid soil wetting in a number of these studies and from effects of varying hydraulic gradient in others.

Various soil properties have been identified as potential controls over the rate and degree of aggregate breakdown and surface sealing brought about by the these two important agents. These properties include initial aggregate size distribution and aggregate stability. Soil aggregates increase surface grain size and surface pore size hence promoting hydraulic penetration and surface seal disruption. They imprison fine material that would otherwise reduce surface pore size and resist breakdown compaction and deformation in the compacted layer of the seal. Soil aggregation and aggregate stability vary with inherent soil properties such as texture but they can be increased by conservative crop and tillage management. This has been shown to have small but significant effects on the degree of surface sealing and may also influence the rate of surface sealing. Relationships predicting the effects of surface sealing on

permeability from either aggregate breakdown under rainfall or aggregate stability have generally been evaluated over a limited range of antecedent conditions reducing their utility.

The factors that can influence structural surface sealing of light textured soils are generally known. It is the relationships between these factors and the exact nature of the some mechanisms involved that remain uncertain. It is clear that benefits will follow from improved understanding of the relative importance of rapid soil wetting and energetic raindrop impact in causing aggregate breakdown and surface sealing under rainfall. In addition to advancing mechanistic understanding of aggregate breakdown and surface sealing, it will help land managers to better evaluate tactical and strategic soil management options.

There is also a clear need for relationships predicting the effects of surface sealing from aggregate breakdown or aggregate stability to be extended over a broader range of conditions and to be evaluated for developing seals as well as developed seals. This endeavour will require close consideration of the physical processes controlling infiltration through sealing soils. If successful, such relationships will aid improved management of aggregate breakdown and surface sealing in agricultural soils.

The following chapter describes an experimental study aimed at quantifying the relative importance of rapid soil wetting and energetic raindrop impact and evaluating relationships between aggregate breakdown and surface sealing over a range of soils and conditions.

Chapter 3

THE EXPERIMENTAL STUDY

3.1 INTRODUCTION

In section 2.5 it was concluded that improved understanding of aggregate breakdown and surface sealing under rainfall and improved management of agricultural soils could be promoted by experimental studies that -

a) assess the relative importance of wetting rate and raindrop impact energy as agents of aggregate breakdown and surface sealing under rainfall,
b) assess effects of tillage treatments on aggregate breakdown and susceptibility to surface sealing under rainfall for a range of soils, soil wetting regimes and raindrop kinetic energy levels and
c) evaluate relationships between surface sealing under rainfall and aggregate breakdown or aggregate stability over a range of wetting regimes, raindrop kinetic energy levels, tillage treatments and soils.

These are the general aims of the current study. This chapter describes the specific aims and the rationale underlying the experimental elements of the current study as well as the methods and procedures used.

3.2 THE EXPERIMENTAL STUDY

The specific aims of the current experimental study were -

1) to isolate and quantify the effects of surface sealing under simulated rainfall on hydraulic and hydrologic properties of re-packed soils due to -
    a) rapid soil wetting under rainfall
    b) high kinetic energy raindrop impacts,
2) to isolate and quantify the rate and degree of breakdown of surface aggregates under this simulated rainfall caused by these two agents and
3) to determine aggregate stability,

for light textured surface soils from long term tillage trials at Cowra and Condobolin in New South Wales, Australia.

The core of the experimental study was based on rainfall simulations on repacked soils using a matrix of three wetting pre-treatments and two simulated rainfall treatments to isolate effects of rapid soil wetting and energetic raindrop impact. Two separate series of rainfall simulations were carried out. The R series rainfall-runoff simulations (described in section 3.3) were aimed primarily at quantifying the soil hydraulic effects of surface sealing and quantifying the maximal degree of aggregate breakdown under rainfall. The AT series rainfall simulations (described in section 3.4) were aimed primarily at quantifying the rate and maximal degree of aggregate breakdown under rainfall.

Features common to both series of simulations including the soils used, the method of soil repacking, the wetting pre-treatments and the rainfall treatments are described below. Features unique to each series are described in sections 3.3 and 3.4.

3.2.1 The Simulated Rainfall

The rainfall simulation facility used has been described in detail by Walker *et al.* (1977). Rain was simulated using two rectangular plastic modules (0.5 m by 1.0 m) with 1640 hypodermic needle drop formers, supplied by a metered electric pump. At the rainfall intensities simulated in this study, the 23 gauge needles produced drops of approximately 2.6 to 2.7 mm diameter. The plastic modules were oscillated 100 mm along their longitudinal axis at a frequency of 0.025 Hz in order to reduce spatially dependent variability in cumulative rainfall that can occur if individual drop formers become blocked. Rain fell vertically 11.3 m in a brick enclosure, a distance sufficient for drops to reach greater than 95% of the terminal velocity for this drop size (terminal velocity = 7.6 m s^{-1}, Laws, 1941).

The two levels of cumulative raindrop kinetic energy simulated were "High" (27.3 J m^{-2} mm^{-1}) when rain fell unrestricted for the full height of the simulator, and "Low" (0.3 J m^{-2} mm^{-1}) when raindrops passed through an energy dissipation screen (7) illustrated in Figure 3.1. Raindrop kinetic energy was measured using a Distromet™ distrometer assuming all drops had reached terminal velocity. Measured values were confirmed on one occasion using time-lapse photographic measurements of raindrop velocity and measured sizes of drops collected in oil (Eigel and Moore, 1983b).

Rainfall intensity for the AT series rainfall simulations and 48 of the R series rainfall-runoff simulations was approximately 33 mm h^{-1} (standard deviation = 1.3 mm h^{-1}) as measured with a 200 mm diameter rain-gauge prior to, and following, each simulation. The rain-gauge was placed in exactly the plan location of the repacked soil samples. Rainfall intensity during treatments was monitored using a 100 mm diameter rain-gauge adjacent to the repacked soil samples read manually at 900 s intervals. Duration of rainfall simulations was 7200 s.

With an energy dissipation screen in place, a significant number of drops splashed upwards away from the repacked soil effectively reducing rainfall intensity under the screen to approximately 75% of the un-screened intensity. For low kinetic energy rainfall an identical energy screen was placed over the 200 mm rain gauge ensuring that rainfall intensity measured prior to and following simulations represented the effective rainfall intensity. The electric pump rate was then increased to give an effective rainfall intensity equal to that for un-screened high kinetic energy rainfall.

Chemical properties of the rainwater used are listed in Table 3.1. Temperature, pH and electrical conductivity of the rainwater were determined for a 10^5 mm^3 sample collected during each simulation and stored in a plastic container prior to analyses.

Table 3.1 The chemical properties of water used in rainfall simulations.

Property	Mean
pH(1:5 water)	7.5
electrical conductivity (dS m^{-1})	0.05
Na (mmoles l^{-1})	0.15
K (mmoles l^{-1})	0.02
Ca (mmoles l^{-1})	0.16
Mg (mmoles l^{-1})	0.03
S.A.R.	0.47

3.2.2 Soil Wetting Pre-treatments

Three soil wetting pre-treatments were imposed on repacked soils to produce surfaces with potential for surface aggregate breakdown during treatment from -

1) raindrop impact only;
2) rapid soil wetting only;
3) both raindrop impact and rapid soil wetting.

The respective wetting pre-treatments were -

1). Tension Pre-wetting: Repacked soils were wet from below through fibrous matting in contact with water at -2 kPa potential (relative to the upper surface of the soil) until the wetting front was observed to reach the upper soil surface. Soils were then equilibrated on a ceramic tension plate at a suction of -10 kPa relative to the soil surface. The average velocity of the wetting front upwards through the repacked soil was found to be approximately 6 mm h^{-1}. The average equivalent water application rate as measured by

change in weight during this phase was approximately 1.8 mm h^{-1}. Tension pre-wetting rates were not significantly different between soils.

2). Rapid Pre-wetting: Repacked soils were wet from above under simulated rainfall at approximately 33 mm h^{-1} with an energy dissipation screen in place to give approximately zero raindrop kinetic energy.

3). Dry: Repacked soils were left dry prior to rainfall simulation.

3.2.3 Matrix of Effects Created by Pre-wetting and Raindrop Kinetic Energy Level

The slow wetting rate of the tension pre-wetting treatments was imposed in order to eliminate potential for slaking during rainfall simulations and the rapid pre-wetting treatment was imposed in order to create a similar potential for aggregate slaking as would occur during simulated rainfall on initially dry soils. Table 3.2 identifies aggregate breakdown and surface sealing agents potentially active during soil wetting pre-treatments and subsequent rainfall treatments based on the assumption that pre-treatments were completely successful.

Table 3.2 Agents of aggregate breakdown and surface sealing potentially active during soil wetting pre-treatment and rainfall treatment.

Soil wetting Pre-treatment	Rainfall Energy	Potentially active during pre-treatment	Potentially active during treatment
Tension	High	None	Rain Impact
Rapid	High	Rapid Wetting	Rain Impact
Dry	High	None	Rain Impact and Rapid Wetting
Tension	Low	None	None
Rapid	Low	Rapid Wetting	None
Dry	Low	None	Rapid Wetting

3.2.4 Soils

Properties of the soils used in this study are listed in Table 3.3. Samples were taken from the direct drill (DD) and traditional tillage (TT) treatments within long-term tillage trials at the New South Wales Department of Land and Water Conservation Research Centre at Cowra, described in more detail by Packer *et al*. (1992). Samples were also taken from the reduced tillage plus herbicide (RH) and stubble burnt plus cultivation (BC) treatments within tillage trials at N.S.W. Agricultural Research Centre at Condobolin.

Table 3.3 Soil classification and properties of Cowra and Condobolin soils.

Classification/Property	Cowra	Condobolin
great soil group[1]	red brown earth	red brown earth
principal profile form[2]	Dy2.43	Dr2.13
sub order[3]	Xeralf	Xeralf
Horizon	Ap	Ap
Depth (mm)	0 to 10	0 to 10
Clay %	5	17
Silt % (0.002 to 0.02 mm)	10	7
Fine Sand % (0.02 to 0.2 mm)	41	55
Coarse Sand % (0.2 to 2.0 mm)	44	21
Total C %	TT=0.59, DD=0.90	BC=0.97, RH=0.97
$pH_{1:5}$ water	TT=6.75, DD=6.49	BC=5.92, RH=5.86
Electrical cond. (d S m^{-1})	TT=0.08, DD=0.09	BC=0.005, RH=0.005

Notes: 1. (Stace *et al.*, 1968)
2. (Northcote, 1979)
3. (Soil Survey Staff, 1992)

Soils were sampled under dry, settled conditions following harvest. The surface 100 mm layer was sampled using a square-sided shovel. Samples were transported to the laboratory in plastic containers, mixed, passed through a 10 mm sieve, air dried in a glass-house and stored in plastic containers prior to use.

3.2.5 Soil Repacking

Soil was repacked by pouring dry and thoroughly mixed bulk soil through a Soilcrete™ sample rifling box, with 10 mm wide apertures, until the soil level was 25 mm above the top of the container. Soil was temporarily contained above the top of the containers by thin flexible plastic tubing that was removed prior to rainfall simulation. Repacked soils were leveled and consolidated by vibrating for 5 s on a Syntron™ electric vibrating shaker at a setting of 55. Bulk density was determined from the weight of air dried soil, the moisture content of the air dried soil and the known volume of the container. The resulting surface was slightly domed, with the soil surface in the centre being approximately 5 mm higher than soil surface at the perimeter. The domed shape of the soil surface was rapidly flattened under high kinetic energy rainfall. Mean and standard deviation of bulk densities for repacked soils in the R series simulations are listed in Table 3.4.

Table 3.4 Bulk densities of re-packed columns for Cowra and Condobolin soils.

Soil	Mean Bulk Density ($Mg\ m^{-3}$)	Std. Dev.
Cowra TT	1.402	0.013
Cowra DD	1.376	0.016
Condobolin RH	1.338	0.013
Condobolin BC	1.321	0.011

3.3 R SERIES RAINFALL-RUNOFF SIMULATIONS

Replicated R series rainfall-runoff simulations were carried out to quantify soil hydraulic effects of surface sealing and the maximal degree of aggregate breakdown under rainfall. Spatially averaged rainfall, runoff and sub-seal matric potential were monitored for soils repacked in specially designed infiltration columns. These data were used to calculate spatially averaged surface hydraulic conductivity as a function of time and cumulative raindrop kinetic energy. Calculated surface hydraulic conductivity and rainfall volume at ponding provided two measures of the degree of structural degradation of the soil surfaces under the various pre-treatment and treatment combinations.

In addition, rate and degree of surface sealing was quantified for one soil-tillage treatment-wetting pre-treatment combination under higher and lower rainfall intensity to gain an indication of the sensitivity of the measured rate and degree of surface sealing to rainfall intensity.

3.3.1 Infiltration Columns

Infiltration columns of 150 mm depth and 190 mm i.d., illustrated in Figure 3.1, were constructed from clear tubular plastic with bases of rust-proofed steel mesh (1) to allow free movement of air and water into and out of soil columns.

Water escaping through the 10 mm vertical runoff opening (2) between the top outer edge of the column and the bottom outer edge of the splash collar was arbitrarily defined as runoff. It was observed during rainfall simulations that this runoff consisted of a very thin layer of ponded surface water flowing from the surface plus a considerable volume of air-splashed water from saturated soil surfaces. This water was contained by translucent plastic sheeting surrounding the column (not shown in Figure 3.1) that drained into in an inclined collar (3). This collar drained to an electronic balance logged at 30 s intervals (4).

The splash collar (5) consisted of two sections of the same tubular plastic 30 mm and 200 mm in height. For low kinetic energy simulations, four layers of fibreglass gauze wire mesh (6) with apertures approximately 1.9 mm square were stretched diagonally across the shorter

energy dissipation screen (7) and were held in place by a tightened hose clamp. This energy dissipation screen was therefore positioned approximately 40 mm above the soil surface. Translucent plastic sheeting (not shown in Figure 3.1) draped from the hose clamp on this section provided rain and splash protection for tensiometer pressure transducers, the collecting collar and plumbing associated with the infiltration column. The upper section of the splash collar was located directly above the lower using three brass locating pins. The upper edge of this section was beveled at an angle of approximately 45^{o} away from the centre to ensure that drops falling directly on the circular edge would be deflected away from the column. When the energy screen was in place, during low energy simulations, the upper section of the splash collar was raised 5 mm above the lower. Rain water that splashed from the energy screen upwards onto the inside of the upper section of the splash collar ran down the inside of this section and drained out through the 5 mm opening thus having no further part in simulations.

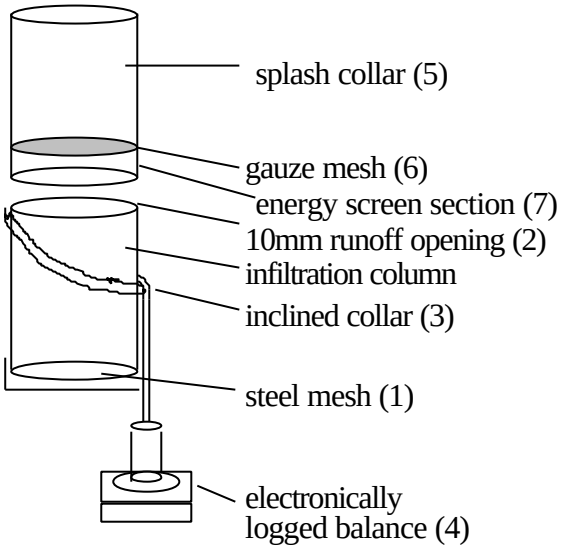

Fig 3.1 Schematic of the infiltration column and related apparatus.

Sub-surface soil water potential was measured using tubular 20 kPa ceramic tensiometers (outside diameter = 4.5 mm, length = 190 mm) located at depths of 10, 40 and 80 mm below the soil surface. Potential was measured by Sensym^{TM} pressure transducers and electronically recorded at 30 s intervals. Steel pins glued into the ends of each tensiometer were inserted into small holes in the ends of steel locating pins (outside diameter = 3 mm, length = 300 mm) placed at the required depths in the infiltration column prior to packing with soil. These locating pins were withdrawn from one side of the column, as the tensiometers were inserted from the other, ensuring precise location, minimal disturbance and good soil contact. Tensiometers were placed in the columns up to 1 hour prior to rainfall for tension pre-wet and rapid pre-wet simulations, allowing adequate time for equilibration. For simulations on initially dry soils, tensiometers could not be placed in the columns until approximately 8 to 10

mm of simulated rain had fallen to wet the soil and increase the soil water potential above the lower operating limit of the tensiometers.

3.3.2 Surface Sealing Assessment

Surface sealing was assessed by -

1. Rainfall volume required to induce ponding over 50% and 90% of the surface determined by visual assessment,
2. Spatially averaged saturated hydraulic conductivity given by -

$$f = Ksat \frac{\Delta H}{\Delta z} = Ksat \frac{((-h10) + \Delta z)}{\Delta z}, \quad (t > tp) \qquad \text{[Eqn 3.1]}$$

where f = infiltration rate

Ksat = saturated hydraulic conductivity

ΔH = total hydraulic potential difference

Δz = depth across seal (assumed to be 5mm)

h10 = measured matric potential head at 10mm depth

tp = time of ponding

Assumptions implicit in the application of Equation 3.1 to post-ponding data include the following -

1. The sealed layer has a constant thickness of 5 mm after the time of ponding.
2. The seal is fully saturated after the time of ponding.
3. Hydraulic properties of the seal layer are uniform throughout the 5 mm depth.

Possible effects of these assumptions on the measured data are discussed in section 4.5.4. Further, it is assumed that infiltration flux is equal to the measured rainfall intensity minus runoff rate (as measured by the incremental increase in weight of the runoff collection container on the electronic balance at each 30 s interval). This assumption will be valid providing that-

1. The volume of depressional storage on the soil surface and changes in this volume are negligible throughout the simulation.
2. Routing effects due to overland surface flow and flow through the plumbing connecting the column to the electronic balance are negligible.

Initial surface saturated hydraulic conductivity (K_{sat}) was measured independently for tension pre-wet and rapidly pre-wet soils. Cylindrical metal columns (inside diameter = 98 mm, length = 76 mm) were repacked using a sample divider box and a vibrating shaker and

were pre-treated identically to infiltration columns. Replicate constant positive head permeameter analyses (Klute and Dirksen, 1986) were used to determine initial K_{sat}.

3.3.3 Erosion Loss and Mass Balance

Infiltration columns were weighed immediately prior to and following each rainfall-runoff simulation. Mass was balanced for each simulation to confirm that the sum of infiltration calculated from the difference between rainfall and runoff for each 30 s time period was consistent with total infiltration calculated from the net gain in soil column weight over the duration of the simulation plus the weight of any through flow (ie., water flowing through the mesh base of the column).

The dry weight of soil contained in runoff water, trapped in the inclined collar and adhering to the splash collar was determined for each simulation to give an estimate of the amount of soil removed from the surface by raindrop and flow driven processes.

3.3.4 Varying Simulated Rainfall Intensity

Rate and degree of surface sealing was also quantified under higher and lower intensity rainfall following tension wetting pre-treatment for the Condobolin soil sampled from the conservative tillage treatment (RH). This was done to partially assess the sensitivity of rate and degree of surface sealing to rainfall intensity. For these additional simulations, experimental conditions remained identical to those described above except for the higher and lower simulated rainfall intensities of 16.5 mm h^{-1} and 66 mm h^{-1}.

3.4 AGGREGATE BREAKDOWN UNDER SIMULATED RAINFALL

Aggregate breakdown under simulated rainfall was quantified using three sets of aggregate samples under simulated rainfall.

3.4.1 The AT Series Aggregate Samples

Replicate soil samples, prepared and pre-treated in identical manner to soils packed in infiltration columns, were wet sieved following application of a range of simulated rainfall volumes (the AT series).

Rainfall volumes of 5, 10, 15, 30 and 60 mm were applied at approximately 33 mm h^{-1} to the AT series soils packed in plastic containers (88 mm^2 area) with steel mesh bases identical to infiltration columns. The packing procedure used was identical to that for infiltration columns with soil poured through the Soilcrete™ sample rifling box and leveled and consolidated by vibrating for 5 s on the Syntron™ electric vibrating shaker. Tension and rapid wetting pre-treatments were applied to packed containers in a manner identical to infiltration

columns. Following application of the appropriate volume of simulated rain, soil surfaces were photographed from above using black and white print film. They were then sampled to a depth of 5 mm using the sampling tool illustrated in Figure 3.2. Samples were weighed and stored on wetted filter papers overlying wetted sponge material. They were covered to prevent evaporative water loss. Sub-samples were taken at the time of sampling and weighed to determine gravimetric water content. All AT series aggregate samples were then wet using a modified Yodder wet sieving mechanism (Kemper and Rosenau, 1986) with a nest of sieves (Yodder, 1936). Water used in wet sieving was taken from rainfall simulator modules prior to the corresponding rainfall simulation to ensure that water quality during wet sieving was identical to that during rainfall treatment. Material was collected on a nest of sieves with apertures of 5, 2, 1, 0.5, 0.25, 0.125 and 0.063 mm. Material passing the finest sieve was analysed using the pipette method (Kemper and Rosenau, 1986) without dispersion, to determine the amount of material in the size ranges 0.000 to 0.020 mm and 0.020 to 0.063 mm. Particle size distribution at the surface was determined using additional samples taken from each infiltration column. These samples were chemically dispersed using 10 ml sodium tri-poly phosphate and physically dispersed using a rubber tipped stirrer (Kemper and Rosenau, 1986). All samples were sieved within three hours of initial sampling.

Containers to be sampled were arranged immediately adjacent to each other in a three by two rectangular matrix centered under simulated rainfall directly over the

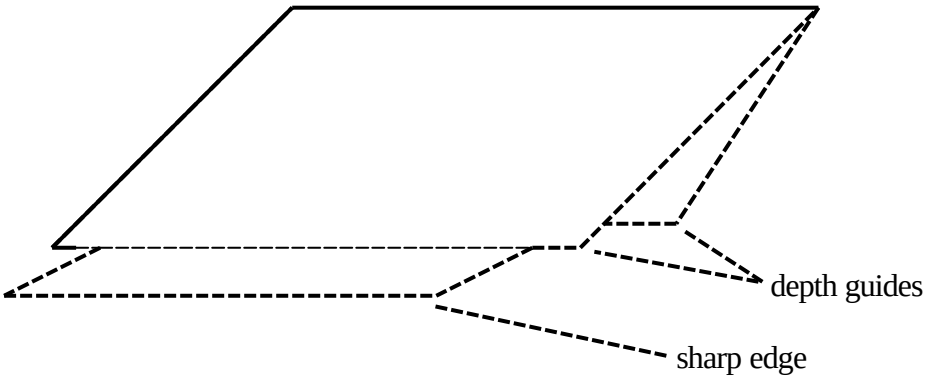

Fig 3.2 Schematic of the tool used for aggregate sampling.

location used for infiltration columns. A further row of 14 packed and pre-treated soil containers surrounded the inner matrix to ensure that a minimum distance of 88 mm in any direction was available for soil splash return to each sampled container. This distance is of similar magnitude to the distance surrounding soil at the centre of the surface in the infiltration columns. Five additional packed and pre-treated soil containers were subject to the same rainfall and were moved into the inner matrix to replace the sampled containers as each was removed.

3.4.2 The R Series Aggregate Samples

The degree of aggregate breakdown under rainfall was further quantified by wet sieving of two samples taken from pre-determined locations in the surface of the infiltration columns immediately following each infiltration simulation (hereafter referred to as the R series). These samples were extracted using a cylindrical metal corer (inside diameter = 44 mm). The inside of the corer was cone-shaped to reduce sample compression. The sample was extracted from the corer by moving the corer downwards while supporting the sample from underneath on a round wooden base which fitted neatly inside the corer. When the required 10 mm depth of sample protruded from the top of the corer it was removed with a spatula. Whilst the depth of sampling could be controlled using this method, surface samples often remained intact when sampled and aggregates protruding below 10 mm were sometimes included in the surface samples.

All R series samples were wet sieved for 15 minutes using a modified Yodder wet sieving mechanism (Kemper and Rosenau, 1986) with a nest of sieves and whole soil samples (Yodder, 1936). Water used in wet sieving was taken from rainfall simulator modules prior to the corresponding rainfall simulation to ensure that water quality during wet sieving was identical to that during rainfall treatment. Material was collected on a nest of sieves with apertures of 10, 2, 1, 0.5, 0.25, 0.125 and 0.063 mm. Material passing the finest sieve was analysed using the pipette method (Kemper and Rosenau, 1986) without dispersion, to determine the amount of material in the size ranges 0.000 to 0.020 mm and 0.020 to 0.063 mm. Particle size distribution at the surface was determined using additional samples taken from each infiltration column. These samples were chemically dispersed using 10 ml sodium tri-poly phosphate and physically dispersed using a rubber tipped stirrer (Kemper and Rosenau, 1986).

Aggregate size distributions for the initial state prior to rainfall were determined using two sets of samples. Infiltration columns were packed according to the standard procedure with dry soil. They were sampled according to the standard procedure for R series samples except that 4 samples were taken instead of 3. The dry samples were placed on filter papers and wet under a tension of -2 kPa. These samples were then wet sieved as for R series samples. Another column was packed and wet under tension as for tension pre-wet columns. Four samples were again taken and wet sieved to determine aggregate size distribution prior to pre-treatment.

The following statistics were calculated for all aggregate samples -

1. Geometric Mean Diameter (GMD) (Mazurak, 1950) see Equation 2.11,

2. Mean Weight Diameter (MWD) (Van Bavel, 1949) see Equation 2.10,

3. Median diameter by weight (D50) corresponds to the 50th percentile on a graph of cumulative weight against aggregate diameter,

4. Percentage by weight finer than 0.125 mm in diameter (%<0.125 mm) also referred to as P125 by Loch and Foley (1994).

3.4.3 The L Series Aggregate Samples

A further set of samples (the L series samples) were taken from the soil surface following completion of each of the R series rainfall-runoff simulations. These samples were collected using a spatula according to the method described by Loch (1989). Again, aggregate samples were stored on wetted filter papers overlying wetted sponge and were covered to prevent drying. These samples were sieved within 2 hours of initial sampling using only a single 0.125 mm aperture sieve and only the proportion by weight < 0.125 mm diameter was determined (Loch, 1989).

3.4.4 Visual Observations

Qualitative visual observations relating to aggregate breakdown processes occurring at the soil surface during rainfall simulations were recorded during rainfall simulations. Inferences from these observations are drawn in Chapters 4 and 5.

3.5 AGGREGATE STABILITY

In addition to the measurements of aggregate breakdown during simulated rainfall described above, aggregate stability of Cowra and Condobolin soils was determined by wet sieving (Kemper and Rosenau, 1986) following immersion and tension wetting. This procedure has been discussed in section 2.3.4 and limitations including aggregate breakdown due to mechanical agitation have been identified. However, such data are routinely gathered in many studies relating to soil management and their potential to predict aggregate breakdown and surface sealing under rainfall is of interest. These data are used to assess relationships between aggregate stability and surface sealing in Chapter 6.

3.6 SUMMARY

This chapter has described the experimental elements of the current study as summarised in Table 3.5. It has explained how a matrix of three wetting pre-treatments and two simulated rainfall treatments isolate effects of rapid soil wetting and energetic raindrop impact. Surface soil hydraulic data measured under this matrix of pre-treatments and

Table 3.5 Summary of the experimental study.

i). R Series

Objective: Quantifying soil hydraulic response and degree of aggregate breakdown.				
Design:	**x**	**x**	**x**	**x**
3 Wetting pre-treatments	2 Rainfall Energies	2 Soils	2 Tillage treatments	1 Rainfall depth applied
• Rapid • Tension • Dry (none)	• Low • High	• Cowra • Condo	• Conservative • Traditional	• 66 mm
Measurements: 1. Rainfall volume required for ponding 2. Runoff and infiltration 3. Sub-seal water potential 4. Initial and final surface aggregate size distribution				

ii). AT Series

Objective: Quantifying temporal patterns of aggregate breakdown				
Design:	**x**	**x**	**x**	**x**
3 Wetting pre-treatments	1 Rainfall Energy	2 Soils	2 Tillage treatments	6 Rainfall depths applied
• Rapid • Tension • Dry (none)	• High	• Cowra • Condobolin	• Conservative • Traditional	• 0 mm • 5 mm • 10 mm • 15 mm • 30 mm • 60 mm
Measurements: 1. Surface aggregate size distribution				

treatments in the R series rainfall-runoff simulations (described in section 3.3) are presented in Chapter 4. These data are used to quantify the relative influence of rapid soil wetting and energetic raindrop impact (and interactions between the two) over the rate and degree of surface sealing under rainfall. They are also used to examine effects of tillage treatment on rate and degree of surface sealing, effects of rapid soil wetting and energetic raindrop impact on temporal patterns of hydraulic conductivity decline and effects of rainfall intensity on rate and degree of surface sealing under a limited range of conditions. Aggregate breakdown data measured under the same matrix of wetting pre-treatments and rainfall treatments in both the R series and AT series rainfall simulations (described in section 3.4) are presented in Chapter 5.

These data are used to quantify the relative influence of rapid soil wetting and energetic raindrop impact over the rate and degree of aggregate breakdown under rainfall. They are also used to examine effects of soil and tillage treatment on rate and degree of aggregate breakdown under rainfall. Data presented in both Chapter 4 and Chapter 5 are re-used in Chapter 6 along with aggregate stability data (described in section 3.5) to evaluate relationships predicting soil hydraulic effects of surface sealing from aggregate breakdown under rainfall and aggregate stability.

Chapter 4

SOIL SURFACE HYDRAULIC BEHAVIOUR AS AFFECTED BY WETTING RATE, RAINDROP ENERGY, RAINFALL INTENSITY, SOIL AND TILLAGE TREATMENT

4.1 INTRODUCTION AND OBJECTIVES

Published literature, reviewed in section 2.1, identifies a range of processes contributing to the development of surface structural seals and discusses factors controlling their occurrence (eg., Romkens *et al.*, 1990a). Slaking of aggregates in response to rapid soil wetting and surface compaction caused by energetic raindrop impact are two processes that have been widely identified as important in structural sealing. (eg., Eigel and Moore, 1983a; Le Bissonnais, 1990). Other processes such as chemical dispersion (Agassi *et al.*, 1988) and "washing in" of finer aggregates (McIntyre, 1958b) have been less universally identified.

The relative importance attributed to rapid soil wetting and energetic raindrop impacts as agents of surface sealing varies among published studies. Using samples collected from field experiments Valentin and Bresson (1992) have identified "slaking crusts" primarily caused by aggregate slaking on rapid soil wetting and give a range of final infiltration rates from 5 to 20 mm h^{-1}. Eigel and Moore (1983a) have also observed surface sealing of a mixture of loam soils repacked in columns and subjected to simulated rainfall with negligible kinetic energy. However, the majority of experimental studies using repacked soil or cultivated soil have concluded that surface compaction by energetic raindrop impacts is of primary importance in reducing surface infiltrability (eg., McIntyre, 1958a; Loch and Foley, 1994). As a result of such conclusions early attempts to model infiltration into sealing soils proposed threshold levels of kinetic energy individual raindrops below which sealing would not occur (eg., Seginer and Morin, 1970). Interaction between rapid soil wetting and concurrent energetic raindrop impact has been examined in relation to breakdown of single aggregates by Farres (1980). He found that increasing the time interval between consecutive raindrop impacts reduced susceptibility to breakdown. He concluded that greater time intervals allowed for greater relaxation of the stresses that developed within the aggregate as a result of wetting. However,

potential interactions between these two important agents in relation to hydraulic behaviour of whole soils have received little attention. The relative importance of these two agents of surface sealing and potential interactions between them has significant implications for agricultural soil management. Quantifying the relative importance and any interactions is a major objective of the current chapter.

The combined effects of agents of surface sealing lead to rapid decline in surface permeability. Under simulated rainfall post-ponding this decline in surface hydraulic conductivity or conductance has commonly been described by exponential decay as a function of cumulative rainfall kinetic energy (eg., Moore, 1981a; Brakensiek and Rawls, 1983; Eigel and Moore, 1983a). The generality of such functions has been challenged. Baumhardt *et al.* (1990) concluded that surface conductance decline in the post ponding phase was better described by a linear function of cumulative rainfall kinetic energy limited by the initial conductance of the bulk soil and a soil specific final conductance. More significantly, the validity of backwards extrapolation of the post-ponding rate of conductivity decline into the pre-ponding phase has been challenged by Silburn and Foley (1994). Their measurements of surface hydraulic conductivity using a suction permeameter indicate that decline for one of two soils studied differed markedly from exponential decay. Measured hydraulic conductivity actually increased during the pre-ponding phase for that soil. The second soil studied by Silburn and Foley (1994) exhibited rapid initial decline in surface conductivity with energetic raindrop impact on the dry soil surface. The authors attributed the difference in soil hydraulic response primarily to differences in susceptibility to aggregate slaking caused by rapid soil wetting. The generality of exponential decline in surface conductivity as a function of cumulative kinetic energy proposed by Moore (1981a) and mechanisms explaining deviations from such functions affect the utility of models predicting infiltration into sealing soils. These issues are examined in the current chapter.

Rainfall intensity has long been identified as a factor influencing surface sealing processes and potentially influencing rate and degree of sealing. During the pre-ponding phase, rainfall intensity will control soil wetting rate providing that the soil is initially relatively dry. Rainfall intensity during the pre-ponding phase will also, in conjunction with sub-surface soil hydraulic properties, strongly influence the rainfall duration required for the surface soil to approach saturation. The former mechanism determines the potential for aggregate breakdown due to slaking (Quirk and Panabokke, 1962) whilst the later influences the processes of surface particle sorting (Moss, 1991c) and the effectiveness of compaction caused by raindrop impacts (Loch, 1989). A threshold rainfall intensity of 50 mm h^{1} has been proposed for the occurrence of both mechanisms (Quirk and Panabokke, 1962, for aggregate slaking and Loch, 1989, for surface saturation). Later in the rainfall event, when the soil surface is ponded, rainfall intensity directly influences rainfall excess and hence depth of surface ponding and surface runoff flux. Surface ponding can reduce the flux of raindrop kinetic energy reaching the surface through the cushioning of drop impacts (Moss and Green, 1983) whilst flux of surface runoff

may influence rates of surface seal erosion (eg., Baumhardt *et al*., 1991). This chapter presents a limited analysis of the influence of rainfall intensity on surface sealing.

The surface sealing response of soil under rainfall has been shown to depend on prior agricultural management (eg., Sharma *et al.*, 1981; Loch, 1994b). However, Loch argued that improved aggregate stability induced by conservative tillage management has a much smaller effect on degree of surface sealing than the effect of surface soil protection afforded by the plant residue retained under such systems. He argued therefore that significant reductions in runoff under conservative tillage management are not residual and will be lost as soon as surface residue is removed. In contrast, Packer *et al.* (1992) concluded that reductions in runoff brought about by conservative tillage systems are due to biologically created macropores and that effects of cover and aggregate stability are secondary. Again the implication is that benefits from conservative tillage may be rapidly lost if cultivation involving full soil disturbance is carried out. The magnitude of the effect of tillage management on surface sealing and the nature of the mechanisms by which the effect occurs have significant implications for agricultural management. This chapter examines possible mechanisms for the effect and assesses practical consequences using measured sealing responses and one-dimensional water balance simulations.

This chapter presents the results of the experimental study, that relate to surface soil hydraulic behaviour. It uses these results to examine the issues prefaced above. To summarise Chapter 3, the current study used three soil wetting pre-treatments and two rainfall kinetic energy levels to isolate the relative effects of rapid soil wetting (both preceding and concurrent with rainfall simulation) and energetic raindrop impact on aggregate breakdown (see Tables 3.3 and 3.4). The effect of energetic raindrop impact was isolated using rainfall with High (27.3 J m^{-2} mm^{-1}) and Low (0.3 Jm^{-2} mm^{-1}) raindrop kinetic energy. Rates of surface sealing following surface ponding were evaluated by decline in spatially averaged saturated hydraulic conductivity (K_{sat}) of the soil surface. Rates of surface sealing prior to ponding were assessed by two means. The cumulative rainfall volume required to induce surface ponding was measured and the rate of hydraulic conductivity decline was also inferred from surface K_{sat} following surface ponding and measured values of antecedent K_{sat}. Discrepancies between the two are discussed in section 4.8. Degree of surface sealing was evaluated using final K_{sat} of the soil surface.

An indication of possible effects of tillage treatment and soil is gained by comparing the hydraulic behaviour of soil sampled from Conservative and Traditional tillage treatments at both Cowra (Cowra DD and Cowra TT respectively) and Condobolin (Condobolin RH and Condobolin BC respectively). Possible explanations for these effects based on an understanding of the important structural seal forming processes are discussed. In the course of this discussion references are made to findings from the current study (presented in Chapter 5) relating to the effects of wetting rate, raindrop kinetic energy and soil stability on aggregate breakdown.

Cumulative rainfall volumes required to induce surface ponding are presented and discussed firstly. Infiltration and sub-seal matric potential data are presented and discussed separately followed by presentation and discussion of calculated surface saturated hydraulic conductivity. Results from a limited set of rainfall simulator experiments using higher and lower rainfall intensities are presented and discussed to provide an indication of the generality of the findings resulting from the main set of rainfall simulator experiments. This chapter concludes with a summary and discussion of soil surface hydraulic behaviour and surface sealing processes under rainfall highlighting the insights into improved understanding of surface sealing provided by this study.

4.2 CUMULATIVE RAINFALL VOLUME AT THE TIME OF SURFACE PONDING

Among soils with identical initial soil water content or potential, time to ponding, cumulative rainfall volume at ponding and cumulative rainfall kinetic energy at ponding have all been used to indicate relative rates of surface sealing (eg., Sharma *et al.*, 1981; Eigel and Moore, 1983a). This study uses cumulative rainfall volumes at the time when 90% of a soil surface area was visually assessed as ponded as an indicator of relative rates of surface sealing prior to ponding.

Surface ponding is initiated when infiltration flux through a surface soil layer falls below the rainfall rate applied. According to Darcy's Law (see Equation 2.1), infiltration flux through a uniform layer will equal the product of the hydraulic conductivity of the layer and the hydraulic potential gradient across the layer. In the case of a thin, saturated, horizontal surface seal layer under rainfall, depth of ponded water on the soil surface will be zero during the pre-ponding stage of infiltration and gravitational potential gradient across the seal will be equal to unity. The hydraulic potential gradient across the surface layer will generally be dominated by the matric potential gradient during this pre-ponding stage. During early stages of rainfall, the matric potential gradient will be determined, to a large degree, by initial soil water content or soil water potential of the soil below the surface layer. It follows that, cumulative rainfall volume at surface ponding, as an assessment of the effects of surface sealing on surface hydraulic conductivity, will only be comparable between soils having initially similar soil water content or potential. In this study, useful comparisons can only be made among the tension and rapidly pre-wet soils (that were initially equilibrated at matric potential of -10 kPa), or among dry soils (that may be assumed to have had similar, very low initial water content).

4.2.1 Cumulative Rainfall Volume at the Time of Surface Ponding for the R series Simulations

Ponding on soil surfaces under low kinetic energy rainfall used in this study could not be visually assessed during rainfall simulation, as the surfaces were obscured by the energy screen described in section 3.3.2. The only significant runoff measured under low kinetic energy rainfall occurred during the two replicate rainfall simulations on rapidly pre-wet Condobolin BC soil. It has therefore been assumed that only these two surfaces ponded under low kinetic energy rainfall, and that for the remaining low kinetic energy rainfall simulations cumulative rainfall volume required to induce surface ponding was in excess of the total rainfall depth applied (ie., greater than 66 mm). In contrast, high raindrop kinetic energy resulted in a large decrease in volume required for ponding (mean reduction greater than 55 mm or 83%). This result strongly suggests that raindrop kinetic energy is a very significant factor in determining cumulative rainfall volume required to induce surface ponding.

Analysis of variance using only results under high kinetic energy rainfall indicates that effects of soil, wetting pre-treatment, soil by tillage treatment interactions and soil by wetting pre-treatment interactions were significant at P=0.05 and that tillage treatment effects were almost significant at that level of probability. Mean values presented in Tables 4.1 to 4.5 for these factors indicate that the effects of soil and wetting pre-treatment have the greatest magnitude.

Mean values show that Cowra soil required an additional 6.6 mm of rainfall relative to Condobolin soil to cause ponding. This difference is similar in magnitude to the mean increase of 6.8 mm caused by tension pre-wetting relative to rapid pre-wetting. Whilst Conservative tillage treatment increased the volume required for ponding by 3.0 mm at Cowra there was no significant effect at Condobolin.

Table 4.1 The cumulative volume of high kinetic energy rainfall required to induce 90% surface ponding by area for Cowra and Condobolin soil.

Soil	Volume when 90% Area Ponded (mm)
Cowra	11.0[a]
Condobolin	4.4[b]
Least sig. diff. P=0.05	1.6

Notes: Superscripts denote significant differences (P=0.05)
n=12

Table 4.2 The cumulative volume of high kinetic energy rainfall required to induce 90% surface ponding by area under Conservative and Traditional tillage treatments (averaged for both soils).

Tillage Treatment	Volume when 90% Area Ponded (mm)
Traditional Tillage	6.9
Conservative Tillage	8.4
Least sig. diff. P=0.05	1.6

Notes: Superscripts denote significant differences (P=0.05)
n=12

Table 4.3 The cumulative volume of high kinetic energy rainfall required to induce 90% surface ponding by area as affected by wetting pre-treatment (averaged for both soils).

Wetting Pre-treatment	Volume when 90% Area Ponded (mm)
Dry	10.1[a]
Tension	9.9[a]
Rapid	3.1[b]
Least sig. diff. P=0.05	2.0

Notes: Superscripts denote significant differences (P=0.05)
n=8

Table 4.4 Effects of soil and tillage treatment on the cumulative volume of high kinetic energy rainfall required to induce 90% surface ponding by area.

Soil	Tillage Treatment	Volume when 90% Area Ponded (mm)
Cowra	Traditional	9.4[a]
	Conservative	12.6[b]
Condobolin	Traditional	4.5[c]
	Conservative	4.3[c]
Least sig. diff. P=0.05		2.3

Notes: Superscripts denote significant differences (P=0.05)
n=6

Table 4.5 Effects of soil and wetting pre-treatment on cumulative volume of high kinetic energy rainfall required to induce 90% surface ponding by area.

Soil	Wetting Pre-treatment	Volume when 90% Area Ponded (mm)
Cowra	Dry	14.4[a]
	Tension	14.4[a]
	Rapid	4.1[bc]
Condobolin	Dry	5.9[b]
	Tension	5.4[b]
	Rapid	2.0[c]
Least sig. diff. P=0.05		2.8

Notes: Superscripts denote significant differences (P=0.05)
n=6

Whilst cumulative rainfall volumes at ponding provide an indication of relative rates of surface sealing in the pre-ponding stage, several reasons why they may not accurately quantify relative rates of surface permeability decline should be noted. Firstly, hydraulic potential gradients across two soil surface layers may be initially identical, following equilibration at identical potentials, but may differ when ponding occurs despite having had identical infiltration up to that point (equal to total rainfall). This may result from differences in sub-surface hydraulic conductivity and sub-surface soil water retention that may cause differences in wetting front depths and soil water distribution. Secondly, comparisons based on cumulative rainfall volume at ponding do not account for differences in initial hydraulic conductivity. For example, a soil, that has an initial saturated hydraulic conductivity that is only slightly higher in magnitude than the incident rainfall rate, may pond after a small volume of rainfall despite having a slow *rate* of surface sealing. In contrast, a soil undergoing a more rapid *rate* of surface sealing may require a greater rainfall volume to induce ponding because of a much higher initial surface hydraulic conductivity.

4.3 INFILTRATION

4.3.1 Infiltration Rate as a Function of Time for R Series Simulations

Decline in infiltration rate as a function of time or cumulative raindrop kinetic energy has been widely used to quantify effects of surface sealing (eg., Mohammed and Kohl, 1986).

Figures 4.1 and 4.2 present infiltration rate (assumed to equate to the difference between rainfall intensity and runoff rate) as a function of time for two example high kinetic

energy rainfall simulations on Cowra soil (Appendix A presents similar data for all simulations in this study that resulted in runoff). The pattern of declining infiltration rate with time after ponding illustrated in Figures 4.1 and 4.2 was repeated for all high raindrop kinetic energy simulations. The time at which the decline began (approximately the time of ponding) varied with soil, tillage treatment and wetting pre-treatment as did the rate of decline and the final infiltration rate.

Exponential decline functions of the form given in Equation 4.1 (Horton, 1940) were fitted to post-ponding infiltration rates estimated by difference between rainfall intensity and runoff rate. Final infiltration rates were estimated over the final 600 s of each rainfall simulation. This form of infiltration equation was fitted because it is applicable to situations involving changing hydraulic conductivity and it provides a simple parameter (k) quantifying rates of decline in infiltration rate with time. There is no intended implication that this form of infiltration equation is more appropriate or provides a superior description of the data than alternative infiltration equations.

$$I(t) = I_f + (I_i - I_f)\, e^{-kt} \qquad \text{[Eqn. 4.1]}$$

where $I(t)$ = infiltration rate at time t (h) after ponding
I_f = final infiltration rate (mm h^{-1})
I_i = initial infiltration rate (mm h^{-1})
k = fitted rate constant (h^{-1}) (Horton, 1940)

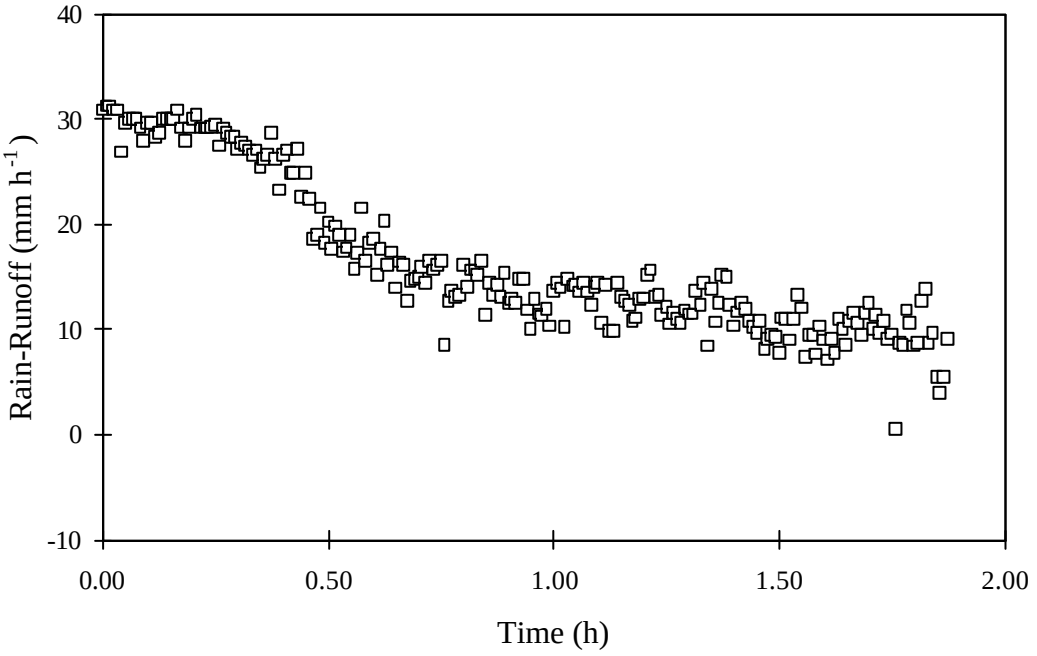

Fig 4.1 Decline in the difference between rainfall and runoff rates for Run R15 Cowra DD soil under high kinetic energy rainfall after tension pre-wetting.

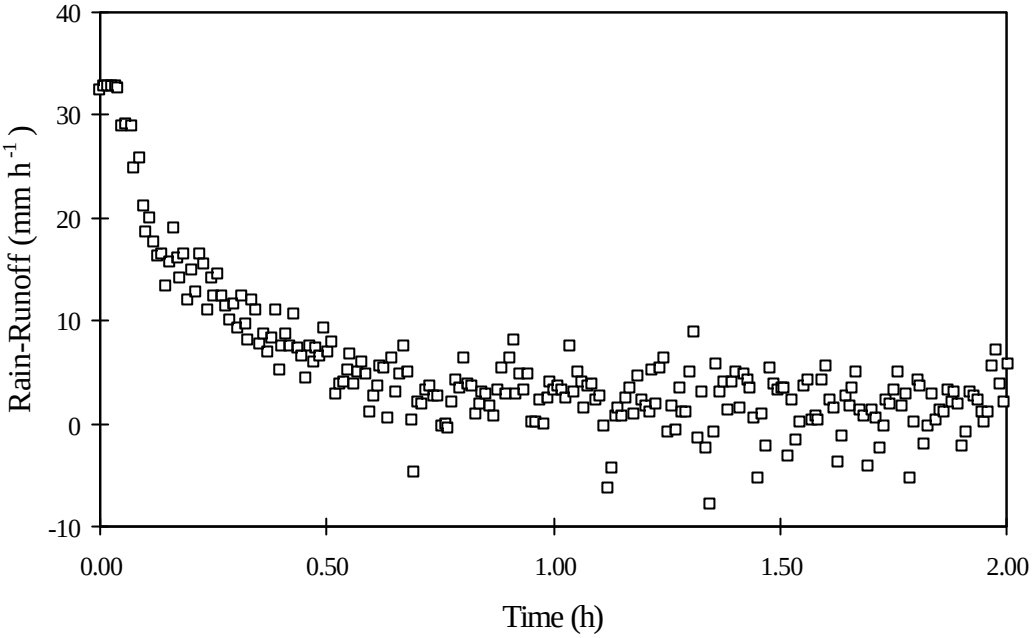

Fig 4.2 Decline in the difference between rainfall and runoff rates for Run R8 Cowra TT soil under high kinetic energy rainfall after rapid pre-wetting.

Infiltration rate can be strongly influenced by soil water potential gradient and that in turn can be strongly influenced by initial water content. As with rainfall volume required to induce surface ponding, comparisons between infiltration rates of soils with differing initial soil water potential do not provide useful information about relative rates of surface sealing. Declining surface permeability, resulting from surface sealing, cannot be quantified using infiltration data alone without knowledge of, or assumptions about, the soil water potential gradient across the sealing layer.

At the time of incipient ponding, infiltration rates equalled rainfall intensity (approximately 33 mm hr^{-1}). Following ponding, infiltration rates declined for all soil surfaces under high kinetic energy rainfall and for the two soil surfaces under low kinetic energy rainfall that were mentioned above. Fitted rates of decline in infiltration rate were analysed statistically using a generalised linear modelling procedure (Genstat 5 Committee, 1993, p.349). This analysis indicated that soil, tillage treatment, soil by wetting pre-treatment interactions and soil by tillage treatment by wetting pre-treatment interactions were all significant ($P<0.05$) and that wetting pre-treatment was almost significant at the same level of probability.

Tables 4.6 to 4.10 present mean values for significant factors and interactions. Mean values of the k parameter are consistent with slower rates of decline for Cowra soil than Condobolin soil and slower rates of decline for Conservative tillage treatments than Traditional tillage treatments. Whilst mean rates of decline were, on average, slower for tension pre-wet soils than rapidly pre-wet soils, the level of significance was only $P=0.06$. Infiltration rates for the two low kinetic energy rainfall simulations on rapidly pre-wet Condobolin BC soil declined much more slowly as a function of time.

Table 4.6 The rate of infiltration decline under high kinetic energy rainfall for Cowra and Condobolin soil.

Soil	Infiltration decline rate k from Eqn. 4.1 (h^{-1})
Cowra	4.9[a]
Condobolin	6.8[b]
Least sig. diff. P=0.05	0.8

Notes: Superscripts denote significant differences (P=0.05)
n=12

Table 4.7 The rate of infiltration decline under high kinetic energy rainfall for Conservative and Traditional tillage treatments (averaged for both soils).

Tillage Treatment	Infiltration decline rate k from Eqn. 4.1 (h^{-1})
Traditional Tillage	6.6[a]
Conservative Tillage	5.2[b]
Least sig. diff. P=0.05	0.8

Notes: Superscripts denote significant differences (P=0.05)
n=12

Table 4.8 The rate of infiltration decline under high kinetic energy rainfall as affected by soil wetting pre-treatment (averaged for both soils).

Wetting Pre-treatment	Infiltration decline rate k from Eqn. 4.1 (h^{-1})
Dry	5.4[a]
Tension	5.7[a]
Rapid	6.5[b]
Least sig. diff. P=0.05	0.9

Notes: Superscripts denote significant differences (P=0.05)
n=8

Table 4.9 Effects of soil and wetting pre-treatment on rate of infiltration decline under high kinetic energy rainfall.

Soil	Wetting pre-treatment	Infiltration decline rate k from Eqn. 4.1 (h^{-1})
Cowra	Dry	3.8[a]
	Tension	5.6[b]
	Rapid	5.4[b]
Condobolin	Dry	7.0[c]
	Tension	5.9[b]
	Rapid	7.6[c]
Least sig. diff. P=0.05		1.1

Notes: Superscripts denote significant differences (P=0.05)
n=4

Table 4.10 Effects of soil, tillage treatment and wetting pre-treatment on rate of infiltration decline under high kinetic energy rainfall.

Soil	Tillage Treatment	Wetting Pre-treatment	Infiltration decline rate k from Eqn. 4.1 (h^{-1})
Cowra	Traditional	Dry	4.2^{ab}
		Tension	7.7^{de}
		Rapid	5.8^{bc}
	Conservative	Dry	3.4^{a}
		Tension	3.5^{a}
		Rapid	5.0^{abc}
Condobolin	Traditional	Dry	7.9^{de}
		Tension	5.3^{abc}
		Rapid	8.8^{e}
	Conservative	Dry	6.2^{cd}
		Tension	6.4^{cd}
		Rapid	6.5^{cd}
Least sig. diff. P=0.05			1.9

Notes: Superscripts denote significant differences (P=0.05)
n=2

4.3.2 Final Infiltration Rate for R Series Simulations

Whilst all high kinetic energy rainfall simulations resulted in ponding and decreased infiltration, only two low kinetic energy rainfall simulations resulted in ponding (see sections 4.1 and 4.2.1). This clearly indicates that raindrop kinetic energy was the most important determinant of final infiltration rate. Among high kinetic energy rainfall simulations, analysis of variance indicates that soil, tillage treatment, wetting pre-treatment, and soil by tillage interactions are significant ($P<0.05$). Tables 4.11 to 4.14 present mean final infiltration rates for these factors and interactions. These mean values indicate that final infiltration rates were lower for rapidly pre-wet soils and dry soils than for tension pre-wet soils, lower for Condobolin soil than Cowra soil and lower for Traditional tillage at Cowra (difference = 3.7 mm h^{-1}) but not Condobolin (difference = 0.8 mm h^{-1} was not significant at P=0.05).

Table 4.11 Final infiltration rates under high kinetic energy rainfall for Cowra and Condobolin soil.

Soil	Final infiltration rate ($mm\ h^{-1}$)
Cowra	6.6[a]
Condobolin	2.2[b]
Least sig. diff. P=0.05	1.4

Notes: Superscripts denote significant differences (P=0.05)
n=12

Table 4.12 Final infiltration rates under high kinetic energy rainfall for Conservative and Traditional tillage treatments (averaged for both soils).

Tillage treatment	Final infiltration rate ($mm\ h^{-1}$)
Traditional	3.3[a]
Conservative	5.6[b]
Least sig. diff. P=0.05	1.4

Notes: Superscripts denote significant differences (P=0.05)
n=12

Table 4.13 Final infiltration rates under high kinetic energy rainfall as affected by soil wetting pre-treatment (averaged for both soils).

Wetting pre-treatment	Final infiltration rate ($mm\ h^{-1}$)
Dry	3.9[a]
Tension	6.0[b]
Rapid	3.4[a]
Least sig. diff. P=0.05	1.7

Notes: Superscripts denote significant differences (P=0.05)
n=8

Table 4.14 Effects of soil and tillage treatment on final infiltration rate under high kinetic energy rainfall.

Soil	Tillage treatment	Final infiltration rate ($mm\ h^{-1}$)
Cowra	Traditional	4.8^{a}
	Conservative	8.5^{b}
Condobolin	Traditional	1.8^{c}
	Conservative	2.6^{c}
Least sig. diff. P=0.05		1.9

Notes: Superscripts denote significant differences (P=0.05)
n=6

Differences in final infiltration rates observed in the current study are consistent with differences of similar magnitude between conservative and traditional tillage treatments found by Loch (1989).

Differences between temporal patterns of infiltration rate under rainfall for tension pre-wet soils and initially dry soils observed in the current study are not entirely consistent with differences observed by Le Bissonnais and Singer (1992) despite the comparable rainfall intensity (40 mm h^{1}). In that study, tension pre-wet soils maintained considerably higher infiltration rates than initially dry soils throughout three simulated rainfall events, despite having lower initial soil water potential gradients driving infiltration. The apparent discrepancy between the two studies may be related to differences in the nature of soils used. Soils that are more susceptible to slaking may remain more resistant to reduction in surface hydraulic conductivity by raindrop impacts following tension pre-wetting. For such soils, the effect of tension pre-wetting in maintaining greater aggregate stability and hence greater surface hydraulic conductivity may outweigh the effects of greater initial water content reducing hydraulic potential gradient across the sealing layer. Le Bissonnais and Singer proposed that reduced infiltration into initially dry surfaces observed in their study resulted from a greater degree of aggregate slaking and consequently more rapid and more effective surface sealing. While this may explain results of their study, it should be noted that effects of initial water content had not been isolated from effects of soil wetting rate as treatments in their study differed in both initial water content and in soil wetting rate. In the current study, rapidly pre-wet soils and tension pre-wet soils had similar initial water contents but different soil wetting rates while rapidly pre-wet and initially dry soils had identical wetting rates but different initial water contents.

4.3.3 Total Infiltration Volume for R Series Simulations

As a measure of surface sealing, total infiltration volume integrates effects of differences in volume required for ponding, rate of decline in infiltration rate with time and final infiltration rate. In addition, it can provide a gross indication of practical consequences of surface sealing under intense rainfall. It is evident from the failure of most low kinetic energy simulations to cause ponding and restrict infiltration that raindrop kinetic energy level was the most important determinant of total infiltration. Hence, analysis of variance was again restricted to high kinetic energy rainfall simulations. Mean values for significant factors presented in Tables 4.15 to 4.18 indicate that soil had a slightly greater effect on total infiltration than other factors with Cowra soil exhibiting greater total infiltration volume. The effect of wetting pre-treatment was almost as great with tension pre-wetting leading to greater total infiltration volume than rapid wetting. They also indicate that Conservative tillage treatment can have an effect of similar magnitude to the above two factors. This effect was evident for Cowra soil but not Condobolin soil.

Table 4.15 Total infiltration volume under high kinetic energy simulated rainfall for Cowra and Condobolin soils.

Soil	Total infiltration (mm)
Cowra	25.0[a]
Condobolin	15.2[b]
Least sig. diff. P=0.05	2.6

Notes: Superscripts denote significant differences (P=0.05)
n=12

Table 4.16 Total infiltration volume under high kinetic energy simulated rainfall for Conservative and Traditional tillage treatments (averaged for both soils).

Tillage treatment	Total infiltration (mm)
Traditional	18.2[a]
Conservative	22.0[b]
Least sig. diff. P=0.05	2.6

Notes: Superscripts denote significant differences (P=0.05)
n=12

Table 4.17 Total infiltration volume under high kinetic energy simulated rainfall as affected by soil wetting pre-treatment (averaged for both soils).

Wetting pre-treatment	Total infiltration (mm)
Dry	22.0[a]
Tension	23.3[a]
Rapid	15.1[b]
Least sig. diff. P=0.05	3.2

Notes: Superscripts denote significant differences (P=0.05)
n=8

Table 4.18 Effects of soil and tillage treatment on total infiltration under high kinetic energy rainfall.

Soil	Tillage treatment	Total infiltration (mm)
Cowra	Traditional	21.2[a]
	Conservative	28.9[b]
Condobolin	Traditional	15.2[c]
	Conservative	15.2[c]
Least sig. diff. P=0.05		3.7

Notes: Superscripts denote significant differences (P=0.05)
n=6

Differences in total infiltration volume integrate differences in rainfall volume to ponding, differences in rate of decline in infiltration rate and differences in final infiltration rate. The relative contributions of these factors will be specific to the soil and rainfall conditions simulated in this study. Likewise, the absolute magnitude of increases in total infiltration volume brought about by tillage treatment and pre-wetting treatment are specific to the duration and intensity of the rainfall simulated in this study as well as the depth, preparation methods and initial water conditions of the soil columns.

4.3.4 Mass Imbalance

The accuracy of infiltration rates, calculated as difference between rainfall intensity and runoff rate, can be assessed, to a degree, by examination of mass imbalance for rainfall simulations (see section 3.3.4). The mean of absolute values of mass imbalance, calculated for high raindrop kinetic energy simulations using Eqn. 4.2, was 41.7g (equivalent to 1.5 mm of rainfall volume). This mean imbalance is considered to be within the combined limits of the accuracy

of measurement of simulated rainfall volume, runoff measurement, through-flow measurement, and soil column weight change. Mass imbalance was negative in most high energy simulations (ie., the sum of measured storage change and measured outflows exceeded rainfall inflow) and positive for most low energy simulations.

mass imbalance = mass inflow - (change in storage + mass outflow) [Eqn. 4.2]

where: mass inflow = mass of rainfall
change in storage = change in column mass
mass outflow = runoff + through-flow + erosion losses
through-flow = mass of water draining from base of soil column
erosion losses = mass of soil collected in runoff

Imbalances in excess of the limits of accuracy of measurement of rainfall occurred in three simulations. These may have resulted from erroneous column weight gain due to extraneous splash on the infiltration column, erroneous runoff measurement due to extraneous splash on runoff containers, variability in the priming of column plumbing or erroneous through flow measurement due to unavoidable losses across the mesh base of the column.

Total infiltration volume for high energy simulations calculated using Eqn. 4.3 was generally consistent with the sum of infiltration calculated for 30 s time intervals. The average absolute discrepancy of 40.2 g (equivalent to 1.4 mm of rainfall volume) is within the combined accuracy of the measurement of the components of the mass balance. The maximum absolute discrepancy was 118 g (equivalent to 4.1 mm of rainfall volume). Positive and negative discrepancies were equally frequent.

Infiltration volume = Column weight gain + Through-flow + Erosion loss [Eqn. 4.3]

Calculated mass imbalances indicate that major extraneous gains or losses did not occur. Hence, there is no evidence of gross errors in estimated infiltration during rainfall simulations. This lack of gross error and the lack of significant storage on soil surfaces and in the plumbing system (supported by the observation that measured runoff was negligible following cessation of rainfall) increases confidence in the estimated infiltration rates.

4.4 SUB-SEAL MATRIC POTENTIAL

As indicated in section 2.2.1, development of negative sub-seal matric potentials beneath saturated surface seals has commonly been observed (eg., Sharma *et al.*, 1981; Bosch and

Onstad, 1988) and is consistent with declining saturated hydraulic conductivity of an overlying sealing layer. Declining surface K_{sat} reduces infiltration flux through the surface relative to the potential saturated flux through the bulk soil. Flux downward from the sub-seal zone is greater than the flux infiltrating from above and thus the sub-seal zone becomes less saturated. As the degree of saturation decreases, hydraulic conductivity of the bulk soil, and flux downward from the sub-seal zone, decreases. This negative feedback results in stabilisation of sub-seal matric potential at a level dependent on the degree of sealing (ie., the reduced surface hydraulic conductivity) and the hydraulic conductivity of the unsealed soil (Hillel, 1980).

Sub-seal matric potentials were measured in the present study for two reasons. Primarily, the measurement of the matric potential gradient allows calculation of seal hydraulic conductivity (or hydraulic conductance). In addition, the temporal pattern of sub-seal matric potential can aid interpretation of the processes of seal formation and its final value may provide some indication of the total degree of sealing (Romkens *et al.*, 1990a; Mualem *et al.*, 1990a).

4.4.1 Sub-seal Matric Potential Measured During R Series Simulations

Figures 4.3 and 4.4 illustrate sub-seal soil matric potential measured with three tensiometers (placed at depths of 10 mm, 40 mm and 80 mm below the soil surface) as a function of time for two high raindrop kinetic energy simulations on Cowra soil (Appendix B presents similar data for all rainfall simulations in this study). In general, replicates show similar temporal patterns of sub-surface matric potential under simulated rainfall. Discrepancies evident in some simulations were associated with equipment failure or imperfect placement of tensiometers.

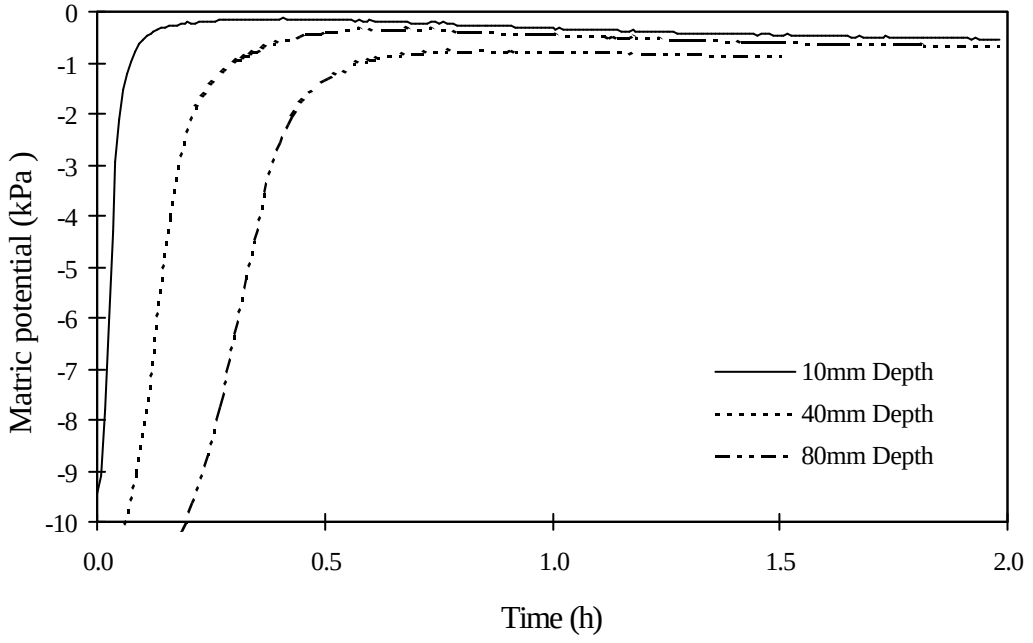

Fig 4.3 Changes in soil matric potential at three depths under high kinetic energy rainfall for Run R15 Cowra DD soil following tension pre-wetting.

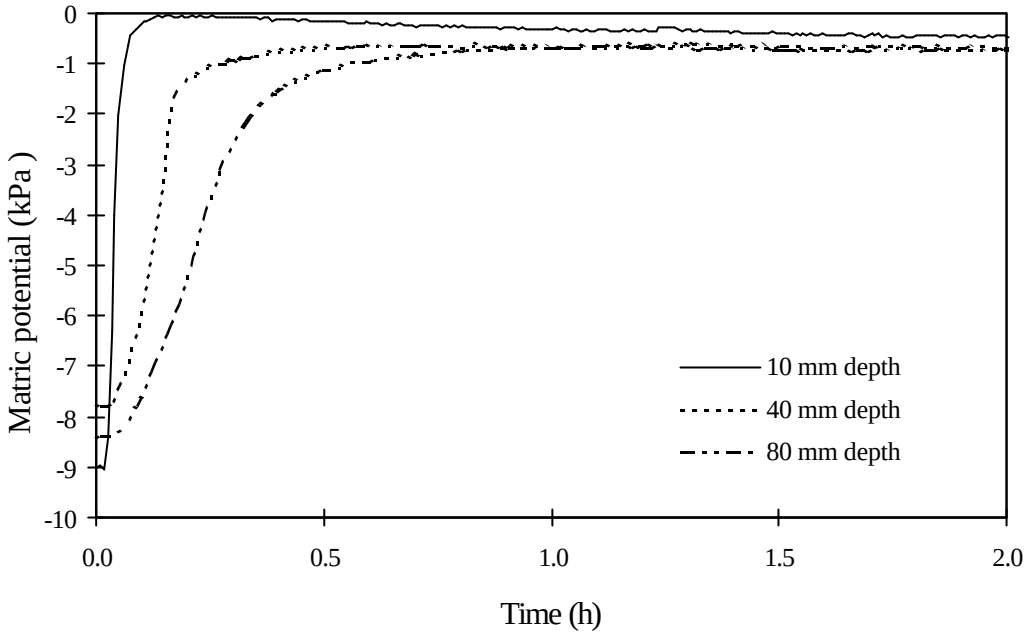

Fig 4.4 Changes in soil matric potential at three depths under high kinetic energy rainfall for Run R8 Cowra TT soil following rapid pre-wetting.

Soil matric potential in tension pre-wet and rapidly pre-wet soils, under both high and low kinetic energy rainfall, showed the expected initial response with a rapid increase in matric potential from the initial condition (approximately -10 kPa) to near saturation as the wetting front passed each depth in turn.

During high kinetic energy rainfall on pre-wet soils and low kinetic energy rainfall on the two rapidly pre-wet Condobolin BC replicates, soil matric potential at 10 mm depth declined with time from near saturation to more negative sub-seal matric potentials of the order -0.5 to -2.5 kPa.

Measurements of sub-seal soil matric potential under rainfall on initially dry soils were confounded in some cases by equipment problems, tensiometer placement problems and delays waiting for wetting fronts to reach the tensiometer depths and raise soil matric potentials to within the operating range of the tensiometers. In general, sub-seal soil matric potential of initially dry soils rose more slowly than pre-wet soils. Under high kinetic energy rainfall they increased towards steady values rather than declining from near saturation towards steady values as tension and rapidly pre-wet soils did.

Under low kinetic energy rainfall on all soil by tillage treatment by pre-wetting combinations, with the exception of rapidly pre-wet Condobolin BC, sub-seal matric potentials remained at relatively constant values close to saturation, consistent with the absence of surface seal development.

Matric potentials at the three depths trended towards singular values in all simulations where complete data exist. These singular values were reached quickly in the case of tension and rapidly pre-wet soils but were not always reached in initially dry soils even after 66 mm of

simulated rainfall. Convergence toward similar sub-seal matric potentials at the three depths indicates sub-seal hydraulic potential gradients trending towards unity. This trend to unit potential gradient is consistent with the analysis of Hillel (1980) for one dimensional flow through a uniform soil overlain by a uniform seal. However, hydraulic potential gradients measured in this study for initially dry soils remain considerably greater than unity for all, or the greater part of, the duration of rainfall.

Analysis of variance for final sub-seal matric potentials under all high kinetic energy rainfall simulations, indicates that soil, wetting pre-treatment, soil by tillage treatment interactions and soil by wetting pre-treatment interactions are significant ($P<0.05$). Mean values over the final 600 s of rainfall for each of the significant factors and interactions are presented in Tables 4.19 to 4.22.

Table 4.19 Final sub-seal matric potential under high kinetic energy rainfall for Cowra and Condobolin soil.

Soil	Final sub-seal matric potential (kPa)
Cowra	-0.86[a]
Condobolin	-1.52[b]
Least sig. diff. P=0.05	0.16

Notes: Superscripts denote significant differences (P=0.05)
n=12

Table 4.20 Final sub-seal matric potential under high kinetic energy rainfall as affected by soil wetting pre-treatment (averaged for both soils).

Wetting pre-treatment	Final sub-seal matric potential (kPa)
Dry	-2.03[a]
Tension	-0.80[b]
Rapid	-0.74[b]
Least sig. diff. P=0.05	0.19

Notes: Superscripts denote significant differences (P=0.05)
n=8

Table 4.21 Effects of soil and tillage treatment on final sub-seal matric potential under high kinetic energy rainfall.

Soil	Tillage treatment	Final sub-seal matric potential (kPa)
Cowra	Traditional	-0.83[a]
	Conservative	-0.89[a]
Condobolin	Traditional	-1.65[b]
	Conservative	-1.39[c]
Least sig. diff. P=0.05		0.22

Notes: Superscripts denote significant differences (P=0.05)
n=6

Table 4.22 Effects of soil and wetting pre-treatment on final sub-seal matric potential under high kinetic energy rainfall.

Soil	Wetting pre-treatment	Final sub-seal matric potential (kPa)
Cowra	Dry	-1.32[c]
	Tension	-0.63[a]
	Rapid	-0.63[a]
Condobolin	Dry	-2.74[d]
	Tension	-0.96[b]
	Rapid	-0.86[ab]
Least sig. diff. P=0.05		0.28

Notes: Superscripts denote significant differences (P=0.05)
n=4

Mean final sub-seal matric potentials were most negative for the initially dry state for both soils, with little difference between tension pre-wet soils and rapidly pre-wet soils. Soil had an effect of smaller magnitude with Condobolin soil, on average, having more negative final sub-seal potential than Cowra soil. Tillage treatment had a statistically significant effect on Condobolin soil, with slightly more negative potential under the Traditional tillage treatment, but not on Cowra soil.

As stated in the beginning of this section, the sub-seal suction that develops under rainfall should provide an indication of the relative degree of surface sealing for soils with similar sub-seal unsaturated hydraulic conductivity. However, it is possible that sub-seal hydraulic conductivity may not remain constant through the differing pre-wetting treatments used in this study. A wetting front passing through dry sub-surface soil, during either pre-treatment or treatment, may alter soil structure and change the hydraulic conductivity of the sub-surface soil. Initial hydraulic conductivity for tension and rapidly pre-wet soils (presented and discussed in section 4.4) are not identical, indicating that hydraulic conductivity of the underlying bulk soil is affected by wetting rate. Further doubt on the validity of sub-seal suction as an integrating measure of sealing arises from the apparently significant effect of soil water potential below the wetting front in initially dry soils and from the considerable potential for errors in the experimental measurement of soil water potentials. Sharma *et al.* (1981) also found little difference in sub-seal suctions developing in "stable and unstable soils" that had significantly different infiltrability.

This point may be further illustrated by examination of the similar sub-seal matric potential measured under tension and rapidly pre-wet soils. Reduced rainfall volume to ponding and more rapid rates of decline in infiltration rates (presented in sections 4.2 and 4.3) are consistent with either rapid pre-wetting reducing surface hydraulic conductivity prior to

rainfall simulation and or rapid pre-wetting causing greater susceptibility to surface hydraulic conductivity decline under rainfall. Similar final sub-seal matric potentials for rapid and tension pre-wet soils may be consistent with these effects if, and only if, the reduction in hydraulic conductivity extended to a depth well below the surface sealing zone. If hydraulic conductivity was not reduced in the sub-seal soil by rapid pre-wetting, or by rainfall following rapid pre-wetting, then relatively more negative sub-seal matric potentials would be expected for these rapidly wet soils. Sub-seal matric potentials were measured at 10 mm depth and morphological effects of surface sealing are rarely observed below 7 mm depth (Mualem and Assouline, 1989). Therefore the patterns in sub-seal matric potential data are consistent with rapid pre-wetting causing a reduction in hydraulic conductivity to depth greater than 10 mm prior to rainfall treatment.

4.5 SATURATED SEAL HYDRAULIC CONDUCTIVITY

Spatially averaged saturated hydraulic conductivity (K_{sat}) of surface soil has often been used as a measure of surface seal development (eg., Eigel and Moore, 1983a). In the current study saturated seal hydraulic conductivity following ponding was estimated using Equation 3.1 calculated for a seal assumed to be uniform, fully saturated and with a constant thickness of 5 mm. It is used as the primary measures of rate and degree of surface sealing through the rate of decline of surface K_{sat} with cumulative rainfall kinetic energy and the final mean value of K_{sat}. This section begins by presenting measured hydraulic conductivity data. This is followed by discussion of some potential effects of the assumptions underlying these data and brief discussion of the potential influence of seal erosion on the results. The following section, 4.6 examines the data in terms of the processes of surface sealing and the importance of rapid wetting, energetic raindrop impact and differences in soil stability brought about by tillage treatment or inherent soil properties. The following section, 4.7 examines the practical significance of differences in sealing induced by tillage treatment for soil water balance. Section 4.9 presents a limited investigation of the effect of differing rainfall intensity on decline in saturated seal hydraulic conductivity.

4.5.1 Hydraulic Conductivity Following Ponding

Figures 4.5 and 4.6 plot saturated hydraulic conductivity calculated for a 5 mm thick seal against cumulative raindrop kinetic energy for two simulations on Cowra soil (corresponding graphs for all high kinetic energy simulations are presented in Appendix C). Calculated seal hydraulic conductivity declined with increasing cumulative raindrop

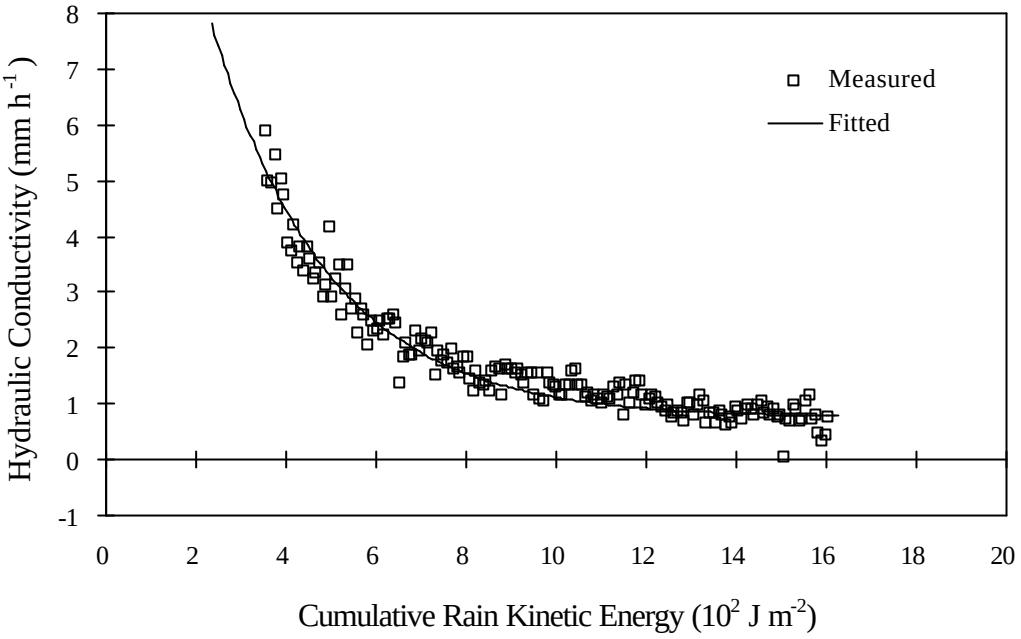

Fig 4.5 Declining hydraulic conductivity of a 5 mm thick surface layer as a function of cumulative raindrop kinetic energy for Run R15 Cowra DD soil following tension pre-wetting.

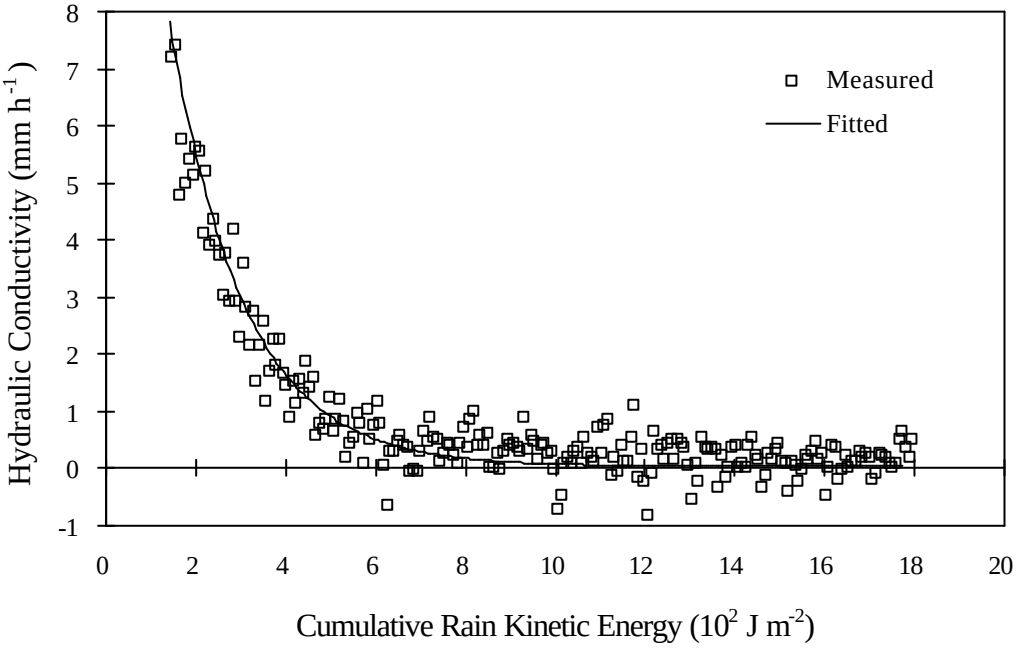

Fig 4.6 Declining hydraulic conductivity of a 5 mm thick surface layer as a function of cumulative raindrop kinetic energy for Run R8 Cowra TT soil following rapid pre-wetting.

kinetic energy following ponding under high kinetic energy rainfall for all pre-wetting treatments, on both soils under both tillage treatments. The rates of decline themselves declined with increasing cumulative raindrop kinetic energy.

Exponential conductivity decline functions of the form,

$$K(E) = (K_i - K_f)\, e^{-SE} + K_f \qquad \text{[Eqn. 4.4]}$$

where:

K = Hydraulic conductivity (mm h^{-1})

K_i = Initial hydraulic conductivity (mm h^{-1})

K_f = Final hydraulic conductivity (mm h^{-1})

S = Soil stability factor (m^2 J^{-1})

E = Cumulative raindrop kinetic energy (J m^{-2})

(Brakensiek and Rawls, 1983)

were fitted to K_{sat} measured over 900 s directly following ponding and to final K_{sat} (K_f) averaged over the final 600 s under high kinetic energy rainfall. Fitting was carried out using the modified Newton method of maximising likelihood provided in a commercial statistical computing package. Residuals were plotted against cumulative raindrop kinetic energy to check for systematic deviations. Residuals for only one replicate, R9, showed a possible dependence on cumulative raindrop kinetic energy. Linear regression of K_{sat} against cumulative raindrop kinetic energy was used to confirm statistically that K_{sat} had reached steady final values and was not declining or increasing significantly over the final 600 s of rainfall simulations.

The validity of using S to quantify the relative susceptibility of soils to surface sealing is dependent on the existence of single exponential decline functions that apply throughout the range of K_{sat}. The current study does not provide conclusive evidence that such functions do apply over the full range of K_{sat}.

Soil stability factors calculated from the exponents of fitted functions are presented in Table 4.23 along with fitted initial K_{sat}, fitted K_{sat} at the initiation of runoff and final K_{sat}. The data in Table 4.23 are discussed in the sections 4.6 to 4.9.

Table 4.23 The effects of soil, tillage treatment and wetting pre-treatment on fitted soil stability factors (S) and saturated hydraulic conductivity initially, at runoff and finally for high raindrop kinetic energy simulations on Cowra and Condobolin soils.

Rep	Wetting pre-treatment	Rainfall kinetic energy	Soil stability factor (S) from Eqn. 4.4 and std.err ($\times 10^3$ mm^2 J^{-1})		Initial K_{sat} (mm h^{-1})	K_{sat} at runoff (mm h^{-1})	Final K_{sat} (mm h^{-1})
Cowra TT							
R6	Dry	high	2.70	(0.03)	1.23	0.71	0.06
R10	Dry	high	2.96	(0.03)	3.70	1.92	0.16
R9	Tension	high	8.34	(0.10)	36.8	2.79	0.51
R7	Tension	high	8.54	(0.08)	565.7	4.33	0.70
R2	Rapid	high	6.18	(0.06)	15.3	5.95	0.28
R8	Rapid	high	6.12	(0.05)	16.7	7.49	0.20
Cowra DD							
R18	Dry	high	2.50	(0.08)	1.13	0.63	0.33
R19	Dry	high	3.22	(0.05)	2.75	0.73	0.31
R14	Tension	high	4.08	(0.10)	11.8	2.23	0.53
R15	Tension	high	3.87	(0.05)	17.4	4.21	0.75
R16	Rapid	high	3.68	(0.08)	3.84	2.83	0.33
R17	Rapid	high	3.87	(0.06)	6.22	2.98	0.58
Condobolin RH							
R28	Dry	high	5.65	(0.13)	1.13	0.34	0.09
R29	Dry	high	4.01	(0.05)	0.55	0.31	0.03
R30	Tension	high	6.75	(0.03)	6.61	1.75	0.17
R31	Tension	high	6.13	(0.02)	6.04	1.78	0.20
R26	Rapid	high	5.69	(0.07)	2.86	1.49	0.12
R27	Rapid	high	6.25	(0.06)	3.57	1.92	0.10
Condobolin BC							
R32	Dry	high	7.87	(0.07)	1.93	0.54	0.02
R35	Dry	high	7.75	(0.06)	3.21	0.74	0.02
R33	Tension	high	7.95	(0.10)	35.0	7.34	0.12
R36	Tension	high	8.20	(0.15)	12.2	1.43	0.10
R34	Rapid	high	8.56	(0.06)	8.61	3.68	0.08
R37	Rapid	high	9.23	(0.11)	8.83	1.82	0.13

4.5.2 Initial Hydraulic Conductivity

Initial saturated hydraulic conductivity was independently measured for tension and rapidly pre-wet soils using a constant positive head permeameter analyses (Klute and Dirksen, 1986) on smaller soil cores packed and pre-treated in an identical manner to infiltration simulation columns. These data are presented in Table 4.24. The estimated error of +/- 6 mm h^{-1} was based on accumulation of the experimental errors involved in the measurement of infiltration flux and hydraulic gradient. This estimate does not account for variability resulting from soil sub-sampling and column packing.

Table 4.24 Initial saturated hydraulic conductivity for Cowra and Condobolin soils.

Soil / Tillage treatment	Tension pre-wet (mm h^{-1})	Rapidly pre-wet (mm h^{-1})
Cowra TT	297	59
Cowra DD	180	140
Condobolin RH	1498	447
Condobolin BC	1784	185

Notes: Estimated measurement error +/- 6 mm h^{-1}

Comparison of values in Tables 4.23 and 4.24 indicates significant discrepancies between fitted and measured initial conductivities. Extrapolating backwards using an exponential decline function necessarily leads to estimates of initial K_{sat} that are extremely sensitive to errors in S. It would be unwise to over-emphasise the significance of these fitted values. However, it should be noted that with one exception, initial K_{sat} values listed in Table 4.23 are lower than independently measured initial conductivities listed in Table 4.24. The corollary is that rates of hydraulic conductivity decline fitted to post-ponding measured data (ie., soil stability factors in Table 4.23) are insufficient to reduce K_{sat} from the measured initial values to the values calculated at initiation of runoff.

There are three possible explanations for the discrepancies between rates of K_{sat} decline prior to and following ponding that relate to experimental procedures used. Firstly, it is possible that the measured and assumed initial saturated hydraulic conductivities listed in Table 4.24 may be inappropriate to infiltration under rainfall. The procedure used to measure initial saturated hydraulic conductivity involved ponding depths of approximately 100 mm of water on the soil surface and resulted in infiltration rates that are greater than the rainfall intensity used in simulations by more than an order of magnitude. The forces exerted on the soils by the greater flux of infiltrating water may have resulted in structural changes to the soil surface through compaction or translocation of soil material. Whilst surface collapse or compaction may be expected to reduce measured K_{sat} and hence reduce the apparent discrepancies, it may be possible that downward translocation of soil material by infiltrating water increased

conductivity by causing "tunnel" erosion. Secondly, it may be possible that surface seals formed under rainfall were not completely saturated due to entrapment of air in vesicles within the sealing layer. Such vesicles have been observed in seals (Moss, 1991a) but there is no evidence to indicate that they have occurred in this study with the high frequency that would be necessary to drastically alter measured saturated hydraulic conductivities. The third and simplest explanation for discrepancies between rates of pre-ponding and post-ponding K_{sat} decline is that the physical processes leading to decline in K_{sat} under simulated rainfall are not adequately represented by a single exponential decline of the form given in Eqn. 4.4. The significance of these discrepancies is examined further in section 4.8.

4.5.3 Post-ponding Rates of Surface Sealing for R Series Simulations

Soil stability factors presented in Table 4.23 are of similar magnitude to those calculated from the data of Sharma (Moore, 1981a) and those given by Bosch and Onstad (1988) (ie., 4.1 to 8.8 x 10^3 mm^2 J^{-1}).

Analysis of variance indicates statistically significant effects of soil, tillage treatment and soil wetting pre-treatment on soil stability factors as well as significant effects of soil by wetting pre-treatment interactions, tillage treatment by wetting pre-treatment interactions and soil by tillage treatment by wetting pre-treatment interactions ($P<0.05$). Mean values presented in Tables 4.25 to 4.27 indicate less rapid post-ponding rates of surface sealing for Cowra soil, soil under Conservative tillage treatments and soil that was initially dry.

Table 4.25 Post-ponding surface sealing rates for Cowra and Condobolin soil.

Soil	Soil stability factor ($\times 10^3$ mm^2 J^{-1})
Cowra	4.67[a]
Condobolin	7.00[b]
Least sig. diff. P=0.05	0.39

Notes: Superscripts denote significant differences (P=0.05)
n=12

Table 4.26 Post-ponding surface sealing rates for Traditional and Conservative tillage treatments.

Tillage Treatment	Soil stability factor ($x 10^3$ mm^2 J^{-1})
Traditional	7.03[a]
Conservative	4.64[b]
Least sig. diff. P=0.05	0.39

Notes: Superscripts denote significant differences (P=0.05)
n=12

Table 4.27 Post-ponding surface sealing rates for wetting pre-treatments.

Wetting pre-treatment	Soil stability factor ($x 10^3$ mm^2 J^{-1})
Dry	4.58[a]
Tension	6.73[b]
Rapid	6.20[c]
Least sig. diff. P=0.05	0.48

Notes: Superscripts denote significant differences (P=0.05)
n=8

4.5.4 Degree of Surface Sealing in R Series Simulations

Analysis of variance among measured values of final K_{sat} indicates significant effects of soil, tillage treatment, wetting pre-treatment and soil by wetting pre-treatment interactions. Mean values presented in Tables 4.28 to 4.30 show a greater final degree of surface sealing of Condobolin soil and soil under Traditional tillage treatments. Initially dry soil had a significantly greater degree of sealing while tension pre-wet soil exhibited a less severe degree of sealing.

Table 4.28 Final degree of surface sealing for Cowra and Condobolin soils.

Soil	Final K_{sat} ($mm\ hr^1$)
Cowra	0.395[a]
Condobolin	0.098[b]
Least sig. diff. P=0.05	0.075

Notes: Superscripts denote significant differences (P=0.05)
n=12

Table 4.29 Final degree of surface sealing for Traditional and Conservative tillage treatments.

Tillage Treatment	Final K_{sat} (mm hr^{-1})
Traditional	0.198[a]
Conservative	0.295[b]
Least sig. diff. P=0.05	0.075

Notes: Superscripts denote significant differences (P=0.05)
n=12

Table 4.30 Final degree of surface sealing as affected by soil wetting pre-treatment.

Wetting pre-treatment	Final K_{sat} (mm hr^{-1})
Dry	0.128[a]
Rapid	0.228[b]
Tension	0.385[c]
Least sig. diff. P=0.05	0.092

Notes: Superscripts denote significant differences (P=0.05)
n=12

4.5.5 Effects of Assumptions Made in Calculating Seal Hydraulic Conductivity

Four assumptions underlie the calculation of hydraulic conductivity of the surface seal using Equation 3.1. Firstly, it is assumed that the matric potential measured by the shallowest tensiometer is the true matric potential at the base of the sealed layer. Secondly, the seal is assumed to have a constant thickness of 5 mm. Thirdly, hydraulic conductivity is assumed to be constant throughout the thickness of the seal. Fourthly, the seal is assumed to be completely saturated. The influence on calculated hydraulic conductivity of deviation from any of these four assumptions needs to be considered.

In the current study, as in other studies, sub-seal matric potential at the base of the seal has been assumed to equal matric potential measured by the shallowest tensiometer (located nominally 5 mm below the lower boundary of the seal assumed in the current study). Such assumptions have commonly been justified on the basis that the hydraulic gradient in a uniform sub-seal zone should tend to unity. However, matric potential data presented in Appendix C indicate that for initially dry soils, hydraulic gradients below 10 mm depth can remain greater than unity for more than 1 hour under rainfall. If greater than unit hydraulic potential gradients exist above the shallowest tensiometer at 10 mm depth, then matric potentials at the sub-seal interface may be over-estimated and hydraulic conductivity of the seal may be under-

estimated. This under-estimate is likely to be greater in cases where the potential gradient is greater due to drier underlying soil or greater suction applied to wet soil.

Other workers have adjusted measured sub-seal matric potentials on the basis of hydraulic gradients measured below the shallowest tensiometer (eg., Baumhardt *et al*., 1990). However, such adjustments are themselves sensitive to the seal depth assumed and the assumption that the hydraulic gradient is identical above and below the shallowest tensiometer, both of which are uncertain. An indication of the potential magnitude of this effect can be estimated using Equation 3.1. Consider the case of final hydraulic conductivities calculated for initially dry Cowra DD soil using an assumed seal depth of 5 mm. Adjusting sub-seal matric potential using the gradient measured between tensiometers at 10 mm and 40 mm depth gives a sub-seal suction at 5 mm depth that is more negative by 5 mm to 10 mm than the value measured at 10 mm depth. Such an adjustment results in an increase in calculated conductivity of only 5% to 10%. This increase is insufficient to account for the differences in final hydraulic conductivity between dry and rapidly pre-wet soils observed in the current study. However, the adjustment may result in greater increases in calculated hydraulic conductivity during earlier stages of rainfall when the gradients measured below the shallowest tensiometer were greater.

The effect of error in the assumed thickness of a constant, uniform and fully saturated seal on calculated seal K_{sat} can also be assessed by examining Equation 3.1. As in other studies, matric potential differences measured across the sealing layer following ponding in the current study (ie., h10 in Equation 3.1) are much greater than likely range of seal thickness. The effect of error in assumed seal thickness on calculated seal K_{sat} will therefore be approximately proportional to the ratio of the assumed and true seal thickness (ie., calculated seal K_{sat} /true seal K_{sat} equals assumed seal thickness/true seal thickness). For the purposes of comparison, errors due to inappropriate assumptions concerning seal thickness will be practically significant only when true seal thickness differs significantly between soils, tillage treatments or wetting pre-treatments being compared.

Differences in seal thickness between soils have been related to initial aggregate size in other studies. For high intensity rainfall (121 mm h^{-1}) on oven dried Hamble series soil aggregates, Farres (1978) observed that seal thickness was positively related to initial aggregate size. Intense rainfall on oven dried aggregates as used by Farres is likely to produce conditions conducive to maximal aggregate slaking. It is unclear whether such a relationship might apply under the conditions simulated in this study. However, it should also be noted that initial aggregate size distributions do not differ greatly between soils and tillage treatments used in this study. Differences in true seal thickness between wetting pre-treatments used in the current study are considered to be a more likely source of error.

In addition, the effect on calculated seal K_{sat} of the assumption of a constant seal thickness after ponding may be dynamic. If true seal thickness actually increases after ponding, then the constant seal thickness assumption could lead to an over-estimation of the seal K_{sat} in the early post-ponding phase and an under-estimation later in the simulation. This may lead to

an over-estimation of the rate of decline in K_{sat}. The actual effect of the assumption on hydraulic conductivities calculated in this study cannot be determined because no data were collected that quantify post-ponding change in seal thickness for the soils used and rainfall characteristics simulated. Likewise, the relativity of effects on different soils, tillage treatments and pre-treatments can only be speculated upon. In the study referred to above, Farres (1978) found slightly greater rates of vertical seal extension for larger aggregates but he found that each of three aggregate size classes used in his study had reached an equilibrium depth after a relatively small amount of rainfall (approximately 7 mm). Soils and simulated rainfall characteristics used by Farres were clearly different from those in this study but if surface seals formed in this study had reached maximal depth after similarly small amounts of simulated rainfall, then vertical extension of seal depths would have been virtually complete prior to ponding of dry and tension pre-wet soils. If this were the case, then there would be little potential for vertical extension of the seal to result in erroneous calculated post-ponding hydraulic conductivity for these pre-treatments.

The effects on calculated K_{sat} of the related assumptions of complete saturation and uniformity of hydraulic properties throughout the seal cannot be quantified without knowledge of the actual variation in hydraulic properties as a function of depth within the seal layer. Seals have been modelled as a non-uniform layers (eg., Mualem and Assouline, 1989) but such modeling requires knowledge of, or assumptions about, hydraulic conductivity and soil water retention as functions of depth within the seal. The experimental study carried out here did not provide such information.

Again, relative differences in the depth distribution of hydraulic properties between soils and pre-treatments could lead to erroneous comparative conclusions.

4.5.6 Surface Seal Erosion

Erosion losses from the surface of high kinetic energy rainfall simulations were estimated from the sum of dry weights of sediment in collected runoff and airsplashed soil material collected from the splash collar at the conclusion rainfall simulations. Average erosion loss was 47 g, representing approximately 1 mm soil depth at a bulk density of 1.6 Mg m^{-3}.

On average, sediment collected in runoff made up less than 25% of the eroded material in each simulation with airsplash material making up 75% of the eroded material. Negligible erosion losses occurred under low raindrop kinetic energy simulations. These two results are consistent with qualitative visual observations that airsplash was the dominant mechanism removing material from the soil surfaces and that effects of flow transport processes were negligible. Observations made during the initial stages of high energy simulations indicated that individual raindrops penetrated the soil surface without obvious disturbance and that soil movement was negligible. As soil surfaces became saturated and approached surface ponding, airsplash of soil associated with raindrop impacts appeared to increase dramatically. Airsplash

diminished rapidly after ponding to negligible levels as the surface seal extended over a significant area of the soil surface.

Surface seal erosion has been proposed as a partial explanation for significant differences in experimentally measured seal hydraulic conductivities (eg., Baumhardt *et al.*, 1990) but may itself be strongly influenced by experimental conditions such as slope and soil area. The subjective visual observations of the mechanisms and temporal pattern of soil removal combined with measurements of sediment in runoff support the proposition that erosion of surface seals following ponding and runoff is unlikely to have been significant under the experimental conditions of the current study. This suggests that it is unlikely that erosion of surface seals has greatly influenced measured post-ponding seal hydraulic conductivities reported here.

4.6 EFFECTS OF RAPID SOIL WETTING AND ENERGETIC RAINDROP IMPACT ON SURFACE PERMEABILITY

4.6.1 Effects of High Raindrop Kinetic Energy on Surface Sealing

All high kinetic energy rainfall simulations resulted in surface ponding, restricted infiltration and reduction of surface hydraulic conductivity to below 1 mm hr^{1}. In contrast, low kinetic energy rainfall resulted in surface ponding only on the least stable surface (ie., Condobolin BC following rapid pre-wetting). High kinetic energy raindrop impact is clearly an important agent of surface sealing under the conditions simulated in this study. This finding is consistent with findings of Moss (1991a), Loch (1994b) and others who have attributed the importance of high kinetic energy raindrop impacts to surface compaction effects.

4.6.2 Threshold Raindrop Kinetic Energy Required for Surface Sealing

Whilst kinetic energy flux was the major determinant of surface seal development in the current study, two low rainfall kinetic energy simulations did result in surface restriction of infiltration indicative of surface sealing (see section 4.2). Results from these two rainfall simulations are consistent with findings of Eigel and Moore (1983a) and indicate that there is no universally applicable threshold for individual raindrop kinetic energy that is required for surface sealing to occur.

4.6.3 Effects of Rapid Soil Wetting on Surface Sealing

Effects of rapid soil wetting on surface sealing are considered separately for pre-ponding and post-ponding phases of sealing.

4.6.3.1 Effects Prior to Ponding

In the current study, rapid wetting of dry soil in the absence of raindrop kinetic energy resulted in a significant decrease in saturated hydraulic conductivity as measured by a constant positive head permeameter analysis (Klute and Dirksen, 1986) (see Table 4.24). In all but two cases, this decrease in hydraulic conductivity was insufficient to result in surface ponding and restricted infiltration without the effects of high kinetic energy impacts in subsequent rainfall. In addition, pre-ponding surface sealing, as indicated by volume required for ponding, occurred more rapidly following rapid soil pre-wetting than tension pre-wetting. Results presented in section 5.4.1 confirm that rapid soil wetting resulted in significantly greater aggregate breakdown under high kinetic energy rainfall prior to ponding than had tension pre-wetting, presumably due to aggregate slaking. Aggregate size continued to decline rapidly under the first few millimetres of high kinetic rainfall on rapidly pre-wet soils and remained finer than for tension pre-wet soils throughout rainfall simulations.

The observation from the current study that pre-ponding sealing occurs more rapidly following rapid pre-wetting than following tension pre-wetting appears to contrast with conclusions of Le Bissonnais and Bruand (1995) and Nishimura *et al.* (1995). Le Bissonnais and Bruand found that surface sealing was delayed for an initially dry soil subject to rapid rainfall wetting relative to a soil that was "field moist" prior to rapid rainfall wetting. They attributed the difference primarily to increased aggregate stability of the dry soil due to cementing processes and hydrophobicity associated with a wetting and drying cycle. They also mentioned the potential effects of the initially greater hydraulic gradient on the dry soil without quantifying these effects. Nishimura *et al.* (1995) found sealing delayed for an initially dry soil undergoing rapid rainfall wetting relative to tension pre-wet soils subject to the same rapid rainfall wetting. They attributed their findings to the small drop sizes of simulated rainfall supplying insufficient volumes of water to result in slaking of dry surface aggregates.

The apparent discrepancy may be explained by the fact that in both of the studies referred to above effects of rapid soil wetting had not been isolated from effects of differences in hydraulic gradient due to differing initial soil water conditions. Compounding the problem is the fact that the occurrence of surface runoff (which has been used to assess surface sealing in all three studies) does not account for differences in hydraulic gradient resulting from differing initial soil water conditions. In the current study, rates of pre-ponding sealing for tension pre-wet and rapidly pre-wet soils have only been compared on the basis of identical initial soil water potentials. Comparison of results for tension pre-wet and initially dry soils in the current study (see Table 4.3) indicates that the delay in occurrence of runoff caused by greater hydraulic potential driving increased infiltration into an initially dry soil compared to a wet soil (-10 kPa) more than negates the effect of more rapid aggregate breakdown and surface sealing due to rapid soil wetting. These results suggest that the occurrence of surface runoff in the studies of Le Bissonnais and Bruand (1995) and Nishimura *et al.* (1995) may have been largely controlled by differences in initial hydraulic gradient rather than differences in rates of

surface sealing prior to ponding. In the absence of data on sub-seal water potentials in these other studies, this proposal cannot be evaluated.

4.6.3.2 Effects Following Ponding

In contrast to the finding for pre-ponding sealing rates, post-ponding rates of surface sealing, as indicated by soil stability factors are slightly slower for rapidly pre-wet soils than tension pre-wet soils (see Table 4.23).

This apparent contradiction may possibly be explained as follows. Tension pre-wetting significantly reduced the slaking forces breaking down surface aggregates as a result of rapid wetting in the early part of rainfall simulations. During the post-ponding phase when soil wetting is complete, energetic raindrop impact becomes the primary agent of sealing. Tension wetting may have had a much smaller influence on the inherent stability and breakdown of saturated aggregates under post-ponding raindrop impacts. Tension pre-wetting may thus lead to a reduction in pre-ponding surface sealing and greater surface hydraulic conductivity at ponding without reducing the rate of surface sealing in the post-ponding phase. If this explanation is valid, then tension and rapidly pre-wet surfaces could possibly be considered as two samples of the same soil, with identical inherent aggregate stability. Because of differences in hydraulic gradient and hydraulic conductivity they have entered the post-ponding phase of surface with significantly different levels of aggregation and surface seal development, but they follow similar exponential rates of aggregate breakdown and surface sealing.

Previous studies that have found effects of wetting rate on aggregate stability do not provide sufficient evidence to evaluate this possible explanation. These studies, either did not isolate effects of rate of soil wetting from initial soil water content (eg., McCalla, 1944) or evaluated aggregate size after only one relatively large increment of input energy (eg., Cernuda *et al.*, 1954; Panabokke and Quirk, 1957; Francis and Cruise, 1983) thus preventing determination of the *rate* of breakdown of aggregates. To adequately evaluate this hypothesis it is necessary to determine rates of aggregate breakdown as a function of input energy following different pre-wetting rates. This issue is discussed further in Chapter 5 in relation to rates of aggregate breakdown observed in the present study.

In the current study, rapid soil wetting was also found to increase the final degree of surface sealing resulting from subsequent high kinetic energy rainfall. The most obvious explanation for this effect is that rapid soil wetting caused greater aggregate breakdown due to slaking and that under subsequent energetic raindrop impact the resulting finer aggregate size distribution compacted to form a seal of lower conductivity. Results presented in Chapter 5 confirm that rapid pre-wetting leads to final aggregate size distributions under high kinetic energy rainfall that are finer than those following tension pre-wetting.

Interactions between rapid soil wetting and concurrent energetic raindrop impact are examined in section 4.6.6.

4.6.4 Threshold Soil Wetting Rates Required for Surface Sealing

Loch (1989) has suggested that a threshold rainfall intensity exists for surface sealing. He argues that a threshold rainfall intensity is one that causes rapid saturation of the soil surface and suggests that it may be approximately 50 mm h^{-1}. In support of the proposition he also cites previous studies supporting threshold soil wetting rates required for slaking or incipient failure of surface aggregates that are equivalent to rain falling at an intensity of 50 mm h^{-1} on initially dry soil (eg., Quirk and Panabokke, 1962; Glanville and Smith, 1988). Results from the current study contrast with such a proposition. The rainfall intensity used in the current study, and hence the wetting rate of initially dry soil, was well below 50 mm h^{-1} but rapid surface sealing of initially dry soil still resulted. Results from the current study also indicate that even a very slow rate of wetting of dry soil (approximately 1.8 mm h^{-1} during tension pre-wetting) did not preclude subsequent surface sealing under 33 mm h^{-1} high kinetic energy rainfall.

The discrepancy between the findings of the two studies may potentially be explained by differences in soils and the experimental procedures used. As mentioned above, Loch (1989) proposed that a threshold rainfall intensity was one that leads to rapid soil surface saturation. Clearly, the onset of surface saturation may depend on a number of factors other than rainfall intensity, including soil hydraulic properties of the underlying unaffected soil and the rate of decline in surface hydraulic conductivity due to sealing. Such factors are likely to vary between the soils studied and vary with methods of soil preparation and soil packing and are unlikely to be universally applicable. In addition, the soil wetting rate required to cause slaking of aggregates due to entrapment of air or differential clay swelling may vary with soil texture, clay mineralogy and other soil properties. Further, it is feasible that the response of the surface hydraulic properties to aggregate slaking may differ between soils due to differences in the size of aggregate breakdown products.

It can be concluded that either the concepts of threshold rainfall intensities and threshold soil wetting rates, as proposed by Loch (1989), are inappropriate to the soils used in this study or that threshold wetting rates for these soils are below 1.8 mm h^{-1}. Such a finding suggests that processes controlled by soil wetting rate are not the major determinants of rates of surface sealing for the soils investigated in the current study. Further, the results of the current study indicate that threshold soil wetting rates required for surface sealing are not universally applicable. The soil wetting rate required for surface sealing in a given situation is likely to be dependent on the properties of the soil under examination as well as initial soil water conditions and the flow conditions imposed.

4.6.5 The Relative Importance of Rapid Soil Wetting and Energetic Raindrop Impact in Reducing Surface Permeability

Most experimental studies simulating rainfall on repacked soil or cultivated fields have emphasised the dramatic effects that surface compaction by highly energetic raindrop impacts has on time to surface ponding and subsequent surface permeability or infiltration (eg., Glanville

and Smith, 1988; Loch and Foley, 1994). However, reduced surface permeability due to surface sealing as a consequence of rapid soil wetting alone without raindrop kinetic energy has been observed under experimental conditions (eg., Eigel and Moore, 1983a) and inferred under field conditions (Valentin and Bresson, 1992). In the morphologically based classification scheme of Valentin and Bresson infiltration rates predicted for "slaking crusts" range from 5 to 20 mm h^{-1} while infiltration rates observed by Eigel and Moore for repacked soil declined to around 30 mm h^{-1} after 120 minutes of zero kinetic energy rainfall.

Results from the current study confirm that rapid soil wetting can result in a significant reduction in surface hydraulic conductivity in the light textured weakly structured soils studied (up to 90% reduction) to values around 30 mm h^{-1}. They also confirm that energetic raindrop impact is necessary to achieve the very low surface hydraulic conductivities (< 5 mm h^{-1}) commonly associated with well developed surface seals. Studies that measure infiltration only in the presence of rapid wetting and concurrent energetic raindrop impact (eg. Loch, 1989) or that do not measure infiltration in the absence of both rapid soil wetting and energetic raindrop impact (eg., Glanville and Smith, 1988) are unable to evaluate reduction in surface permeability due to rapid wetting alone. The practical significance of disregarding this decline in permeability will depend on soil and rainfall characteristics. It may be particularly significant when loose well aggregated soil (eg., immediately following cultivation) in a relatively dry state is subjected to rainfall with relatively low kinetic energy (due either to naturally small drop size or due to surface protection by plant residue).

4.6.6 Interactions Between Concurrent Rapid Soil Wetting and Energetic Raindrop Impact

Few, if any, studies have isolated interactions between rapid soil wetting and concurrent energetic raindrop impact in relation to surface sealing. Results presented in Table 4.30 clearly indicate that a greater final degree of sealing occurred when rapid soil wetting and energetic impact occurred concurrently (on initially dry soils) than when they occurred sequentially (on rapidly pre-wet soils), despite identical soil wetting rates and identical cumulative raindrop kinetic energy.

The greater degree of sealing of initially dry soils observed in the current study would be consistent with a physical interaction between effects of rapid soil wetting and concurrent energetic raindrop impact on degree of aggregate breakdown and hence surface sealing. However, it would also be consistent with differences in hydraulic gradient across the sealing layer causing a greater degree of surface sealing.

There are at least five possible explanations that should be considered for the results observed in the current study.

Three of these explanations relate to possible mechanisms by which physical interactions between rapid wetting and raindrop impact could possibly affect aggregate breakdown under rainfall. Firstly, raindrop impacts may more effectively break aggregates and

hence reduce K_{sat} if they coincide with rapid wetting, rather than follow 24 hours or more after rapid pre-wetting. Farres (1980) showed that increased "relaxation time" between raindrop impacts increased the stability of aggregates to single drops and he proposed that aggregates are more stable if greater time is allowed for stresses, related to rapid wetting, to be accommodated. Secondly, an interaction may occur due to strengthening of aggregates and inter-aggregate contacts due to thixotropic clay hardening (Utomo and Dexter, 1982) associated with cycles of wetting and drying. However, in the current study, the drying that occurred following pre-treatment of rapidly pre-wet soils did not occur below field capacity. Thirdly, an opposing interaction may also occur because initially dry aggregates may be stronger at the time of impact, simply as a result of lower water content.

Final aggregate size distributions presented in Table 5.6 do indicate that significantly greater aggregate breakdown occurred in the surface of initially dry soils. However, this effect was observed irrespective of the kinetic energy level of the raindrops thus suggesting that interactions between rapid wetting and raindrop impact on aggregate breakdown are not the likely cause of the greater degree of sealing observed.

The fourth possible explanation relates to the size of drops involved in the wetting of the rapidly pre-wet and dry soils. While both rapidly pre-wet and initially dry treatments were effectively wet at the same average rainfall intensity (approximately 33 mm h^{-1}), the low kinetic energy raindrops were of the order of 0.3 to 0.6 mm in diameter while the high kinetic energy raindrops were 2.6 to 2.7 mm in diameter (a difference of at least two orders of magnitude in volume). Individual aggregates in the surface of initially dry soils would have had initial contact with much larger volumes of free water and may therefore have undergone a greater degree of breakdown than rapidly pre-wet surfaces that would have had initial contact with smaller volumes of free water. This explanation is consistent with greater aggregate breakdown observed in the surface of initially dry soils irrespective of the kinetic energy level of the raindrops.

A fifth possible explanation follows from the fact that the comparison of initially dry soils and rapidly pre-wet soils also involves a contrast in soil water potential gradients across the sealing layer. Given that the initially dry soils had greater final hydraulic potential gradients across the sealing layer (as indicated in Table 4.20), the lower final surface conductivities are consistent with the data of Rose (1962), the data of Morin *et al.* (1981) and the findings of Silburn and Foley (1994). Data from those studies show negative correlation between the hydraulic gradient imposed on soils under rainfall and seal hydraulic conductance. Possible differences in the degree of aggregate breakdown referred to above and found in the current study (presented in Table 5.6) are unlikely to explain the observations of either Morin *et al.* (1981) or Rose (1962) since soil samples with differing sub-seal suctions had consistent pre-treatment within each of those studies. Effects of sub-seal soil water potential on surface conductivity may be of significance and potential explanations for such an effect are discussed in the following section (4.6.7).

Rates of surface sealing are also significantly different for initially dry soils than for rapidly pre-wet soils.

Initially dry soils required a greater rainfall volume for ponding and had lower measured K_{sat} at runoff than rapidly pre-wet soils. Whilst this might appear to suggest that slower rates of surface sealing occurred for initially dry soils prior to ponding, the effects of initial hydraulic gradient on infiltration and ponding need to be considered. Delayed ponding on initially dry soils may have resulted simply from greater hydraulic gradients driving higher rates of infiltration irrespective of relative surface hydraulic conductivity.

During the post-ponding phase of rainfall, fitted rates of soil surface sealing were significantly slower for initially dry soils than for rapidly pre-wet soils (see Table 4.27). A clear explanation for this effect is not readily apparent but two possible explanations exist. Firstly, it may result because the calculated hydraulic conductivities had declined to such an extent by the time of ponding for all initially dry soil surfaces (see Table 4.23 and Appendix C) that they were approaching the final degree of surface sealing. Thus rates of sealing fitted after ponding may have appeared to be negligible. This apparent effect is enhanced by the greater volume of rainfall required for ponding (see Table 4.1) resulting from the greater hydraulic gradients across the sealing layer of initially dry soils. Secondly, the effect of more negative sub-seal matric potentials in increasing the degree of surface sealing (referred to above in this section and discussed in section 4.6.7) should be most pronounced during the pre-ponding stages of rainfall on initially dry soil. This effect may have caused more rapid decline in calculated K_{sat} during the early stages of rainfall when hydraulic gradient was greatest. Rates of decline in calculated K_{sat} may therefore appear to be slower during the post-ponding phase as surface sealing approaches its final degree.

4.6.7 Potential Explanations for Negative Correlation Between Seal Hydraulic Conductivity and Hydraulic Gradient Across the Seal

The cause of negative correlation between seal hydraulic conductivity and hydraulic gradient across the seal, evident in the data of Rose (1962), the data of Morin *et al.* (1981), the findings of Silburn and Foley (1994) and the results from the current study has not been established. Four possible explanations are identified in this section.

Firstly, Mualem *et al.* (1990a) proposed that the relationship among the data of Morin *et al.* may have been due to increased clogging of pores by downward migration of finer material carried by the increased infiltration flux resulting from the greater hydraulic gradient applied. The importance attributed to downward migration of finer particles varies greatly among published studies of surface sealing from major (eg., McIntyre, 1958a) to negligible (eg., Eigel and Moore, 1983a). In the current study there was no attempt to quantify differences in the degree of downward particle migration between wetting pre-treatments. However, it should be noted that the total volume of water infiltrating during wetting pre-treatment and rainfall simulation in the current study was much greater for rapidly pre-wet soils

than for dry soils. If the potential for downward particle migration and consequent blocking of pores was positively related to the flux of infiltrating water, then lower conductivity could have been expected for rapidly pre-wet soils relative to initially dry soils. The opposite effect was observed in the current study.

Secondly, an explanation was proposed by P.J. Ross, (cited as a personal communication, by Silburn and Foley, 1994) to explain data showing a dependence of seal hydraulic conductivity on the degree of applied sub-seal suction. It was suggested that increased suction applied to the base of a soil sample consisting of sealed soil overlying unsealed soil could lead to de-saturation of the lower unsealed soil. Further, it was suggested that the resulting unsaturated soil would have lower hydraulic conductivity leading to reduction in the apparent saturated hydraulic conductivity of the whole sample.

Thirdly , Silburn and Foley (1994) also concluded that the potential for increasing sub-seal suction to reduce hydraulic conductivity by changing the physical structure of the soil seal could not be ruled out.

Lastly, error in estimating sub-seal matric potential using matric potential measured by the shallowest sub-seal tensiometer (as explained in section 4.5.4) may have affected calculated hydraulic conductivity of initially dry soils to a greater degree than rapidly pre-wet soils.

The mechanism proposed by P.J. Ross (Silburn and Foley, 1994) may have relevance to a number of the important findings of the current study. In the following section, the potential effects of this mechanism on apparent surface hydraulic conductivity are examined. This is done through simulation modelling of flow through a soil sample consisting of a sealed soil layer overlying an unsealed soil layer using the **S**oil **W**ater **I**nfiltration and **M**ovement model (Ross, 1990a,b).

The SWIM model is a one-dimensional water balance model utilising an efficient numerical solution of the Richards equation. In this application, the surface sealing algorithm incorporated in SWIM that specifies an infinitely thin layer of declining hydraulic conductance was not used. Instead, the sealed layer and the underlying layer were each parameterised as 5 distinct soil layers of 1 mm thickness. Rainfall and depression storage were set to provide a constant depth of 5 mm of surface ponded water overlying the soil surface. The lower boundary of the soil sample was defined as having a constant potential which was varied between simulations in order to investigate the proposed mechanism. Figure 4.7 depicts this profile geometry and the parameter values specified for the initial SWIM simulations. Air entry potential and Campbell b parameters were measured in another study by Geeves *et al.* (1995b) on unsealed samples of Cowra soil. Steady flow rates, water potential profiles and volumetric soil water content profiles from each of the SWIM simulations are presented in Appendix D. An example SWIM input file is also presented in Appendix D. The water potential profiles and steady flow rates provide the information required to calculate apparent hydraulic conductivities are summarised in Table 4.31.

Results of the first three SWIM simulations (S1 to S3) confirm the apparent effect observed by Silburn and Foley (1994). As the constant potential applied to the lower boundary of the 10 mm sample was made more negative from -0.10 kPa to -0.50 kPa and then to -1.00 kPa, the apparent hydraulic conductivity of the combined sealed soil and underlying unsealed soil declined from 0.45 to 0.41 mm h^{-1} and then to 0.30 mm h^{-1}. However, the soil water potential profiles and soil water content profiles together with the steady flow rates indicate that de-saturation of the unsealed soil below the sealed layer had little effect on the apparent hydraulic conductivity of the soil sample (these data are presented in Figures 4.8 and 4.9 for simulation S3). The significantly

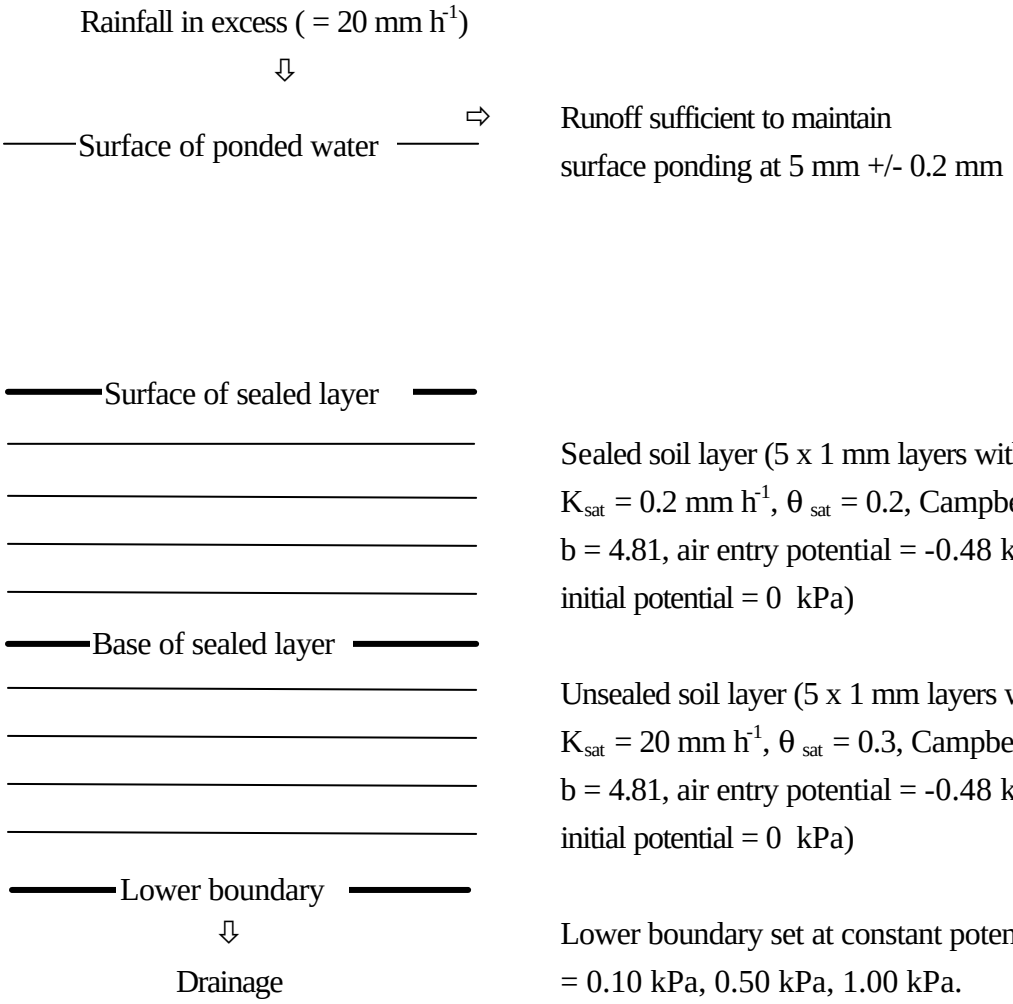

Fig. 4.7 The profile geometry, boundary conditions and soil parameters used to demonstrate effects of lower boundary potential on apparent hydraulic conductivity.

Table 4.31 The apparent hydraulic conductivity of sealed soil overlying unsealed soil as a function of constant hydraulic potential applied at the lower boundary.

SWIM Simulation	Lower Boundary Potential (kPa)	Seal Air Entry Potential (kPa)	Potential at Seal Surface (kPa)	Steady Flux ($mm\ h^{-1}$)	Apparent Hydraulic Conductivity ($mm\ h^{-1}$)
S1	-0.10	-0.48	0.05	1.14	0.45
S2	-0.50	-0.48	0.05	2.64	0.41
S3	-1.00	-0.48	0.05	3.42	0.30
S4	-0.10	-2.08	0.05	1.14	0.46
S5	-0.50	-2.08	0.05	3.04	0.47
S6	-1.00	-2.08	0.05	5.01	0.44

greater unsaturated hydraulic conductivity arbitrarily specified for the underlying unsealed layer resulted in only a very slight loss in matric potential in conducting the relatively low flux of water infiltrating through the overlying sealed layer. In effect, the matric potential predicted at the base of the sealed layer is almost equal to the potential applied at the lower boundary of the soil sample. This suggests that the presence of the underlying unsealed soil is not a necessary requirement for the proposed mechanism and that the constant bottom boundary potential could be specified directly at the base of the 5 mm sealed layer without affecting the apparent response of the soil. The volumetric soil water content profile also indicates that the lower part of the sealed layer would be de-saturated. Loss of matric potential in conducting the steady flow through this sealed layer appears to be the cause of lower apparent hydraulic conductivity rather than loss of matric potential in the underlying unsealed layer.

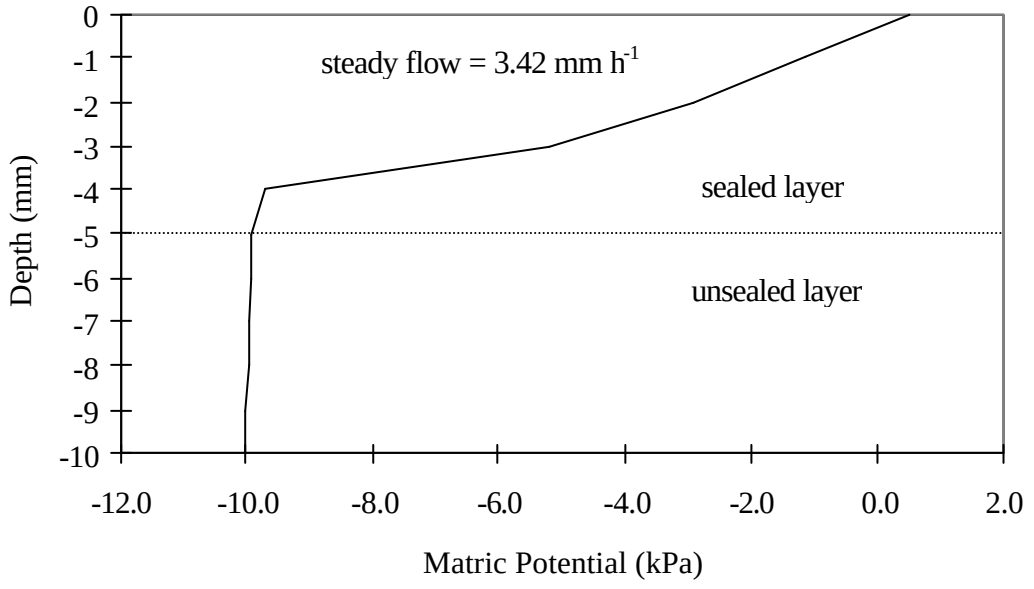

Fig. 4.8 The soil matric potential profile and steady flow rate for SWIM simulation S3 showing the negligible influence of sub-seal matric de-saturation on apparent hydraulic conductivity.

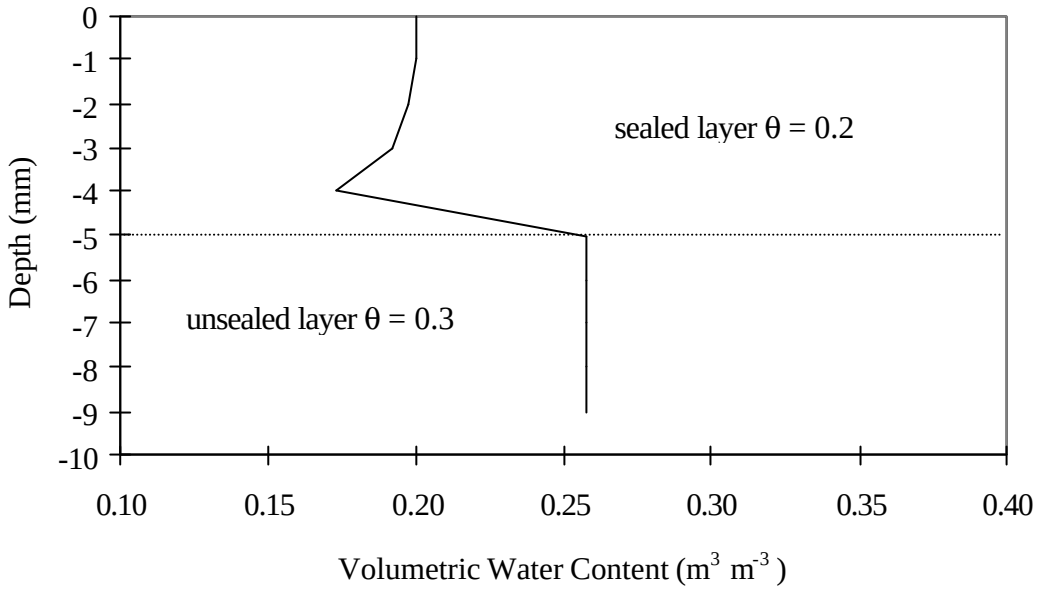

Fig. 4.9 The volumetric soil water content profile for SWIM simulation S3 showing de-saturation in both sealed and unsealed layers.

The air entry potential of -0.48 kPa specified for both sealed and unsealed soil in SWIM simulations S1 to S3 was measured on unsealed soil. In reality, a sealed soil layer could be expected to have considerably more fine pores and is likely to have a more negative air entry potential. The effect of this was investigated using a further three SWIM simulations (S4 to S6). These simulations were essentially repeats of S1 to S3 with only the air entry value of the sealed soil layers arbitrarily made more negative by 1.6 kPa to -2.08 kPa. Apparent hydraulic conductivities calculated in Table 4.31 using output from these SWIM simulations indicate that the predicted influence of the mechanism proposed by P.J. Ross (cited by Silburn and Foley, 1994) is drastically diminished when the seal layer has a more negative air entry potential. This occurs because the predicted de-saturation of the lower part of the sealed layer is essentially prevented.

The simulations carried out are illustrative only and use arbitrary geometry and parameter values. However, the results suggest that the mechanism proposed by P.J. Ross (cited by Silburn and Foley, 1994) to explain the apparent relationship between sub-seal suction and seal conductivity may be limited to cases where the suction acting at the base of the seal exceeds the air entry value of the sealed soil. The present experimental study did not provide information on the air entry potential of surface seals formed. However, it should be noted that McIntyre and Watson (1975) quantified soil water characteristics for unstructured, silt and fine-sand sized material and found air entry potentials more negative than -10 kPa, and much more negative than the final sub-seal suctions measured in this and other studies

4.7 EFFECTS OF SOIL AND TILLAGE TREATMENT ON SURFACE SEALING

Results presented in this chapter indicate that both rate of surface sealing and final degree of surface sealing are significantly affected by both soil and tillage treatment.

4.7.1 Effects of Soil

Rates of surface sealing observed in the current study are more rapid, on average, for Condobolin soil than Cowra soil during both the pre-ponding phase (see Table 4.1) and the post-ponding phase (see Table 4.25). Likewise, the final degree of surface sealing is greater for Condobolin soil than Cowra soil (see Table 4.28). This later finding is in general accordance with negative relationships between clay content and steady seal hydraulic conductivity found by others (eg., Moldenhaur and Kemper, 1969).

4.7.2 Effects of Tillage Treatment

Sharma *et al.* (1981), Packer *et al.* (1992), Loch (1994b), Packer *et al.* (1995) and others have found statistically significant effects of prior agricultural management on soil surface sealing response. Sharma *et al.* attributed the differences to changes in aggregate stability. Loch also found differences in aggregate breakdown of repacked soil under rainfall, presumably due to increased aggregate stability. However, he concluded that the magnitude of effects of increased aggregate stability was small compared to potential effects of increased surface cover under conservative tillage treatments. In apparent contrast, Packer *et al.* (1992) attributed differences in infiltration into settled soils (including soil from Cowra site referred to in the current study) to increased frequency of biologically created macropores under conservative tillage treatments. Packer *et al.* (1995) attributed increased infiltration under rainfall observed following a crop of canola (again at the Cowra site referred to in the current study) to increased aggregate stability.

Rates of surface sealing observed in this study were more rapid, on average, for Traditional tillage treatments than Conservative tillage treatments during the pre-ponding phase (see Table 4.2) and the post-ponding phase (see Table 4.26). Final degree of surface sealing was also greater for Traditional tillage treatments (see Table 4.29).

The findings of the current study contrast with the conclusion of Packer *et al.* (1992) that biologically created macropores are responsible for differences in infiltration response under different tillage treatments. The current study found significant differences despite the soil collection and repacking process that eliminated biologically created macropores. The use of settled post-harvest soil surfaces in the study of Packer *et al.* (1992) can explain this difference. Soil surfaces under such conditions have generally been subjected to repeated wetting and drying cycles and significant rainfall impact during the growing season. They may

also have been subjected to vehicular traffic during the growing season and during and after harvest. Such conditions are likely to have reduced the hydraulic conductivity of the soil surface and the underlying soil matrix considerably relative to freshly cultivated soil considered in the current study. Clearly the conclusions of the study of Packer *et al.* (1992) and the findings of the current study are relevant to very different antecedent soil conditions that are likely to exist at opposite ends of the growing season.

As mentioned in section 2.1.3.7, Loch (1994b) used a relationship between percentage of aggregates < 0.125 mm quantified by Loch and Foley (1994) to infer effects of increases in soil aggregate stability on final infiltration rate under high energy rainfall. He concluded that expected reductions in steady runoff rate associated with improved aggregate stability were approximately one seventh of reductions expected to result from soil surface protection provided by retained crop residue. He concluded that stubble retention provided by far the more important benefit from conservative tillage systems under environmental conditions expected in the Darling Downs region of Queensland, Australia.

Discussion of results presented in this section in relation to the findings of Loch (1994b) is further developed using water balance simulations in the following section.

4.7.3 Effects on Simulated Soil Water Balance of Differences in Rate and Degree of Sealing Induced by Tillage Treatments at Cowra

The most commonly used measures of rate and degree of surface seal development have been infiltration rate and surface hydraulic conductivity (or hydraulic conductance) under constant intensity rainfall of a fixed duration delivered by either a field or laboratory simulator to relatively flat, smooth soil at a specified initial water content or potential. While these measures may provide a useful comparison of susceptibility to surface sealing between soils or management treatments, they do not necessarily indicate the practical significance of the differences in sealing for the soil water balance under conditions likely to be experienced in the field. The magnitude of reductions in infiltration and increases in runoff caused by surface sealing under field conditions will depend on various rainfall factors (eg., intensity, duration and raindrop kinetic energy), soil factors (eg., antecedent water content, surface depression storage, surface detention, surface cover or protection, underlying soil hydraulic properties) and site factors (eg., slope, area) as well as the nature of the seal formed. Water balance simulation using both historical rainfall records (eg., Cresswell *et al.*, 1992) and designed rainfall events (eg., Bristow *et al.*, 1995) has been used to gain insight into the complex relationship combining these highly dynamic factors. Such an approach is used here to illustrate potential effects of structural surface sealing on the water balance of cultivated cropping soil in the Cowra region.

One dimensional water balance simulations were carried out using the SWIM model (Ross, 1990a,b) introduced in section 4.6.7. In this application of SWIM the surface sealing algorithm was used. This algorithm simulates an infinitely thin surface seal with conductance that

declines exponentially with cumulative rainfall kinetic energy (as described in section 2.2.1). In section 4.8 it is concluded that an algorithm such as this may lead to errors in predicted infiltration due to initially more rapid exponential rates of decline in conductivity or conductance during the early stages of surface sealing. However, in the absence of field measurements of surface conductivity over the period of interest, the algorithm has been used to illustrate relative effects of differing tillage treatments. Surface soil hydraulic behaviour measured in this study for Cowra TT and DD (without pre-wetting) was used to parameterise this sealing algorithm. Simulations used historic rainfall recorded at the Cowra site and underlying sub-surface soil hydraulic properties measured by Geeves *et al.* (1995b) for the Cowra soil under TT tillage.

The soil water balance was simulated for a fully disturbed layer of soil overlying a settled soil profile under rainfall measured for the month of June over the years from 1949 to 1988. The month of June was chosen for this illustration because winter cereal crops are commonly planted at Cowra during late May or early June and crop planting, even under conservative tillage treatments, commonly involves one full soil disturbance. This full soil disturbance is used to prevent carry over of disease caused by fungal root pathogens. It should produce starting soil conditions for the comparison of hydraulic behaviour under the two tillage treatments that are comparable to rainfall simulations in the current study. Historic pluviograph and evaporation records for the site were provided by the New South Wales Department of Land Water Conservation. Daily evaporation was calculated from long term mean monthly pan evaporation adjusted using a pan factor of 0.7. In an attempt to obtain realistic antecedent soil water potential profiles for the water balance simulations, soil water potential was simulated using the measured rainfall for the preceding two months of April and May for each year with the same profile configuration. The resulting simulated water potential profile was used as the antecedent condition for both tillage treatments. Runoff parameters were arbitrarily set to ensure that surface water in excess of surface depression storage was rapidly removed and simulated runoff would represent point runoff with no routing or possibility for re-infiltration within the slope. Gravitational drainage was assumed at the bottom boundary of both soil profiles throughout all simulations. A summary of water balance simulation results and an example input file are included in Appendix E.

Of the field factors affecting the partitioning between infiltration and runoff that were listed in the first paragraph of this section, surface depression storage is one that is directly influenced by soil tillage treatment. In order to isolate the effect of differences in susceptibility to surface sealing from the potentially significant effects of depression storage, the simulation results are summarised in Figure 4.10 as relationships between mean depth of point runoff and depth of depression storage for each tillage treatment. Depression storage was assumed to be constant within each simulation but was varied over the range from 0 to 10 mm for both tillage treatments in order to cover a slightly wider range than suggested by the data of Moore and Larson (1979).

Figure 4.10 illustrates the likely magnitude of two potential advantages that the conservative tillage treatments offer over traditional tillage treatments in terms of ameliorating surface sealing and reducing runoff.

Firstly, conservative tillage treatments can improve surface soil aggregate stability over the longer term because tillage is less frequent and less aggressive and soil organic matter content increases due to crop residue being retained rather than burnt. The likely magnitude of the effect of this improved stability is indicated by the comparing curves [1] and [2] in Figure 4.10. It is evident that reduction in runoff resulting from the slower rate and marginally lower degree of surface sealing of bare soil following conservative tillage treatment would be equivalent to the reduction brought about by 3 to 4 mm of depression storage. This indicates that there can be significant residual benefits for soil structure from conservative tillage treatments.

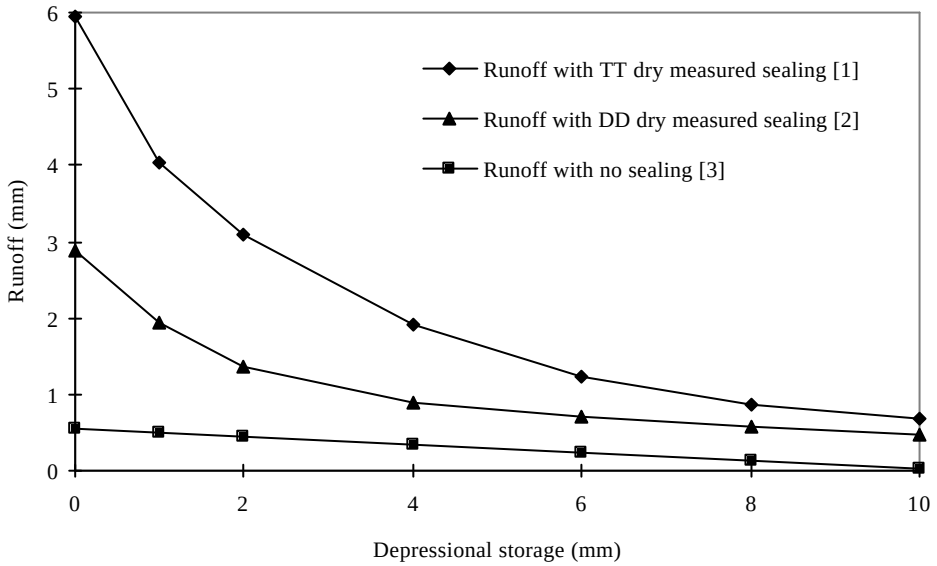

Fig 4.10 The effect of differences in sealing susceptibility brought about by tillage treatment on mean June point runoff from Cowra soil as influenced by depth of depression storage.

Secondly, conservative tillage treatments retain crop residue that protects the soil surface from energetic raindrop impact. It has been shown that rainfall with reduced or minimal raindrop kinetic energy is ineffective in forming surface seals on this soil (Geeves *et al.*, 1995a) and many other soils (eg., Loch, 1994b). This later benefit has been widely promoted in Australia as a major benefit of such conservative cropping systems. The likely magnitude of this reduction, suggested by the difference between curves [1] and [3] in Figure 4.10, is approximately twice that from improved aggregate stability. The much lower relative importance of the surface protection effect of conservative cropping systems found in this study compared to the study of Loch (1994b) results, to a large degree, from the differing rainfall regimes considered. Loch explicitly considered very high rainfall intensities because he believed

that these events posed the major erosion hazard in the area of south-eastern Queensland in which he was interested. The rainfall intensities he simulated (>100 mm h^{-1}) are rarely experienced for significant duration under the less intense winter rainfall regime of the Cowra region.

The simulations presented here use field and laboratory measured inputs but the output terms of the simulated water balance have not been validated by field measurement. Furthermore they are subject to various simplifying assumptions including assumptions that - the SWIM model realistically represents the physical processes actually occurring; the measured hydraulic properties are representative of the areas under the tillage treatments; effects of soil spatial heterogeneity and three dimensional soil water flow are minor.

4.8 INITIALLY MORE RAPID DECLINE IN SURFACE HYDRAULIC CONDUCTIVITY

As found in other rainfall simulation studies (eg., Moore, 1981b), post-ponding declines in surface hydraulic conductivity observed in this study are reasonably well described by a single rate of exponential decay towards a limiting value as a function of cumulative rainfall kinetic energy. However, results presented in this chapter clearly show more rapid rates of decline in K_{sat} inferred prior to ponding (using independently measured initial K_{sat}) than measured after ponding for all soils. The reverse situation where pre-ponding decline in surface hydraulic conductivity is retarded relative to post-ponding decline has also been reported by Silburn and Foley (1994) and modelled by Ahuja and Ross (1983).

Many models of infiltration into sealing soil incorporate a single rate of exponential decay of surface hydraulic conductivity or conductance towards a limiting value as a function of cumulative rainfall kinetic energy (eg., Ross, 1990b). The findings of the current study and the study of Silburn and Foley cast some doubt upon the predictions of infiltration behaviour in the early stages of rainfall on loose soils similar to those used in the current study.

In order to better predict infiltration behaviour, the mechanisms contributing to surface sealing under such circumstances and hence to the discrepancies observed must be well understood.

Discrepancies between the inferred rapid initial decline in hydraulic conductivity and subsequently slower and apparently exponential decline in hydraulic conductivity indicate that at least two phases of surface sealing may exist for all soils and all wetting pre-treatments used in the current study.

For initially dry soils, it is feasible that the initial phase of surface sealing is dominated by aggregate slaking associated with rapid wetting resulting in very rapid decline in hydraulic conductivity, controlled only by the wetting rate (rainfall intensity). This accords with the findings of Silburn and Foley (1994) who attributed initially rapid decline in surface hydraulic

conductivity observed for one soil to severe aggregate slaking resulting from rapid wetting of dry soil by the first few millimetres of rainfall. By the time surface ponding occurs potential for rapid soil wetting is exhausted, and the later phase of sealing may be dominated by effects of energetic raindrop impact. These impacts result in a slower K_{sat} decline, controlled at least partially, by the rate of raindrop kinetic energy impacting the soil surface. However, in the current study initially more rapid rates of decline were observed irrespective of differences in soil wetting rate imposed. Rapidly pre-wet soils underwent pre-wetting at similar wetting rates to those applied to dry soils during simulations. If similar degrees of slaking occurred on rapidly pre-wet soils during pre-treatment they should not experience significant additional slaking during the early stage of surface sealing under rainfall, but instead should exhibit the second phase almost immediately.

The results are therefore consistent with a pre-ponding phase of surface sealing controlled, partially or completely, by processes other than aggregate slaking associated with rapid wetting. Results presented in Chapter 5 show initially more rapid rates of aggregate breakdown irrespective of whether aggregate slaking has been precluded by tension pre-wetting or not. An alternative mechanism that can explain initially more rapid aggregate breakdown for repacked soils irrespective of the occurrence of rapid soil wetting is proposed and discussed in section 5.5.4.

4.9 EFFECTS OF RAINFALL INTENSITY ON SURFACE HYDRAULIC CONDUCTIVITY DECLINE

Current understanding is that, prior to ponding, intensity of rain falling on dry soil can affect soil wetting rate initially and hence the potential for sealing resulting from aggregate breakdown due to slaking (eg., Quirk and Panabokke, 1962; Loch, 1982). After ponding, intensity affects the amount of rainfall excess available for surface ponding and runoff. Surface ponding can protect the soil surface from further raindrop impact and more severe sealing (eg., Moss and Green, 1983). Local runoff may lead to increased infiltration into heterogenous soil surfaces if the rainfall excess is redistributed to less severely sealed areas with under-utilised infiltration capacity. Global runoff may lead to increased infiltration through increased erosion of surface seals (eg., Romkens *et al*., 1985; Baumhardt *et al*., 1991).

In order to indicate whether the rates and degrees of surface sealing measured in this study under 33 mm h^{-1} rainfall may be more generally applicable, a limited number of rainfall simulations were repeated at varying rainfall intensities (see section 3.3.9). Since rate of wetting of dry soil was explicitly isolated as a factor in the main body of the study, only post-ponding effects of rainfall intensity were considered here and only one tension pre-wet soil (Condobolin RH) was used. Figure 4.11 illustrates the fitted decline in spatially averaged

hydraulic conductivity with cumulative raindrop kinetic energy, under three rainfall intensities for this soil.

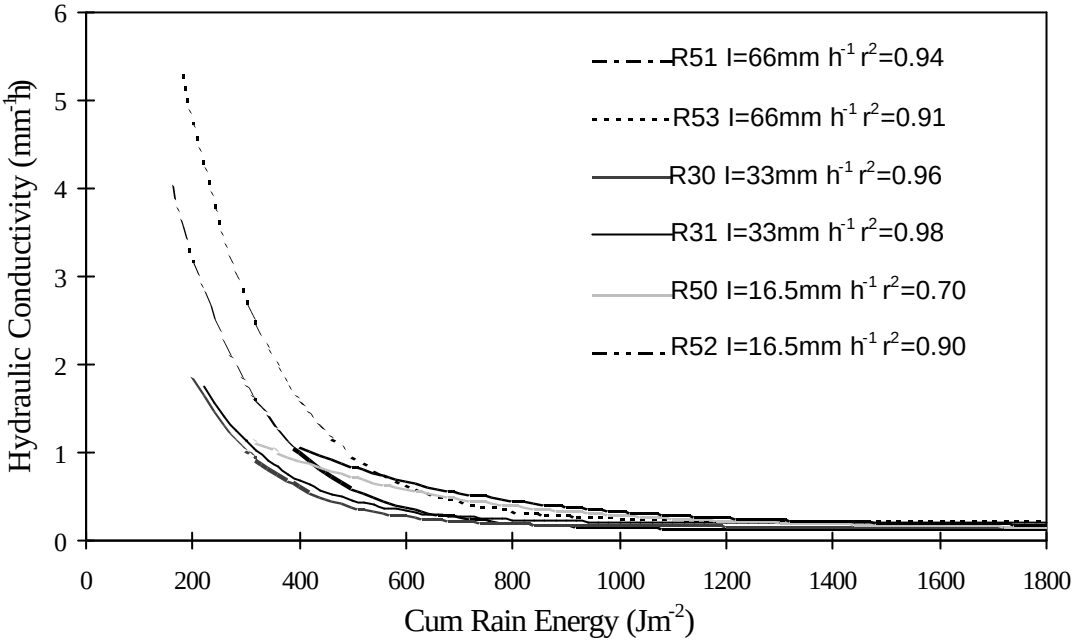

Fig. 4.11 Decline in calculated hydraulic conductivity of a 5 mm thick surface layer of Condobolin RH soil under varying intensities of simulated rainfall following tension pre-wetting. (Data for each rainfall simulation are presented in Appendix C.)

Raindrop size and fall height remained constant for the range of rainfall intensities simulated and hence cumulative raindrop kinetic energy was proportional to rainfall depth. Under the higher intensity rainfall a smaller depth of rainfall and lower cumulative raindrop kinetic energy were required to cause surface ponding. Surface hydraulic conductivity at that time was higher under higher intensity rainfall. These two effects occurred because declining infiltration rate was exceeded by the rainfall rate at an earlier stage under the higher intensity.

Soil stability factors presented in Table 4.32 were similarly higher for the intermediate and high intensity rainfall and significantly lower for the low intensity rainfall. This suggests that rates of surface sealing for the Condobolin soil measured under 33 mm h^{-1} high energy rainfall may be applicable to high energy rainfall at higher intensities up to 66 mm h^{-1} but may be inappropriate for intensities as low as 16.5 mm h^{-1}. Despite the difference in fitted decline rates, it is evident from Table 4.32 that surface hydraulic conductivities after 400 to 500 J m^{-2} and final surface hydraulic conductivities did not differ significantly over the range of rainfall intensities tested. This suggests that the final degree of surface sealing measured under 33 mm h^{-1} high energy rainfall may be applicable to a wider range of intensities providing that ponded water depth and overland flow are not great enough to cause significant reduction in raindrop impact or significant interrill erosion respectively.

Table 4.32 Soil stability factors and hydraulic conductivity for Condobolin RH soil under varying intensities of simulated rainfall following tension pre-wetting.

Simulation	Intensity ($mm\ h^{-1}$)	Soil stability factor ($x\ 10^3\ mm^2\ J^{-1}$)	Mean K_{sat} between 400 and 500 $J\ m^{-2}$ ($mm\ h^{-1}$)	Final K_{sat} ($mm\ h^{-1}$)
R51	66	6.00[a]	0.75[a]	0.14[a]
R53	66	6.24[a]	1.11[a]	0.23[a]
R30	33	6.65[a]	0.59[a]	0.17[a]
R31	33	6.42[a]	0.69[a]	0.21[a]
R50	16.5	2.80[b]	0.86[a]	0.15[a]
R52	16.5	2.85[b]	0.96[a]	0.17[a]

Notes: Superscripts denote significant differences (P=0.05)

The observations from the current study on the effect of rainfall intensity on post-ponding surface hydraulic conductivity contrast with some findings of Romkens *et al*. (1985). Fitted curves presented by Romkens *et al*. indicate that surface hydraulic conductance of an Atwood soil declined much more rapidly as a function of cumulative raindrop kinetic energy during the pre-ponding phase under lower intensity rainfall but more rapidly during the post-ponding phase under higher intensity rainfall. They also found that final surface hydraulic conductance remained significantly greater under higher intensity rainfall.

Romkens *et al*. concluded that surface seal erosion and ponded water cushioning the soil surface from raindrop impacts were likely explanations for the effects of rainfall intensity on final surface hydraulic conductance that they observed. Experimental conditions in the present study differed from that of Romkens *et al*. in ways that may have significantly reduced the importance of these two processes. Firstly, Romkens *et al*. inclined their columns to 9% and this may have lead to greater flow velocities and greater potential for interrill erosion than in the current study. Secondly, they used larger diameter soil columns and removed excess rainfall by aspiration from the lowest part of the surface rather than allowing it to flow or splash from the full perimeter of the soil column as in the current study. This may have lead to differences in the potential for water to accumulate on the soil surface.

A third possible explanation not considered by Romkens *et al*. (1985) is based on consideration of sub-seal soil water potentials under differing rainfall intensities. For any given degree of sub-surface permeability, lower rainfall intensity prior to ponding should result in more negative sub-seal soil water potentials at the time of ponding. Romkens *et al*. presented calculated sub-seal soil water potentials at the time of incipient ponding and these data indicate that lower rainfall intensity applied to initially dry soil lead to more negative sub-seal soil water potentials. As mentioned in section 4.6.7, correlation between lower soil water potential under

the soil surface and lower surface hydraulic conductance has been observed by Rose (1962), Morin *et al.* (1981) and Silburn and Foley (1994) and a similar association has been observed for initially dry soils subjected to high kinetic energy rainfall in the current study. It may be possible that differences in surface hydraulic conductance observed by Romkens *et al.* under different rainfall intensities were partially caused by differences in hydraulic gradient across the sealing layer.

In the present study, the Condobolin RH soil was initially relatively wet (-10 kPa). This prevented development of the range of differences in sub-surface soil water potentials under differing rainfall intensities calculated in the study of Romkens *et al.* At the time of ponding soil water potentials at 10 mm depth differed much less in the current study, averaging -0.73 kPa for 66 mm h^{-1}, -0.67 kPa for 33 mm h^{-1} and -0.63 kPa for 16.5 mm h^{-1} compared with -3.04 kPa for 61.2 mm h^{-1}, -4.64 kPa for 29.7 mm h^{-1} and -5.26 kPa for 19.4 mm h^{-1} in the study of Romkens *et al.* Both the soils used and the range of sub-seal suctions applied by Silburn and Foley differed considerably from those in the current study and in the study of Romkens *et al.*. However, the results of Silburn and Foley suggest that a significant proportion of the difference in surface conductance observed by Romkens *et al.* may have been due to differences in sub-seal suction at ponding. As indicated in section 4.6.7, the exact mechanism by which this occurs is yet to be established.

4.10 IMPLICATIONS FOR SOIL MANAGEMENT UNDER AGRICULTURE

In southern and central New South Wales, soil water can limit plant growth and dryland cereal crops generally suffer where surface sealing reduces rainfall infiltration rates. Results presented in this chapter indicate that energetic raindrop impact can lead to severe surface sealing that restricts infiltration rates into loose soil to below 1 mm h^{-1}. The most obvious implication from this finding for dryland cereal crop and soil management is that protection of the soil surface from energetic raindrop impact is of prime importance in preventing structural sealing and reducing runoff from loose soils. The results presented in this chapter also indicate that rapid soil wetting alone can significantly reduce infiltrability of loose soil, but only to around 30 mm h^{-1}. Rainfall events of significant duration at this intensity are not common in central New South Wales. This suggests that rapid wetting alone will generally not lead to significant runoff from the soils studied. However, rapid wetting does increase the pre-ponding rate of sealing under high kinetic energy rainfall leading to more rapid ponding and runoff. It also

slightly increases the degree of surface sealing under high kinetic energy rainfall. Subject to other agronomic constraints, rapid wetting should be minimised.

Both of these agents of surface sealing can be ameliorated to some extent by maintaining a surface cover of plants or plant residue.

It is well known that surface cover can reduce the kinetic energy of surface impacts thus ameliorating the primary agent of surface sealing. In particular, narrow leaves and stems of living plants or their residue are effective in splitting larger raindrops and reducing their kinetic energy (Moss and Watson, 1991).

Surface cover can also help to ameliorate the effects of rapid soil wetting. It may do so through intercepting rainfall and reducing the volume that would otherwise contact the soil surface. Relatively dense surface cover may also redirect rainfall preferentially to a limited number of sites on the soil surface. If soil wetting is sufficiently delayed by surface cover over the intervening areas, then these areas may actually be wet by capillarity from the adjacent infiltration sites. Wetting by capillarity is generally adequate to reduce slaking potential. In addition, surface cover may reduce soil evaporation between rainfall events and help to maintain higher antecedent surface water potentials thus reducing potential for rapid soil wetting.

The results and interpretation presented in this chapter indicate that improved aggregate stability, brought about by conservative tillage management, retards and reduces surface sealing. This residual benefit from conservative tillage has effects that last at least beyond the first major rainfall event following initial cultivation and is sufficient to significantly reduce point runoff under the lower intensity rainfalls expected in central New South Wales. Conservative tillage management should continue to be promoted in this region on the basis of benefits from increased surface cover, and the potential to improve aggregate stability.

The relative significance and magnitude of measured effects of each of the factors examined in the current study will be specific to the levels and ranges used as well as the conditions simulated. That is, the magnitude of the effects of soil or tillage management found in this study reflect differences between the Cowra and Condobolin soils or between the particular tillage management systems. More similar, or more disparate, soils or tillage management systems may give effects of different magnitude. Likewise, the magnitude of effects of wetting rates and raindrop kinetic energy levels may vary under conditions other than simulated in this study.

4.11 SUMMARY OF SOIL SURFACE HYDRAULIC BEHAVIOUR UNDER RAINFALL

It has been widely observed that intense rainfall, with significant raindrop kinetic energy, can drastically reduce surface soil hydraulic conductivity leading to more rapid ponding, earlier and

more rapid declines in infiltration rate, development of negative sub-seal matric potentials and reductions in total infiltration volume (eg., Eigel and Moore, 1983a). Results from this study strongly support such findings.

The presence or absence of high raindrop kinetic energy in simulated rainfall was found to have the greatest effect on the rate and degree of surface sealing of the soils studied. Rainfall with high kinetic energy caused surface sealing on all soil treatment combinations following all pre-wetting treatments while low kinetic energy rainfall caused ponding and measurable reduction in surface K_{sat} only on the least stable soil following rapid pre-wetting.

Soil wetting rate was also found to influence the rate and degree of decline in surface K_{sat} and infiltration rate but the magnitude of these effects was considerably less than the effects of raindrop kinetic energy. While post-ponding rates of K_{sat} decline for rapidly pre-wet soils were found to be only slightly greater, initial K_{sat} and rainfall volume to ponding were drastically reduced by rapid pre-wetting relative to tension pre-wetting. Final infiltration rate and K_{sat} were also lower following rapid pre-wetting.

In general, experimental results from the current study relating to surface hydraulic behaviour are not inconsistent with results observed in many published studies relating to the processes leading to surface sealing under rainfall and factors controlling those processes. However, observations and interpretations discussed in preceding have contributed to improved understanding of surface sealing in the following ways -

1. Whilst it has been confirmed that energetic raindrop impact is necessary to create surface seals with very low hydraulic conductivity (<1 mm h^{-1}) on the soils studied, it has been shown that rapid soil wetting alone can significantly reduce infiltration rates to approximately 30 mm h^{-1} for loose cultivated soils of the type studied. This suggests that both rapid soil wetting and raindrop kinetic energy effects must be accounted for in the prediction of infiltration into sealing soils under higher intensity rainfall.

2. An apparent interaction has been identified resulting in a greater degree of surface sealing when rapid soil wetting occurs concurrently with energetic raindrop impact than when it precedes energetic raindrop impact. An explanation for this effect has been proposed based on the reduction in seal hydraulic conductivity in response to greater hydraulic gradients across the sealing layer of initially dry soils observed in other studies.

3. Effects of rapid soil wetting on pre-ponding surface sealing have been successfully isolated from effects of initial hydraulic gradient. The results show that the difference in initial soil water potential between air dry soil and soil at -10 kPa can have as much effect on the volume of rainfall required for ponding as preventing slaking by pre-wetting soils under tension. Future assessments of the importance of rapid soil wetting in pre-ponding surface sealing should isolate the influence of differences in hydraulic gradient due to differences in

initial soil water potential.

4. Statistically significant increases in seal permeability for repacked soil from under conservative soil management found by Sharma *et al.* (1981), Loch (1994b) and others have been confirmed in the current study. SWIM Simulation studies suggest that such increases in permeability can be relatively effective in reducing surface runoff under moderate rainfall intensities at the time when cropping soils are cultivated and freshly sown to winter cereal crops.

5. It has been shown that inferred rates of decline in surface hydraulic conductivity prior to ponding are more rapid than rates of decline predicted by backwards extrapolation of surface hydraulic conductivity measured after ponding. Therefore soil infiltration models relying on a single rate of exponential decline in surface hydraulic conductivity or conductance may be in error when applied to loosely packed soils similar to those studied.

6. The cause of this relatively more rapid decline in hydraulic conductivity during the pre-ponding phase has been shown to be unrelated or only partially related to aggregate slaking due to rapid soil wetting. An alternative explanation for the effect is proposed in Chapter 5.

7. It has been shown that threshold soil wetting rates and threshold raindrop kinetic energy levels required for surface sealing are inappropriate for the soils studied or are so low as to be practically insignificant.

8. It has been shown that changes in rainfall intensity over the range 16.5 to 66 mm h^{-1} following tension pre-wetting have little effect on surface sealing behaviour for soil under the conservative tillage treatment at Condobolin.

9. It has been proposed that an alternative explanation exists for increased surface seal hydraulic conductivity under higher rainfall intensity found in other published studies. It is suggested that increased surface seal hydraulic conductivity may result as a consequence of less negative sub-seal soil water potentials that occur under higher rainfall intensities in accordance with observations in other studies (eg., Rose, 1962; Morin *et al.*, 1981; Silburn and Foley, 1994). The actual physical mechanism by which this occurs remains uncertain.

10. Water movement simulation studies have been used to show that the mechanism proposed by P.J. Ross to explain the negative correlation between seal conductivity and hydraulic gradient across the seal observed by Silburn and Foley (1994) may not require underlying

unsealed soil and may be limited to cases where the sub-seal water potential is below the air entry value of the surface seal.

Chapter 5

AGGREGATE BREAKDOWN AS AFFECTED BY WETTING RATE, RAINDROP KINETIC ENERGY, SOIL AND TILLAGE TREATMENT

5.1 INTRODUCTION AND OBJECTIVES

Published literature (see section 2.4.) identifies rapid soil wetting and energetic raindrop impact as the more important agents of aggregate breakdown under rainfall. It also identifies, in a general way, antecedent soil water conditions and rainfall intensities as determinants of the relative importance of these agents (eg., Le Bissonnais, 1990). Further, the inferred importance of these agents and of other processes has been related to seal micromorphology and has been used to categorise a range of crusts on loamy and sandy soils and predict their infiltrability (eg., Valentin and Bresson, 1992).

Studies seeking to quantify the magnitude of aggregate breakdown related to rapid soil wetting and highly energetic raindrop impact for a given soil or soils have generally compared breakdown of dry soil aggregates under rainfall with high and low kinetic energy (eg., Loch and Foley, 1994). In section 2.4.1 potential deficiencies were identified in these types of studies. Initially dry soil conditions maximise the potential for aggregate breakdown due to rapid soil wetting and hence reduce the potential effect of highly energetic raindrop impacts. The current chapter aims to remedy the deficiency by quantifying the degree of aggregate breakdown caused by highly energetic raindrop impact both in the presence of rapid wetting (comparing high and low kinetic energy rainfall on dry soil) and in the absence of rapid wetting (comparing high and low kinetic energy rainfall on soil pre-wet slowly under tension). These data provide an estimate of the upper and lower bounds of the effect of an amount of energetic raindrop impact over varying antecedent soil water conditions.

Further, the current chapter aims to assess differences in the degree of aggregate breakdown when energetic raindrop impact occurs subsequent to rapid soil wetting (the case for high kinetic energy rain falling on rapidly pre-wet soil) rather than concurrently with rapid soil wetting (the case for high kinetic energy rain falling on dry soil). It is well known that the strength of soil aggregates may vary with water content. The degree of aggregate breakdown caused by initial raindrop impacts may therefore differ between the two cases despite identical soil wetting rates. In addition, Farres (1980) proposed a mechanism for interaction whereby energetic impacts may be less effective in breaking aggregates when they are rapidly pre-wet

without impact. He proposed that a time interval between wetting and impact allowed for relaxation of the stresses caused within an aggregate by rapid wetting.

Studies quantifying rates of aggregate breakdown in addition to degree of breakdown are less common. As identified in section 2.4.1, there are also potential shortcomings in those studies that focus on breakdown under rainfall only for initially dry soils (eg., Glanville and Smith, 1988). In such studies, the magnitude of the effects of rapid soil wetting under rainfall is only assessed by comparing soil that has been wet rapidly under very low energy rainfall with soil that has been pre-wet slowly under tension but not subjected to any rainfall simulation. Any aggregate breakdown caused by mechanical forces during preparation and low energy rainfall simulation may be inappropriately attributed to rapid soil wetting. The current study seeks to remedy this deficiency by quantifying rates of aggregate breakdown under high kinetic energy rainfall for soil that has been pre-wet slowly under tension as well as initially dry soil.

The response of soil to rapid wetting and energetic raindrop impact is moderated by aggregate stability. Aggregate stability will be influenced by inherent soil properties such as soil texture and clay type that are related to soil classification. It may also be influenced by transient soil properties, such as organic matter content, that can lead to increased aggregate stability under conservative agricultural management. Previous studies have observed (eg., Loch, 1994b) or inferred (eg., Sharma *et al.,* 1981) that significantly less aggregate breakdown under rainfall occurs in soil that has been under more conservative agricultural management. It has been argued that the practical significance of the greater aggregate stability through increasing infiltration of limited rainfall is small relative to benefits from retaining crop residue for protection of the soil surface (Loch, 1994b). However, in Chapter 4, water balance simulations using measured hydraulic property data suggested that reduced and retarded surface sealing of soil from conservative tillage treatments could significantly influence infiltration under rainfall intensities expected in the cropping zone of central New South Wales. This chapter examines the influence of tillage management on both the rate and degree of aggregate breakdown caused by rainfall under varying soil wetting conditions and raindrop kinetic energy. The findings are used draw conclusions on the relative magnitude of the capacity of the two agents to cause breakdown and to evaluate potential explanations for the significant differences in soil hydraulic behaviour associated with tillage treatments that are described in Chapter 4.

To summarise Chapter 3, the current study used three soil wetting pre-treatments and two rainfall kinetic energy levels to isolate the relative effects of rapid soil wetting (both preceding and concurrent with rainfall simulation) and energetic raindrop impact on aggregate breakdown (see Table 3.2). The effect of energetic raindrop impact was isolated by High (27.3 J m^{-2} mm^{-1}) and Low (0.3 J m^{-2} mm^{-1}) kinetic energy rainfall treatments (both at an intensity of 33 mm h^{-1}). The effect of rapid soil wetting was isolated by different wetting pre-treatments. Slow wetting under the Tension wetting pre-treatment was contrasted with rapid soil wetting both prior to rainfall treatment under the Rapid wetting pre-treatment and concurrent with rainfall treatment under the Dry pre-treatment. Soils were sampled from

Conservative and Traditional tillage treatments at both Cowra (Cowra DD and Cowra TT respectively) and Condobolin (Condobolin RH and Condobolin BC respectively).

Three sets of data on aggregate breakdown were gathered under the treatments and pre-treatments described above. The first two quantify the total degree of aggregate breakdown and the third quantifies both the rate and degree of aggregate breakdown under energetic raindrop impact. The first set consists of initial and final aggregate size distributions (and associated summary statistics) for samples taken from the uppermost 10 mm deep layer of soil following R series rainfall-runoff simulations (the R series). The second set of samples was also taken following R series rainfall-runoff simulations. The samples were taken from three of the four soil/tillage treatment combinations according to the procedure of Loch (1994a) (the L series). Both R and L series data provide information on the total degree of aggregate breakdown brought about by pre-treatment and treatment combinations for each soil. The third set of information consists of aggregate size distributions of 5 mm deep samples subjected to 5, 10, 15, 30 and 60 mm of high kinetic energy rainfall following pre-treatments identical to infiltration simulations (the AT series).

Samples of bulk soil and packed columns were taken to determine initial aggregate size distributions, and the effects of column packing and sampling on these distributions. Routine aggregate stability determinations using wet sieving (Kemper and Rosenau, 1986) were also made for bulk samples of the four soil/tillage treatment combinations.

This chapter begins with a discussion of initial aggregate size distributions and the effects of packing and sampling. It presents data indicating the total degree of aggregate breakdown under simulated rainfall. This is followed by data indicating the rate of aggregate breakdown under rainfall followed by routine aggregate stability data. As well as being used to achieve the objectives prefaced above, the data presented in this chapter are used in Chapter 4 to evaluate various explanations hypothesised for surface soil hydraulic behaviour under rainfall described in that chapter. The data are also used in Chapter 6 to evaluate relationships between aggregate breakdown and surface hydraulic behaviour and hydraulic properties under rainfall.

Throughout this and other chapters four summary statistics, Geometric Mean Diameter (GMD), Mean Weight Diameter (MWD), median diameter (D50) and percentage of particles less than 0.125 mm in diameter (%<0.125 mm) are used to quantify aggregate size distributions. These statistics are defined in section 2.3.6.

5.2 INITIAL AGGREGATE SIZE DISTRIBUTION AND THE EFFECTS OF COLUMN PACKING AND SAMPLING.

5.2.1 Initial Aggregate Size Distribution

Figure 5.1 shows the cumulative aggregate size distribution of bulk samples of the four soil/tillage treatment combinations determined by dry sieving. These distributions represent the mean of two replicate determinations.

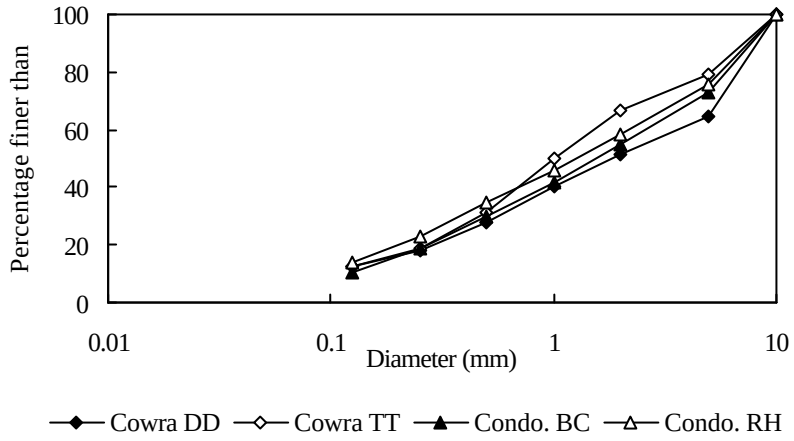

Fig 5.1 Initial aggregate size distribution of Cowra and Condobolin soils under Traditional and Conservative tillage treatment as determined by dry sieving.

Summary statistics from the size distributions of bulk soil samples in Figure 5.1 are listed in Table 5.1. It is evident from the data in Table 5.1 that, on average, Cowra and Condobolin soils have relatively similar initial aggregate size distributions and that the more conservative tillage treatment at each site has a slightly coarser aggregate size distribution. The dry sieving procedure used to determine these size distributions (Kemper and Rosenau, 1986) incorporates a correction to account for aggregate breakdown caused during sieving. Therefore the differences among the data in Table 5.1 should represent differences in initial size distribution of aggregates and particles rather than differences in dry aggregate stability.

Table 5.1 Statistics summarising aggregate size distributions for Cowra and Condobolin soils under Traditional and Conservative tillage treatment determined by dry sieving (Kemper & Rosenau, 1986).

Soil	GMD (mm)	MWD (mm)	D50 (mm)	%<0.125 mm
Cowra DD	1.50	3.42	1.40	12.6
Cowra TT	1.07	2.46	1.00	12.3
Condo. RH	1.36	3.04	1.32	10.5
Condo. BC	1.14	2.76	1.36	13.6

Assessment of the initial degree of aggregation of each soil, as opposed to aggregate size distribution, requires consideration of the primary particle size distribution. Table 5.2 list the summary statistics calculated from the cumulative size distribution of bulk soil samples

following chemical and physical dispersion. These data indicate that Cowra and Condobolin soils have a similar particle size distribution. Comparison of values listed in Tables 5.1 and 5.2 suggests that the coarser aggregate size distribution found under the more conservative tillage treatments at each site result from a greater degree of aggregation rather than coarser primary particle size distribution.

Table 5.2 Statistics summarising particle size distributions for Cowra and Condobolin soils under Traditional and Conservative tillage determined by wet sieving following chemical and physical dispersion.

Soil	GMD (mm)	MWD (mm)	D50 (mm)	%<0.125 mm
Cowra DD	0.50	0.43	0.19	45.6
Cowra TT	0.50	0.45	0.20	44.0
Condo. BC	0.51	0.42	0.17	43.0
Condo. RH	0.51	0.42	0.17	42.3

5.2.2 Effects of Column Packing and Sampling

The effect of column packing procedures and aggregate sampling procedures on measured aggregate size distribution is illustrated for the Cowra TT soil in Figure 5.2. This figure shows cumulative aggregate size distributions for [1] bulk Cowra TT soil determined by wet sieving after tension wetting, [2] identical soil prepared and packed in a column, then sampled while dry and wet sieved following tension wetting, and [3] identical soil prepared and packed in a column, then tension pre-wet, then sampled and wet sieved. Assuming that the sampling procedure itself does not significantly damage dry soil aggregates, then differences between [1] and [2] are attributable to column packing while differences between [2] and [3] are attributable to breakdown of wet soil aggregates during the sampling procedure.

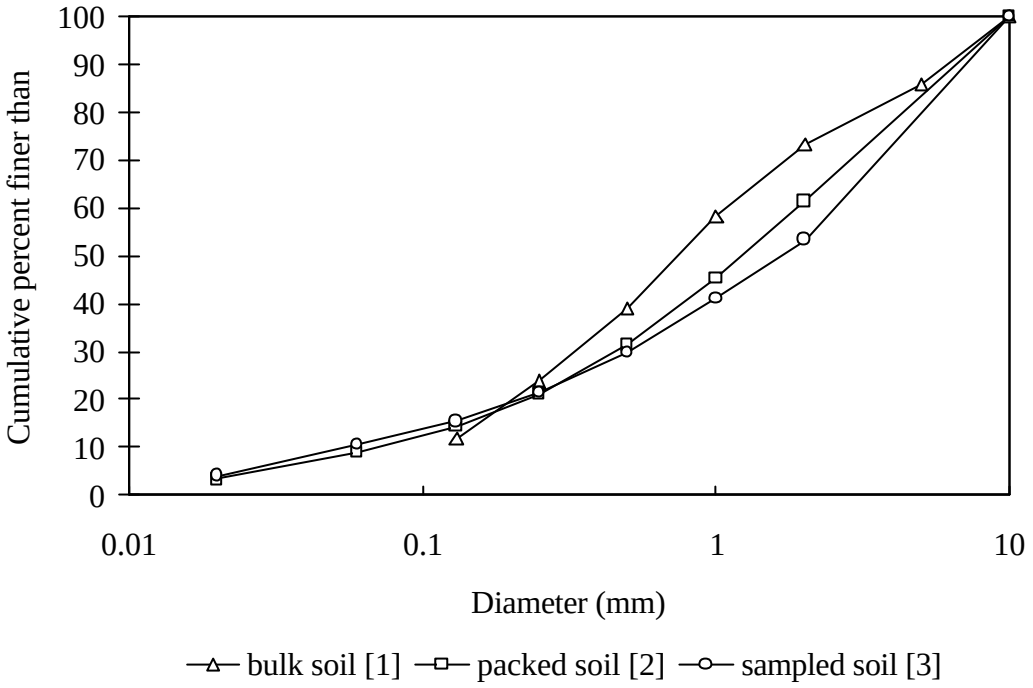

Fig 5.2 Changes in aggregate size distribution caused by column packing and aggregate sampling of Cowra TT soil.

The significance of the effects of column packing and aggregate sampling are further illustrated by the summary statistics in Table 5.3 calculated from the size distributions in Figure 5.3.

Table 5.3 Changes in aggregate size distribution caused by column packing and aggregate sampling of Cowra TT soil.

	GMD	MWD	D50	%<0.125 mm
Bulk soil	0.835[a]	1.9589[a]	0.784[a]	11.79[a]
Packed soil	1.026[b]	2.7254[b]	1.300[b]	14.47[b]
Sampled soil	1.126[b]	3.0635[b]	1.850[c]	15.56[b]

Notes: Each value is the mean of four replicates.
Superscripts denote statistically significant differences (P = 0.05).

Analysis of variance indicates that there are significant differences in mean values of GMD, MWD, D50 and %<0.125 mm among the bulk samples and the packed and tension pre-treated samples (P<0.05). Three of these summary statistics indicate that packing produced a coarser aggregate size distribution than the bulk soil and that sampling caused no significant change. Mean %<0.125 mm indicates that whilst the packed soil surfaces had disproportionately more large aggregates, they also had disproportionately more fine material indicating a bi-modal effect of packing on surface aggregate size distribution.

A degree of aggregate breakdown during column packing, sampling and aggregate size measurement is unavoidable. The significantly finer distribution for Cowra TT R series samples extracted from a column compared with samples taken from the bulk soil and then tension wet indicates that there is a degree of aggregate sorting and or aggregate breakdown caused by the packing process.

Whilst the use of the sample rifling box may have reduced the degree of non-random packing, the consolidation using the vibrating electric shaker, that was necessary to achieve a realistic bulk density without wetting or mechanically damaging surface aggregates, may have resulted in unavoidable aggregate sorting.

Comparison of aggregation statistics for bulk Cowra TT soil (see Table 5.1) with R series data (presented in Table 5.3) for the same soil indicates that the magnitude of the effect of sorting is approximately one quarter to one third of the total difference in aggregate size distribution between bulk soil and post-rainfall surfaces, as measured by change in MWD or GMD. While aggregate sorting during column packing is generally not desirable, it is extremely difficult to avoid. There are two potential disadvantages of aggregate sorting during column packing. Firstly, the extent of sorting may be dependent on the aggregate size distribution of the soil packed hence producing a soil dependent bias. Secondly, results may not be comparable with results from other studies using different packing procedures. In an attempt to minimise the effect of sorting, consistent locations within the column were used for all aggregate sampling in the R series. If the degree of sorting is systematically related to column geometry across all packed columns then the sorting effect of packing will have been accounted for in measured initial aggregate size distributions and should not influence treatment comparisons.

The effect of the sampling procedure used in R series samples was determined using Cowra TT soil only. There was a significant difference between aggregate size distributions of Cowra TT samples taken from a dry column and then tension wet and size distributions of samples of the same soil taken from a tension pre-wet column, but only for the D50 statistic (see Table 5.3). D50 for the sample taken dry and then tension wet was lower than that for the sample taken directly after tension wetting. This is contrary to the expectation that greater aggregate breakdown during sampling would occur if the aggregates were sampled when wet due to lower aggregate strength. It appears unlikely that any significant aggregate breakdown was caused by the R series sampling procedure.

Bulk samples of Cowra TT soil have statistically significantly finer aggregate size ($P<0.05$) as measured by D50 and MWD but not GMD or %<0.125 mm following wet sieving after tension wetting than following dry sieving. The dry sieving procedure involves a back-correction for the erosive effects of the slight mechanical energy involved in gentle hand-sieving (Kemper and Rosenau, 1986). Providing that this back-correction is adequate and providing that tension pre-wetting prior to wet sieving was sufficient to eliminate potential for aggregate slaking, the data indicate that the mechanical action involved in wet sieving can result in some degree of aggregate breakdown.

Disruptive effects involved in aggregate sizing by wet sieving or any other method of aggregate sizing have been recognised by others and is it generally accepted that the determination of aggregate size and stability are inseparable. The appropriate method of aggregate size/aggregate stability determination is that which best simulates the processes of interest (Kemper and Rosenau, 1986). In the absence of an aggregate sizing technique without disruptive forces, some breakdown involved in wet sieving must be accepted. This may result in erroneous conclusions where samples differ in their relative stability to the mechanical energy involved in sieving.

5.3 THE DEGREE OF AGGREGATE BREAKDOWN MEASURED UNDER SIMULATED RAINFALL.

5.3.1 Final Aggregate Size Distribution and the Degree of Aggregate Breakdown

As indicated above, three alternative sets of data quantify the final aggregate size distribution and hence the degree of breakdown. The R series samples were taken from 0 to 10 mm deep below the surface of each rainfall-runoff simulation following approximately 66 mm rainfall. The L series samples were taken at the same time as R series samples but using the method of Loch (1994a). No L series samples were taken for Cowra TT simulations. The final sampling of the AT series was taken from the 0 to 5 mm depth range following approximately 60 mm high kinetic energy rainfall on soil in separate containers prepared and pre-treated identically to high raindrop kinetic energy R series samples.

5.3.1.1 R Series Results

Figures 5.3 a) to d) show cumulative size distributions for aggregates in R series surface samples following pre-treatment and treatment of the soils. Distributions shown represent means taken over two samples from each of two replicate simulations. All pre-treatment and treatment combinations produced finer surface aggregate size distributions relative to the untreated tension pre-wet surface. Tension pre-wetting and rainfall with zero energy resulted in the coarsest final aggregate size distribution.

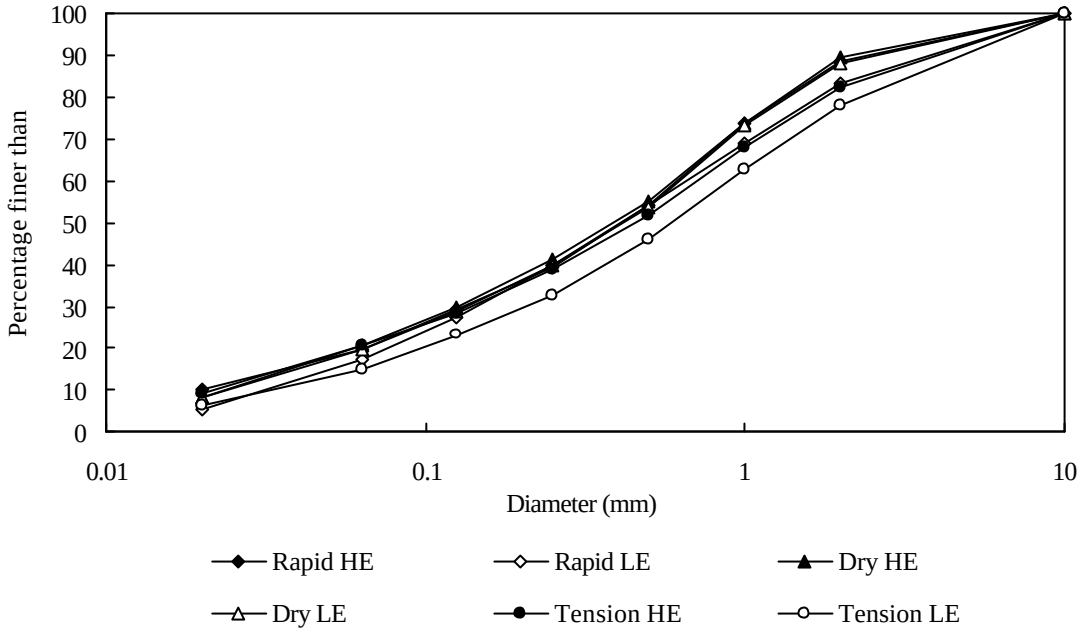

Fig 5.3a) The effects of wetting pre-treatments and raindrop kinetic energy level on cumulative aggregate size distribution of Cowra TT (HE = high kinetic energy rainfall and LE = low kinetic energy rainfall).

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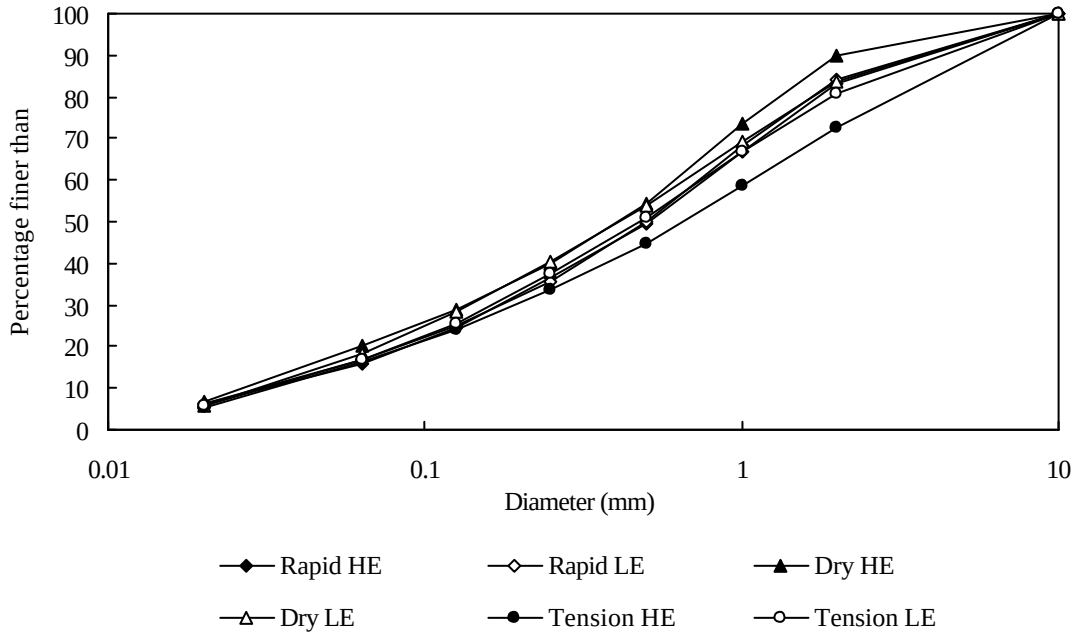

Fig 5.3b) The effects of wetting pre-treatments and raindrop kinetic energy level on cumulative aggregate size distribution of Cowra DD (HE = high kinetic energy rainfall and LE = low kinetic energy rainfall).

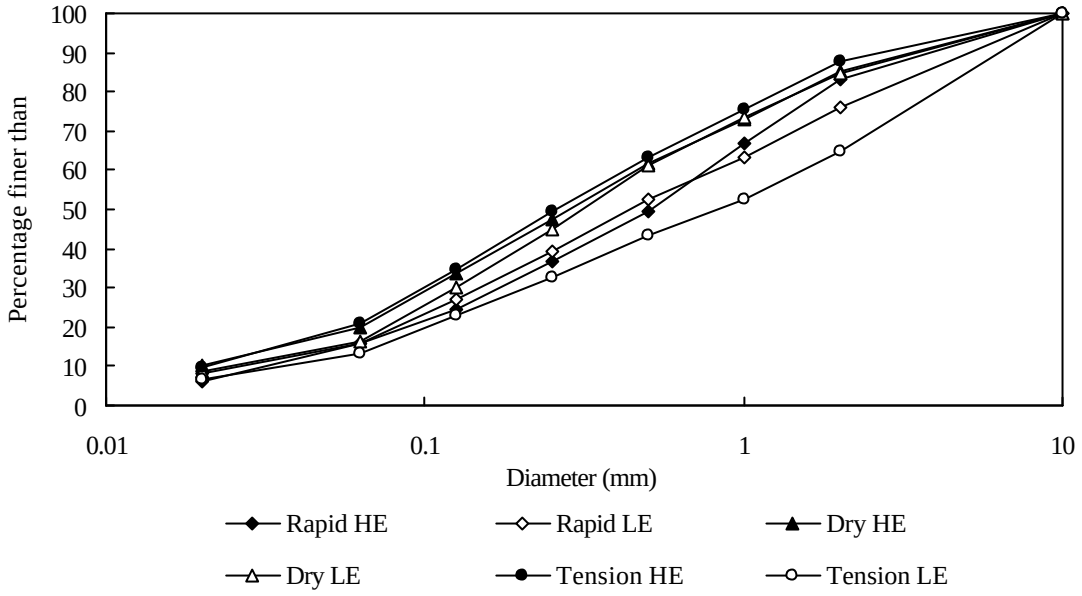

Fig 5.3c) The effects of wetting pre-treatments and raindrop kinetic energy level on cumulative aggregate size distribution of Condobolin RH (HE = high kinetic energy rainfall and LE = low kinetic energy rainfall).

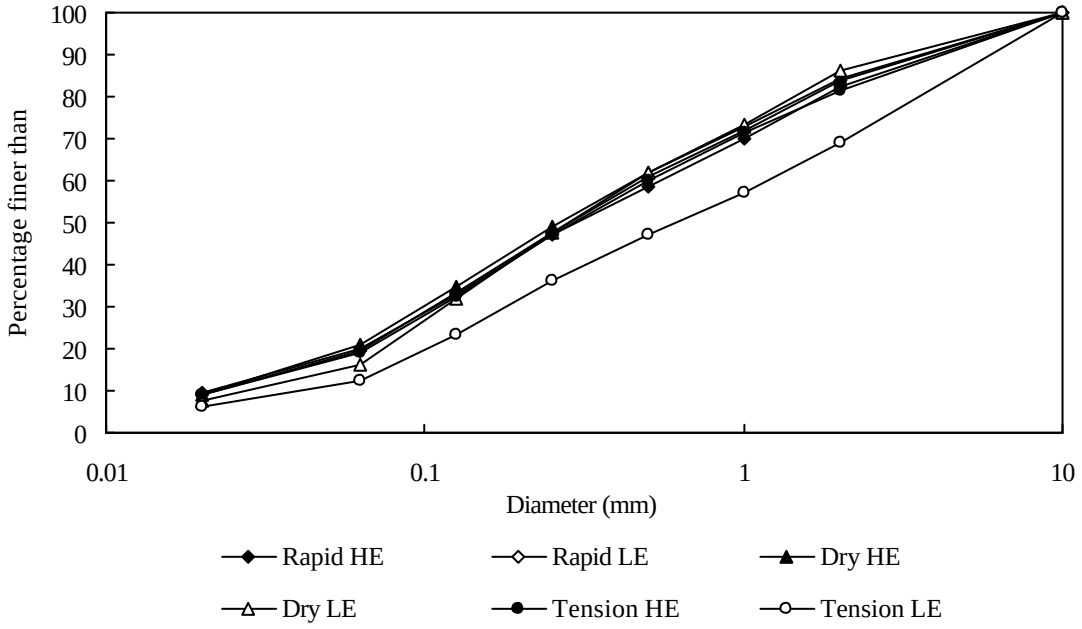

Fig 5.3d) The effects of wetting pre-treatments and raindrop kinetic energy level on cumulative aggregate size distribution of Condobolin BC (HE = high kinetic energy rainfall and LE = low kinetic energy rainfall).

Analysis of variance among aggregation statistics indicates that wetting pre-treatment and raindrop kinetic energy level had significant effects as measured by all of the aggregation

statistics (P<0.05). Tillage treatment had significant effects as measured by all of the aggregation statistics except MWD (P<0.05). Soil had significant effects as measured by D50 and %<0.125 mm (P<0.05). Tables 5.4 to 5.8 present mean values of each of the aggregation statistics for each of the main factors.

Table 5.4 Final aggregate size distribution following rainfall as affected by soil wetting pre-treatment.

Pre-wetting	GMD (mm)	MWD (mm)	D50 (mm)	%<0.125 mm
Dry	0.34[a]	1.22[a]	0.39[a]	30.9[a]
Rapid	0.38[a]	1.39[a]	0.42[a]	29.0[b]
Tension	0.53[b]	1.85[b]	0.63[b]	25.9[c]
Least. sig. diff. P=0.05	0.06	0.19	0.09	2.0

Notes: Superscripts denote significant differences (P<0.05)
n=32

Mean values in Table 5.4 indicate that tension pre-wet samples had coarser final aggregate size distributions, than dry and rapidly pre-wet samples as measured by all statistics. The data also suggest that rain falling on initially dry soils results in finer final aggregate size distributions than rain falling on rapidly pre-wet soils. This effect was statistically significant for %<0.125 mm (P<0.05) and almost significant for MWD (P<0.08). Variance was slightly greater for tension pre-wet samples and two-tailed t-tests with unequal variances were subsequently carried out for MWD and GMD with tension pre-wet results omitted. These tests indicated that mean values for statistics calculated from final aggregate size distributions (presented in Table 5.4) were significantly finer for initially dry samples than for rapidly pre-wet soils as measured by GMD and MWD (P<0.05). Such a finding under high kinetic energy rainfall may suggest some form of interaction between energetic raindrop impact and concurrent rapid wetting resulting in a greater degree of breakdown. However, it is apparent from data in Table 5.6 that this effect also occurred under low kinetic energy rainfall. This occurrence would be consistent with either an interaction between raindrops and concurrent rapid wetting that occurred irrespective of kinetic energy level or with an effect whereby lower initial soil water content lead to greater aggregate breakdown independent of soil wetting rate.

High raindrop kinetic energy treatments produced finer size distributions than the low kinetic energy treatments. Mean values, listed in Table 5.5, indicate that the magnitude of the effect of highly energetic raindrop impact, as measured by final aggregate size distribution for the 0 to 10 mm layer, is generally less than the magnitude of the effect of rapid soil wetting or pre-wetting indicated by Table 5.4. The relative magnitude of the former effect is generally around half or less than half when considered across all three wetting pre-treatments.

Table 5.5 Final aggregate size distribution following rainfall as affected by raindrop kinetic energy level.

Kinetic Energy	GMD (mm)	MWD (mm)	D50 (mm)	%<0.125 mm
High energy	0.38[a]	1.40[a]	0.44[a]	30.0[a]
Low energy	0.45[b]	1.58[b]	0.53[b]	27.1[b]
Least. sig. diff. P=0.05	0.03	0.15	0.07	1.6

Notes: Superscripts denote significant differences (P=0.05)
n=48

Table 5.6 lists mean values for each kinetic energy level by wetting pre-treatment combination. The effect of high raindrop kinetic energy in the absence of rapid soil wetting is estimated by the difference between tension pre-wet soil under high and low kinetic energy rainfall. The effect of rapid soil wetting alone is estimated by the difference between tension pre-wet and either the dry or rapidly pre-wet soil under low energy rainfall. It is apparent from these data that the effect of high raindrop kinetic energy was 50% to 70% of that of rapid soil wetting alone.

Closer inspection of the data reveals that for Condobolin soil and for Cowra soil under Traditional tillage treatments the influence of high kinetic energy raindrop impact on final aggregate size distribution is greater for tension pre-wet soils than rapidly pre-wet or initially dry soils. However, the energy by wetting pre-treatment interaction terms proved to be statistically non-significant (P=0.05) for all aggregation statistics. This was apparently due to the influence of two anomalous replicates for Cowra DD. Results for Condobolin soil and Cowra TT for GMD, MWD and D50 suggest that surface aggregate breakdown can be caused by either rapid soil wetting or by high kinetic energy raindrop impact. Such an interaction is physically feasible since both rapid soil wetting and energetic impact can readily break surface aggregates and the potential for aggregate breakdown is limited by the particle size distribution. Initial soil water condition and the amount of surface protection from raindrop impact will determine which of the two agents occurs in a given instance. Where soil is initially dry, rapid soil wetting (see Section 2.3.3.2) will be the dominant cause of breakdown. Where soil is initially wet, energetic raindrop impact (see Section 2.3.3.1) will be the dominant cause of further breakdown.

Table 5.6 The effects of raindrop kinetic energy and soil wetting pre-treatment on final aggregate size distribution following rainfall.

Kinetic Energy/ Pre-wetting	GMD (mm)	MWD (mm)	D50 (mm)	%<0.125 mm
High energy/Dry	0.32	1.18	0.36	31.8
Low energy/Dry	0.35	1.26	0.42	29.9

High energy/Rapid	0.35	1.28	0.41	30.4
Low energy/Rapid	0.41	1.51	0.44	27.5
High energy/Tension	0.47	1.72	0.54	27.9
Low energy/Tension	0.59	1.98	0.72	23.8

Final aggregate size distributions were coarser for conservative tillage treatments at each site (see Table 5.7) as measured by GMD, D50 and %<0.125 mm (P<0.05). The magnitude of this effect was similar to the effect of high kinetic energy raindrop impact. Final aggregate size distributions were also coarser for Cowra soil than Condobolin soil (see Table 5.8) but only as measured by D50 and %<0.125 mm (P<0.05).

Table 5.7 Final aggregate size distribution following rainfall under Traditional and Conservative tillage treatments.

Tillage treatment	GMD (mm)	MWD (mm)	D50 (mm)	%<0.125 mm
Traditional	0.39[a]	1.42	0.43[a]	29.5[a]
Conservative	0.45[b]	1.56	0.54[b]	27.6[b]
Least. sig. diff. P=0.05	0.03	0.15	0.07	1.6

Notes: Superscripts denote significant differences (P=0.05)
n=48

Table 5.8 Final aggregate size distribution following rainfall for Cowra and Condobolin soil.

Soil	GMD (mm)	MWD (mm)	D50 (mm)	%<0.125 mm
Cowra	0.42	1.42	0.52[a]	27.1[a]
Condobolin	0.41	1.56	0.45[b]	30.1[b]
Least. sig. diff. P=0.05	0.03	0.15	0.07	1.6

Notes: Superscripts denote significant differences (P=0.05)
n=48

Whilst the four aggregation statistics used each vary in the weighting given to various aggregate size classes (discussed in section 2.3.6), there is a high degree of correlation between them as indicated by the correlation matrix for the R series data presented in Table 5.9.

Table 5.9 A correlation matrix for alternative statistics measuring aggregation.

	GMD	MWD	D50	%<0.125 mm
GMD	1.000			
MWD	0.938	1.000		
D50	0.928	0.810	1.000	
%<0.125 mm	0.865	0.717	0.791	1.000

Slightly lower correlation between %<0.125 mm and the other statistics may reflect the fact that each of these other statistics can be directly affected by changes in aggregation throughout the full size range, whereas, %<0.125 mm is only affected by changes in aggregation at or below fine sand size ranges.

5.3.1.2 AT Series Results

Mean values of each aggregate size statistic for wetting pre-treatments in the final sampling in the AT time series (after 60 mm of high kinetic energy rainfall) are listed in Table 5.10.

Table 5.10 Final aggregate size distribution following high kinetic energy rainfall in AT simulations as affected by soil wetting pre-treatment.

Pre-wetting	GMD (mm)	MWD (mm)	D50 (mm)	%<0.125 mm
Dry	0.218[a]	0.634[a]	0.23[a]	39.9[a]
Rapid	0.255[b]	0.759[b]	0.24[a]	36.2[b]
Tension	0.319[c]	1.072[c]	0.31[b]	33.6[b]
Least. sig. diff. P=0.05	0.029	0.096	0.04	2.9

Notes: Superscripts denote significant differences (P=0.05)
n=8

As for the R series samples, tension pre-wet samples have significantly coarser aggregate size distribution while initially dry samples have significantly finer aggregate size distribution. The finer aggregate size distribution for initially dry samples is consistent with some form of interaction between energetic raindrop impact and concurrent rapid wetting or with an effect of initial soil water content on aggregate breakdown that is independent of soil wetting rate.

The AT series did not include low raindrop kinetic energy treatments and hence the change in aggregate size attributable to high raindrop kinetic energy cannot be determined. The change in aggregate size attributable to the total high kinetic energy rain input can be estimated by the difference between initial and final aggregation statistics for each wetting pre-treatment, shown in Table 5.11.

While these data will include any non-energy related effects of the raindrop impact that may occur, they still suggest that the energetic raindrop impact is of much greater relative importance for the shallower AT samples than for the deeper R series samples. This further suggests that effects of the energetic raindrop impact may be depth dependent.

Table 5.11 Change in aggregate size under high kinetic energy rainfall in AT simulations as affected by soil wetting pre-treatment (initial - final).

Pre-wetting	GMD (mm)	MWD (mm)	D50 (mm)	%<0.125 mm
Rapid	0.168	0.860	.23	-10.1
Tension	0.584	1.708	.62	-9.6

Unlike the R series results, mean values for the final samples of the shallower AT series presented in Table 5.12 indicate that tillage treatment had no statistically significant effect on final aggregate size distribution. The statistical comparison between tillage treatments presented in Table 5.12 is based on a considerably smaller sample than that in Table 5.7. However, variance in the latter data set was lower and least significant differences are of similar magnitude. This suggests that the lack of significant differences in Table 5.12 did not result from the smaller sample size. Rather, it suggests that the shallower depth of sampling in the AT series encompassed a zone of greater aggregate breakdown and that any differences in aggregate stability that exist between tillage treatments were relegated to insignificance.

Table 5.12 Final aggregate size distribution following high kinetic energy rainfall in AT simulations for soil under Traditional and Conservative tillage treatments.

Tillage treatment	GMD (mm)	MWD (mm)	D50 (mm)	%<0.125 mm
Traditional	0.260	0.806	0.266	36.3
Conservative	0.268	0.837	0.278	36.8
Least. sig. diff. P=0.05	0.023	0.078	0.033	2.4

Notes: No significant differences (P=0.05)
n=12

Mean values for soils given in Table 5.13 are consistent with the pattern observed for R series samples that Cowra soils maintained a significantly coarser aggregate size distribution but only as measured by D50 and %<0.125 mm.

Table 5.13 Final aggregate size distribution following high kinetic energy rainfall in AT simulations for Cowra and Condobolin soil.

Soil	GMD (mm)	MWD (mm)	D50 (mm)	%<0.125 mm
Cowra	0.254	0.823	0.319[a]	34.8[a]
Condobolin	0.274	0.820	0.226[b]	38.3[b]
Least. sig. diff. P=0.05	0.023	0.078	0.033	2.4

Notes: Superscripts denote significant differences (P=0.05)
n=12

Comparison of the data in Tables 5.5, 5.10 and 5.14 indicates that the coarsest aggregate size distribution was found in the R series samples taken from 0 to 10 mm depth followed by the AT series samples taken from 0 to 5 mm depth followed by the L series samples taken from a less controlled depth range (approximately 0 to 3 mm depth). The most obvious possible explanation for this disparity is that energetic impact was more effective in disrupting aggregates in the shallower soil layers.

5.3.1.3 L Series Results

Table 5.14 lists mean values of %<0.125 mm for L series samples taken according to the method of Loch (1994a) (as described in section 3.4.3) following simulated rainfall on three soil-tillage treatment combinations.

Table 5.14 Final % < 0.125 mm following high and low kinetic energy rainfall for three soil-tillage treatment combinations.

Soil	Pre-treatment					
	Dry		Tension pre-wet		Rapidly pre-wet	
	high energy	low energy	high energy	low energy	high energy	low energy
Cowra DD	44.6	43.5	45.0	48.6	44.3	42.7
Condo RH	56.8	42.4	46.8	45.8	55.7	50.9
Condo BC	62.4	53.9	59.5	54.1	56.6	53.1

Note: n=2

Consistent with the R series data, mean %<0.125 mm values for the L series generally indicate that high raindrop kinetic energy has resulted in finer aggregate size distributions and that this effect is more pronounced on Condobolin soils, (although no L series samples were taken for Cowra TT). Further, conservative tillage reduced %<0.125 mm for Condobolin soil in L series samples as in R series samples.

In contrast with R series and AT series samples, soil wetting pre-treatment did not result in significant differences among the shallower L series samples. Mean values for %<0.125 mm for the three soil wetting pre-treatments in Table 5.10 are within 0.5% of each other. This similarity suggests that the lack of significant difference between soil wetting pre-treatments cannot be explained by the smaller sample number used in the L series. Rather, it appears that the degree of aggregate breakdown observed in the L series samples is controlled chiefly by the presence or absence of highly energetic raindrop impact and that soil wetting is relatively unimportant as a determinant of aggregate breakdown in this shallower layer. This is further supported by comparison of the data in Tables 5.4, 5.10 and 5.14 showing that the coarsest aggregate size distribution was found in the R series samples taken from 0 to 10 mm depth followed by the AT series samples taken from 0 to 5 mm depth followed by the L series samples taken from a less controlled depth range (approximately 0 to 3 mm depth).

As the method of Loch captures a shallower sampling depth range there is less potential for dilution by deeper aggregates less affected by energetic rain-drop impacts. However, this reasoning cannot explain the apparent discrepancy of almost equal magnitude that occurs between R series and L series results under low kinetic energy rainfall. Further, the mean effect of high raindrop kinetic energy is an increase in %<0.125 mm over low kinetic energy of 2.7% in the 10 mm deep R series samples and an increase of only 3.9% in the shallower L series samples. This differential is not sufficient to allow the considerable differences between absolute values in the three sets of data (of the order of 20%) to be explained by depth dilution.

There are three alternative possible explanations. Firstly, the increased %<0.125 mm referred to in section 5.2.2, that was attributed to sorting of surface aggregates during column packing, may have lead to finer initial aggregate size distributions in the 0 to 5 mm layer than the 0 to 10 mm layer. Secondly, there may have been some aggregate sorting process brought about by raindrop impacts (irrespective of kinetic energy level) in the near surface soil that resulted in a difference between the two depth layers. Visual observations of soil surfaces under low kinetic energy rainfall indicated that soil movement was minimal and suggest that this explanation is unlikely. Thirdly, there may have been depth dependent effects of wetting rate. That is, wetting or pre-wetting may actually have occurred more quickly at the very surface resulting in greater aggregate breakdown. At the very surface, individual soil aggregates came into contact with relatively large amounts of free water in the form of raindrops, whereas soil aggregates beneath the surface may have been wetted by infiltrating water under an effective tension equivalent to the sub-seal suction (data from Chapter 4 indicate that this may be of the order of -2 kPa when rain falls on initially dry soil). However, this third explanation is subject to doubt as the large differences in %<0.125 mm between the deeper R series samples and the shallower L series samples were still observed following tension pre-wetting (which should have eliminated any depth dependent effects of wetting).

The values for Cowra DD in Table 5.14 are also considerably greater than the value of 27% given by Loch (1989) for % < 0.125 mm after high energy rainfall simulation on similar soil from the Conservative tillage treatment at the same location sampled at an earlier date. This further discrepancy may possibly be caused by differences in aggregate sorting due to different soil packing methods but the difference in degree of sorting necessary would be extreme.

5.4 TEMPORAL PATTERNS OF AGGREGATE BREAKDOWN MEASURED UNDER SIMULATED RAINFALL

Results from the R series and the final AT sampling define aggregate stability under the considerable forces associated with soil pre-treatment followed by approximately 60 to 66 mm of simulated rainfall. The effect of aggregate stability in moderating the rate at which this breakdown occurs may be of interest both in terms of understanding the relative importance of aggregate breakdown processes and in terms of implications for soil management. The AT series data quantify the temporal pattern of aggregate breakdown as affected by soil, wetting pre-treatment and tillage treatment.

5.4.1 AT Series Results

Temporal patterns of aggregate breakdown under high kinetic energy rainfall simulations illustrated in Figures 5.4 to 5.11 show decline in each summary statistic plotted against cumulative raindrop kinetic energy. For clarity, separate graphs are presented for Cowra and Condobolin soil illustrating aggregate breakdown for soil from Conservative and Traditional tillage treatments. Each point plotted represents the mean of two measurements. Lines plotted on these figures simply identify points in the same series and do not represent fitted or implied functions.

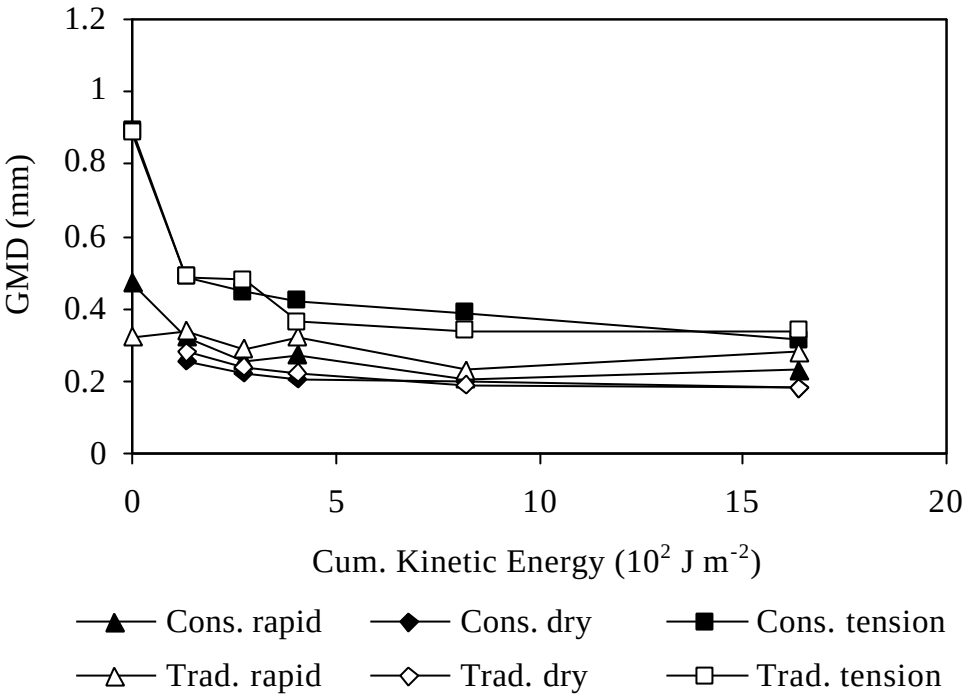

Fig 5.4 Decline in surface aggregation (as measured by declining GMD) as a function of cumulative raindrop kinetic energy for Condobolin soil as affected by soil wetting pre-treatment tillage treatment.

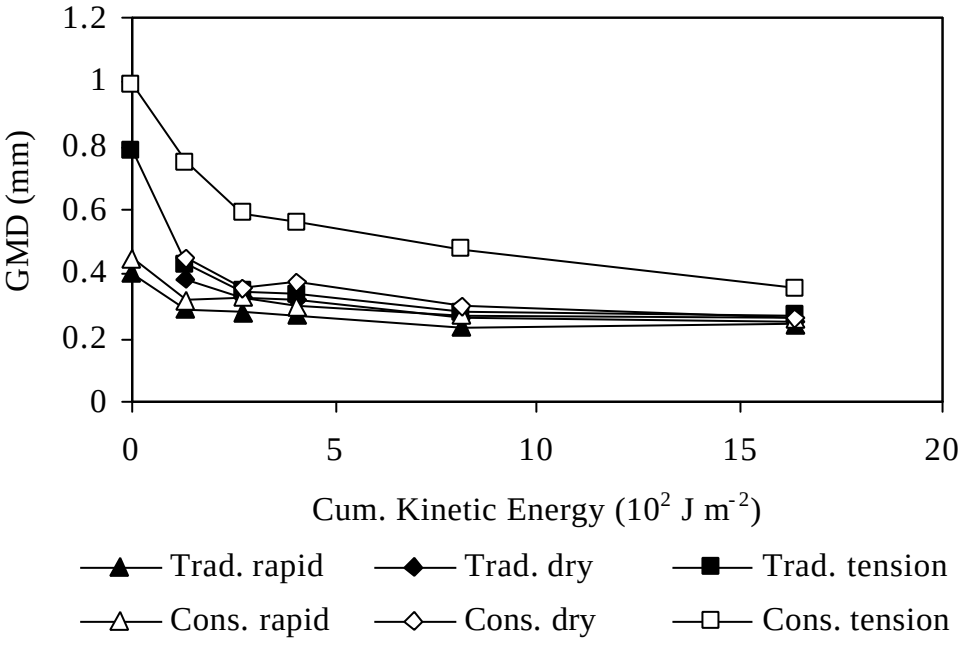

Fig 5.5 Decline in surface aggregation (as measured by declining GMD) as a function of cumulative raindrop kinetic energy for Cowra soil as affected by soil wetting pre-treatment and tillage treatment.

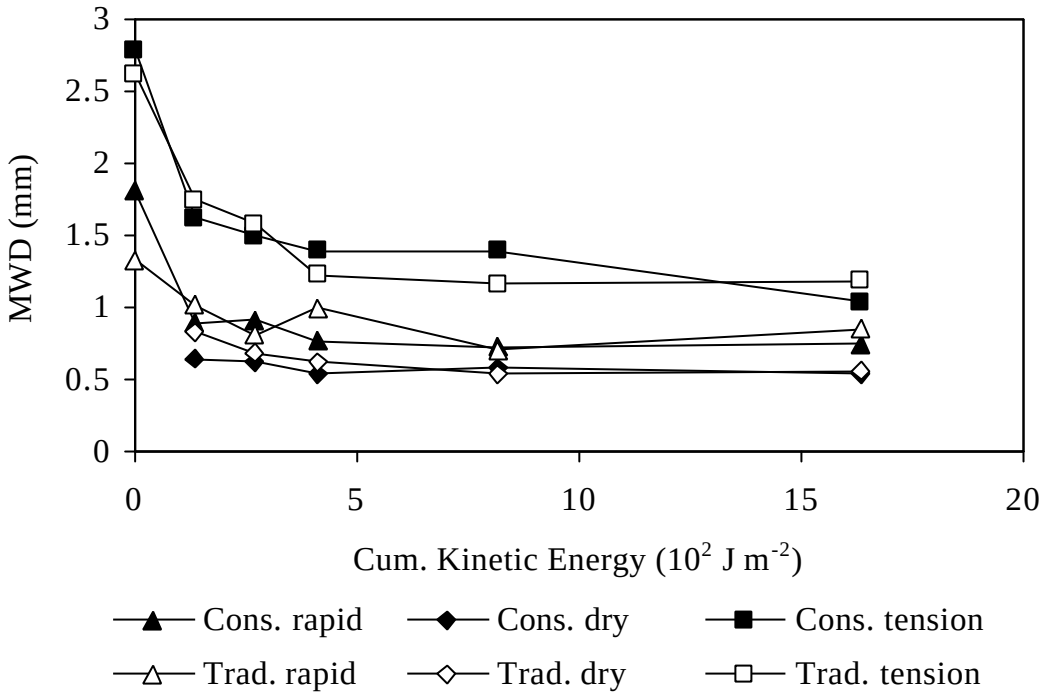

Fig 5.6 Decline in surface aggregation (as measured by declining MWD) as a function of cumulative raindrop kinetic energy for Condobolin soil as affected by soil wetting pre-treatment and tillage treatment.

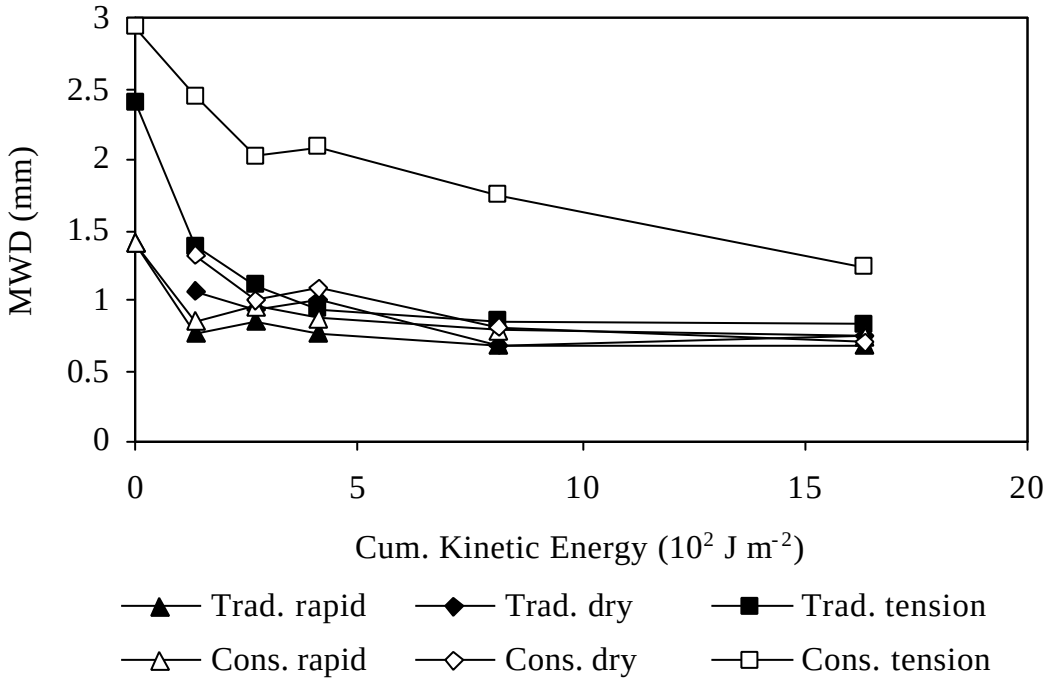

Fig 5.7 Decline in surface aggregation (as measured by declining MWD) as a function of cumulative raindrop kinetic energy for Cowra soil as affected by soil wetting pre-treatment and tillage treatment.

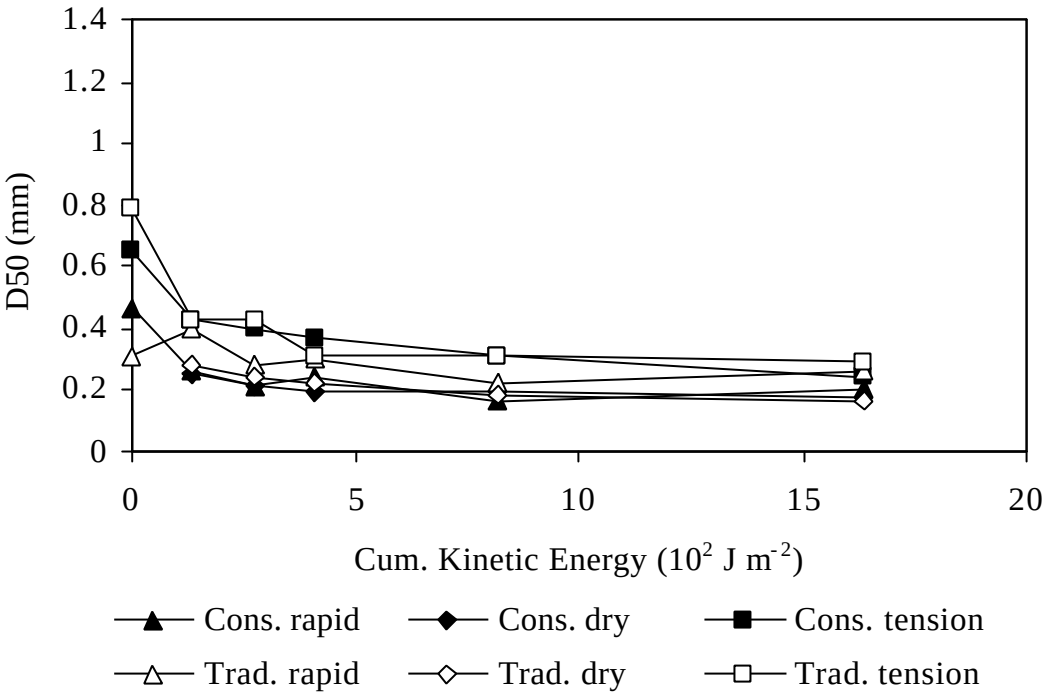

Fig 5.8 Decline in surface aggregation (as measured by declining D50) as a function of cumulative raindrop kinetic energy for Condobolin soil as affected by soil wetting pre-treatment and tillage treatment.

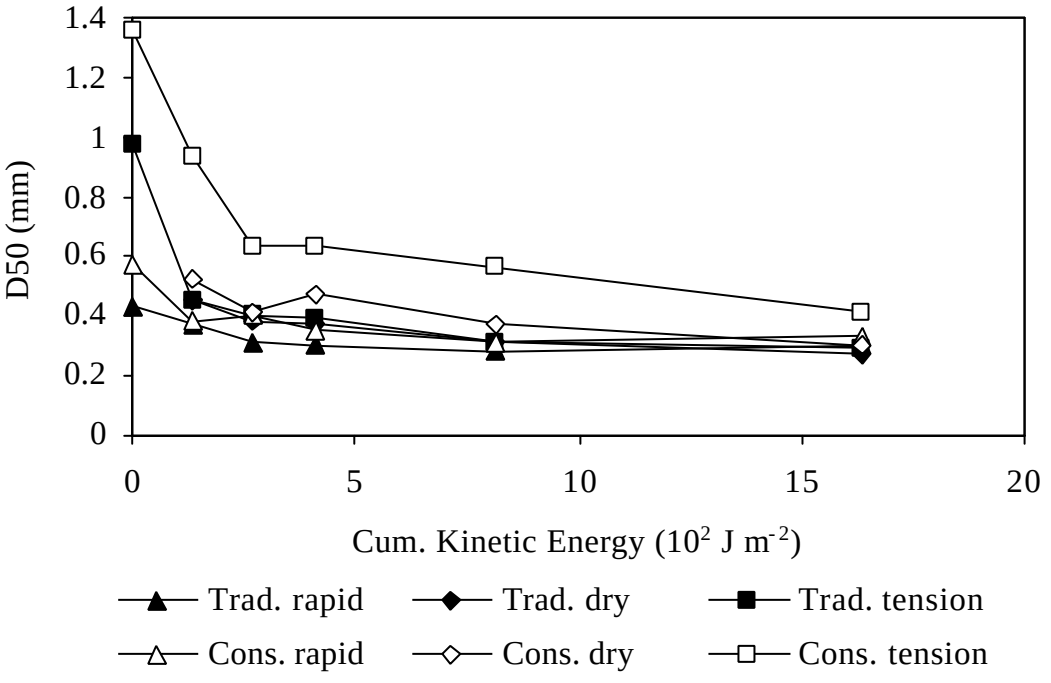

Fig 5.9 Decline in surface aggregation (as measured by declining D50) as a function of cumulative raindrop kinetic energy for Cowra soil as affected by soil wetting pre-treatment and tillage treatment.

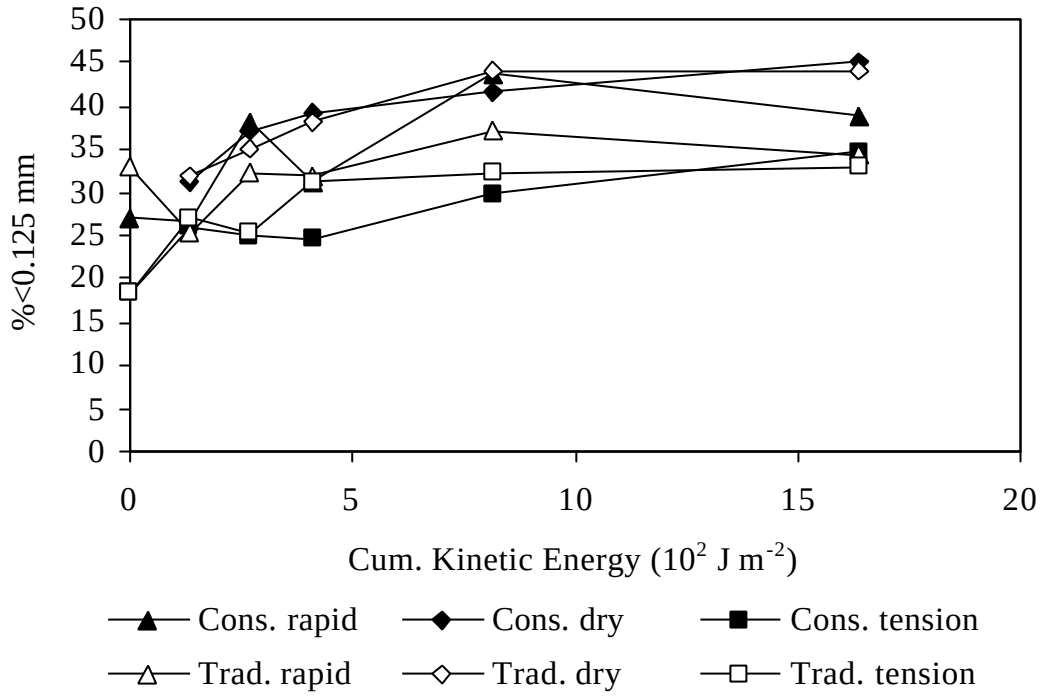

Fig 5.10 Decline in surface aggregation (as measured by increasing % < 0.125 mm) as a function of cumulative raindrop kinetic energy for Condobolin soil as affected by soil wetting pre-treatment and tillage treatment.

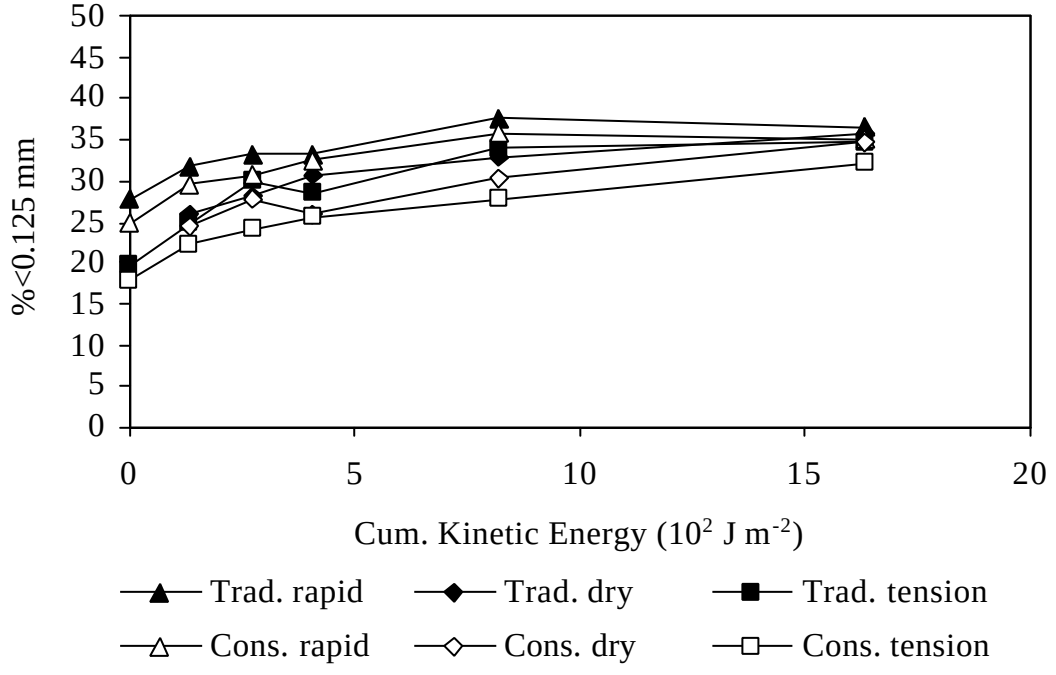

Fig 5.11 Decline in surface aggregation (as measured by increasing % < 0.125 mm) as a function of cumulative raindrop kinetic energy for Cowra soil as affected by soil wetting pre-treatment and tillage treatment.

It is evident from Figures 5.4 to 5.11 that rapid pre-wetting greatly reduced aggregation prior to rainfall and that within the first 5 mm of high energy rainfall initially dry soils have undergone similar breakdown. Aggregate size of both dry and rapidly pre-wet soils continues to decline with high raindrop kinetic energy but appears to approach a lower limit. The initial decline in aggregation is less pronounced for tension pre-wet soils than for dry soils and, with the exception of Cowra TT, tension pre-wet soils maintain coarser aggregate size distribution throughout the duration of the simulations. Nevertheless, tension pre-wet soils exhibit significant breakdown within the first 10 mm of rainfall.

It is also evident from Figures 5.4 to 5.11 that differences in 0 to 5 mm deep sample aggregate size after 60 mm of rainfall are small relative to initial differences associated with soil and tillage treatment. This may be interpreted as an indication that the amount of energetic raindrop impact and the rate of rapid soil wetting used in this study have similar capacity to cause surface aggregate breakdown on these soils and each will do so in the absence of the other. Clearly, the depth of rainfall required to achieve the rapid soil wetting is only of the order of one twelfth of the depth of rainfall required to deliver the total amount of raindrop impact simulated.

The data plotted in Figures 5.4 to 5.11 suggest exponential decline in aggregate size approaching a lower limit. In order to parameterise these temporal patterns of aggregate breakdown under high kinetic energy rainfall, exponential functions of the form

$$A(E) = (A_i - A_f)\, e^{-DE} + A_f \qquad \text{[Eqn. 5.1]}$$

where: $A(E)$ = The value of an aggregate size statistic (ie.,GMD, MWD, D50 or % < 0.125 mm) as a function of cumulative raindrop kinetic energy

A_i = Initial value of the aggregate size statistic

A_f = Final value of the aggregate size statistic

D = A generic fitted aggregation stability factor $mm^2\ J^{-1}$

E = Cumulative Raindrop Kinetic Energy $J\ m^{-2}$

were fitted to 5, 10, 15, 30 and 60 mm data points of each series plotted in Figures 5.4 to 5.11. The form of this function is analogous to that used by Brakensiek and Rawls (1983) to describe declining K_{sat} (presented as Equation 4.4 in section 4.5.1). The fitted aggregation stability factors listed in Table 5.15 allow direct comparison of rates of decline in aggregate size and surface K_{sat}.

Table 5.15 The effects of soil, wetting pre-treatment, and tillage treatment on aggregation stability factors (D) for high raindrop kinetic energy AT simulations.

Soil/Tillage Treatment	Pre-wetting	D(GMD)	D(MWD) (10^4 mm^2 J^{-1})	D(D50)	D(%<0.125 mm)
Cowra TT	Rapid	0.302	0.170	nf	0.309
Cowra TT	Dry	0.278	0.301	0.237	0.222
Cowra TT	Tension	0.404	0.529	0.224	0.278
Cowra DD	Rapid	0.223	0.129	0.307	0.323
Cowra DD	Dry	0.227	0.242	0.166	0.140
Cowra DD	Tension	0.213	0.152	0.302	0.152
Condo BC	Rapid	0.501	0.715	1.036	0.759
Condo BC	Dry	0.337	0.535	0.305	0.321
Condo BC	Tension	0.397	0.514	0.367	0.268
Condo RH	Rapid	0.611	0.419	0.555	0.717
Condo RH	Dry	0.378	0.243	0.462	0.271
Condo RH	Tension	0.151	0.117	0.164	0.111

Notes: nf = not fitted

The aggregation stability factors listed in Table 5.15 were fitted only using aggregate size of samples exposed to 5, 10, 15, 30 and 60 mm of high kinetic energy rainfall. Functions of the same form were refitted using an additional initial value for each statistic determined from samples pre-treated in the same way but not subject to rainfall. Initial aggregate size distributions for dry soils could not be determined using wet sieving without significant breakdown due to slaking. For the purposes of fitting aggregate decline functions they were assumed to be equivalent to those of the corresponding tension pre-wet soil. Re-fitted aggregation stability factors are presented in Table 5.16.

Each of the aggregation stability factors in Table 5.16 was fitted to mean values of aggregate size for two replicates and thus n = 1 for each cell in Table 5.16. This limitation dictated that analysis of variance be carried out on the basis of variance over and above that of the highest order interaction (soil by tillage treatment by pre-wetting).

This analysis of variance indicates that the rate of decline in aggregation with high kinetic energy rainfall was significantly slower for Cowra soil as measured by MWD, %<0.125 mm ($P<0.05$) and almost GMD ($P=0.076$). It also indicates that decline was significantly slower for conservative tillage as measured by MWD and %<0.125 mm. Only %<0.125 mm data indicated significantly more rapid decline for rapidly pre-wet soil.

Table 5.16 The effects of soil, pre-wetting, and tillage treatment on refitted aggregation stability factors (D) for high raindrop kinetic energy AT simulations.

Soil/Tillage Treatment	Pre-wetting	D(GMD)	D(MWD) (10^4 mm^2 J^{-1})	D(D50)	D(%<0.125 mm)
Cowra TT	Rapid	0.618	0.994	1.703	0.362
Cowra TT	Dry	0.868	1.022	0.830	0.274
Cowra TT	Tension	0.749	0.685	0.853	0.308
Cowra DD	Rapid	0.548	0.812	0.768	0.365
Cowra DD	Dry	0.842	0.781	0.973	0.194
Cowra DD	Tension	0.295	0.186	0.426	0.180
Condo BC	Rapid	0.286	0.810	0.251	0.197
Condo BC	Dry	1.351	1.390	1.073	0.431
Condo BC	Tension	0.719	0.605	0.740	0.402
Condo RH	Rapid	0.683	1.317	1.038	0.350
Condo RH	Dry	1.546	2.112	1.269	0.403
Condo RH	Tension	0.601	0.501	0.347	0.146

In almost all cases, the re-fitted aggregation stability factors were higher, indicating more rapid rates of decline in aggregate size when the effects of initial period of rainfall (from 0 to 5 mm) were included. As with the decline in surface K_{sat} described in Section 4.5, the more rapid initial decline indicates that either the exponential form of function fitted is inappropriate or that there are two phases of aggregate breakdown with an initially more rapid rate of aggregate size decline followed by a slower rate of decline.

For the re-fitted aggregation stability factors, listed in Table 5.16, analysis of variance indicates that aggregate size decline was significantly slower for Cowra soil, as measured by GMD and MWD ($P<0.05$), significantly faster for dry soil, as measured by GMD and MWD ($P<0.05$) and significantly faster for traditionally tilled soil at Cowra but not at Condobolin as measured by GMD ($P<0.05$).

5.5 AGGREGATE STABILITY

Table 5.17 lists aggregate stability determined by wet sieving (after Kemper and Rosenau, 1986) of the 1 to 2 mm fraction of the bulk soils following immersion wetting and tension pre-wetting. The proportions of water stable aggregates are expressed in terms of the 1 to 2 mm size fraction, the larger than 1 mm size fraction and the whole soil.

Table 5.17 Water stable aggregation (1-2 mm diameter aggregates) for Cowra and Condobolin soils under Traditional and Conservative tillage.

Soil/Tillage	% of 1-2 mm fraction		% of whole soil		% of soil > 1 mm	
	immersed	tension wet	immersed	tension wet	immersed	tension wet
Condo BC	7.2[a]	62.0[b]	0.9	7.8	3.9	33.5
Condo RH	8.8[b]	66.2[c]	1.2	8.7	5.1	38.8
Cowra TT	17.6[c]	56.9[a]	3.0	9.2	8.9	27.1
Cowra DD	25.5[d]	66.8[c]	2.9	7.6	15.3	40.1
std. error.	0.5	2.0	-	-	-	-

Notes: Superscripts denote statistically significant differences at P = 0.05

The data in Table 5.17 indicate that Tension pre-wetting, increased aggregate stability by a large degree and that Conservative tillage treatments also increased aggregate stability irrespective of aggregate pre-wetting method. These increases in stability due to tillage are greater for Cowra soil than Condobolin soil. The differences in aggregate stability under immersion wetting associated with soil are considerably greater than the increases induced by Conservative tillage treatments. The data suggest that Condobolin soils are more susceptible to aggregate breakdown caused by slaking, resulting from rapid wetting, than Cowra soils.

5.6 COMPARISON WITH PUBLISHED WORK

5.6.1 The Relative Importance of Rapid Soil Wetting and Energetic Raindrop Impact

The potential of both rapid wetting and raindrop impact to cause aggregate breakdown has been recognised and the rainfall and antecedent soil water conditions maximising the occurrence of one or the other have been known for some time (eg., Le Bissonnais, 1990). In practice, varying combinations of the two processes are likely to occur. Quantifying the limits to the magnitude of the potential effect of each of theses processes should improve collective understanding of aggregate breakdown when both processes occur together.

Quantitative studies (eg., Glanville and Smith, 1988; Loch and Foley, 1994) of aggregate breakdown have tended to focus on initially dry soil surfaces. Such conditions maximise the potential for rapid soil wetting effects and hence limit the potential effect that energetic impacts can have. Dry surface soil may well be more common under dryland cropping systems, especially in warm, dry environments where surface cover is limited and soil evaporation is spatially uniform and high. Under a contrasting set of soil and rainfall conditions, the potential effect of energetic raindrop impact in causing aggregate breakdown can be of practical significance. Knowledge of this potential influence may be of importance in managing

more spatially variable agricultural production systems. In particular in the design of alternative cropping systems.

This study has evaluated aggregate breakdown on two sandy loam soils caused by energetic impacts both with and without concurrent rapid soil wetting. Results presented in this chapter establish that, when initial soil water condition prevents rapid soil wetting from occurring, raindrop impacts associated with 66 mm of high kinetic energy rainfall (27.3 J m^{-2} mm^{-1}) can result in significant aggregate breakdown in the depth range 0 to 10 mm. Further, the degree of aggregate breakdown caused by such raindrop impact alone may range up to 70% of the degree of breakdown caused by rapid soil wetting alone as measured by GMD, MWD, D50 and %<0.125 mm. Results also indicate that the relative importance of energetic raindrop impact may be greater closer to the soil surface. They indicate that for shallower aggregate samples (0 to 5 mm depth) the effects of a similar quantity of high energy raindrop impact (60 mm at 27.3 J m^{-2} mm^{-1}) may be almost equivalent to the effects of the rapid soil wetting rate simulated (33 mm h^{-1}).

In terms of *rates* of aggregate breakdown, the rapid wetting of dry soil simulated here (from air dry to saturation or near saturation at a rate of 33 mm h^{-1}) is clearly more expeditious in causing breakdown. The majority of breakdown occurring under rapid wetting was evident following only 5 mm of rainfall, whereas, ongoing breakdown due to raindrop impact in the absence of rapid wetting was still evident after 30 mm of rainfall.

As with any experimental study that simulates rainfall of constant intensity and constant raindrop kinetic energy, extrapolation of these findings to other antecedent conditions and other rainfall conditions should be approached with caution. It may be tempting to extrapolate the effects of raindrop impact on the basis of cumulative kinetic energy of rainfall and extrapolate the effects of soil wetting on the basis of rainfall intensity. Further, statistical analysis of historical rainfall records would reveal the relative probabilities of occurrence for rainfall events sufficient to exceed the soil wetting rate and events with raindrop kinetic energy in excess of that simulated here. However, as the conceptual model of Le Bissonnais (1990) suggests, antecedent water potential of aggregates at the time of raindrop impact or the commencement of soil wetting may moderate the effectiveness of both agents of breakdown. Clearly, extrapolation should only be attempted within the framework of a soil water balance model that has the capacity to account for such antecedent soil water potential as well as for the temporal pattern of rainfall intensity and rainfall energy. In addition, any model would need the capacity to account for temporal patterns of surface cover and antecedent soil aggregation.

Whilst such modeling is beyond the scope of this study, the results clearly show that energetic raindrop impact has the potential to cause a similar degree of aggregate breakdown to that caused by rapid soil wetting. When antecedent soil water potential is high or soil wetting rate is slow (because of low initial rainfall intensity or intermittent initial rainfall) then this potential will be realised.

5.6.2 Interaction Between Energetic Raindrop Impact and Concurrent Rapid Wetting or Antecedent Soil Water Condition on Degree of Aggregate Breakdown

In Chapter 4, a greater degree of surface sealing (as indicated by surface K_{sat}) was observed for initially dry soil than for rapidly pre-wet soil despite both having been subjected to similar wetting rates and simulated rainfall. Greater aggregate breakdown, potentially resulting from less time for aggregate relaxation between wetting and raindrop impact (Farres, 1980), was suggested as one of two possible explanations. The results of the current study do clearly show a small but statistically significant increase in degree of aggregate breakdown when rapid soil wetting and rainfall impact occur concurrently (see Section 5.3.1.1). However, they do not appear to be consistent with the mechanism proposed by Farres as greater aggregate breakdown is evident irrespective of the kinetic energy of the rainfall simulated (see Table 5.6).

One possible explanation could be that a shorter time period elapsed between the rapid soil wetting and wet sieving for the initially dry soils than the rapidly pre-wet soils. This may have lead to slightly greater breakdown during wet sieving process rather than under rainfall impact.

A second line of reasoning is based on consideration of sub-seal water potentials. The comparison made above between rapidly pre-wet and initially dry soils incorporates multiple contrasts. Not only does the timing of the rapid wetting relative to the timing of raindrop impact differ but the antecedent soil water condition at the commencement of raindrop impact also differs. It is possible that the initial soil water condition may affect aggregate strength and hence affect the efficacy of early raindrop impacts in breaking aggregates. Further, the data presented in section 4.4 indicate that initially dry soils remained drier below the surface than rapidly pre-wet soils. However, air dry aggregates are generally mechanically stronger than wet aggregates and therefore such a mechanism would be expected to result in a lower degree of aggregate breakdown for initially dry soils rather than the greater degree observed.

The current study provides insufficient evidence to determine the cause of this observed effect and it therefore remains unexplained. Despite this, the existence of the effect does indicate potential for error when quantifying the effects of rapid soil wetting and the effects raindrop impact together using only initially dry soil.

5.6.3 The Influence of Greater Aggregate Stability Induced by Soil and Tillage Treatment

Loch (1994b) and others have either measured or inferred greater aggregate stability under rainfall following more conservative agricultural management. The results of this study tentatively confirm those findings. They show both reduced degree of aggregate breakdown for the 0 to 10 mm samples of the Cowra and Condobolin soils and the L series samples of the Condobolin soil and a slower rate of aggregate breakdown for the 0 to 5 mm samples under high kinetic energy rainfall. However, the ensuing interpretation differs slightly from Loch's.

Loch (1994b) reported decreases in %<0.125 mm following high energy rainfall due to conservative agricultural management ranging from 3% up to 12%. In a related study Loch (1989, p58.) reported differences in %<0.125 mm following rainfall of high and low kinetic energy of approximately 3%. Clearly, the differences in aggregate breakdown due to conservative agricultural management were of similar or greater magnitude than differences due to high raindrop kinetic energy. However, Loch (1994b) went on to use predicted effects on steady infiltration rate, based on the relationship of Loch and Foley (1994), to conclude that the small increases in aggregate stability found under conservative tillage were, in practical terms, insignificant.

Such an interpretation, based solely on the likely effects of aggregate stability on infiltration under high intensity, high kinetic energy rainfall, may underestimate the advantages of conservative agricultural management. In section 4.7.3 an alternative approach indicated that reduced and retarded surface sealing, presumably due to increased aggregate stability under conservative agricultural management, could be of practical significance under lower intensity rainfall expected to fall on prepared seedbeds in a region of generally lower rainfall intensities. Further, there may be other potential benefits from reduced surface aggregate breakdown relating to both improved seedling emergence and reduced soil erodibility. The magnitude of any potential benefits relating to these other processes will be dependent on numerous soil, rainfall and landscape factors beyond the scope of this study. It is therefore preferable to conclude that increased aggregate stability due to conservative agricultural management can be as significant as protection of the soil surface from raindrop impact in reducing the degree of aggregate breakdown under rainfall within the surface 10 mm of soil and this may have beneficial consequences.

5.6.4 The Cause of Initially Rapid Decline in Aggregation Under Rainfall

In section 4.5.2, measurements of initial K_{sat} and measurements of post-ponding K_{sat} under rainfall were used to infer that pre-ponding rates of surface sealing were more rapid than post-ponding rates. One possible explanation for the effect that was identified in section 4.8 was that aggregate breakdown was more rapid during the initial stages of rainfall. Results presented in Section 5.4.1 confirm that rates of aggregate breakdown during the first 5 mm of energetic rainfall were indeed more rapid than indicated by exponential rates fitted to aggregation statistic measured after 5 mm of rainfall.

Glanville and Smith (1988) measured rapid decline of aggregation for 3 out of 4 dry soils within the first 5 mm of both high and low kinetic energy rainfall. They inferred that this was due to rapid soil wetting at the commencement of rainfall. Results from this study confirm this initially more rapid rate of aggregate breakdown for dry soils undergoing rapid wetting. However, the results also clearly show more rapid initial rates of breakdown under energetic rainfall for all soils even in the absence of rapid wetting. This does not necessarily preclude rapid soil wetting as the major cause of more rapid initial aggregate breakdown observed in the

study of Glanville and Smith or for initially dry soils in this study. Rather it suggests the existence of an additional mechanism that is capable of causing initially more rapid aggregate breakdown in cases where rapid soil wetting effects are precluded because of high initial soil water potential.

A potential mechanism and explanation for this effect is suggested by considering the discrete nature of energetic raindrop impacts and the likely range in aggregate strengths at the commencement of rainfall. While the rate of aggregate breakdown has been quantified in this study in terms of the cumulative raindrop kinetic energy, the impact of an energetic raindrop is actually a discrete event. At the commencement of rainfall none of the re-packed aggregates in the current study had been impacted by an energetic raindrop. Therefore aggregates of any given size may have ranged in strength from just stronger to much stronger than the maximum force applied during sample preparation and pre-treatment. However, it is likely that direct raindrop impacts apply point forces well in excess of forces applied to individual aggregates during preparation and pre-treatment. The first raindrop impacts may have caused greater breakdown than subsequent impacts because they were impacting aggregates that may be considerably weaker. Subsequent raindrops were more likely to impact aggregates or fragments of aggregates that had been strong enough to survive previous raindrop impacts and therefore may have caused less breakdown. Such a mechanism does not rely on the existence of a threshold value for kinetic energy of individual rain drops as proposed by Seginer and Morin (1970).

An indication of the likely duration for completion of this phase of "virgin aggregates" can be gained by the following simple calculation of the expected time required for raindrops to impact every point on the soil surface. Based on spherical drops of 2.7 mm diameter and a rainfall intensity of 33 mm h-1, approximately 320 drops per hour fall on each square centimetre. Assuming that the area impacted is twice the plan area of the spherical drop, approximately 17.5 drops would be required to cover each square centimetre. The time required for those 17.5 drops is approximately 3.3 minutes during which time approximately 1.8 mm of rain falls. The location of initial raindrop impacts is unlikely to be regular and evenly spaced across the surface. Similarly, the plan area influenced by raindrop impacts may well vary and differ from the area assumed here. However, the result of this rough calculation indicates that this initial phase may be essentially complete by the time of the first aggregate sampling in the AT series in this study.

Sufficient conclusive evidence with which to evaluate the aggregate breakdown mechanism proposed here is not provided by the current experimental study or by the study of Glanville and Smith. However, the occurrence of such a mechanism would provide an alternative explanation of the data presented by Baumhardt *et al.* (1991). Those authors found initially rapid decline in calculated surface conductance for five different rainfall intensities at three different non-zero kinetic energy levels. More interestingly they found that, for each of four rainfall intensities, less cumulative raindrop kinetic energy was required to achieve a given

reduction in surface conductance when the cumulative energy was supplied through lower energy drops. While they did not quantify the difference in cumulative energy required, graphs presented suggested that this difference was greatest between the highest and second highest raindrop kinetic energy levels. The difference appeared to be less between the lower two raindrop kinetic energy levels.

Baumhardt *et al.* proposed alternative potential explanations for this effect, citing reduced seal erosion and reduced cushioning of impacts by surface ponded water. However, the mechanism proposed above may explain the effect equally well. If the prepared aggregates were all of a strength well below the strength required to resist the first impact by drops of the lowest energy level, then the first drops may have caused similar degrees of catastrophic breakdown irrespective of kinetic energy level. Since more lower energy drops are required for a given quantity of cumulative kinetic energy, there may be greater aggregate breakdown and possibly greater reduction in surface conductance.

While this study has not provided sufficient evidence to firmly establish the cause, it has identified that rapid initial aggregate breakdown under rainfall can occur in the absence of rapid wetting and proposed a feasible mechanism. Further, it indicates the need to consider this potential mechanism in order to avoid over-estimation of the relative effects of wetting on aggregate breakdown.

This relatively more rapid initial decline in aggregation irrespective of wetting rate is examined in more detail in Chapter 6 in relation to the relatively more rapid decline in surface conductivity prior to ponding inferred in Chapter 4 for all soil pre-wetting treatments.

5.7 IMPLICATIONS FOR SOIL MANAGEMENT UNDER AGRICULTURE

In southern and central New South Wales, dryland cereal crops generally benefit from the higher soil infiltration, increased soil aeration and easier seedling and root penetration that are associated with well aggregated soil conditions. Results presented in this chapter indicate that for light textured weakly structured dryland cropping soils, similar to those studied, both rapid wetting and energetic raindrop impact have potential to cause significant aggregate breakdown depending on surface protection and antecedent soil water status. In order to maintain aggregation following cultivation of these soils, farmers generally need to minimise the effects of both rapid wetting and raindrop impact.

Bresson (1995) has discussed potential benefits from tillage implements that selectively leave larger aggregates at the surface. In the short term, surface cover provided by growing plants and plant residue retained on the soil surface can provide protection for such aggregates through several mechanisms.

Firstly, interception of raindrops by surface cover can reduce the kinetic energy of surface impacts. Whilst some studies have described relatively large drops with significant kinetic energy that fall from erect plants (eg., Moss and Green, 1983) other studies show that surface cover can absorb impact energy directly and that narrow leafed grasses and cereal crop residue are effective in splitting large drops into smaller drops that decelerate and lose kinetic energy (Moss and Watson, 1991). Secondly, surface cover can provide interception storage that prevents or delays rain from contacting the soil surface, hence reducing the mean rate of soil wetting. Thirdly, relatively dense surface cover, of appropriate geometry, may route rainfall that is relatively spatially uniform to the soil surface in a heterogenous pattern. When rainfall is concentrated towards particular infiltration sites, the intervening soil may experience slower wetting by capillarity and hence less breakdown due to aggregate slaking. Fourthly, complete cover of plant residue on the soil surface may reduce soil evaporation between rainfall events. This can lead to higher antecedent surface water potentials hence reducing the potential for breakdown due to rapid soil wetting.

Clearly dryland farmers have less control over soil wetting rates than irrigation farmers. However, it may be possible to adapt dryland bed-farming systems to create strategic zones that receive water by capillarity, remain moist and are protected from raindrop impact in a manner akin to the Tatura system (Adem *et al.*, 1984) used under irrigation.

In the longer term, conservative tillage management systems that retain plant residue on the soil surface and minimise cultivation can improve soil aggregate stability. The results of the current study indicate that there are measurable residual effects of improved aggregate stability induced by conservative tillage management. In terms of maintaining surface aggregation under rainfall, the improvements induced by Conservation tillage treatments at the Cowra and Condobolin sites have had an effect almost equal in magnitude to the benefit given by complete surface protection of dry soil over the duration of a two hour rainfall simulation at a relatively intense rate.

5.8 SUMMARY OF AGGREGATE BREAKDOWN UNDER RAINFALL

In this study simulated rainfall with high and low levels of raindrop kinetic energy was applied to re-packed columns representing cultivated soil surfaces. Both rapid soil wetting at 33 mm h^{-1} (of rapidly pre-wet and initially dry soils) and high kinetic energy raindrops impact (approximately 1800 J m^{-2}) caused significant reductions in aggregate size distribution for all surface soils. The majority of the data suggest a negative interaction between the effects of the two agents. However, this interaction was not statistically significant at P=0.05. The rate and degree of aggregate breakdown caused by the two agents was moderated by differences between soils and between tillage treatments. Slower rates of aggregation decline and coarser

final aggregate size distributions apparently due to greater aggregate stability were observed for Cowra soil relative to Condobolin soil and for soil under conservative tillage treatments relative to soil under traditional tillage treatments. The rate at which aggregate breakdown occurred as a function of cumulative raindrop kinetic energy was also much greater in the presence of concurrent rapid soil wetting.

Findings of the current study add to current understanding of aggregate breakdown under rainfall in the following ways -

1. It has been demonstrated that, in the absence of rapid soil wetting, energetic raindrop impact can result in significant surface aggregate breakdown. Whilst the rate of aggregate breakdown is considerably slower than that caused by rapid soil wetting, the degree of breakdown can be of similar magnitude within the 0 to 5 mm soil layer. In order to minimise surface aggregate breakdown, agricultural management must ameliorate both mechanisms.

2. Greater aggregate stability induced by Conservative tillage treatments on Cowra and Condobolin soil has been shown to significantly retard the rate and significantly reduce the degree of aggregate breakdown under rainfall. It has been shown that these residual effects of Conservative tillage treatments can be as significant in maintaining aggregation within the 0 to 10 mm layer as the effect of surface protection from energetic raindrop impact.

3. Initially more rapid rates of decline in aggregation under rainfall have been attributed to aggregate slaking due to rapid wetting of dry soil (eg., Glanville and Smith, 1988). A similar effect has been observed in the current study. However, this effect was also observed in soil that had been pre-wet under tension to prevent rapid soil wetting under rainfall. An additional mechanism has been proposed to help explain these observations. It is proposed that initially energetic raindrops may impact aggregates that may have strengths that are much weaker than the forces exerted by those raindrop impacts. Hence initial aggregate breakdown is more likely to occur. Subsequent raindrops may tend to impact aggregates or fragments that have had sufficient strength to survive previous impacts. Hence aggregate breakdown may occur less often under subsequent impacts. Such a mechanism provides a possible alternative explanation for the data of Baumhardt *et al.* (1991).

4. An apparent interaction has been observed whereby a slightly greater degree of aggregate breakdown results from energetic raindrop impact that occurs concurrently with rapid soil wetting rather than subsequently to rapid soil wetting. This effect was also observed under low kinetic energy rainfall suggesting that the mechanism proposed by Farres (1980)

cannot explain the observed effect. Whilst no alternative explanation is proposed, the necessity for this effect to be considered in future studies has been identified.

Chapter 6

RELATIONSHIPS BETWEEN FINAL AGGREGATE SIZE DISTRIBUTION, AGGREGATE BREAKDOWN, AGGREGATE STABILITY AND SURFACE SEALING

6.1 INTRODUCTION AND OBJECTIVES

Greater aggregate stability has been proposed as an explanation for greater surface permeability under rainfall in soil under virgin vegetation (eg., McIntyre, 1958a), in soil under conservative cropping management (eg., Hamblin, 1984), in soil under particular crops (eg., Packer *et al.*, 1995), in soil treated with artificial polymers (eg., Hartmann *et al*., 1981) and in relatively stable soil types (eg., Sharma *et al.*, 1981). An intuitive basis for such propositions is that less stable aggregates will more readily break down under rainfall to produce finer aggregates or primary particles. These finer aggregates or primary particles have the potential to be packed more closely by raindrops thus reducing the volume and size of packing pores. The reduction in pore volume and pore diameter leads to reduced hydraulic conductivity and reduced hydraulic penetration.

Relationships have been sought as a means of predicting the effect of aggregate breakdown on infiltration under rainfall without regular recourse to complex and time consuming measurements of surface hydraulic conductivity. However, studies quantifying such relationships are relatively few (eg., Glanville and Smith, 1988; Loch and Foley, 1994) and relationships identified in these studies have limitations.

The current chapter examines the predictive capability of relationships between surface soil hydraulic behaviour under high kinetic energy rainfall described in Chapter 4 and measures of aggregate breakdown and aggregate stability presented in Chapter 5. An attempt is made to extend current knowledge in this area by considering relationships that -

1. predict measured surface hydraulic conductivity rather than measured infiltration rate or surface hydraulic conductivity estimated from infiltration rate,
2. predict declining surface permeability throughout the post-ponding phase of seal formation not just the steady permeability of a well formed surface seal,

3. apply over a range of soil wetting rates and antecedent conditions,
4. account for the effects of differing tillage treatments.

To recap, the soil wetting pre-treatments used in the current study to isolate effects of rapid soil wetting were, Rapid (soil pre-wet at 33 mm h^{-1} prior to high kinetic energy rainfall) initially Dry (soil wet at 33 mm h^{-1} during high kinetic energy rainfall) and Tension (soil pre-wet under tension to prevent rapid soil wetting). High kinetic energy rainfall (27.3 J m^{-2} mm^{-1}) and low kinetic energy rainfall (0.3 J m^{-2} mm^{-1}) were used to isolate effects of energetic raindrop impacts. As indicated in sections 4.3, surface ponding and runoff occurred under all high kinetic energy rainfall simulations but were only observed during two low kinetic energy rainfall simulations. Hence, relationships in this chapter have been evaluated only for surface sealing under high kinetic energy rainfall. Properties of the Cowra soil from under the Conservative tillage treatment (DD) and the Traditional tillage (TT) as well as the Condobolin soil from under the Conservative tillage treatment (RH) and the Traditional tillage (BC) have been presented in Table 3.3.

6.2 RELATIONSHIPS AMONG THE DATA

The intuitive basis for expecting relationships between aggregate breakdown and surface hydraulic conductivity was outlined in the preceding section. It is clear that the efficiency of raindrops in packing the products of aggregate breakdown is likely to influence the strength and nature of any such predictive relationship. If raindrops impacting the soil surface very rapidly cause a maximal or steady degree of particle packing, then a strong relationship might be expected between surface aggregate size and surface hydraulic conductivity. Such a relationship could be expected to conform with predictions from physically based pore packing models. However, if a maximal or steady degree of packing of surface material by raindrop impacts did not occur very rapidly, then any relationship would incorporate, to some degree, the effectiveness of packing as a function of duration of rainfall. Two forms that potential relationships among the data from this study may follow from the above -

1. If a maximal or steady degree of surface particle packing is achieved relatively rapidly by energetic raindrop impacts, then a relationship may be expected between surface aggregate size distribution within the surface layer (or derived parameters) and measured hydraulic conductivity of that layer at that time.
2. If there was, in addition, a simple relationship between the degree of particle packing by raindrops and the duration of rainfall, then a relationship may also be expected between the rate of change of aggregate size distribution over time and the rate of change in surface hydraulic conductivity over that time.

A third form of relationship may exist -

3. If the condition specified in point 1. was met, and in addition, the rate of change in aggregate size distribution in the surface layer under rainfall was related to aggregate stability then relationships may be expected between measures of aggregate stability and the rate of change in surface hydraulic conductivity over a period of time.

Relationships among the data are discussed below under these headings.

6.3 RELATIONSHIPS BETWEEN AGGREGATE SIZE DISTRIBUTION AND SURFACE HYDRAULIC CONDUCTIVITY AND INFILTRATION RATE

6.3.1 Relationships Between Aggregate Size Distribution Within Surface Layers and Surface Hydraulic Conductivity Under High Kinetic Energy Rainfall

Figures 6.1 to 6.4 present data with which to evaluate relationships between K_{sat} measured under high kinetic energy rainfall (from the R series simulations) and aggregate size distribution (measured by GMD, MWD, D50 and %<0.125 mm) within the upper 5 mm soil layer after the corresponding rainfall volume (from the AT series).

The data presented in Figures 6.1 to 6.4 indicate general trends of decreasing K_{sat} with finer aggregate size distribution. A range of simple functions of the aggregate size statistics can explain similar, modest amounts of the variation in K_{sat}. Aggregate size measured by %<0.125 mm provided slightly higher degrees of explanation. The work of Loch and Foley (1994) suggests that log-linear relationships of %<0.125 mm are appropriate and the following discussion concentrates on such functions fitted using a commercial statistical computing package.

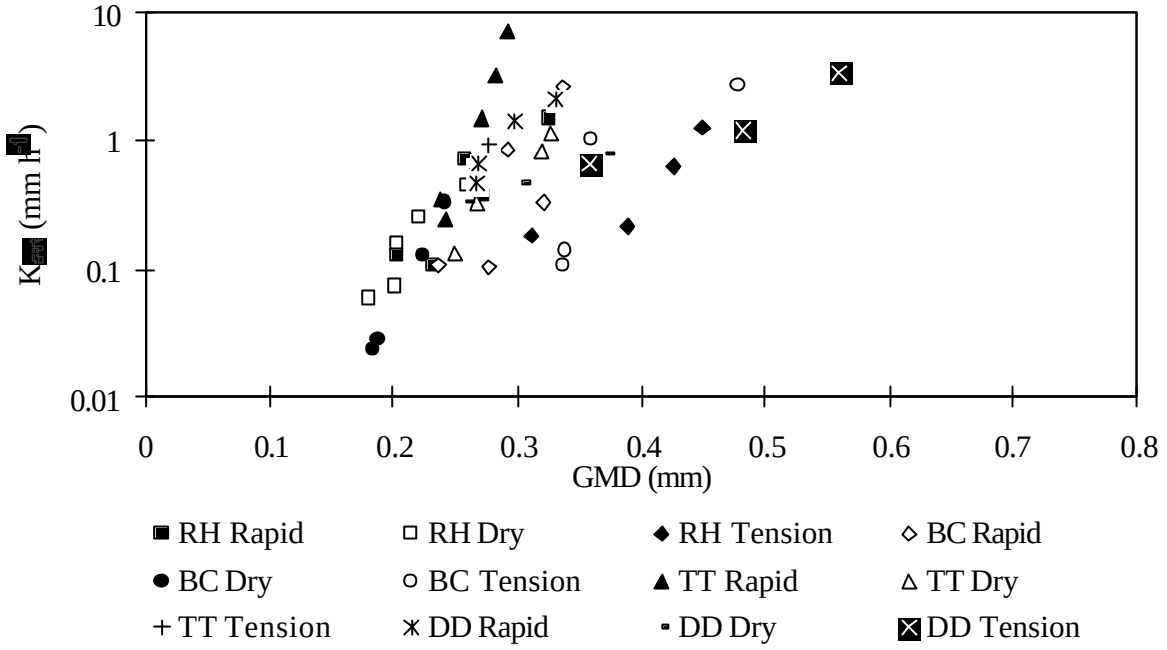

Fig 6.1 The relationship between surface K_{sat} and surface aggregate size measured by GMD as affected by soil, tillage treatment and pre-wetting.

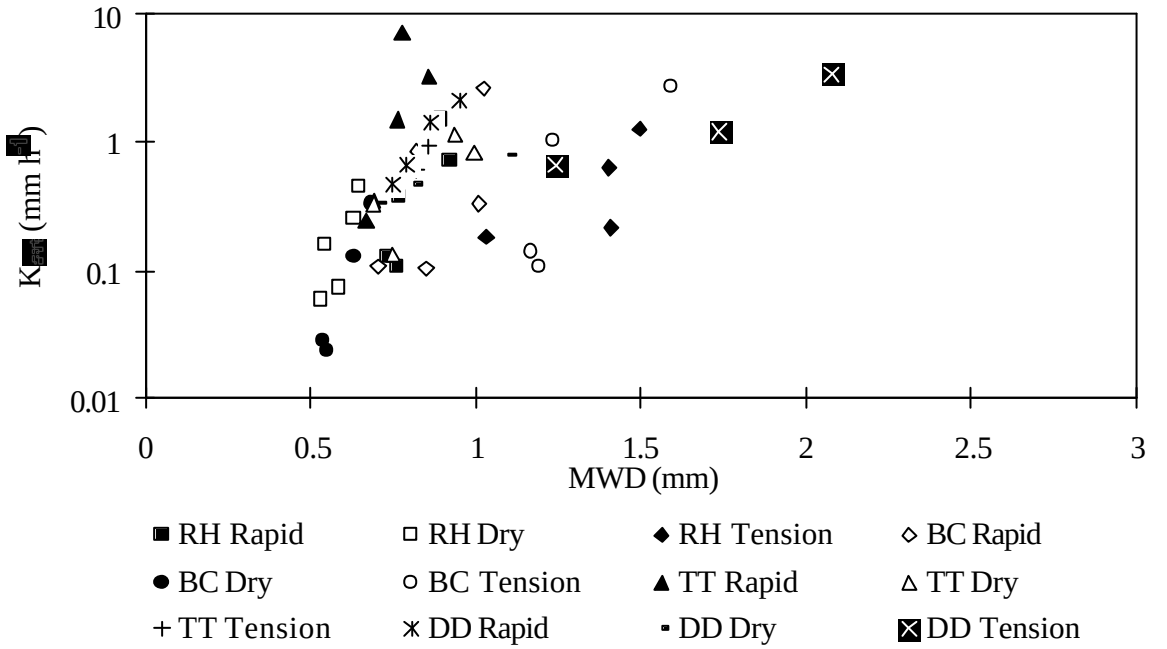

Fig 6.2 The relationship between surface K_{sat} and surface aggregate size measured by MWD as affected by soil, tillage treatment and pre-wetting.

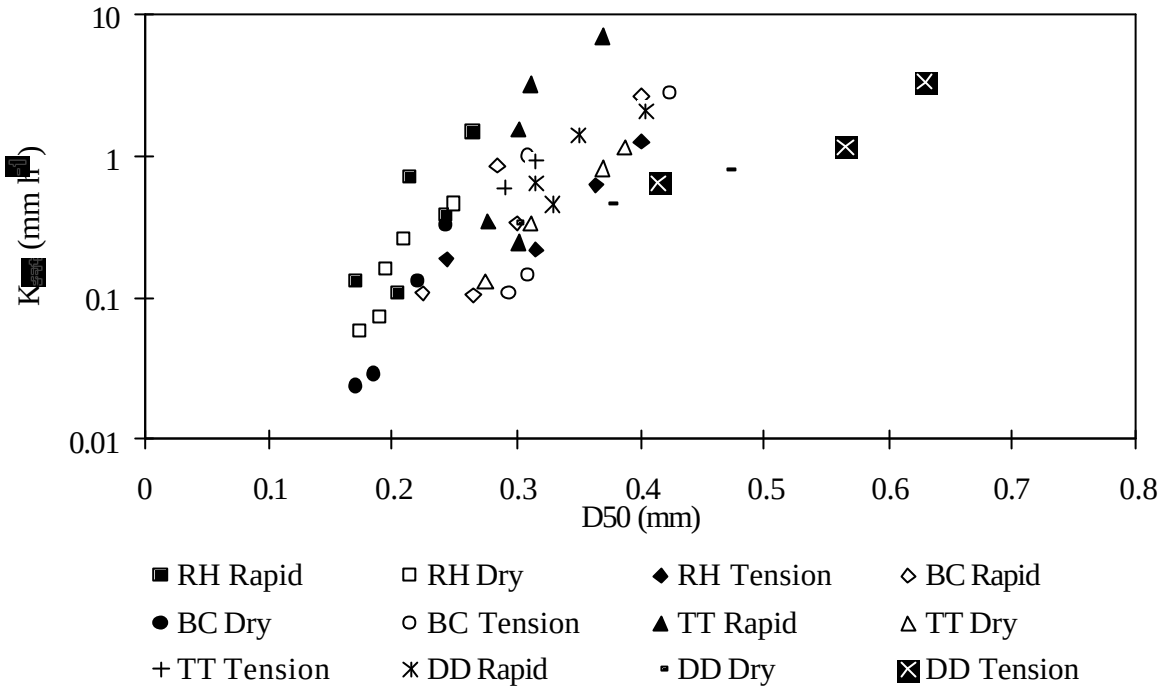

Fig 6.3 The relationship between surface K_{sat} and surface aggregate size measured by D50 as affected by soil, tillage treatment and pre-wetting.

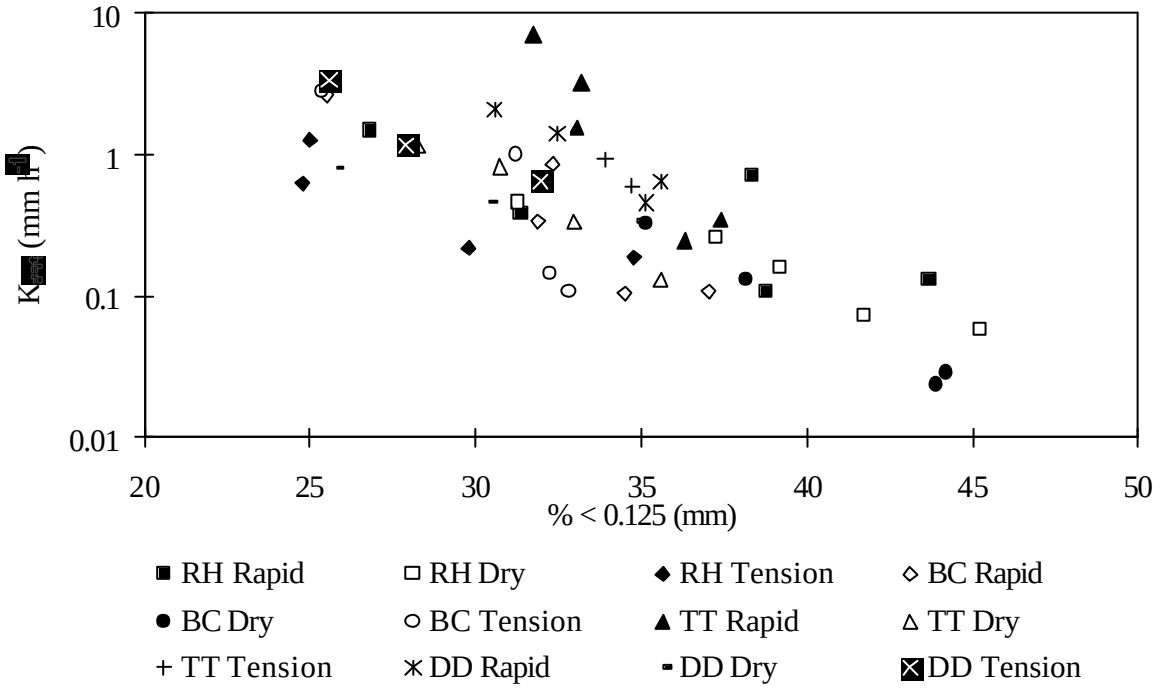

Fig 6.4 The relationship between surface K_{sat} and surface aggregate size measured by %<0.125 mm as affected by soil, tillage treatment and pre-wetting.

A single fitted log-linear relationship (Equation 6.1) explains 55% of the variation in $\log_e K_{sat}$ within the full data set.

$\log_e(K_{sat}) =$ 5.268 - 0.1821 x %<0.125mm ($r^2 = 0.55$) [Eqn. 6.1]

However, regression analyses indicate that statistically significantly improvements in prediction result from fitting separate functions for individual soils ($P < 0.005$) or for individual wetting pre-treatments ($P < 0.005$) or for individual soil and wetting pre-treatment combinations ($P < 0.005$). The proportion of variation within the whole data set explained by these models is 64%, 62% and 74% respectively. In addition, the parallelism and coincidence of the multiple function models was tested by fitting regression models with common slopes and variable constants, common constants and variable slopes or variable constants and variable slopes. Table 6.1 presents the accumulated analysis of variance for the regression model with separate functions for individual soil and wetting pre-treatment combinations. Variance ratios indicate significant improvement due to fitting separate relationships with different intercepts ($P < 0.005$) but no significant improvement due to fitting separate slopes.

Table 6.1 Accumulated analysis of variance table for the regression model fitting separate functions for individual soil and wetting pre-treatment combinations.

Source of variation	d.f.	s.s.	m.s.	v.r.
Fit single log-linear relationship	1	42.4808	42.4808	104.57
Fit separate parallel log-linear relationships	5	16.2170	3.2434	7.98
Fit separate non-parallel log-linear relationships	5	2.6058	0.5212	1.28
Residual	36	14.6254	0.4063	
Total	47	75.9290	1.6155	

This indicates that models with parallel slopes but differing intercepts for individual soils, or for individual wetting pre-treatments or for individual soil and wetting pre-treatment combinations explain variation in $\log_e K_{sat}$ significantly better. The reasonable fit of parallel models suggest that each soil wetting pre-treatment combination has a similar rate of decline in $\log_e(K_{sat})$ for a given increase in fine material (%<0.125 mm) during rainfall.

Equations 6.2 to 6.7 present the parallel model for individual soil and wetting pre-treatment combinations and Figure 6.5 presents this model with the raw data.

$\log_e(K_{sat}) =$ 6.826 - 0.1979 x %<0.125mm (DD and TT - Rapid) [Eqn. 6.2]
$\log_e(K_{sat}) =$ 5.427 - 0.1979 x %<0.125mm (DD and TT - Dry) [Eqn. 6.3]
$\log_e(K_{sat}) =$ 6.181 - 0.1979 x %<0.125mm (DD and TT - Tension) [Eqn. 6.4]
$\log_e(K_{sat}) =$ 5.742 - 0.1979 x %<0.125mm (RH and BC - Rapid) [Eqn. 6.5]

$\log_e(K_{sat})$ = 5.621 - 0.1979 x %<0.125mm (RH and BC - Dry) [Eqn. 6.6]

$\log_e(K_{sat})$ = 5.006 - 0.1979 x %<0.125mm (RH and BC - Tension) [Eqn. 6.7]

($r^2 = 0.74$)

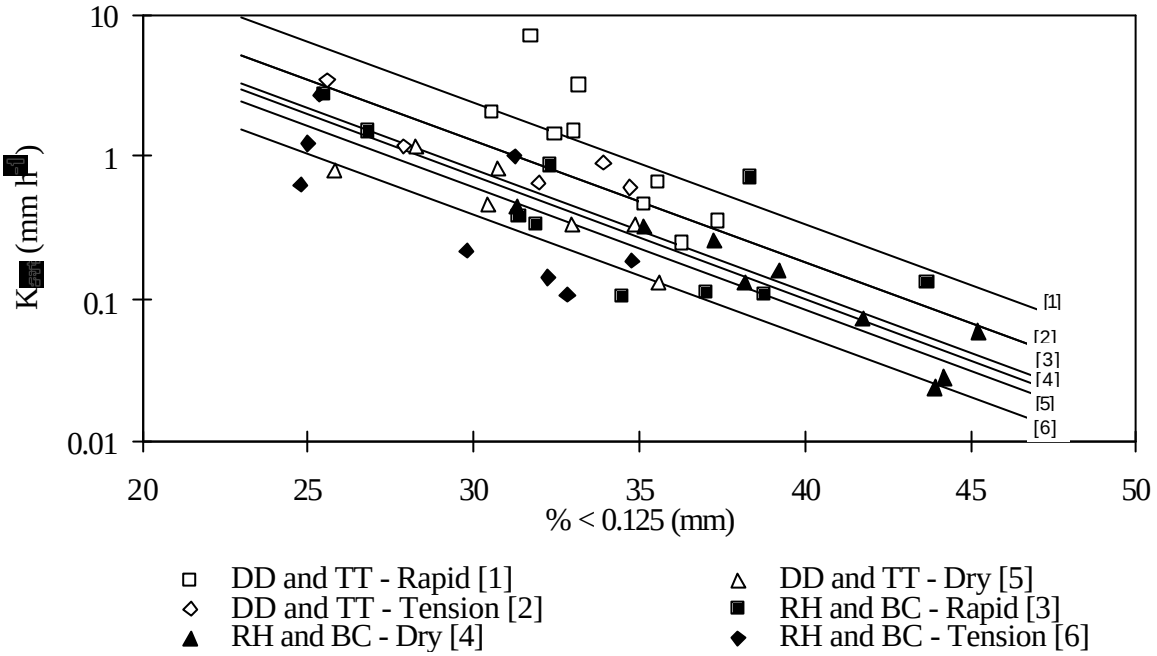

Fig 6.5 Data and fitted relationships between surface K_{sat} and %<0.125 mm for all soil and pre-wetting combinations.

Relationships between % < 0.125 mm and K_{sat} fitted for the three wetting pre-treatments over both soils indicate significantly higher intercepts for rapid wetting pre-treatments ($P < 0.05$). This suggests that, for a given proportion of fine material, rapidly pre-wet soils exhibit higher surface hydraulic conductivity. One possible explanation for this is that rapid pre-wetting leads to aggregate breakdown that is more rapid than the capacity of energetic raindrop impacts to effect the compaction necessary to drastically reduce surface hydraulic conductivity.

Fitted relationships between the size distribution of aggregate breakdown products and surface hydraulic conductivity are likely to be dependent on the degree of packing by energetic raindrop impacts. As such, the relationships fitted here may be applicable only under rainfall of similar drop size and kinetic energy to that used in this study falling on bare soil. The nature of such dependence and limits on applicability cannot be determined from the data generated in this study.

6.3.2 Relationships Between Aggregate Size Distribution Within Surface Layers and Infiltration Rate Under High Kinetic Energy Rainfall.

Data presented in Figures 6.6 to 6.9 also indicate broad trends of decreasing infiltration rate (IR) measured during rainfall simulations with finer aggregate size distribution after the corresponding rainfall volume. Again, log-linear relationships of %<0.125 mm appear appropriate and the following discussion concentrates on these functions.

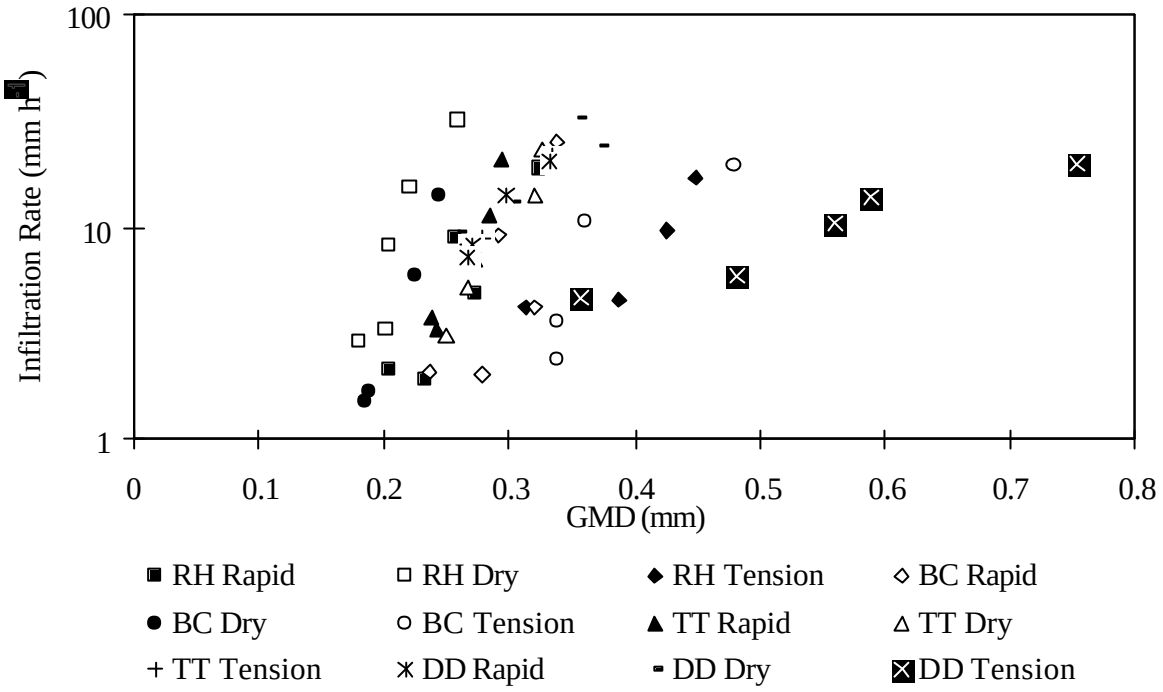

Fig 6.6 The relationship between infiltration rate and surface aggregation measured by GMD as affected by soil, tillage treatment and pre-wetting.

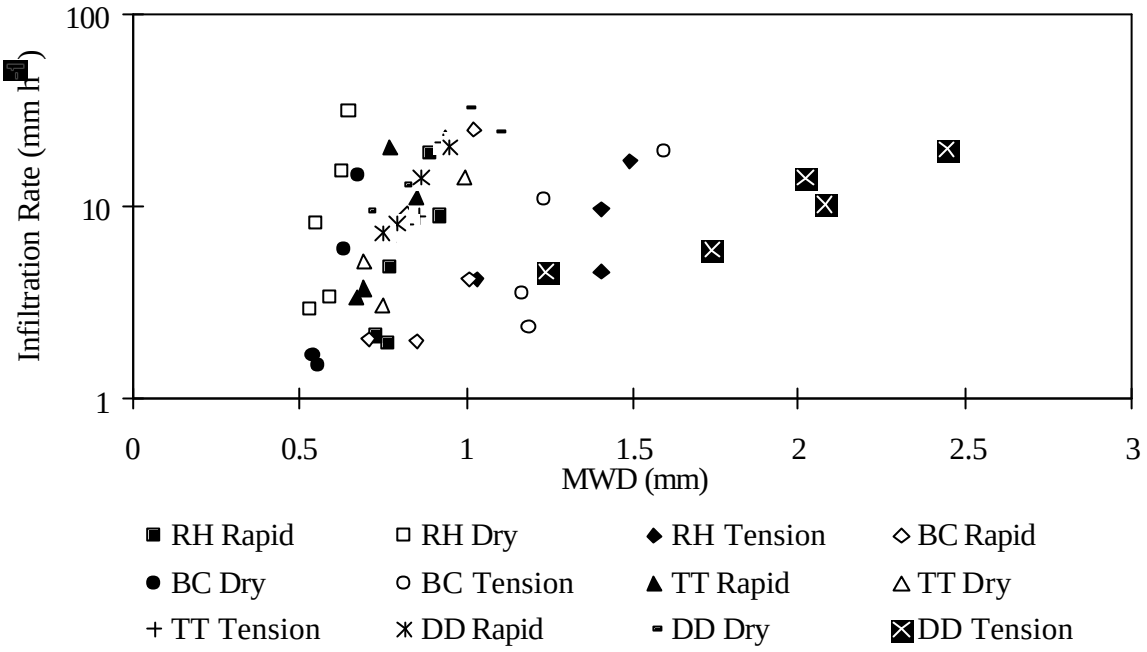

Fig 6.7 The relationship between infiltration rate and surface aggregation measured by MWD as affected by soil, tillage treatment and pre-wetting.

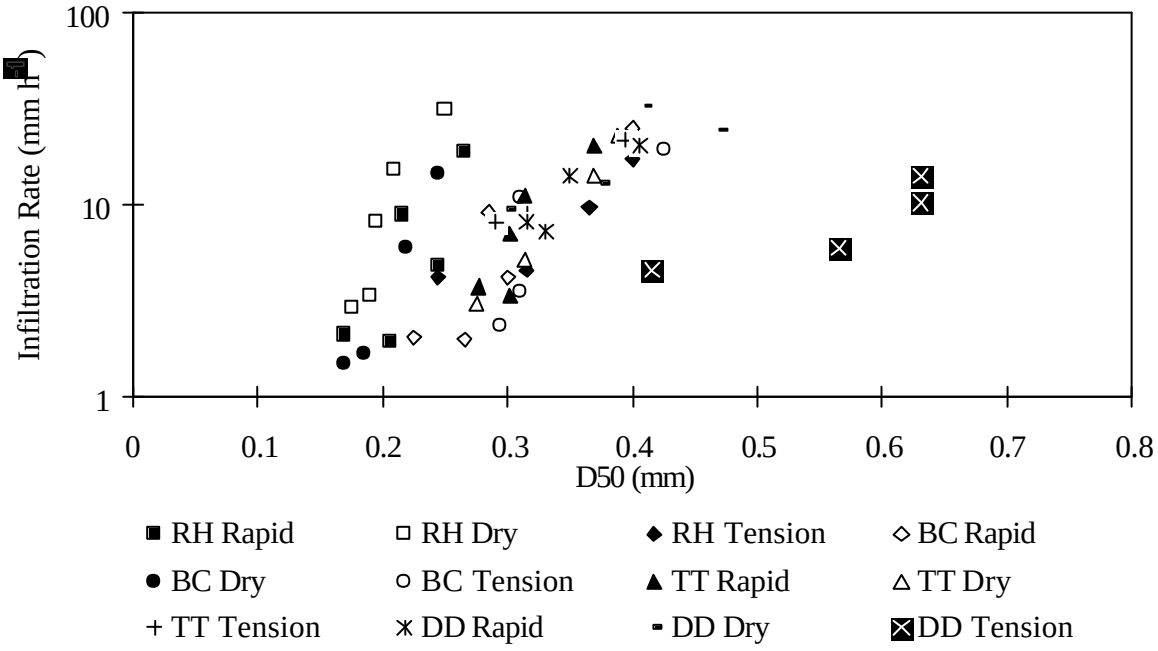

Fig 6.8 The relationship between infiltration rate and surface aggregation measured by D50 as affected by soil, tillage treatment and pre-wetting.

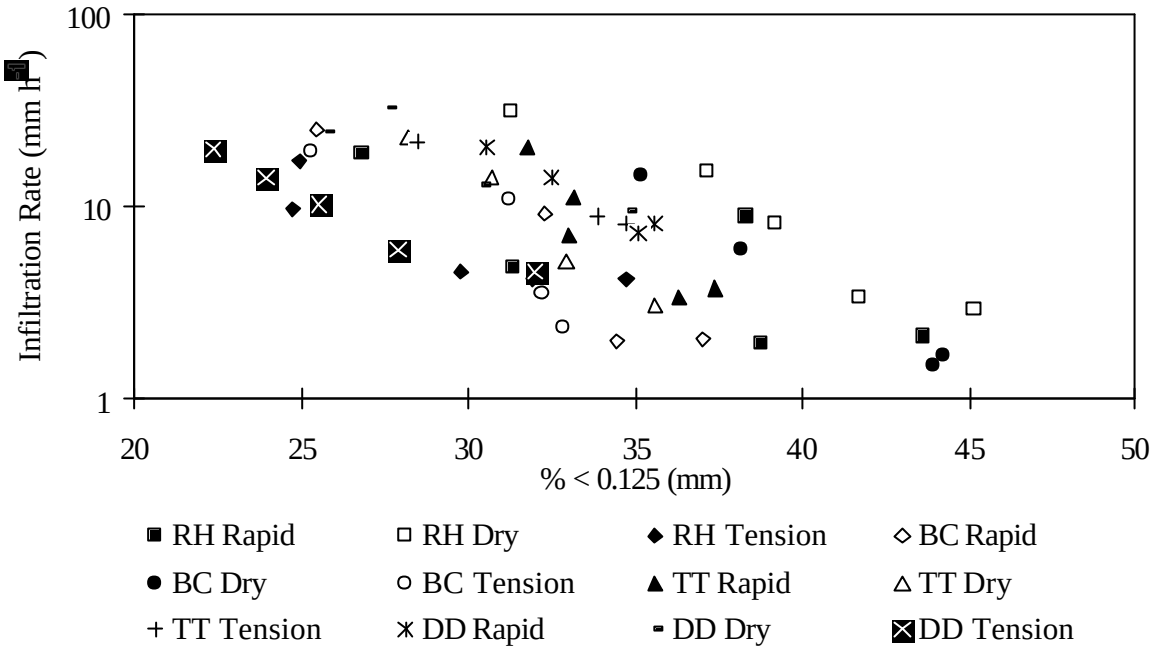

Fig 6.9 The relationship between infiltration rate and surface aggregation measured by % < 0.125 mm as affected by soil, tillage treatment and pre-wetting.

A single fitted log-linear relationship (Equation 6.8) explains only 43% of the variation in $\log_e$ (IR) within the full data set.

$\log_e(IR) = 5.490 - 0.1052 \times \%<0.125mm \quad (r^2 = 0.43)$ [Eqn. 6.8]

Again, regression analyses indicate significant improvements in prediction from fitting separate functions for individual wetting pre-treatments ($P < 0.005$) or for individual soil and wetting pre-treatment combinations ($P < 0.05$) but not for individual soils alone. The proportion of variation within the whole data set explained by these two models is 56% and 52% respectively. Again, the parallelism and coincidence of these multiple function models was tested by fitting regression models and again the analyses suggested parallel slopes but differing intercepts. Equations 6.9 to 6.14 present the parallel model for individual soil and wetting pre-treatment combinations.

$\log_e(IR) = 5.845 - 0.1316 \times \%<0.125mm$	(rapid Cowra)	[Eqn. 6.9]
$\log_e(IR) = 6.406 - 0.1316 \times \%<0/125mm$	(dry Cowra)	[Eqn. 6.10]
$\log_e(IR) = 6.056 - 0.1316 \times \%<0.125mm$	(tension Cowra)	[Eqn. 6.11]
$\log_e(IR) = 6.786 - 0.1316 \times \%<0.125mm$	(rapid Condobolin)	[Eqn. 6.12]
$\log_e(IR) = 6.369 - 0.1316 \times \%<0.125mm$	(dry Condobolin)	[Eqn. 6.13]
$\log_e(IR) = 6.633 - 0.1316 \times \%<0.125mm$	(tension Condobolin) $(r^2 = 0.52)$	[Eqn. 6.14]

Relationships predicting IR for wetting pre-treatments fitted over both locations also differ significantly in intercepts (P = 0.05). The significantly higher intercept for initially dry soils most likely reflects the greater hydraulic gradient driving infiltration while the significantly lower intercept for the tension wetting pre-treatment remains unexplained.

6.3.3 Comparison with Published Work

The relationship between % < 0.125 mm and $\log_e(K_{sat})$ fitted using only data for initially dry soils from the current study (Equation 6.15) has significantly different parameters to a relationship of the same form reported by Loch and Foley (1994) (Equation 6.16).

$\log_e(K_{sat})$ = 5.1459 - 0.1871 x %<0.125mm (r^2 = 0.89) [Eqn. 6.15]

$\log_e(K_{sat})$ = 1.6918 - 0.06575 x %<0.125mm (r^2 = 0.91) [Eqn. 6.16]
(Loch and Foley, 1994)

The two studies used similar wet sieving techniques to determine the size distribution of surface aggregates. The data and fitted relationships, from this study and from the study

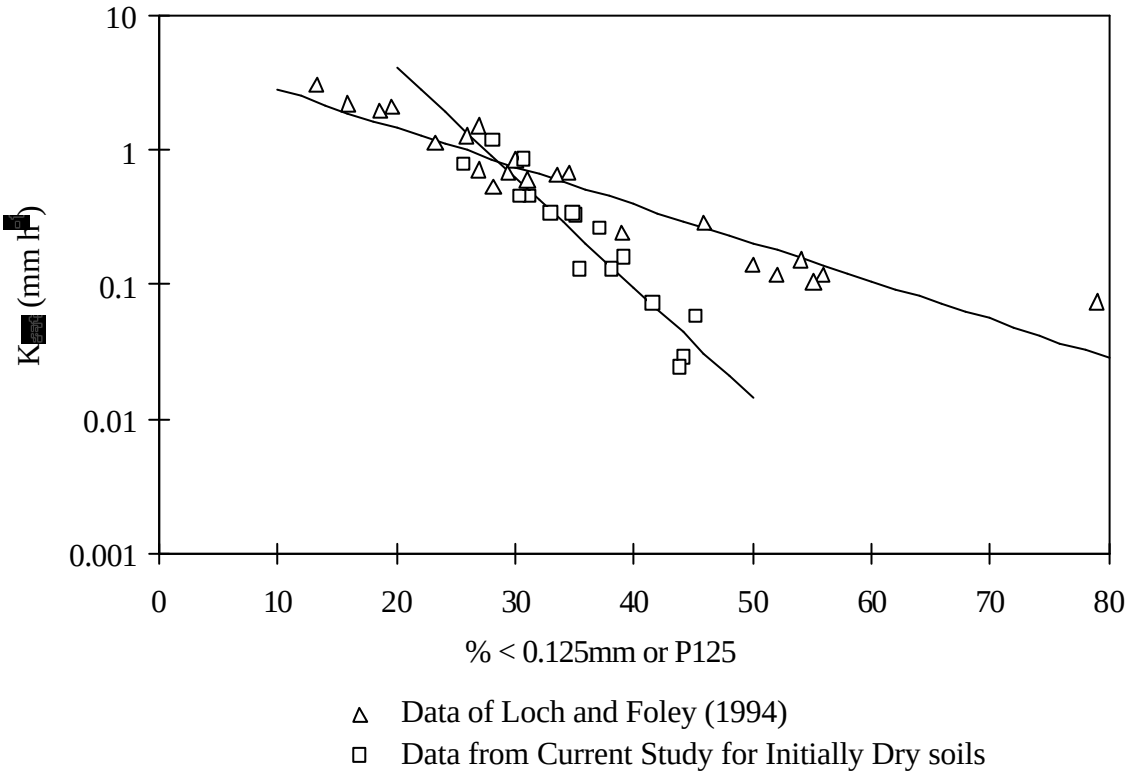

Fig 6.10 Comparison of data and fitted relationships between surface aggregate size and K_{sat} adapted from Loch and Foley (1994) and for initially dry soil in the current study.

of Loch and Foley (1994) are presented in Figure 6.10. These data clearly show that lower surface conductivity was observed for a given proportion of fine material under the conditions simulated in the current study. This discrepancy increased as surface aggregate breakdown increased.

Likewise, the fitted relationship between % < 0.125 mm and infiltration rate for initially dry soils (Eqn. 6.17) is significantly different (P = 0.05) from the relationship explaining steady infiltration rate under high energy rainfall adapted from Loch and Foley and presented as Equation 6.18

$\log_e(IR) = 7.085 - 0.1402 \times \%<0.125mm$ ($r^2 = 0.73$) [Eqn. 6.17]

$\log_e(IR) = 4.050 - 0.0389 \times \%<0.125mm$ ($r^2 = 0.83$) [Eqn. 6.18]
(Loch and Foley, 1994)

There are a number of explanations for differences between the relationships fitted here and those found by Loch and Foley.

Firstly, differences in the characteristics of rainfall-runoff simulations, including plot size, plot preparation, plot slope and rainfall intensity may have influenced measured infiltration rates (and hence calculated K_{sat}). The lower rainfall intensity used in the current study may have lead to a greater final degree of surface sealing through one of the mechanisms outlined in section 4.9. In addition, the smaller plot size used in the current study may be expected to result in lower infiltration rates due to reduced potential for surface detention storage.

Secondly, the stages of surface sealing sampled in the two studies are not comparable. Loch and Foley relate % < 0.125 mm to K_{sat} and infiltration rate for stable, fully developed seals, whereas the current study relates % < 0.125 mm to K_{sat} and infiltration rate for developing seals.

Thirdly, the method of aggregate sampling differs. In the AT series in this study, a constant sampling depth of 5 mm was used. The difference in methods of sampling could be expected to affect results for well developed seals chiefly through differences in the depth of soil sampled. Loch and Foley do not list individual sampling depths for each soil but do state that the depth sampled covered the depth of the compacted zone that ranged from 3 to 5 mm in depth (1994). If a developed seal was uniform and 3 mm thick and the method of sampling used by Loch and Foley sampled only this depth, then a 5 mm deep sample as used here, would contain 2 mm of unaffected bulk soil which should result in a coarser aggregate size distribution. However, final samples of the AT series on the Cowra soils actually had higher % < 0.125 mm than that reported for similar soils by Loch (27% and 33%, p57, 1989), indicating that such depth dilution could not account for observed differences.

Whilst the difference in sampling methods is not able to explain differences for well developed seals, it may do so for less developed seals. If the decline in K_{sat} measured during

the rainfall-runoff simulations resulted from vertical extension of a sealed layer, then a fixed depth sampling method could produce samples which are diluted by unaffected bulk soil material beneath the seal. This could occur up to the point in time when the seal extends to the fixed depth. If the seal was uniform in aggregate size and the bulk soil was uniform in aggregate size and the rate of seal extension increased monotonically with rainfall duration cumulative raindrop kinetic energy, then the degree of depth dilution of a fixed depth sample would be at a maximum at the start of rainfall and decline steadily to the point in time when seal depth equals sample depth. If the effect of depth dilution influenced the relationship evaluated in the current study then it could accentuate the differences in the slopes of the fitted relationships. However, the findings of Farres (1978), (see section 4.5.4) indicate that surface seals may reach their maximum vertical extension by the time ponding occurs and K_{sat} becomes measurable. This would suggest that any depth dilution effect would be constant over the duration of the post-ponding phase.

The fourth potential explanation is linked to the third. The thickness of seal used to calculate K_{sat} is not identical. The current study provided no information on seal thickness with rainfall duration or cumulative raindrop kinetic energy. Such information would be required to determine the effect of arbitrary assumptions of seal depths. If data in the current study were recalculated assuming a 3 mm depth of seal as in the study of Loch and Foley, K_{sat} values would be lower by approximately 40%. However, this would still represent an arbitrary assumption about the seal depth and would actually increase the discrepancy between the two fitted relationships. If the depth of seal was assumed to increase with rainfall volume rather than remain constant, larger K_{sat} values would be reduced to a greater extent than lesser K_{sat} values. This may reduce the magnitude of the discrepancy between slopes but would increase the absolute discrepancy at higher K_{sat} values.

Fifthly, the method of determining sub-seal water potential differed between the two studies. In the current study sub-surface tensiometers were used and the range of potentials observed was of the order of -1.0 to -1.5 kPa. In the study of Loch and Foley sub-seal water potential was measured for a subset of the soils using either disc permeameters placed on the surface immediately after rainfall or gravimetric samples taken immediately after rainfall. Sub-seal water potential for the remaining soils was estimated using a regression relationship between sub-seal water potential and %<0.125 mm. The range of sub-seal water potentials reported by Loch and Foley was considerably lower than for the current study (-0.3 mm to -0.7 kPa). The degree to which differences reflect true differences in sub-seal water potential as a result of different flow and boundary conditions imposed rather than measurement deficiencies in one or other of the studies is unclear.

Lastly, Loch and Foley considered a larger and more diverse range of soils. However, they did examine the two Cowra soils considered in the current study (albeit sampled at a different stage in the tillage trial). The ranges of infiltration rates and % < 0.125 mm determined

by Loch and Foley were similar to those observed in the current study. The nature of the effect of the different range of soils used is not easily determined.

In summary, it can be said that the fitted relationships differ from those of Loch and Foley and that there are a range of interacting reasons that potentially explain the differences. However, the consistency of the two relationships cannot be evaluated because they relate different attributes. Loch and Foley relate a parameter of aggregate size distribution for a variable depth of soil (the "final" sealed layer) to infiltration rate and K_{sat} estimated for that layer. The relationships fitted in the current study relate the same parameter for a fixed depth of soil, that is undergoing changes in aggregate size distribution, to the infiltration rate or K_{sat} estimated for that fixed depth layer, that is also changing.

There may be value in attempting to combine the differing approaches of Loch and Foley (1994) and the current study. The relationship presented by Loch and Foley indicates that final surface hydraulic conductivity can be predicted from the proportion of fine material in the soil surface at the conclusion of rainfall. The relationships presented as Equations 6.2 to 6.7 indicate that the proportion of fine material in the soil surface under rainfall can predict the rate of decline in surface hydraulic conductivity. As presented in Figure 6.10 relationships evaluated in the two studies are inconsistent with each other. However, differences in experimental methods discussed above may account for some or all of this inconsistency and the same relationships, evaluated using a common set of experimental conditions and soils, may be consistent with each other. If this were the case, then the proportion of fine material (eg., % < 0.125 mm) in the soil surface, measured at appropriate times, may help to predict both rate and the final degree of surface sealing. Further data, of the type collected in the current study, would be required in order to quantify the appropriate relationships under identical experimental conditions and evaluate this hypothesis.

It is not possible to compare the results of this study with those of Glanville and Smith (1988), who also related infiltration fraction to the proportion of surface aggregates less than 0.125 mm diameter. Infiltration rates in both studies are dependent on hydraulic gradients that may differ due to differing experimental conditions. Such effects are likely to be significant given that Glanville and Smith used clay soils, a number of which had high potential for swelling.

6.3.4 Mechanisms Explaining Relationships Between Aggregate Size Distribution and Surface Hydraulic Conductivity.

There are at least two mechanisms that potentially explain relationships between aggregate size distribution and hydraulic conductivity and infiltration rate found in the current study. Firstly, aggregate size distribution within the surface layer, may be expected to influence K_{sat} through its effect on packing pore size and total pore volume. For a given degree of compactive effort, soils with finer aggregates and more evenly graded aggregate size distributions may be expected to pack to greater bulk density, lower total porosity and smaller pore size (disregarding effects of aggregate shape and aggregate orientation). Secondly, it has been

proposed that pore size at the very surface of the sealing layer controls the degree of hydraulic penetration when energetic raindrop impacts occur. This determines the balance between soil compaction and seal perturbation resulting from these impacts. This pore size can be related to the size of particles and aggregates at the very surface. (Moss, 1991a; Loch, 1989).

The capacity of the first mechanism to explain surface sealing under particular conditions will depend on the degree to which the packing regime remains constant over the period that the relationship is sought. That is, the degree to which changes in packing porosity and hence hydraulic conductivity result from breakdown to smaller aggregates or particles, rather than closer re-arrangement of existing aggregates or particles. It is unlikely that aggregate breakdown in the surface layer can be caused by raindrop impact without additional compactive force and hence potentially closer packing of existing aggregates. Such a condition may occur late in the surface sealing process when existing aggregates may be already packed to their maximal degree.

In cases where the influence of surface aggregate size distribution on K_{sat} was primarily due to effects on packing pore size and total pore volume and where information describing the state of packing of aggregates throughout the sealing depth was obtained, it may be feasible to predict declining hydraulic conductivity, or least the functional form of its decline, by applying an appropriate particle-pore packing model to the changing aggregate size distribution. Such an approach would be subject to conceptual difficulties given the non-uniform nature of surface seals (Mualem and Assouline, 1989). Detailed consideration of aggregate and particle packing models is beyond the scope of this study and hence potential relationships among the data have been examined only on a statistical basis.

The second mechanism was emphasised by Loch (1989) in his discussion of the relationships between % < 0.125 mm and infiltration rate and hydraulic conductivity of developed seals found on a variety of soils. However, Moss (1991a) concluded that a "silt" layer of only 0.2 mm thickness was the cause of reduced hydraulic penetration into soils which developed surface seals up to 5 mm in thickness. If this were generally the case, then the second mechanism may be less appropriate in explaining the relationships found by Loch and Foley (1994) and in the current study between K_{sat} or infiltration rate and surface aggregate size within the much thicker samples encompassing the surface 3 to 5 mm of soil.

6.4 RELATIONSHIPS BETWEEN THE RATE OF CHANGE IN AGGREGATE SIZE DISTRIBUTION OR AGGREGATION AND THE RATE OF CHANGE IN SURFACE HYDRAULIC CONDUCTIVITY

In section 4.5 soil stability factors (S in Equation 4.4) were fitted to surface hydraulic conductivity data. The goodness of fit of Equation 4.4 indicates that surface hydraulic

conductivity declines exponentially with cumulative raindrop kinetic energy. In section 5.4 aggregation stability factors (D in Equation 5.1) were fitted to each of the four derived aggregate size statistics (GMD, MWD, D50 and %<0.125mm). The fit of Equation 5.1 suggests that surface aggregate size may also decline exponentially with cumulative raindrop kinetic energy. A relationship between the exponents of the two exponential decline functions may therefore be expected. The form of relationship between exponents would depend on the nature of the relationship between K_{sat} and aggregate size. A linear relationship between change in K_{sat} and change in aggregate size would lead to identical exponents while a power function relationship between K_{sat} and aggregate size, that is,

K_{sat} = A (aggregate size ^{z}), [Eqn. 6.19]
where A = constant

would lead to a linear relationship between the exponents with a slope equal to 1/z.

Such relationships would rely on a conceptual basis similar to that discussed in section 6.1. There is no well established physical basis for the exponential decline of either surface hydraulic conductivity or surface aggregation during surface sealing and therefore potential relationships among the data are examined essentially on a statistical basis.

In Figure 6.11 aggregation stability factors (D) are plotted against the corresponding soil stability factors (S) for each of the four aggregate size statistics (GMD, MWD, D50 and %<0.125mm). It is apparent that only weak associations exists between exponents fitted to decline in aggregate size and exponents fitted to decline in hydraulic conductivity. Fitted linear regression relationships explain little more than one

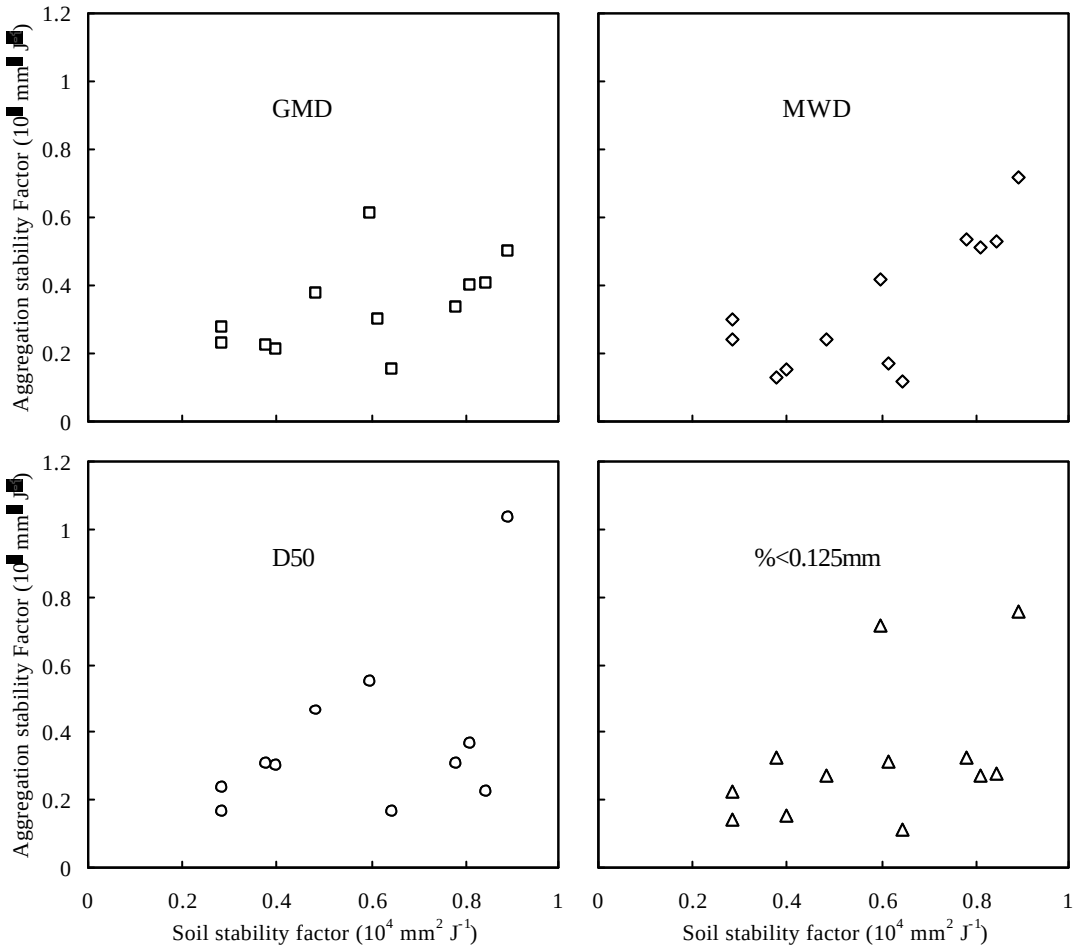

Fig 6.11 The relationship between aggregation stability factors (D) and soil stability factors (S) for all pre-wetting, soils and tillage treatments for each of the four aggregate size statistics (GMD, MWD, D50 and %<0.125mm).

half of the variation in S using D(MWD) and only one third using D(%<0.125mm). D values are generally less than the respective S values and the slopes of relationships fitted for each aggregate size statistic (ranging from 0.4 to 0.6) are consistent with relationships of the form

K_{sat} = fn (aggregate size$^{z)}$, where z ranges from 1.7 to 2.5. [Eqn 6.20]

If aggregate size, as quantified by the statistics, was directly proportional to mean inter-aggregate pore diameter, then the data would be consistent with functions relating hydraulic conductivity to pore size raised to the power of two as developed by others (eg., Marshall, 1958).

The weakness of fitted relationships between soil stability factors (S) and aggregation stability factors (D) may be due to the considerable uncertainty attached to fitted D parameters (due to few data). It may also be due to the fact that D and S exponents were fitted over different ranges of cumulative raindrop kinetic energy. D was fitted over a set range of cumulative raindrop kinetic energies from 136 J m^{-2} to 1630 J m^{-2} whereas S values were

fitted over ranges of early post-ponding data that varied slightly among soil and wetting pre-treatment combinations. Lack of data prevent fitting of D over the same restricted range of cumulative raindrop kinetic energy used for fitting S.

Due to the considerable uncertainty attached to the fitted parameters it is not possible to examine systematic effects of wetting pre-treatment, tillage treatment or soil on the fitted relationships.

6.5 RELATIONSHIPS BETWEEN MEASURES OF AGGREGATE STABILITY AND SURFACE HYDRAULIC BEHAVIOUR.

The relationships that are potentially most useful are those between changes in hydraulic properties such as K_{sat} or infiltration rate and convenient, established measures of aggregate stability, such as wet sieving after tension or immersion wetting (Kemper and Rosenau, 1986). Relationships based on convenient measurement techniques reduce the costs of routine testing and broaden the range of potential users hence encouraging wide-spread adoption. In addition, relationships based on established measurement techniques allow useful comparisons with data accumulated from past studies. However, previous studies indicate that such relationships are least likely to provide high predictive accuracy because measurement of aggregate stability using wet sieving involves forces and processes quite different from those occurring during infiltration under rainfall (eg., Loch, 1989; Glanville and Smith, 1988). The degree to which this disparity reduces the predictive capability of aggregate stability tests varies with the nature of the soils tested (eg., Loch, 1989).

In the current study, only two soils under two tillage treatments were tested and therefore statistical examination of relationships between aggregate stability and other properties would be inappropriate. However, the data can be usefully examined.

A strong relationship between measured aggregate stability and change in aggregate size distribution of soil surfaces under rainfall is a pre-requisite for a physically based relationship between measured aggregate stability and change in surface soil hydraulic properties under rainfall. Figures 6.12 to 6.15 present the percentage of water stable aggregates (Kemper and Rosenau, 1986) plotted against the fitted exponents (aggregation stability factors, D in Equation 5.1) of exponential decline of each of the four aggregate size statistics (GMD, MWD, D50 and %<0.125mm) calculated for the AT series.

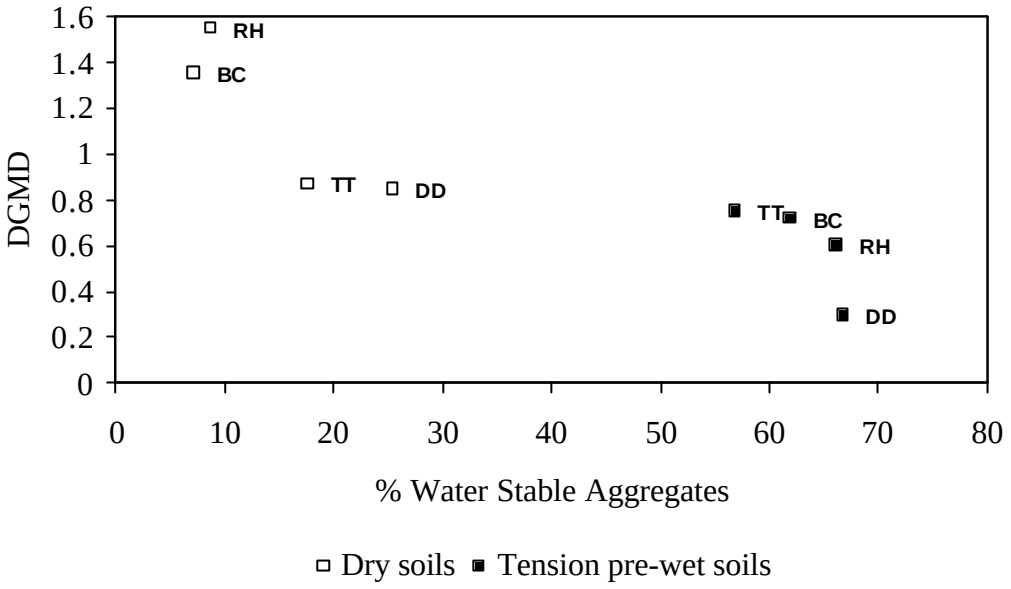

Fig 6.12 The relationships between aggregate stability (measured by water stable aggregation) and rate of change in GMD for tension pre-wet and initially dry soils.

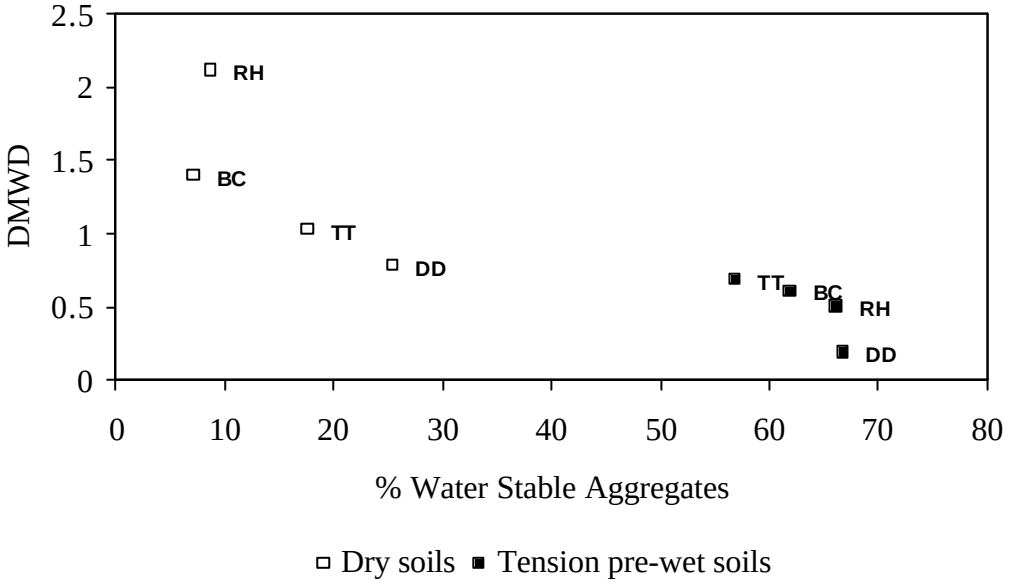

Fig 6.13 The relationships between aggregate stability (measured by water stable aggregation) and rate of change in MWD for tension pre-wet and initially dry soils.

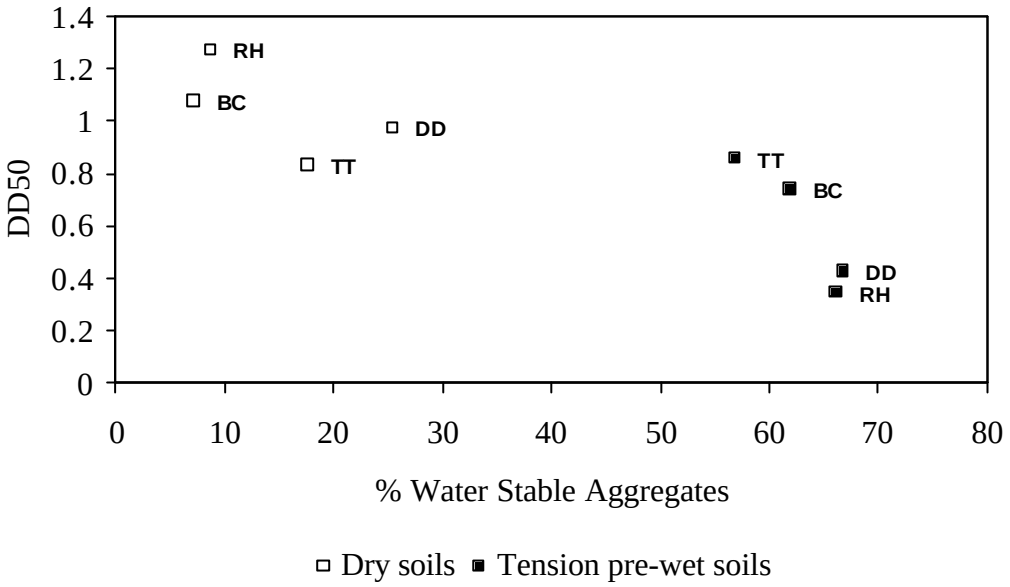

Fig 6.14 The relationships between aggregate stability (measured by water stable aggregation) and rate of change in D50 for tension pre-wet and initially dry soils.

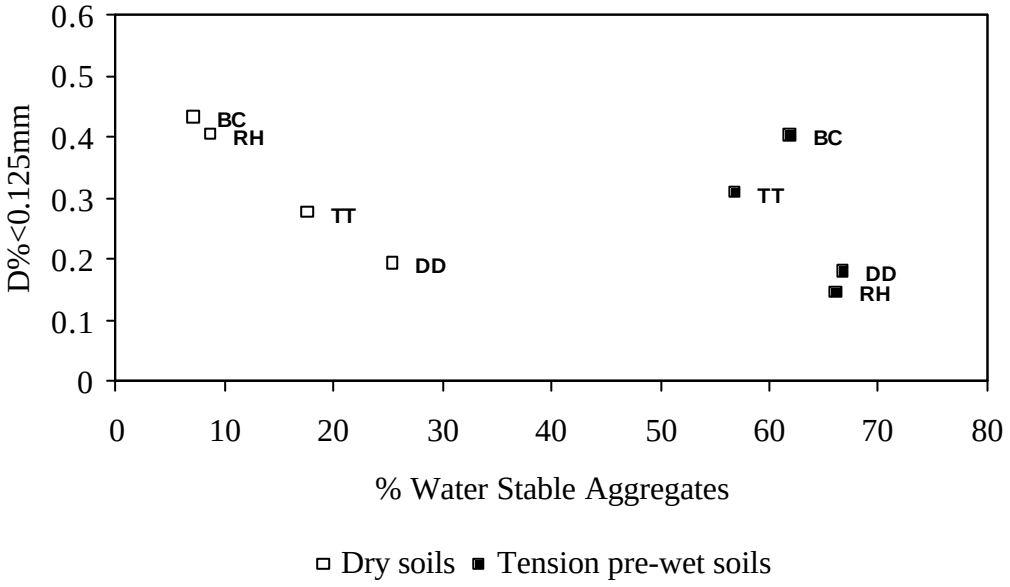

Fig 6.15 The relationships between aggregate stability (measured by water stable aggregation) and rate of change in % < 0.125 mm for tension pre-wet and initially dry soils.

Data in Figure 6.15 are consistent with an association between higher aggregate stability and slower rates of decline in aggregation for initially dry soils. There are insufficient data to attempt to evaluate relationships statistically. However, the data suggest that

relationships between aggregate stability and rates of decline in aggregation may differ between dry and tension wetting pre-treatments.

Water stable aggregation determined by wet sieving may also potentially be related to the final aggregate size distribution at the conclusion of the rainfall simulations. Figures 6.16 to 6.19 plot percentage of water stable aggregates against final values of each of the four aggregation statistics used in the AT series.

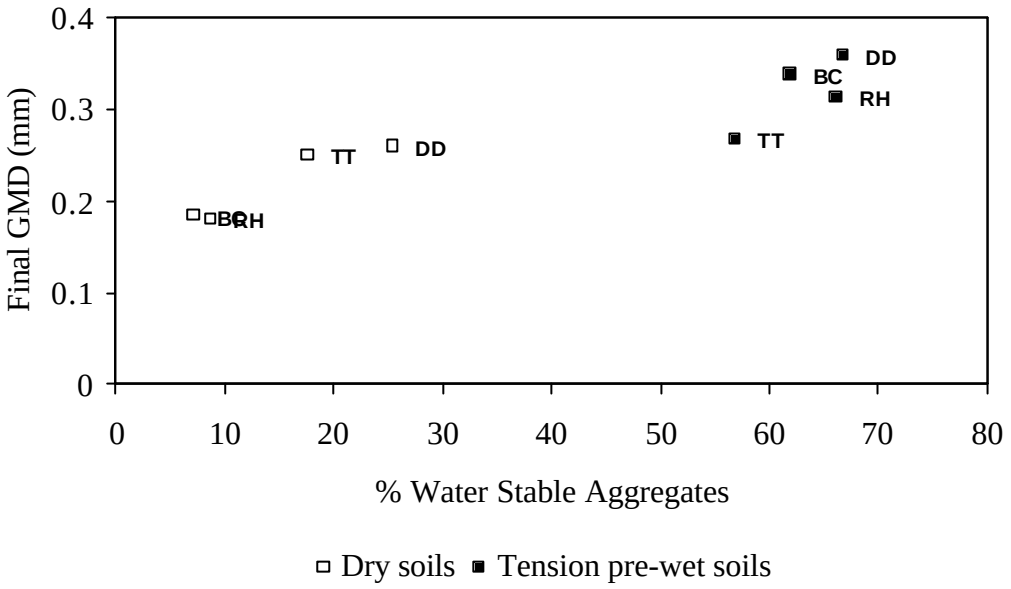

Fig 6.16 The relationship between aggregate stability (measured by water stable aggregation) and final aggregate size as measured by GMD for tension pre-wet and dry soils.

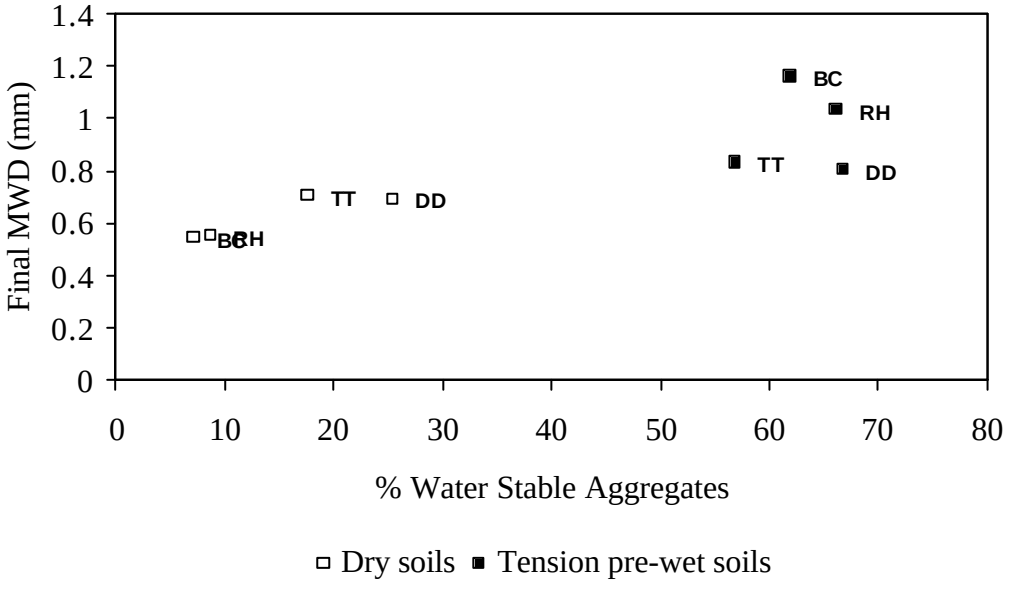

Fig 6.17 The relationship between aggregate stability (measured by water stable aggregation) and final aggregate size as measured by MWD for tension pre-wet and dry soils.

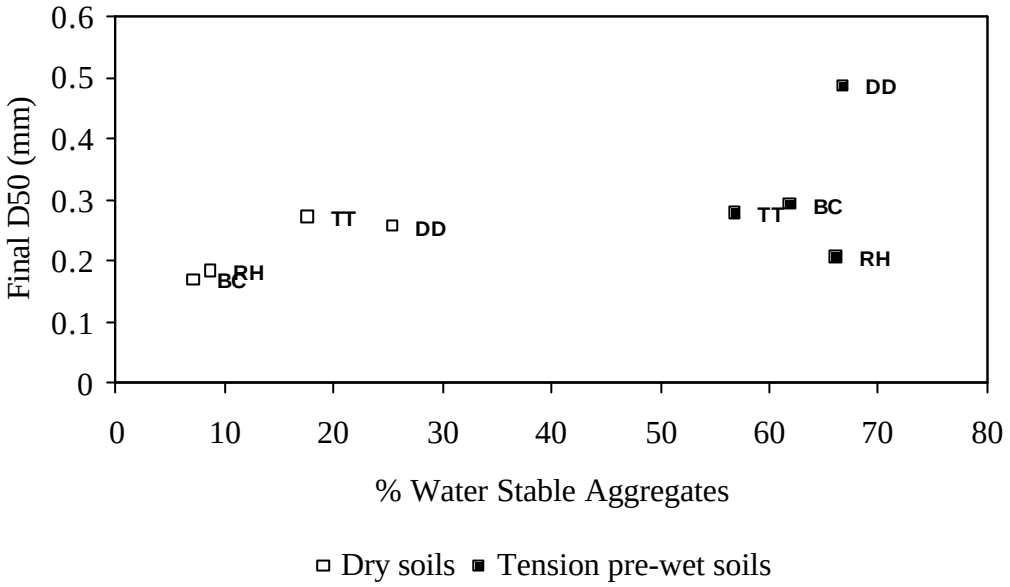

Fig 6.18 The relationship between aggregate stability (measured by water stable aggregation) and final aggregate size as measured by D50 for tension pre-wet and dry soils.

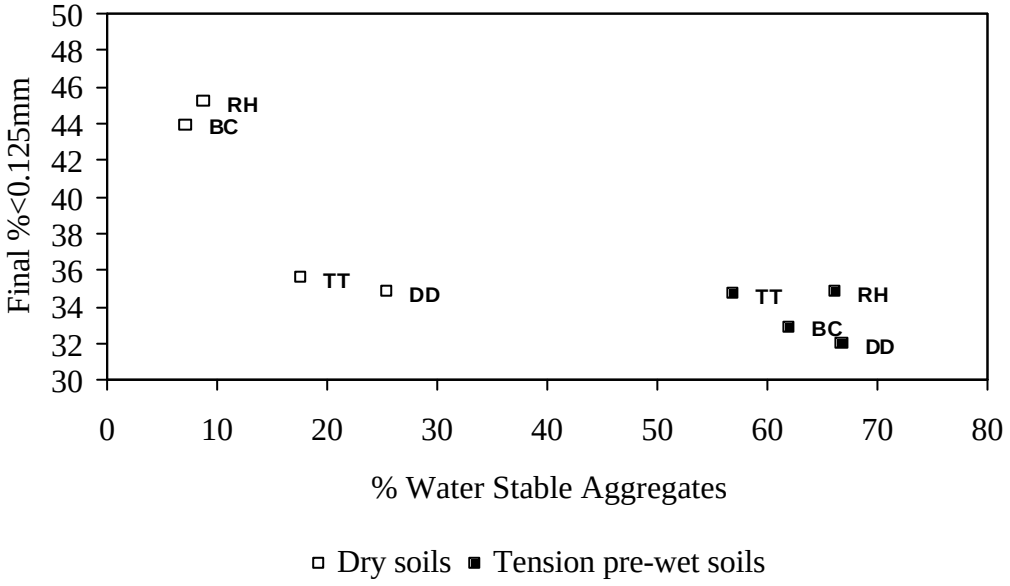

Fig 6.19 The relationship between aggregate stability (measured by water stable aggregation) and final aggregate size as measured by % < 0.125 mm for tension pre-wet and dry soils.

Data presented in Figures 6.16 to 6.19 are consistent with an association between lower aggregate stability (measured by water stable aggregation) and finer final aggregate size distribution for respective soil pre-treatment combinations. This trend is more clearly evident among the data for initially dry soils. It is not possible to meaningfully evaluate a relationship for either wetting pre-treatment due to the small number of data. Linear regression would yield a

relationship with a high coefficient of determination but such an analysis would be inappropriate for this data set because the ordinates are not well distributed across the range of the data.

If a relationship did exist between aggregate stability (as measured by water stable aggregation) and rate of change in aggregation under rainfall, then it would provide a basis for anticipating a relationship between water stable aggregation and rate of change in hydraulic conductivity measured by soil stability factors (S). The relevant data are presented in Figure 6.20.

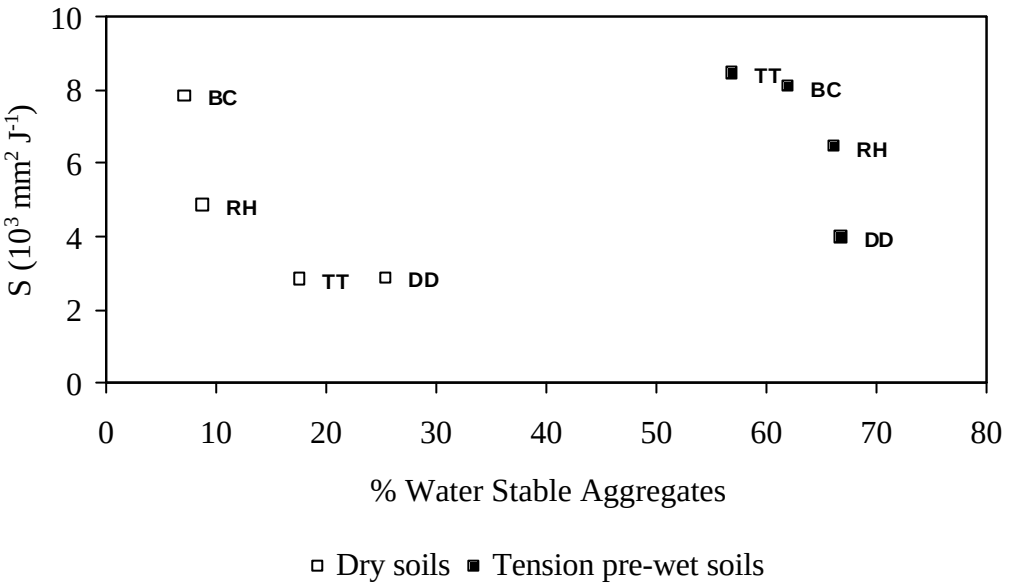

Fig 6.20 The relationship between aggregate stability (measured by water stable aggregation) and soil stability factors for tension pre-wet and dry soils.

There is no clear trend evident for initially dry soils. For tension pre-wet soils, within each location, higher water stable aggregation is associated with slower rate of decline in K_{sat} but the data are not consistent across the two locations. There are potential explanations for the lack of obvious relationships among the data. The most pertinent explanation is that soil stability factors are fitted to the post-ponding period when much of the aggregate breakdown has already occurred. In addition, post-ponding decline in K_{sat} is of much smaller magnitude than pre-ponding decline in K_{sat} and post-ponding rates of decline were found to be inconsistent with inferred rates of decline prior to ponding (see section 4.5).

Given that greater aggregate breakdown occurs in the early stage of rainfall, it may be expected that aggregate stability (as measured by water stable aggregation) may relate more closely to surface sealing prior to ponding (indicated by cumulative rainfall volume required for ponding) or to total decline in K_{sat}. The relevant data (presented in Figure 6.21) are consistent with an association between lower water stable aggregation and lower rainfall volume at ponding for dry soils. Data for tension pre-wet soils are not comparable with dry soils in this case due to differences in initial soil water potential.

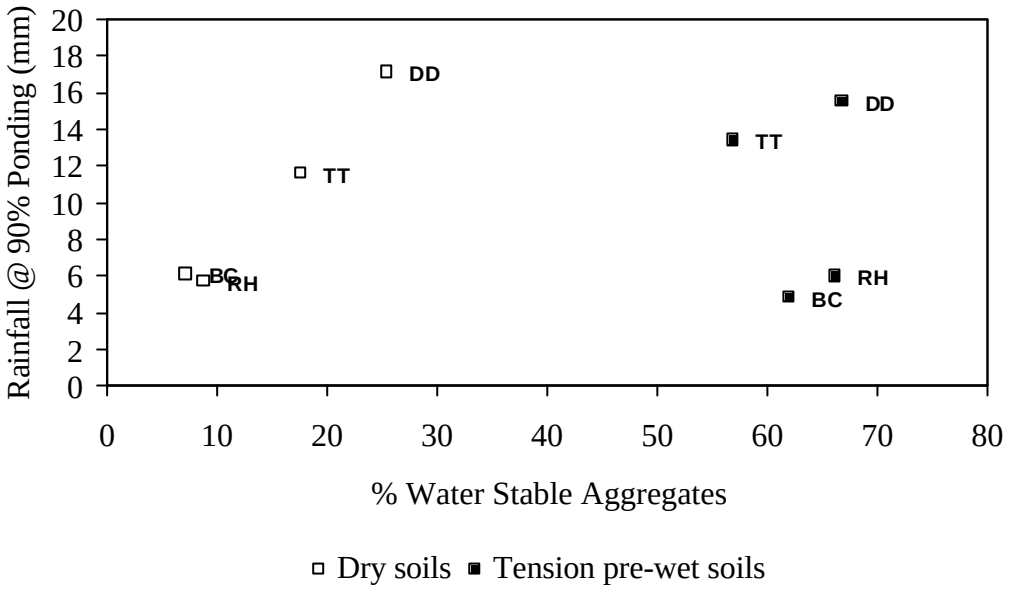

Fig 6.21 The relationships between water stable aggregation and rainfall volume required to induce 90% ponding.

As stated in section 4.1, rainfall volume at ponding provides only an indication of relative pre-ponding decline in K_{sat}. However, the data in Figure 6.21 are consistent with an association between aggregate stability (as measured by water stable aggregation) and surface sealing prior to ponding for initially dry soils.

Possible associations between water stable aggregation and rate of change in aggregate size under rainfall observed for dry soils suggest the possibility of a relationship between aggregate stability (as measured by water stable aggregation) and final K_{sat} or final infiltration rate. Figures 6.22 and 6.23 present the relevant data.

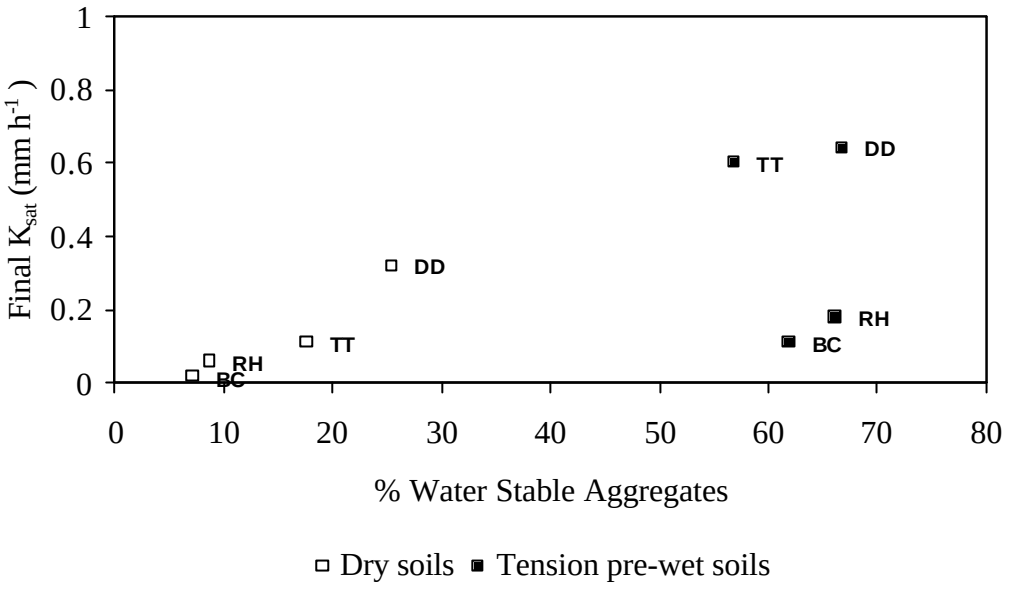

Fig 6.22 The relationship between water stable aggregation and final K_{sat} for tension pre-wet and dry soils.

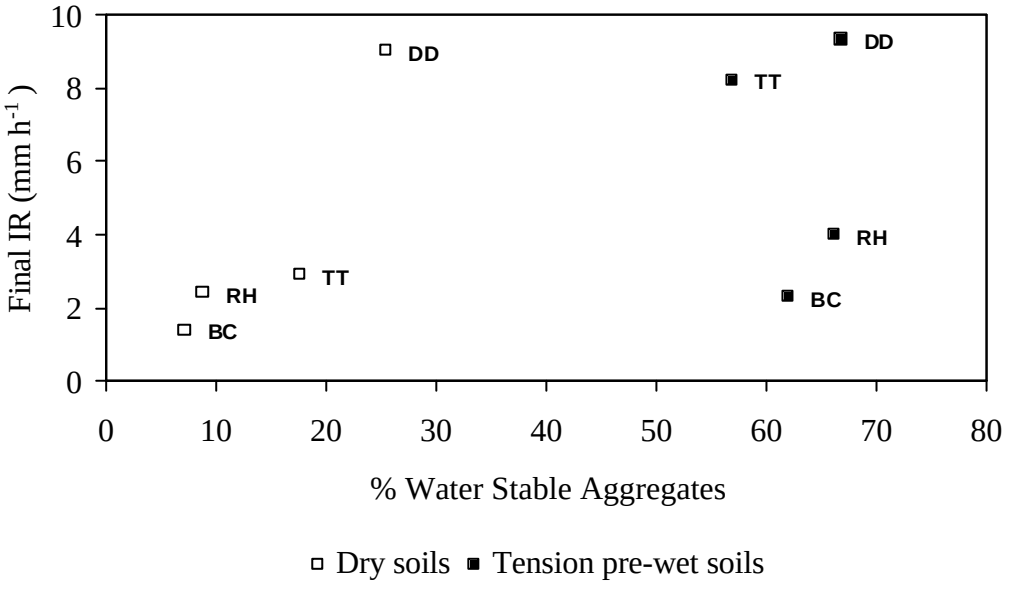

Fig 6.23 The relationship between water stable aggregation and final infiltration rate for tension pre-wet and dry soils.

Again the data are consistent with an association between lower aggregate stability and lower final K_{sat} and infiltration rate, but only for initially dry soils.

6.6 SUMMARY

Relationships have previously been developed by others relating the concentration of surface aggregates and particles less than 0.125 mm in diameter to steady K_{sat} or infiltration rate (Glanville and Smith, 1988; Loch and Foley, 1994). The relationships of Glanville and Smith predict infiltration fraction rather than surface K_{sat} and hence may be unique to the rainfall intensity and hydraulic gradients that existed in their experiments. The relationships of Loch and Foley predict "steady" or final infiltration rate and K_{sat} and cannot be used to predict changes in infiltration in the very early stages of surface sealing. Both sets of relationships were developed using only initially dry soils and may not apply under conditions of less severe soil wetting that may occur when the soil is initially moist.

This chapter presents potentially useful relationships predicting both declining surface K_{sat} and declining infiltration rate, using declining surface aggregate size measured by wet sieving (expressed as four different aggregate size statistics). The more consistent of these relationships are of similar functional form to relationships previously found in other studies but with significantly different parameters. They relate the proportion of fine aggregates (% < 0.125 mm diameter) to K_{sat} and infiltration rate over the post-ponding stages of developing structural seals. Results indicate that soil and wetting pre-treatment may significantly affect the relationships fitted in the current study but that a common rate of decline in $\log_e(K_{sat})$ exists. Results suggest that the influence of sub-seal water potential on surface K_{sat} needs to be considered whenever such relationships are developed or applied.

As with the relationship of Loch and Foley (1994), the relationships fitted in this study have been developed using bare soil conditions. Under such conditions raindrop impacts are likely to rapidly cause a considerable degree of surface compaction. In cases where rainfall is less effective or efficient in packing aggregate breakdown products then surface hydraulic conductivity may be under-predicted by the fitted relationships.

Similarly, the relationships fitted here predict essentially one dimensional K_{sat} and infiltration rate under rainfall. They do not account for the effects of surface sealing and aggregate breakdown on surface detention storage and surface roughness that may influence the infiltration-runoff balance of larger, more heterogenous soil surfaces.

Associations between stability of soil aggregates (determined by wet sieving) and decline in K_{sat} caused by surface sealing have been proposed by others. Data from the current study suggest associations between greater aggregate stability and slower rates of decline in aggregation and slower rates of decline in post-ponding K_{sat}. However the data suggest that the predictive value of relationships may be weak or not consistent across different soil locations and soil wetting pre-treatments. The data also suggest an association between greater water stable aggregation and greater rainfall volume required to induce ponding (under the conditions simulated in this study), greater final K_{sat} and greater final infiltration rate for initially dry soils. However, data for tension pre-wet soils are not consistent with this trend. The

data also indicate that it is unlikely that measures of aggregate stability determined by wet sieving after different wetting pre-treatments can be used to accurately predict effects of surface aggregate breakdown on infiltration under rainfall into soils that experience those same wetting pre-treatments.

Chapter 7

A SUMMARY OF FINDINGS, A CONCEPTUAL MODEL OF STRUCTURAL SEALING AND A DISCUSSION OF POTENTIAL RESEARCH OPPORTUNITIES

7.1 INTRODUCTION

This chapter summarises the major findings of this study (presented in Chapters 4 to 6) in relation to the major objectives. An attempt is made to incorporate these findings into a conceptual model of structural sealing through amendments to the model proposed by Le Bissonnais (1990). Opportunities for future research identified during the study are summarised.

7.2 SUMMARY OF FINDINGS AND CONCLUSIONS

The current study sought to broaden collective understanding of structural surface sealing on light textured soils under rainfall. Its primary objective was to quantify the relative importance of rapid wetting and energetic raindrop impact as agents of aggregate breakdown and surface sealing under rainfall. In doing so, it sought to isolate the effects of soil wetting rate from the effects of initial soil water potential. It also sought to determine the relative importance of increases in aggregate stability, brought about by conservative tillage management systems and to examine the implications for practical soil management. Another major objective was to evaluate measures of aggregate stability and aggregate breakdown that predict the effects of surface sealing on rainfall infiltration. These measures were evaluated under conditions imposed to vary the relative importance of rapid soil wetting, energetic raindrop impact and culturally induced aggregate stability.

The main findings presented in the previous three chapters are discussed below in relation to these objectives.

7.2.1 The Relative Importance of Rapid Wetting, Energetic Raindrop Impact and Management Induced Aggregate Stability for Aggregate Breakdown and Surface Sealing Under Rainfall

7.2.1.1 The Relative Importance for Aggregate Breakdown

Both rapid soil wetting and energetic raindrop impact can cause significant aggregate breakdown under simulated rainfall on light textured soils. When soil is initially dry rapid soil wetting will be the dominant agent causing rapid aggregate breakdown, generally within the first 5 mm of rainfall. When rapid soil wetting is prevented by high antecedent soil water potential, energetic raindrop impact will be the dominant agent and is able to cause aggregate breakdown of an almost equivalent degree. This breakdown can occur over a period lasting for up to 30 mm of rainfall. The majority of the data from the current study indicate that a negative interaction exists between the two effects. Such an interaction is physically sensible since both agents can easily disrupt surface aggregates of the soil studied and the potential for aggregate breakdown is limited by primary particle size. Initial soil water condition and the amount of surface protection from raindrop impact will determine the relative importance of the two agents in a given instance.

The importance of the two agents differs between soils. Both rapid wetting and energetic raindrop impact result in greater aggregate breakdown in Condobolin soil than Cowra soil. The relative importance of the agents also differs between soils. The rapid wetting has a slightly greater effect than energetic raindrop impact on aggregate breakdown in Cowra soil, but the two agents have similar effects in Condobolin soil.

The data also indicate that the importance of the two agents in causing aggregate breakdown is dependent on sample depth. The effect of rapid soil wetting is slightly greater than the effect of energetic raindrop impact for the 0 to 10 mm depth after 60 mm rainfall. However, the effect of rapid soil wetting was slightly reduced for the shallower depth (0 to 5 mm) and it had no consistent effect for the shallowest depth (approximately 0 to 3 mm). In contrast, the effect of energetic raindrop impact on aggregate breakdown increased slightly from the 0 to 10 mm depth to the shallowest depth (0 to 3 mm). The reduced effect of energetic raindrop impact at greater depth is consistent with the dissipation with depth of the shock waves that transmit the impact energy and disrupt sub-seal aggregates. The increased effect of rapid wetting with depth may have been due to reduced aggregate slaking nearer the surface as a result of unavoidably finer aggregate size nearer the surface. However, this proposition remains untested.

Conservative tillage management (including stubble retention and reduced tillage) increases the stability of surface soil aggregates due to increased soil organic matter. This increased aggregate stability can significantly retard the rate and significantly reduce the degree of aggregate breakdown under rainfall within the 0 to 10 mm layer. These residual effects of conservative tillage treatments can be as significant in maintaining aggregation in this 0 to

10 mm layer as the effect of surface protection from energetic raindrop impact (see Chapter 5).

7.2.1.2 The Relative Importance for Surface Sealing

Runoff did not occur during most of the low kinetic energy simulations. Hence, a fully balanced statistical comparison of the relative magnitude of effects of wetting rate and raindrop kinetic energy level on the reduction in infiltration caused by surface sealing was not possible. However, it is clear that the difference in raindrop kinetic energy levels used in this study had a greater effect on rate and degree of surface sealing (as measured by rainfall volume to ponding and decline in hydraulic conductivity) than did the difference in soil wetting rates. Whilst rapid soil wetting under near zero raindrop kinetic energy resulted in considerable reductions in hydraulic conductivity (up to 90% reduction), these were generally not sufficient to induce surface ponding under the 33 mm h^{-1} rainfall intensity simulated. In contrast, the reductions in surface hydraulic conductivity brought about by high kinetic energy raindrop impacts (approximately 99.7 to 99.9% reductions) resulted in surface ponding and runoff on all soil surfaces.

The greater practical significance of reducing the kinetic energy of raindrop impacts is clear when the practicalities of achieving the respective wetting rates and kinetic energy levels in a field situation are considered. In a dryland agricultural field it is far more practical to obtain the range of kinetic energies used in this study (0 to 27.3 J m^{-2} mm^{-1}) by managing surface cover levels, than it is to achieve the limits of the range of wetting rates used (1.8 to 33 mm h^{-1}).

Increased aggregate stability under Conservative tillage treatments (including stubble retention and reduced tillage) can retard surface ponding, retard decline in surface hydraulic conductivity, increase final infiltration rate and increase final surface hydraulic conductivity (see Chapter 4).

7.2.1.3 Implications of this Relative Importance for Soil and Crop Management

Aggregate breakdown in the upper 5 to 10 mm of light-textured surface soils will occur under rainfall when either rapid soil wetting or energetic raindrop impact occurs. Whilst inter-rill erosion rates, and properties of aggregates that relate directly to erodibility, such as settling velocity distribution and surface shear strength, have been not measured in the current study there is potential for this aggregate breakdown to influence erodibility.

Structural surface sealing will occur when energetic raindrops impact on the soil surface. Rates of surface sealing for bare tilled soils can be extremely rapid under intense rainfall events with reductions from high K_{sat} values for tilled soils (150 to 1500 mm h^{-1}) to very low levels (< 1 mm h^{-1}) after only 20 to 30 mm of high kinetic energy rainfall.

This sealing will exert control over infiltration into freshly tilled soils when rainfall intensity is high (> 20 mm h^{-1}), the permeability of sub-surface soil layers is not more limiting

and a significant amount of rain falls (ie., >20 mm). Effects on soil hydrology can influence erosion hazard by decreasing the amount of rainfall required to induce runoff and increasing the rate and total volume of this runoff. Effects on the soil water balance can also influence soil water available for crop and pasture growth, rates of nutrient leaching, rates of acidification and rates of recharge to shallow ground water tables.

There are a number of potential soil management responses to these effects including the following -

1. disrupting surface seals with tillage,
2. implementing conservative crop and tillage management,
3. optimising land-use on the basis of soil susceptibility to aggregate breakdown and surface sealing optimising land-use patterns.

Tillage is often used in bare fallow farming systems to disrupt surface seals that form during the period prior to sowing to improve infiltration rate and capacity. Under bare soil conditions these effects may be short-lived as surface seals can reform rapidly. Farming systems that use tillage in this way can result in significant runoff when rain falls in large events (> 20 mm) or where tillage cannot be carried out between successive rainfall events. Even when rain falls with a temporal pattern that is optimal for promoting water entry and storage such a farming system may require up to ten tillage operations during a short fallow period to prevent surface runoff and loss of useful soil water. Once crops or pastures have been established, options for tillage are limited. Whilst hand tillage of cash crops can be economic in countries with low labour costs, mechanised tillage will generally result in unacceptable plant deaths.

Conservative crop and tillage management systems generally include retention of stubble, reduced frequency of tillage, the use of tined tillage implements rather than disc implements. Such management systems can have significant effects on aggregate breakdown and surface sealing under rainfall through a number of mechanisms.

Firstly, retention of stubble under conservative management can significantly reduce surface sealing by reducing the amount of raindrop kinetic energy impacting the soil surface. An amount and arrangement of soil surface cover, that is completely effective in absorbing raindrop kinetic energy, can prevent infiltration rate decline providing rainfall intensity remains below infiltrability (that is, providing the soil surface remains un-ponded). If the soil surface ponds then surface sealing can occur irrespective of degree of surface protection. However, the rate of surface sealing will be much slower under surface cover that provides complete protection.

Secondly, in the longer term conservative stubble and tillage management systems (including stubble retention and reduced tillage) increase the stability of surface soil aggregates due to increased soil organic matter. Tillage during sowing or seed-bed preparation will

generally expose aggregates to some degree of energetic impact under subsequent rainfall events. When aggregates that are more stable are subject to high kinetic energy rainfall, the rate and degree of breakdown are reduced (see Chapter 5). The increased aggregate stability can retard surface ponding, retard decline in surface hydraulic conductivity, increase final infiltration rate and increase final surface hydraulic conductivity (see Chapter 4). These increases in final surface hydraulic conductivity attributed to conservative tillage treatments are small relative to increases attributed to surface cover. However, soil water balance simulations (see section 4.7.3) predict that these small differences in permeability can be relatively effective in reducing surface runoff under moderate rainfall intensities.

Thirdly, retained plant cover or surface mulches can ameliorate rapid soil wetting. Surface cover may reduce the potential for soil wetting under rainfall by maintaining higher antecedent soil water contents and by increasing detention or abstraction during rainfall. It may reduce the rate of soil wetting by routing rainfall on its path to the soil surface. It may also redistribute rainfall preferentially to a small number of infiltration sites leading to less damaging capillary wetting of intervening the soil. These mechanisms have not been examined directly in the current study. However, results from the current study indicate indirectly that the their potential effect on rate and degree of surface sealing is less than the potential effect of absorption of raindrop kinetic energy.

Fourthly, tillage at appropriate soil water contents can create larger aggregates. Tillage with tined tillage implements can selectively bring these larger aggregates to the soil surface. Reduced tillage frequency may leave these larger aggregates intact at the time of crop establishment and this can delay soil surface sealing and reduce runoff volume (eg., Moldenhauer and Kemper, 1969; Farres, 1978; Braunack and Dexter, 1988; Freebairn, 1989). This has not been investigated in the current study.

A full assessment of the relative advantages of traditional and conservative crop and tillage management in terms of surface soil hydraulic behaviour over a full fallow and growing season may be complex and is beyond the scope of the current study. All soil surfaces in the study were prepared using a standardised procedure designed to simulate a cultivated surface condition and they have been compared over a single intense rainfall event. Clearly, fields managed under traditional tillage systems that involve regular tillage may be more frequently found in a loose soil surface condition, whereas fields under minimum or zero tillage may generally be in a firm or settled surface condition with larger aggregates at the surface, higher bulk density and lower permeability through the soil matrix. Likewise, differences in surface detention or depression storage created by different tillage management systems can alter runoff and infiltration response under rainfall (see Figure 4.10 and discussion in section 4.7.3). Comparisons are further complicated by the potential for biologically produced macro-pores or bio-pores to influence infiltration. In the re-packed soil columns, used in the current study, porosity consists entirely of matrix or packing pores and no opportunity exists for the development of biologically formed pores. Under longer term conservative tillage management

with reduced tillage, maintenance of these bio-pores can potentially enhance hydraulic conductivity. While it has been shown that macro-pores are rapidly sealed under some conditions by high kinetic energy rainfall (Ela, 1990), their potential effects on infiltration have not been investigated during the current study.

Inherent properties of soils, that may relate to parent material and pedogenesis, can affect aggregate stability. Data presented in Chapters 4 and 5 indicate that these properties affect the rate and extent of aggregate breakdown under rainfall and the rate and final degree of surface sealing under rainfall. They also affect the relative importance of rapid wetting and energetic raindrop impact as agents of aggregate breakdown and surface sealing. In theory, it may be possible to reduce the negative impacts of aggregate breakdown and surface sealing by optimising land-use on the basis of soil susceptibility to surface sealing at a catchment or regional scale. However, differences in susceptibility to aggregate breakdown and surface sealing found in this study are relatively small and it is unlikely that any light textured soil in the wheat-belt of southern New South Wales is totally resistant to aggregate breakdown and surface sealing. In addition, alternative land-uses in the region are relatively limited. Therefore little capacity exists to manage aggregate breakdown and surface sealing through optimising patterns of land-use.

7.2.2 Measures of Surface Soil Aggregate Breakdown or Aggregate Stability that Predict Effects of Structural Surface Sealing on Infiltration into Freshly Tilled Soils

The measurement of the proportion of aggregates and particles less than 0.125 mm in diameter following a significant period of high kinetic energy rainfall has been proposed as a routine assessment of aggregate stability (Loch, 1994a). The current study has evaluated relationships predicting declining infiltration rate and surface K_{sat} using %<0.125mm within a fixed sampling depth (0 to 5 mm) measured after a much lower range of cumulative raindrop kinetic energies. These relationship provide a useful predictive tool. However, the parameters of the relationships vary among soils and soil wetting rates and vary with antecedent soil water conditions They have been evaluated only under high kinetic energy rainfall.

The current study has also found that, under some conditions, wet sieving of dry aggregates (Kemper and Rosenau, 1986) can be useful in predicting differences in the rate and degree of aggregate breakdown under high kinetic energy rain but only for initially dry soil. This measure can be useful in predicting rainfall volume required to induce surface ponding, final infiltration rate and final surface K_{sat} for initially dry soil but not rates of decline in K_{sat} (soil stability factors).

7.2.3 Additional Findings

The current study has also contributed to understanding of aggregate breakdown and surface sealing by proposing possible alternative explanations for two effects observed when rain falls on bare soil and partially evaluating a possible explanation for a third.

Firstly, an alternative mechanism that may possibly explain initially more rapid rates of decline in aggregation under rainfall has been proposed. It is proposed that initial energetic raindrops may impact aggregates that have strengths that are much weaker than the forces exerted by those raindrop impacts. Hence aggregate breakdown is likely to occur. Subsequent raindrops may tend to impact aggregates or fragments that have had sufficient strength to survive previous impacts. Hence aggregate breakdown may occur less often under subsequent impacts. Such a mechanism provides an alternative explanation for the data of Baumhardt *et al.* (1991).

Secondly, a possible alternative explanation for increased surface seal hydraulic conductivity under higher rainfall intensity found in other published studies (eg., Romkens *et al.*, 1985). Under more intense rainfall sub-seal soil water potential at the time of ponding will generally be less negative and consequently the hydraulic gradient across the surface soil layer will be lower. It is proposed that this may lead to the increased surface seal hydraulic conductivity in accordance with observations in other studies (eg., Rose, 1962; Morin *et al.*, 1981; Silburn and Foley, 1994).

Thirdly, the mechanism proposed by P.J. Ross (cited by Silburn and Foley, 1994) to explain the negative correlation between seal conductivity and hydraulic gradient across the seal has been partially evaluated. The findings suggest that the mechanism may not be dependent on the presence of underlying unsealed soil. They also suggest that the mechanism may only be effective in cases where the sub-seal water potential is below the air entry value of the surface seal.

7.3 TOWARDS AN IMPROVED CONCEPTUAL MODEL OF AGGREGATE BREAKDOWN AND STRUCTURAL SEALING UNDER RAINFALL

The influence of surface sealing on infiltration and runoff is of considerable practical significance and efforts have been directed toward predictive modelling (eg., Moore and Larson, 1980). However, lack of understanding of the relative significance of the various mechanisms potentially contributing to reduced infiltration has hampered these attempts and most resort to varying degrees of empiricism or apply to limited range of initial and boundary conditions. The conceptual model proposed by Le Bissonnais (1990) (see Figure 7.1) seeks to identify sealing mechanisms and the parameters and relationships governing those mechanisms. Whilst it does not attempt to quantify the relationships, it does provide a mechanistic framework guiding mechanistic consideration of the individual processes and mechanisms potentially involved.

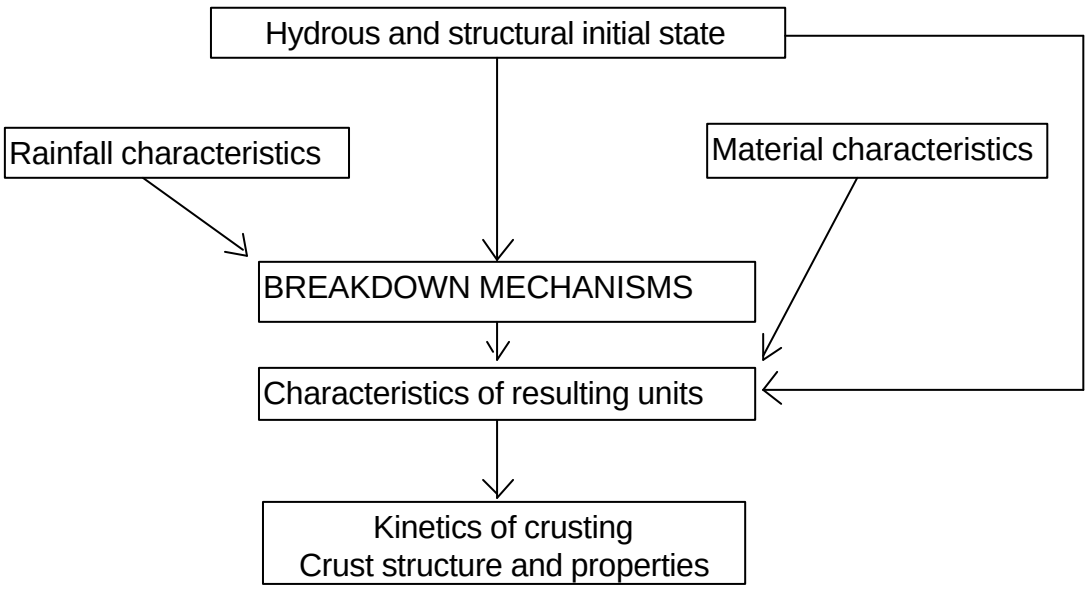

Fig. 7.1 Diagram of the relations between the different parameters of crusting (after Le Bissonnais, 1990).

Findings presented in Chapters 4 and 5 and summarised in the previous section suggest that amendments to Le Bissonnias's model are possible based on the improved understanding of the mechanisms involved. As with the original model of Le Bissonnais, the amended model (see Figure 7.2) does not attempt to quantify relationships. Rather, it seeks to provide a more complete description of the system of interacting mechanisms in order to better direct efforts aimed at quantitatively predicting the influence of surface sealing on infiltration. Whilst minor changes are proposed to the structure and terminology used by Le Bissonnias in order to clarify its original intent, the following discussion concentrates on the two major amendments.

Firstly, the amended model identifies both the influence of rainfall intensity on aggregate breakdown through aggregate slaking controlled by surface soil wetting rate and the influence of rainfall energy on aggregate breakdown. Further, the amended model separates the influence of energetic raindrop impacts on crust hydraulic properties from their influence on aggregate breakdown. In contrast, the original model of Le Bissonnais identified only a single unlabelled relationship between rainfall characteristics and breakdown mechanisms.

Secondly, the amended model separates surface soil water potential and sub-surface soil water potential as dynamic entities from the "hydrous and structural initial state" identified by Le Bissonnais (1990). This allows identification of the effect of the

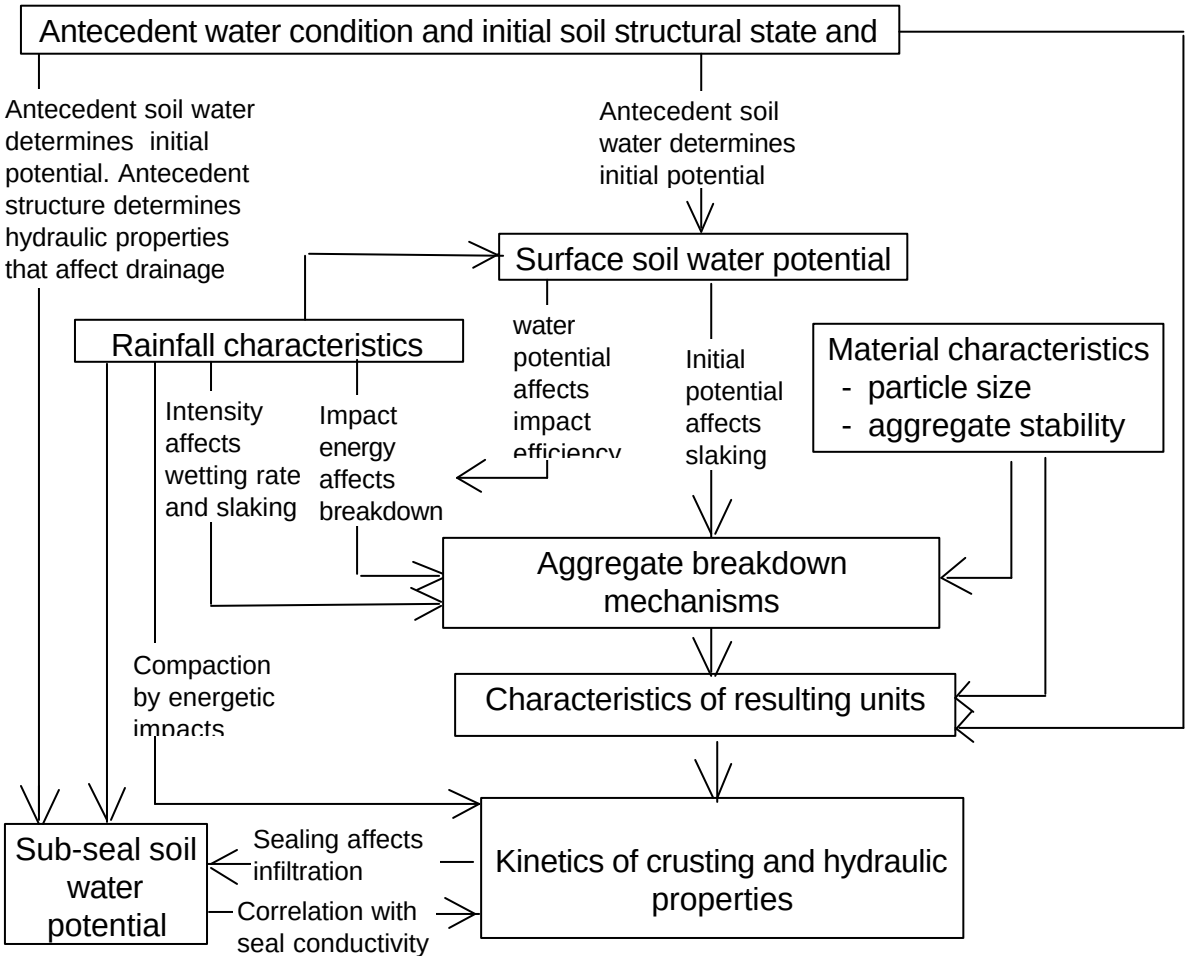

Fig. 7.2 An amended conceptual model of the relations between the parameters of aggregate breakdown and structural sealing.

negative correlation between seal hydraulic conductivity and hydraulic gradient across the sealing layer observed in other studies (eg., Silburn and Foley, 1994). It also allows identification of the influence of degree of surface saturation on partitioning of raindrop impact energy (eg., Nearing, 1987). Separation also recognises the dynamic nature of these effects as

soil water potential responds to rainfall, seal permeability and sub-seal drainage. The exact mechanism by which this influence occurs is uncertain. There are several possible mechanisms. Firstly, clogging of pores could be increased due to increased infiltration flux. Secondly, permeability may be decreased due to de-saturation of the base of seal or underlying soil. Thirdly, the soil matrix within the seal surface may be compressed by greater sub-seal suction. Findings from the current study suggest that it is more likely to be the later (see section 4.6.7) but the nature of the mechanism has been left unspecified in Figure 7.2.

Significant potential remains to broaden the scope of the conceptual model of structural sealing presented in Figure 7.2. For instance, the process of "washing in" identified in some studies (eg., McIntyre, 1958b) is yet to be incorporated. It may be efficient for such conceptual development to precede attempts to advance the model to quantitative or semi-quantitative status. The data obtained in the experimental elements of the current study go some way to empirically quantifying relationships identified in the conceptual model for two soils, under two tillage treatments, over a range of conditions. Further experimental studies that adequately isolate effects of rapid wetting and energetic raindrop impact should add to this. However, for the model to gain widespread applicability, all important relationships need to be understood mechanistically. One of the key mechanisms that is yet to be adequately explained is that causing correlation between sub-seal soil water potential and seal hydraulic conductivity. Until this relationship can be adequately explained the model will remain conceptual or semi-quantitative and empirical.

Soil water potentials in the sealing layer can significantly influence the relative importance of aggregate breakdown mechanisms and soil water potentials in the sub-seal layer can significantly influence seal hydraulic properties. Clearly, the conceptual model can only be made quantitative within the framework of a soil water movement model that accounts for the influence of rainfall, evaporation and drainage on soil water potential.

7.4 POTENTIAL RESEARCH OPPORTUNITIES

Surface sealing is an important process influencing the management of agricultural soils. The surface sealing processes itself and its effects on infiltration and erosion are not yet fully understood. Indications of possible directions for future research that follow from the findings of this study are below.

7.4.1 Improving Understanding of the Processes Involved in, and Factors Controlling, Aggregate Breakdown and Surface Sealing

This study has gone some way to improving collective knowledge of the relative importance of rapid soil wetting, energetic raindrop impact, initial soil water content and culturally induced aggregate stability in the process of surface sealing of light textured surface soils. Further

advances may come from investigating changes in the relative importance of these factors during the specific stages of surface sealing prior to ponding, at the onset of ponding and between ponding and runoff. Of particular interest is the interaction of changes in near surface water content as surface ponding approaches with the above-mentioned factors. Such investigations are complicated by the difficulty of evaluating surface hydraulic conductivity in the period when infiltration is still limited by supply rate. Silburn and Foley (1994) proposed a method for doing such measurements but ideally it should be done without removing the sealing soil from the physical context in which it is forming.

As indicated in section 7.3, a key mechanism that is not yet fully understood is the mechanism responsible for the negative correlation between seal hydraulic conductivity and the hydraulic gradient across the sealing layer. Again, the method of Silburn and Foley (1994) may provide a suitable experimental tool to investigate this mechanism.

7.4.2 Improving Prediction of Surface Sealing Effects on Infiltration

The relationships between surface aggregate size and surface permeability of the sealing layer presented here represent a potentially useful advance for practical prediction of surface sealing effects on infiltration under rainfall. In order to fully realise this potential the relationships must be evaluated over a wider range of soils, initial aggregate and surface arrangements, soil wetting rates, raindrop kinetic energy levels and boundary conditions.

These relationships have been evaluated in an empirical manner. As with other studies, the physical basis for such relationships has not been established beyond doubt. To do so may require investigation of the effects of surface sealing at the individual soil particle scale. Investigating the physical processes involved in surface sealing at such a scale may further clarify the nature of the observed effects of wetting rate, initial water content, occurrence of surface ponding and raindrop kinetic energy. Such an aim may be advanced by development and parameterisation of a physically based packing pore model of the whole of the surface sealing layer. Packing models have been used conceptually to illustrate the critical nature of the size distribution of fine particles in creating small surface pores and promoting the process of surface sealing (eg., Loch, 1989; Moss, 1991a). Such model development could utilise the dynamic changes in aggregate size described in this study but would need to incorporate changes in particle packing as well as incorporating spatial heterogeneity within the sealing layer.

The relationships between aggregate size and surface permeability developed in this and other studies (that use level beds of uniformly packed loose soil) are essentially based on one dimensional treatment of infiltration and water movement. In order to take full advantage of these relationships, a framework is needed to aggregate predictions of infiltration and water movement on heterogenous soil surfaces. Infiltration and soil water movement models for soil surfaces that take account of surface topography and consequential differences in the nature

and rate of surface seal development in different micro-topographic elements need to be more fully developed.

7.4.3 Opportunities for Managing the Soil Surface to Reduce or Prevent Aggregate Breakdown and Surface Sealing Under Rainfall

There are tillage management options available that selectively increase the antecedent size distribution of surface aggregates. Such options are outside the scope of the current study but they are of interest. Likewise, techniques that increase antecedent depression storage can ameliorate the effects of surface sealing on infiltration to some extent (see section 4.7.3) without preventing or reducing aggregate breakdown or surface sealing. However, the current study has concentrated on the relative importance of various factors influencing the rate and degree of breakdown of surface aggregates and the rate and degree of surface sealing under rainfall.

It has been shown that increases in aggregate stability (in this case induced by conservative tillage and crop management) can reduce the rate and degree of surface sealing. There are opportunities for increasing aggregate stability that may be more efficacious or of greater practical value in achieving this aim. Reductions in surface sealing have been achieved by using polymers and other soil conditioners (eg., Shainberg *et al*., 1990) to increase the stability of surface aggregates. Results have varied with conditioner, soil type and other factors. Further investigation is required to identify the most suitable conditioners and determine optimal application rates and techniques for light-textured soils of the wheat-belt of southern New South Wales.

The findings of this study indicate that rapid soil wetting is a major cause of aggregate breakdown and can reduce surface soil permeability, but that processes driven by high kinetic energy raindrop impacts on ponded or near ponded soil are critical in determining the effect of surface sealing on infiltration under rainfall. There are potential opportunities to use this knowledge in engineering the soil surface to reduce the rate and degree of surface sealing in cropping systems -

1. The degree to which surface seal flaws and three dimensional sub-seal flow can reduce the effects of surface sealing on infiltration (Moss and Watson, 1991) indicates possibilities for improving field infiltration by altering the spatial arrangement of surface cover. The effect of different stubble arrangements has been investigated to some extent (eg., Moss and Watson, 1991) but further investigation of such effects and their potential interactions with variable microtopography is warranted.

2. Moss (1991b) proposed a method of long-term amelioration of surface sealing soils using surface applications of 1 to 3 mm diameter primary particles. These primary particles may increase the hydraulic penetration of raindrops, thus disrupting seal formation. They may

also interfere with the formation of a surface "silt" layer of fine material caused by energetic raindrop impacts. This proposal needs to be further investigated to determine its efficacy and practicality.

3. There may be practical surface soil arrangements that allow for strategically located areas of soil that have higher infiltration capacity and maintain the overall infiltration capacity of a heterogenous surface. Such areas may be established and maintained by strategically locating the more stable aggregates, establishing a higher degree of protection from direct raindrop impacts and by maintaining high sub-surface permeability to reduce the occurrence of surface saturation that may predispose soil surfaces to rapid surface sealing.

Chapter 8

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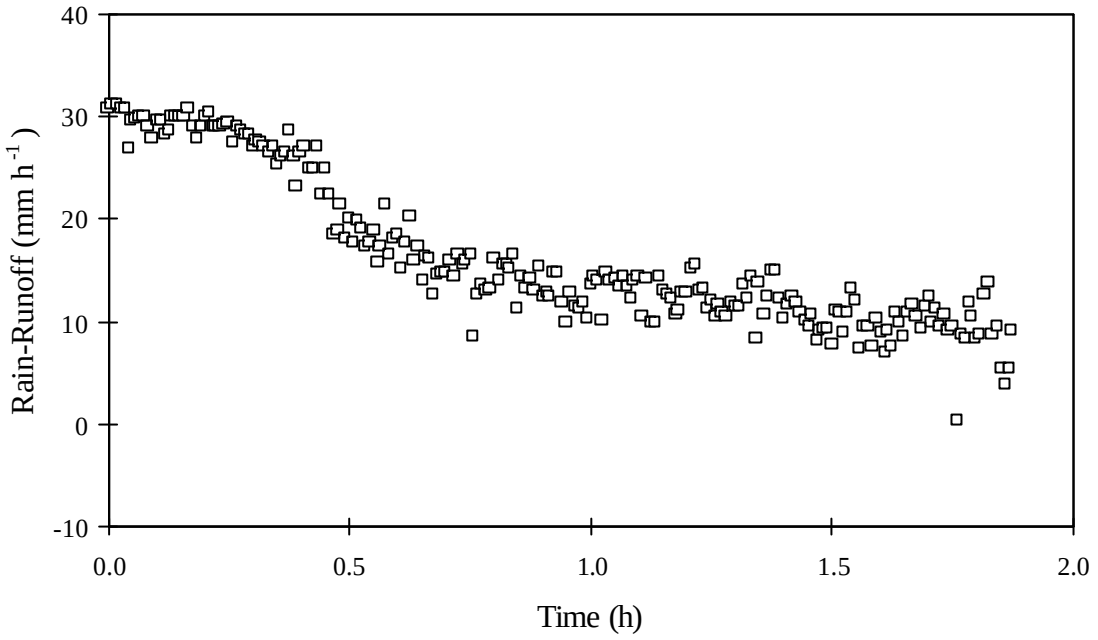
Appendix A

INFILTRATION RATE AS A FUNCTION OF TIME UNDER SIMULATED RAINFALL

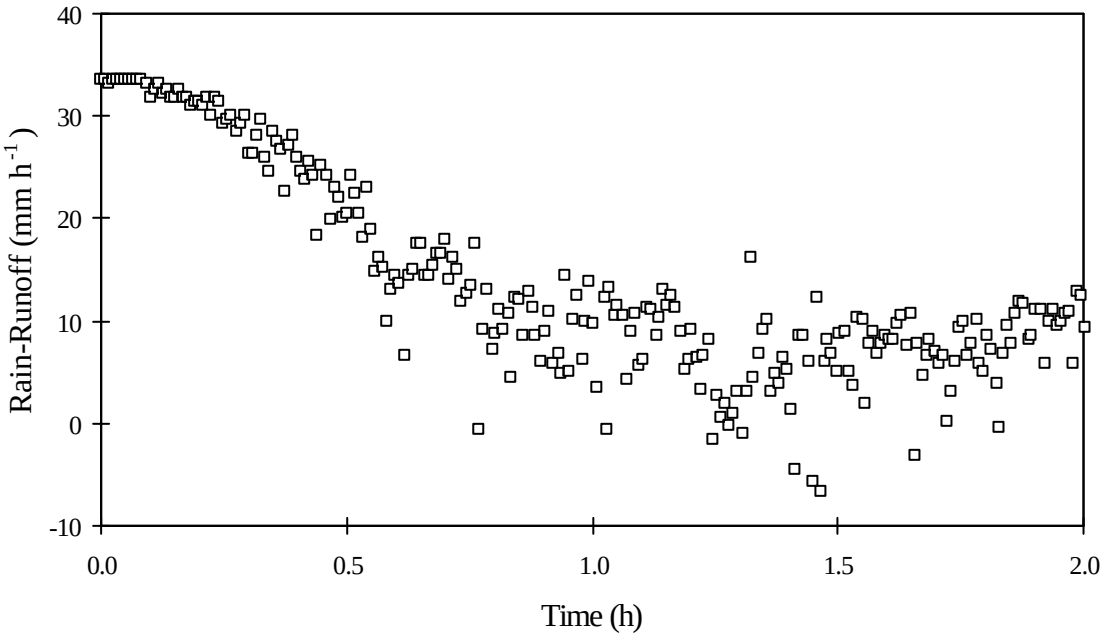
This appendix contains graphs of infiltration rate as a function of time for all R series rainfall simulations that resulted in runoff (referred to in section 4.3) as follows -

pp.	Run	Soil	Tillage Treatment	Rainfall Energy	Rainfall Intensity ($mm\ h^{-1}$)	Wetting Pre-treatment
A2	R14, R15	Cowra	DD	High	33	Tension
A3	R16, R17	Cowra	DD	High	33	Rapid
A4	R18, R19	Cowra	DD	High	33	Dry
A5	R9, R7	Cowra	TT	High	33	Tension
A6	R2, R8	Cowra	TT	High	33	Rapid
A7	R6, R10	Cowra	TT	High	33	Dry
A8	R30, R31	Condobolin	RH	High	33	Tension
A9	R26, R27	Condobolin	RH	High	33	Rapid
A10	R28, R29	Condobolin	RH	High	33	Dry
A11	R33, R36	Condobolin	BC	High	33	Tension
A12	R34, R37	Condobolin	BC	High	33	Rapid
A13	R38, R39	Condobolin	BC	Low	33	Rapid
A14	R32, R35	Condobolin	BC	High	33	Dry
A15	R50, R52	Condobolin	RH	High	16.5	Tension
A16	R51, R53	Condobolin	RH	High	66	Tension

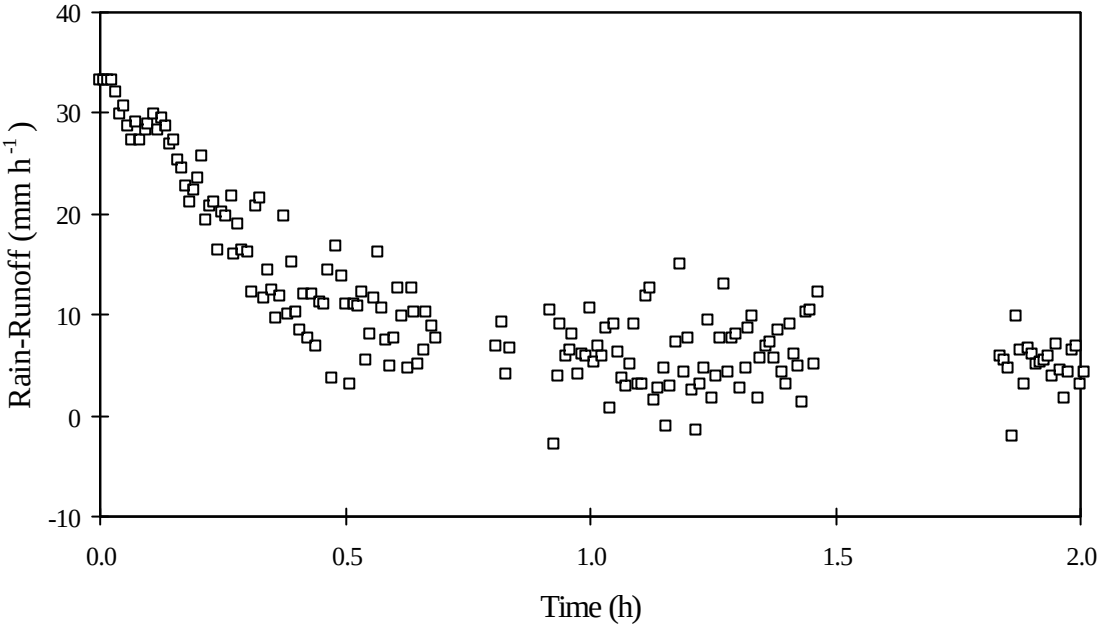
Infiltration rate as a function of time rate for R15 Cowra DD Tension pre-wet under 33 mm h^{-1} rainfall with high kinetic energy



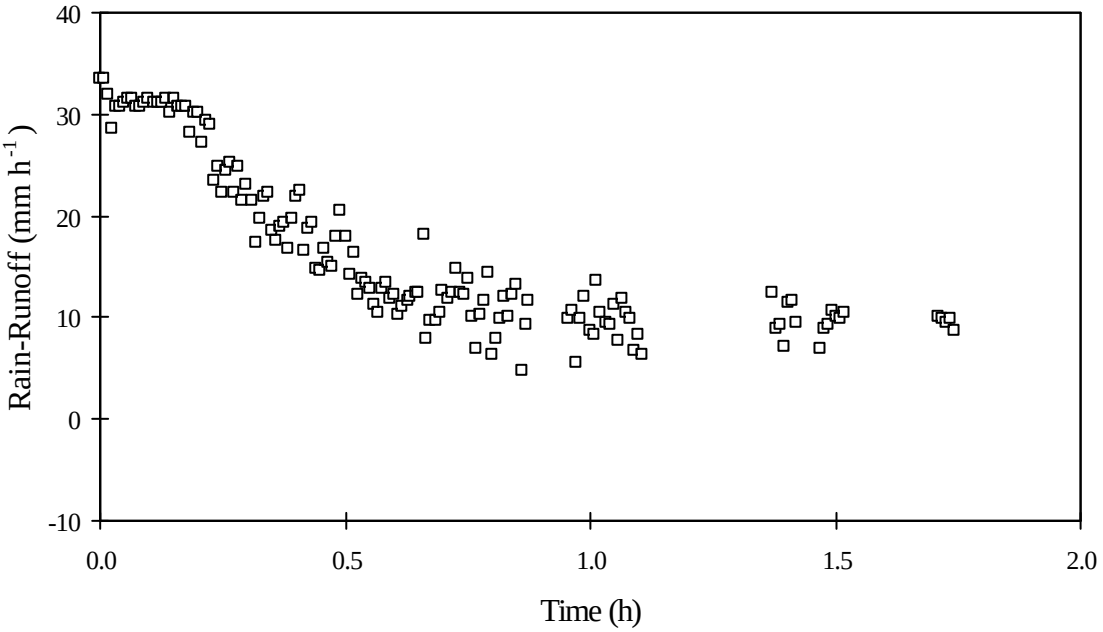
Infiltration rate as a function of time for R14 Cowra DD Tension pre-wet under 33 mm h^{-1} rainfall with high kinetic energy



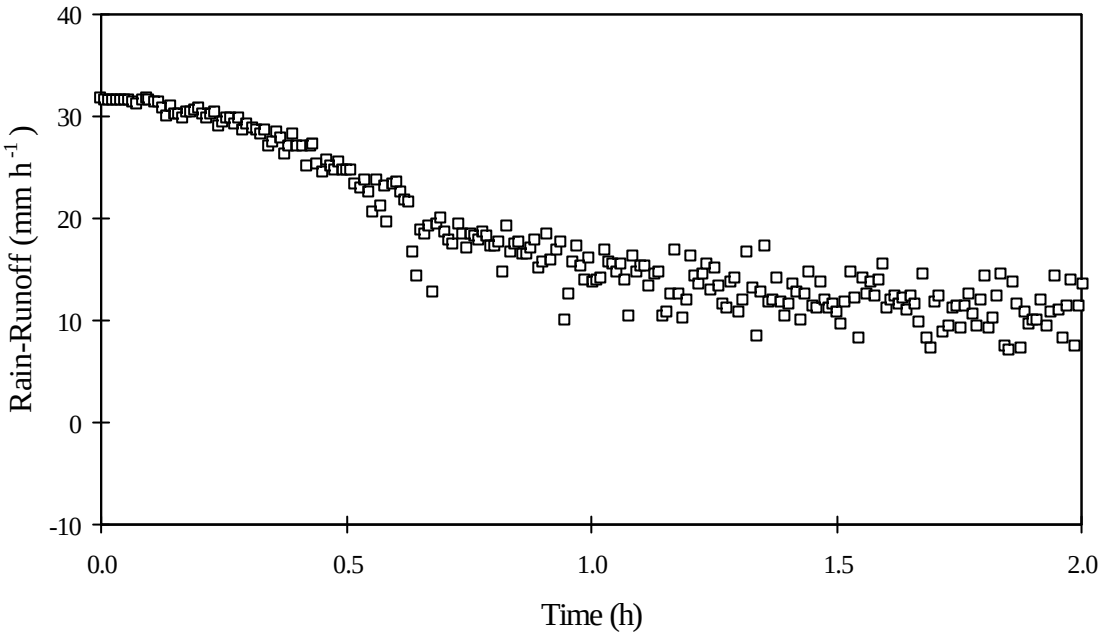
Infiltration rate as a function of time for R16 Cowra DD Rapid pre-wet under 33 mm h^{-1} rainfall with high kinetic energy



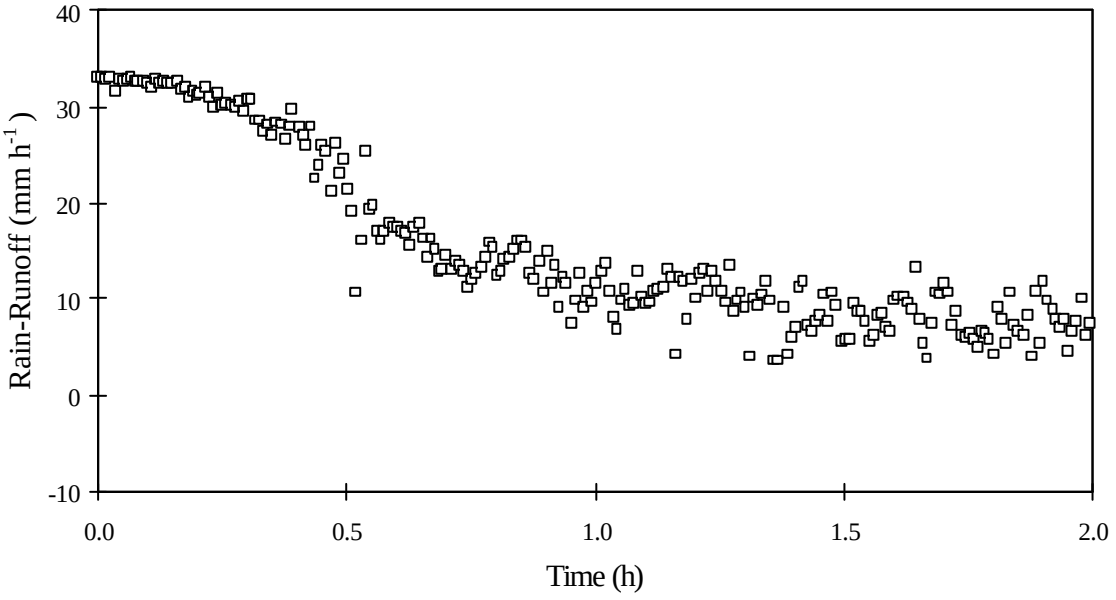
Infiltration rate as a function of time for R17 Cowra DD Rapid pre-wet under 33 mm h^{-1} rainfall with high kinetic energy



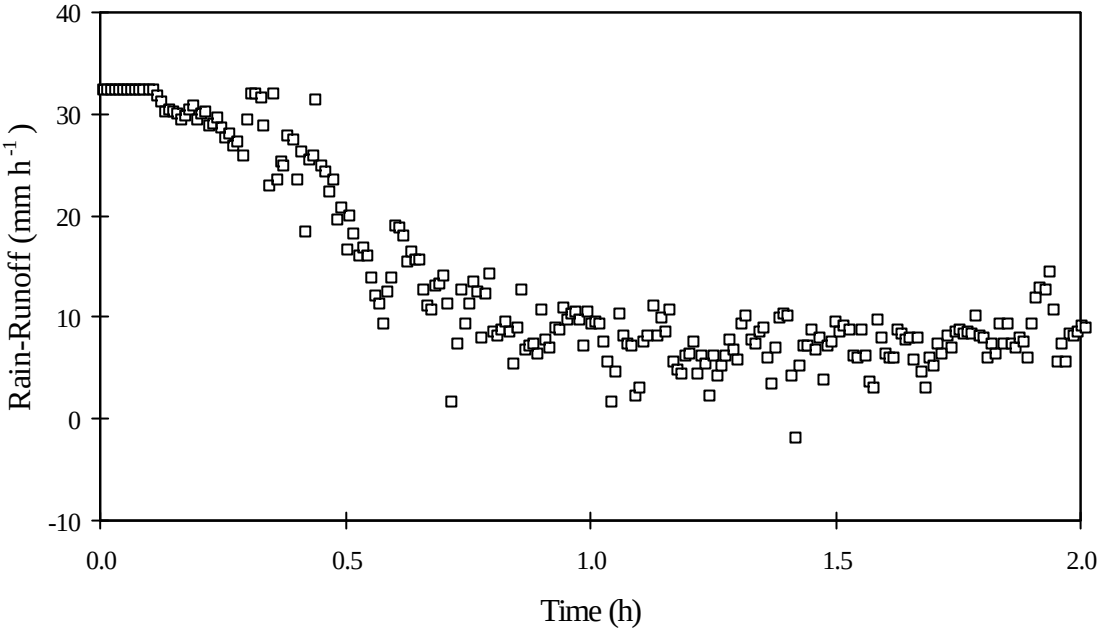
Infiltration rate as a function of time for R18 Cowra DD Dry under 33 mm h^{-1} rainfall with high kinetic energy



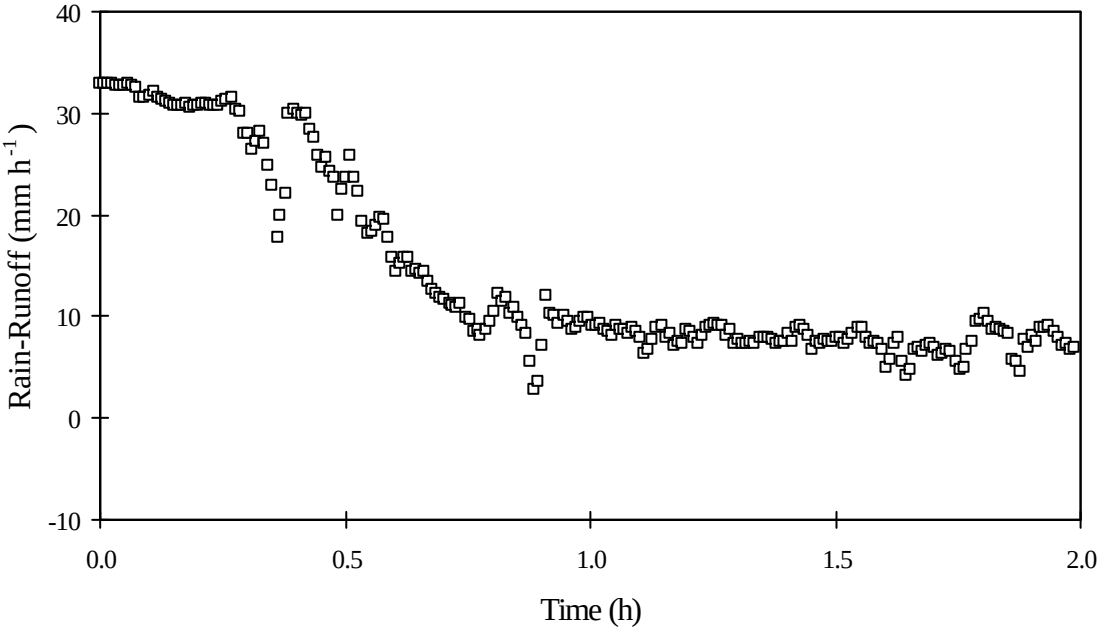
Infiltration rate as a function of time for R19 Cowra DD Dry under 33 mm h^{-1} rainfall with high kinetic energy



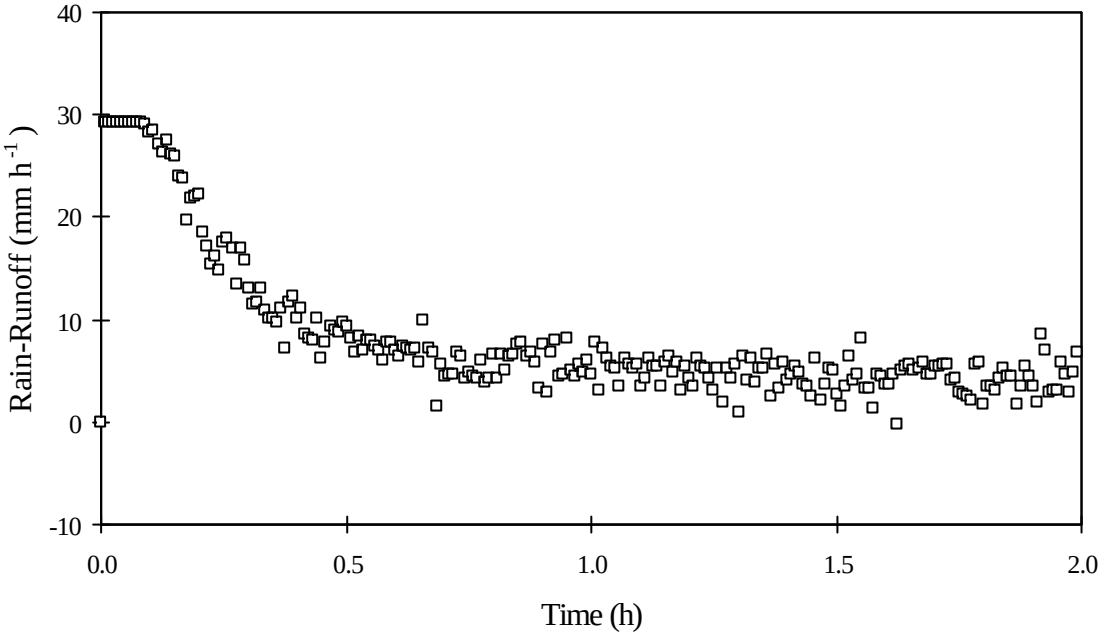
Infiltration rate as a function of time for R9 Cowra TT Tension pre-wet under 33 mm h^{-1} rainfall with high kinetic energy



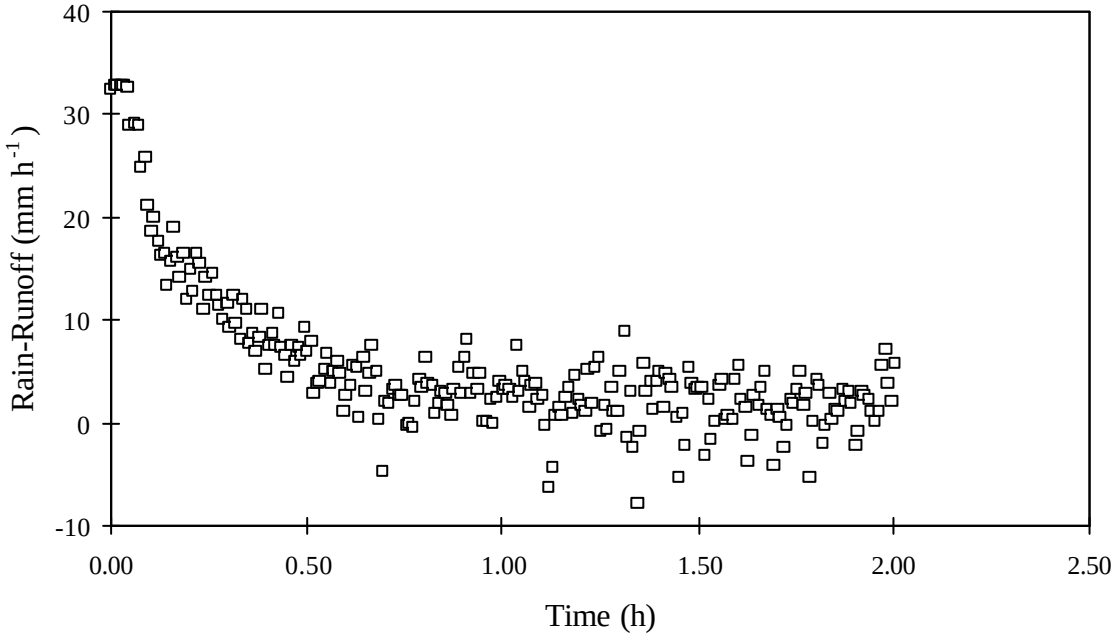
Infiltration rate as a function of time for R7 Cowra TT Tension pre-wet under 33 mm h^{-1} rainfall with high kinetic energy



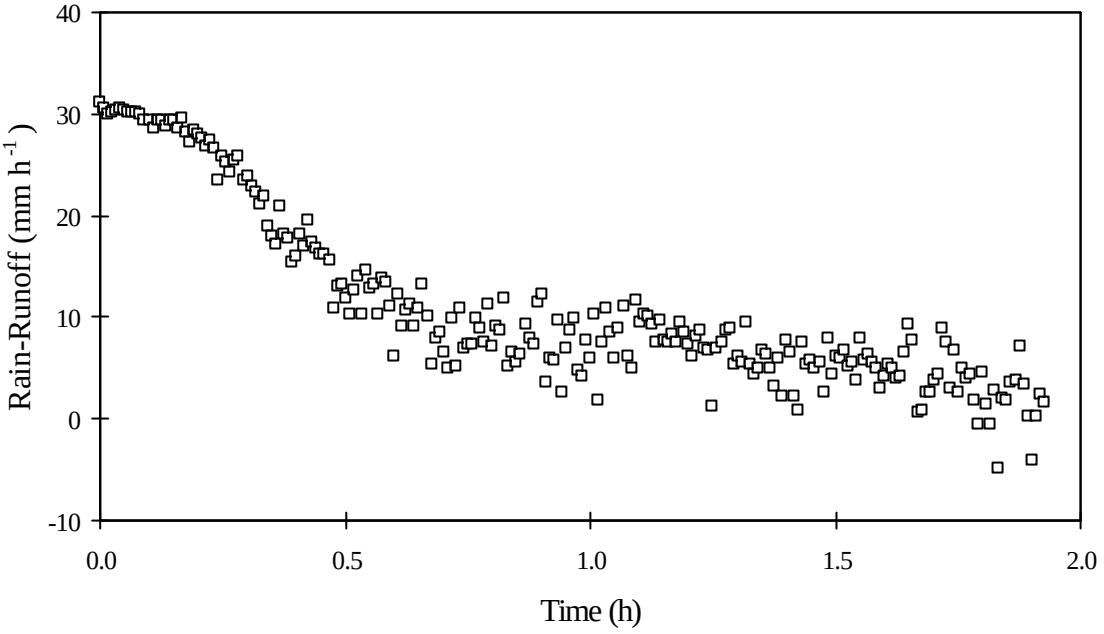
Infiltration rate as a function of time for R2 Cowra TT Rapid pre-wet under 33 mm h^{-1} rainfall with high kinetic energy



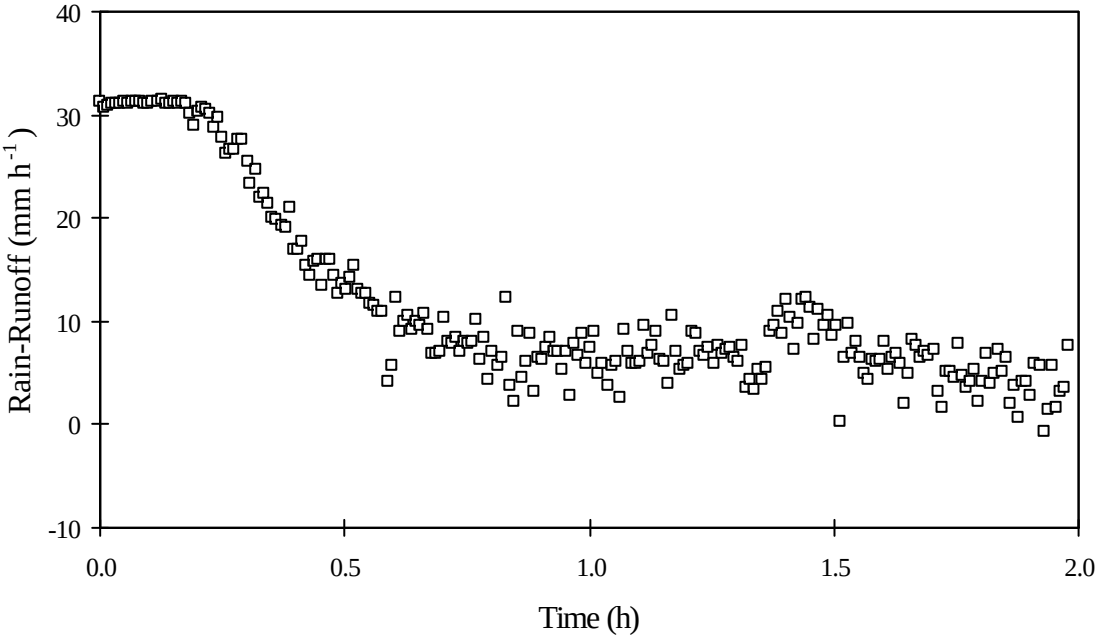
Infiltration rate as a function of time for R8 Cowra TT Rapid pre-wet under 33 mm h^{-1} rainfall with high kinetic energy



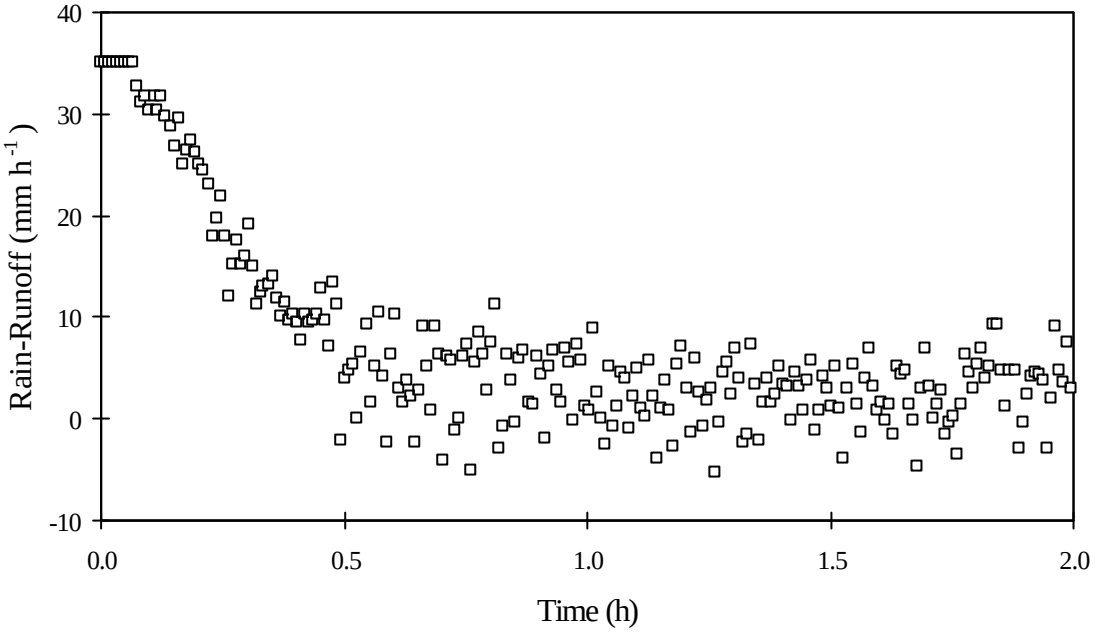
Infiltration rate as a function of time for R6 Cowra TT Dry under 33 mm h^{-1} rainfall with high kinetic energy



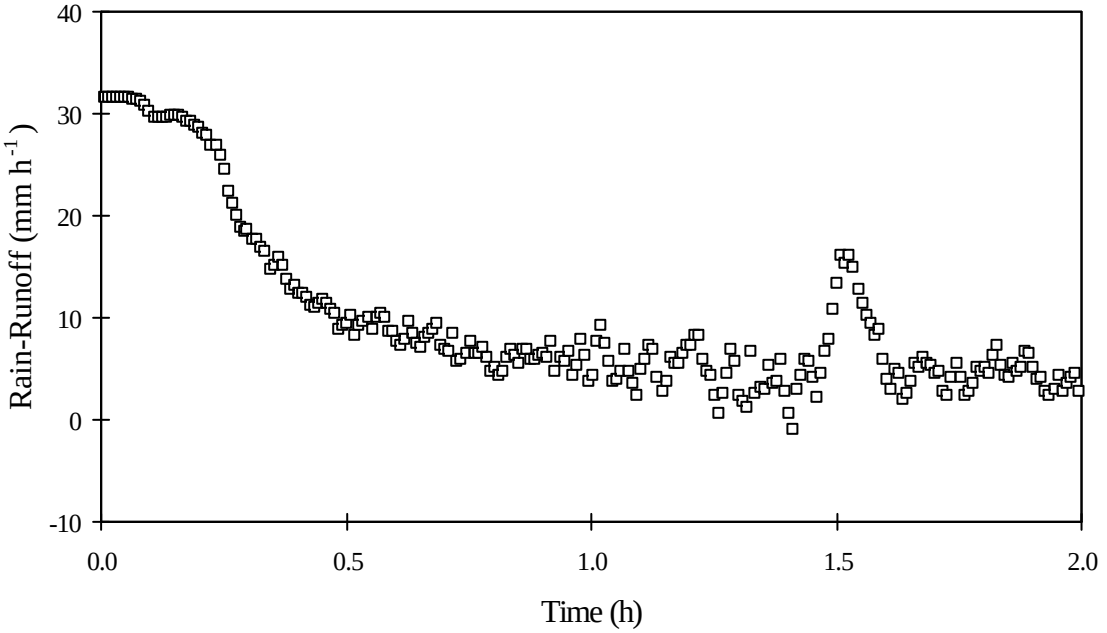
Infiltration rate as a function of time for R10 Cowra TT Dry under 33 mm h^{-1} rainfall with high kinetic energy



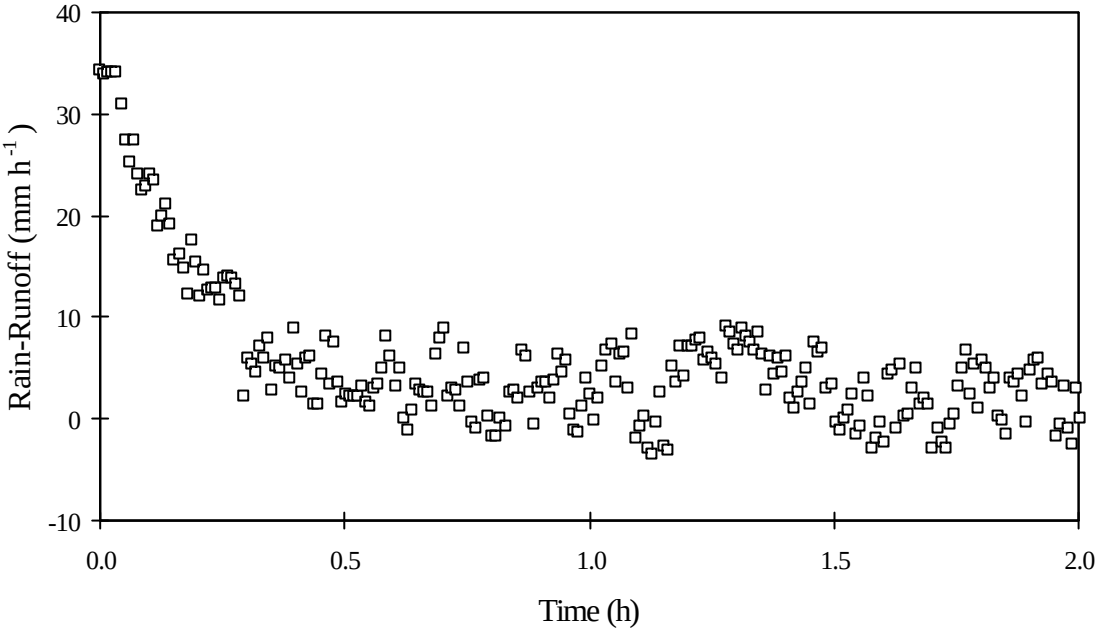
Infiltration rate as a function of time for R30 Condobolin RH Tension pre-wet under 33 mm h^{-1} rainfall with high kinetic energy



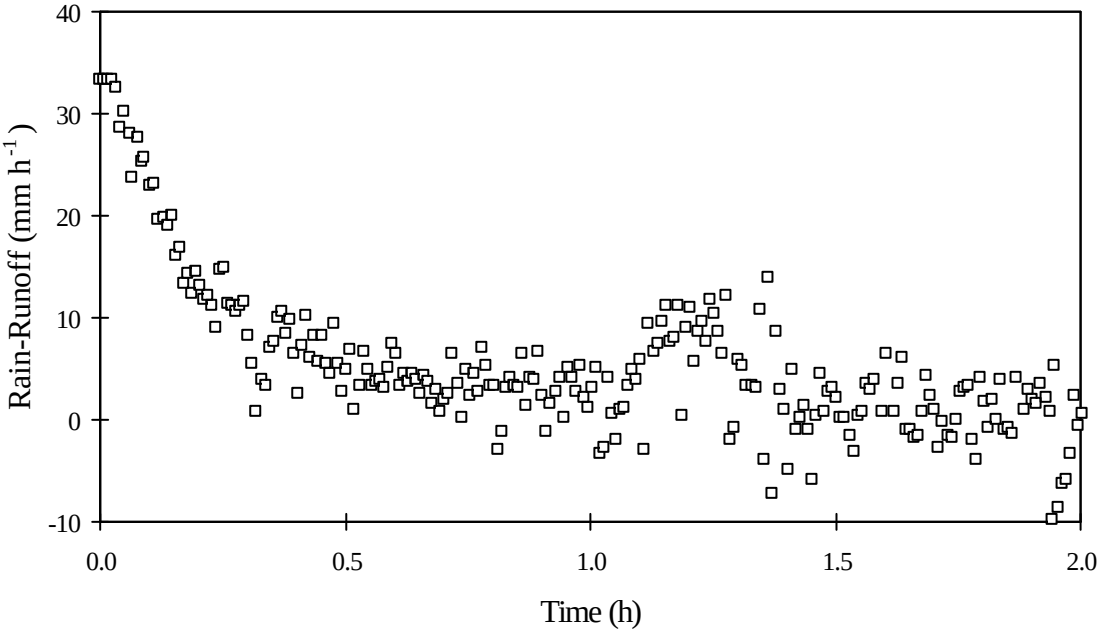
Infiltration rate as a function of time for R31 Condobolin RH Tension pre-wet under 33 mm h^{-1} rainfall with high kinetic energy



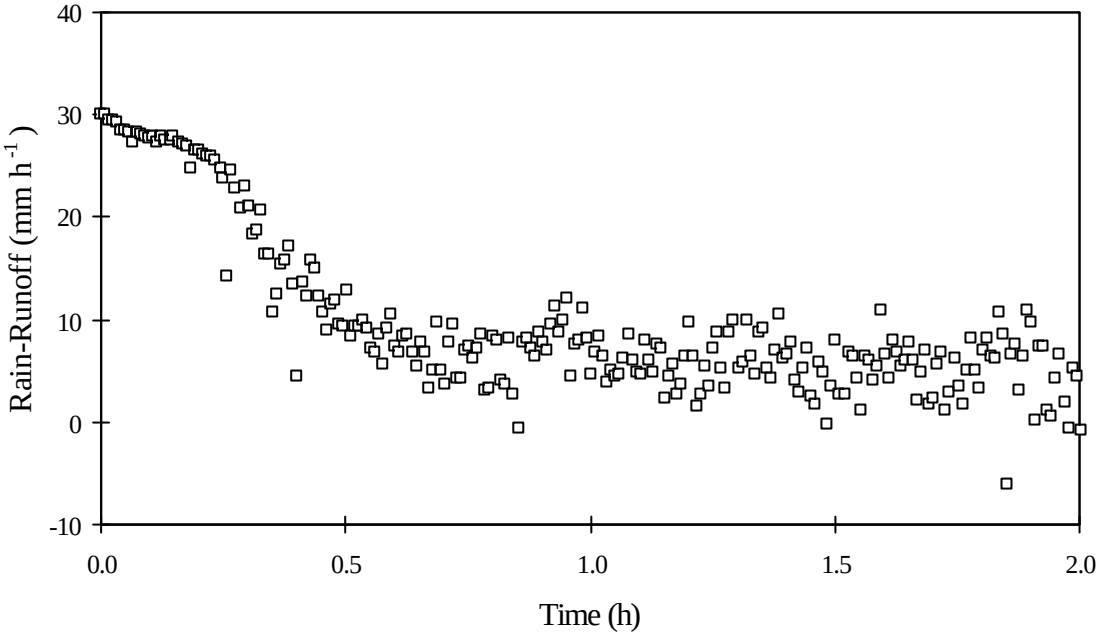
Infiltration rate as a function of time for R26 Condobolin RH Rapid pre-wet under 33 mm h^{-1} rainfall with high kinetic energy



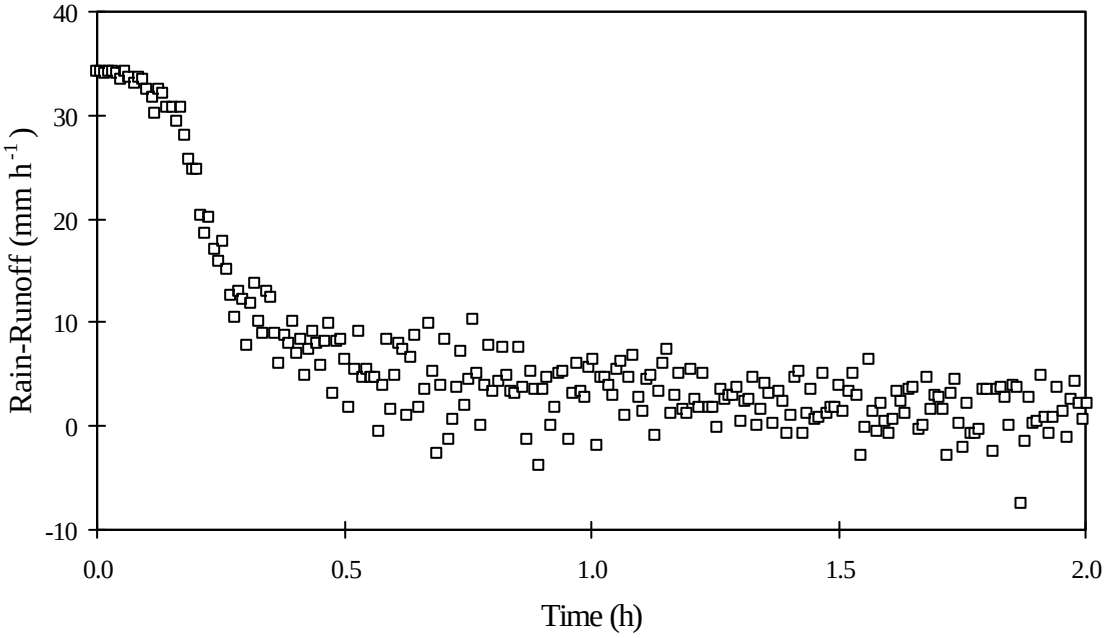
Infiltration rate as a function of time for R27 Condobolin RH Rapid pre-wet under 33 mm h^{-1} rainfall with high kinetic energy



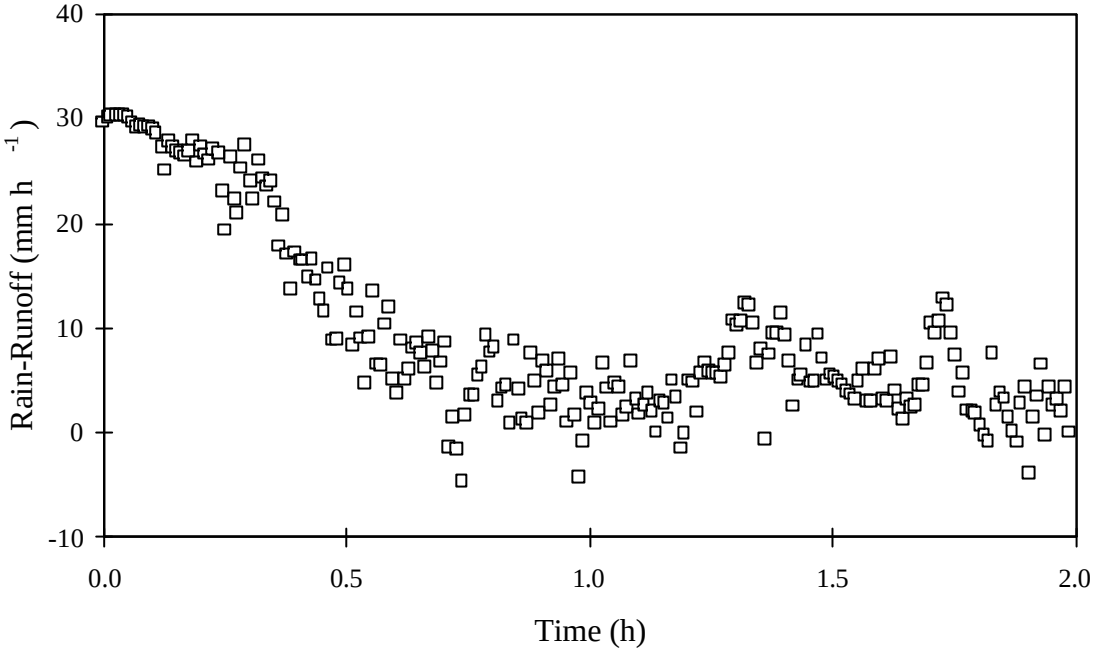
Infiltration rate as a function of time for R28 Condobolin RH Dry under 33 mm h^{-1} rainfall with high kinetic energy



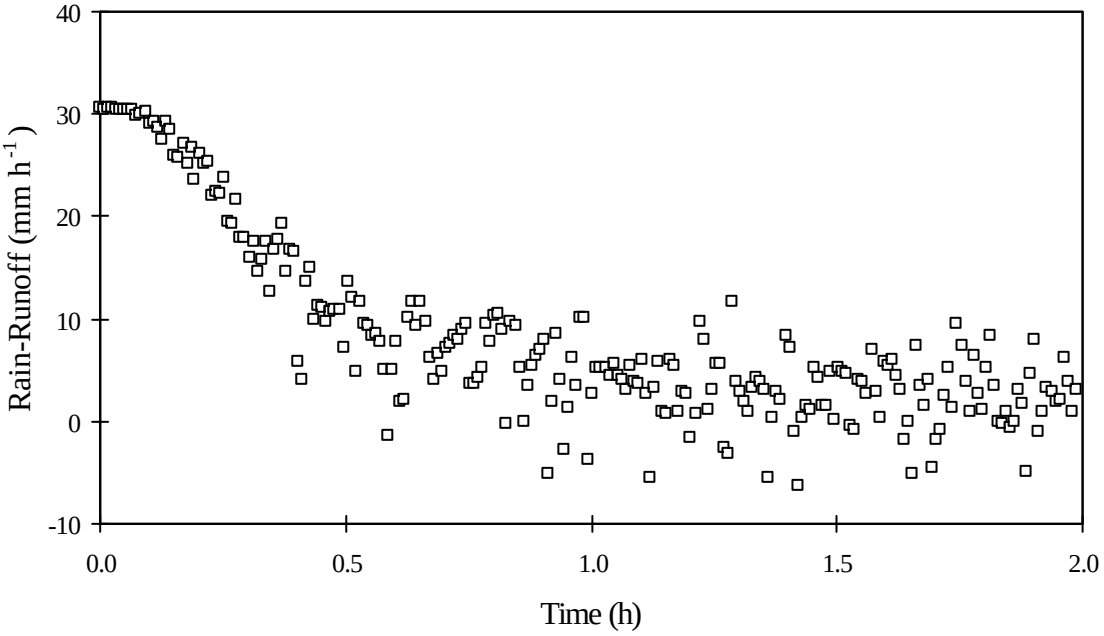
Infiltration rate as a function of time for R29 Condobolin RH Dry under 33 mm h^{-1} rainfall with high kinetic energy



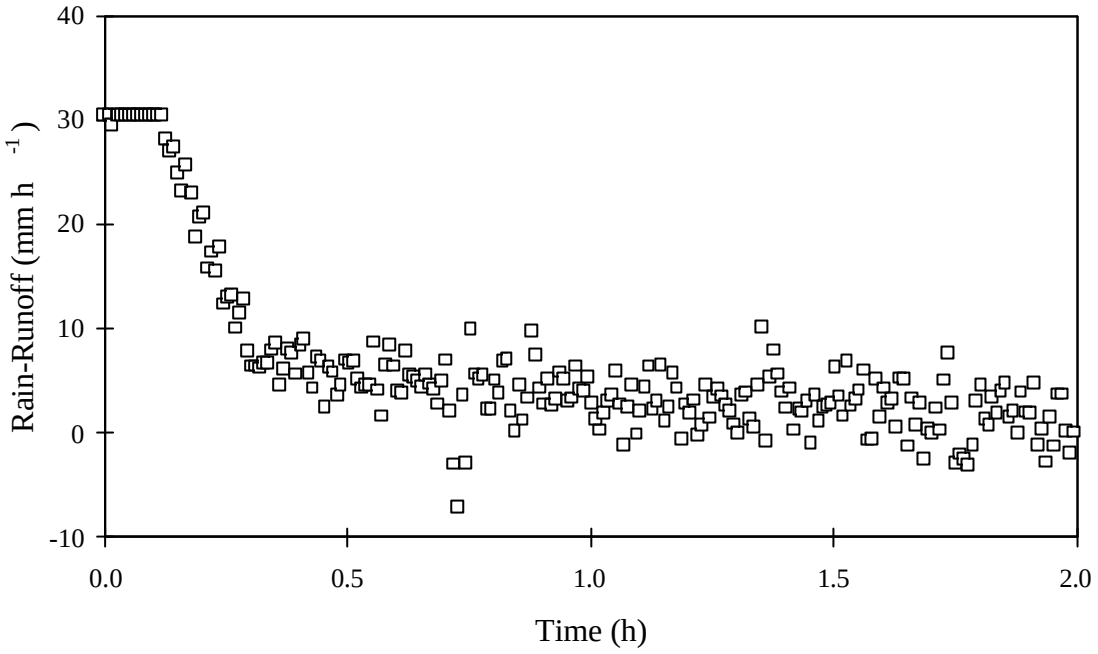
Infiltration rate as a function of time for R33 Condobolin BC Tension pre-wet under 33 mm h^{-1} rainfall with high kinetic energy



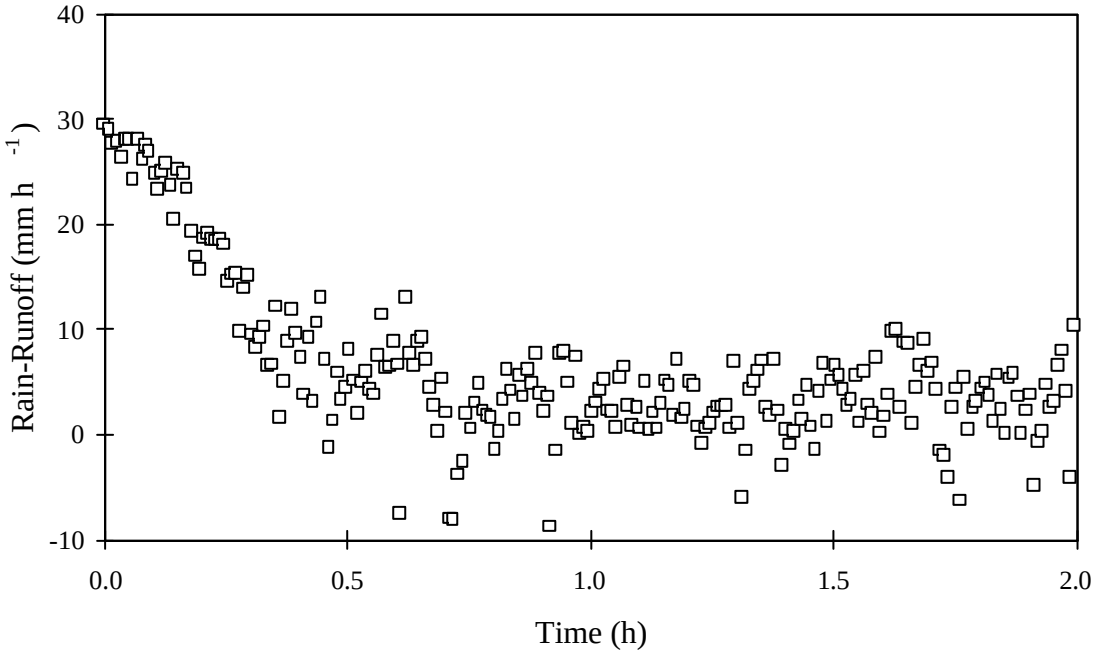
Infiltration rate as a function of time for R36 Condobolin BC Tension pre-wet under 33 mm h^{-1} rainfall with high kinetic energy



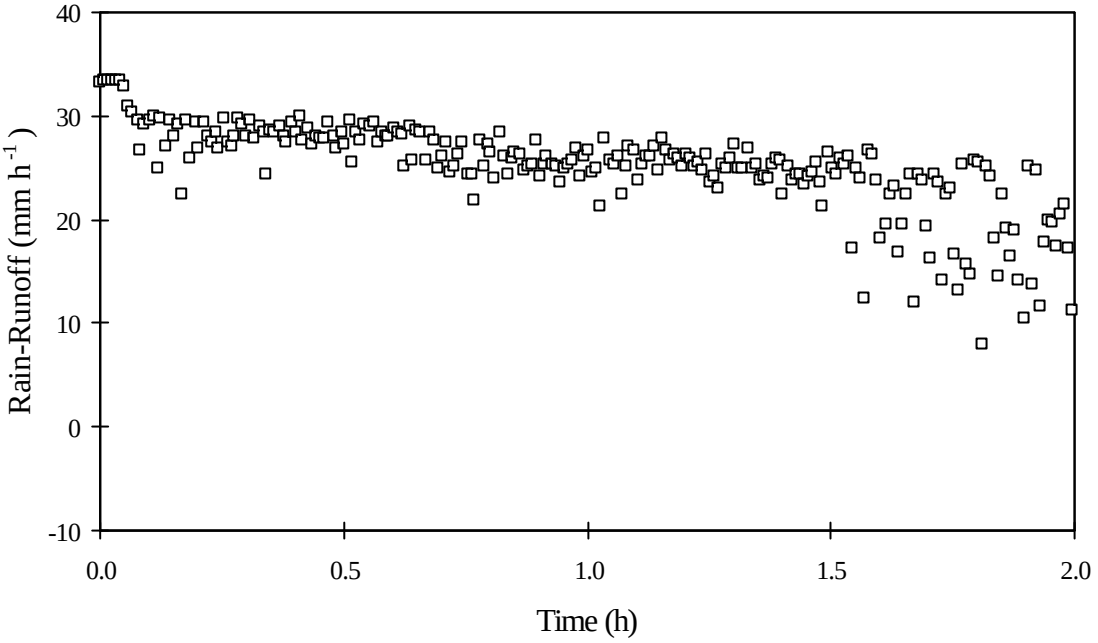
Infiltration rate as a function of time for R34 Condobolin BC Rapid pre-wet under 33 mm h^{-1} rainfall with high kinetic energy



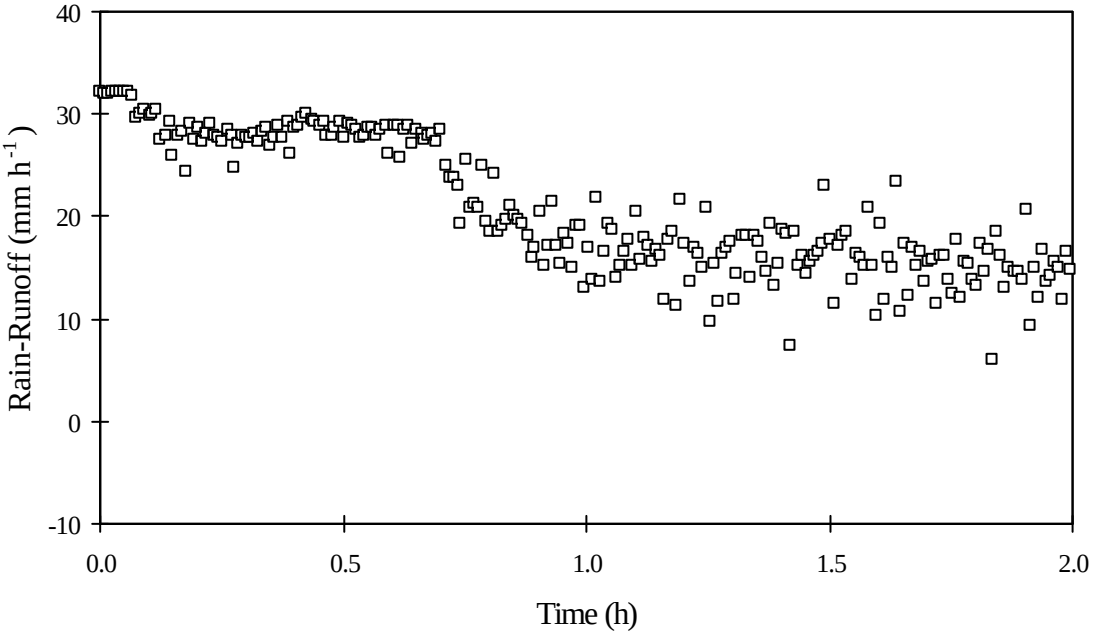
Infiltration rate as a function of time for R37 Condobolin BC Rapid pre-wet under 33 mm h^{-1} rainfall with high kinetic energy



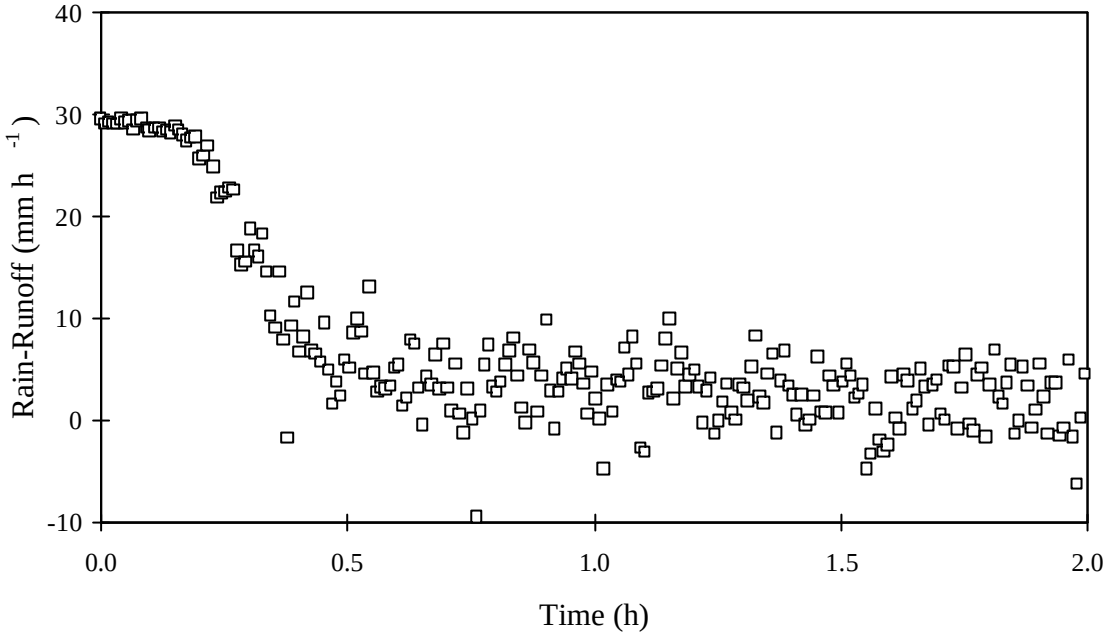
Infiltration rate as a function of time for R38 Condobolin BC Rapid pre-wet under 33 mm h^{-1} rainfall with low kinetic energy



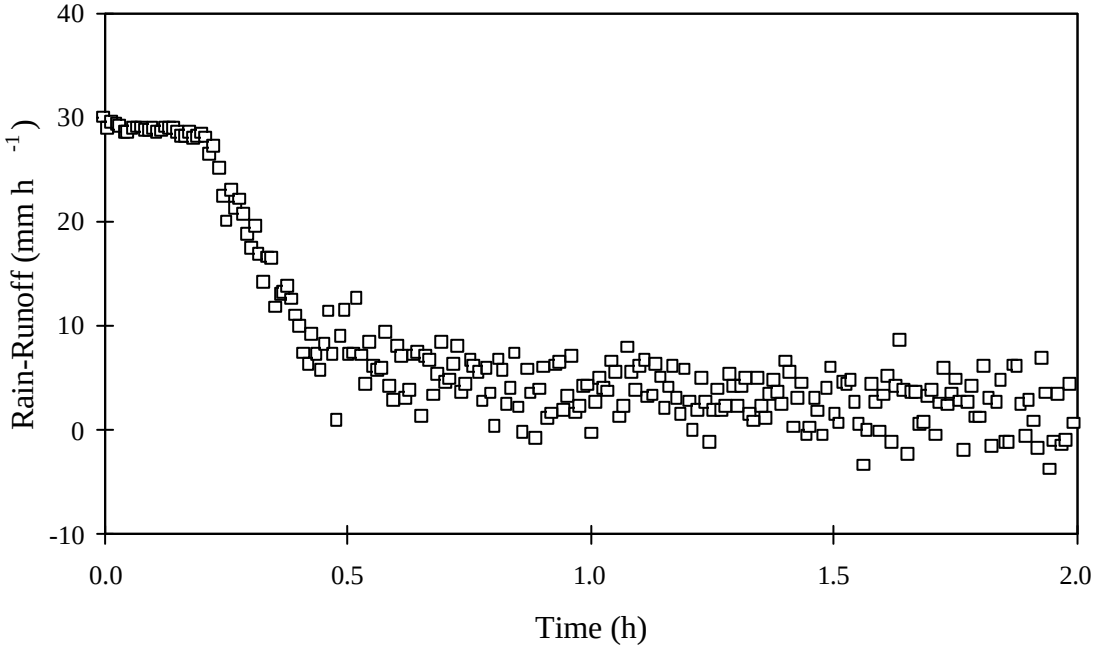
Infiltration rate as a function of time for R39 Condobolin BC Rapid pre-wet under 33 mm h^{-1} rainfall with low kinetic energy



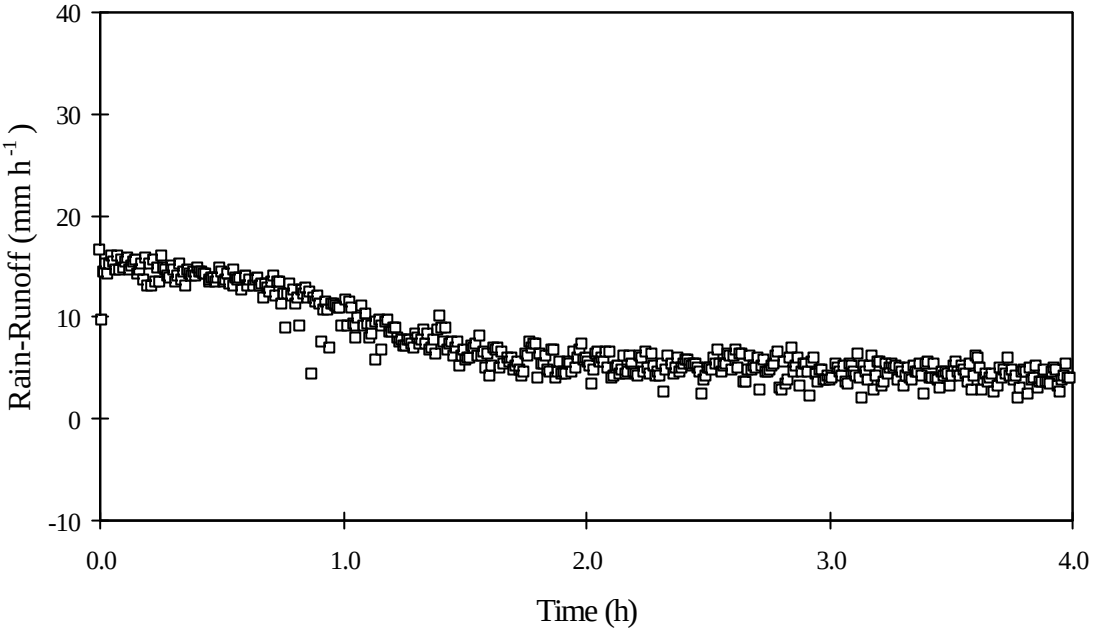
Infiltration rate as a function of time for R32 Condobolin BC Dry under 33 mm h^{-1} rainfall with high kinetic energy



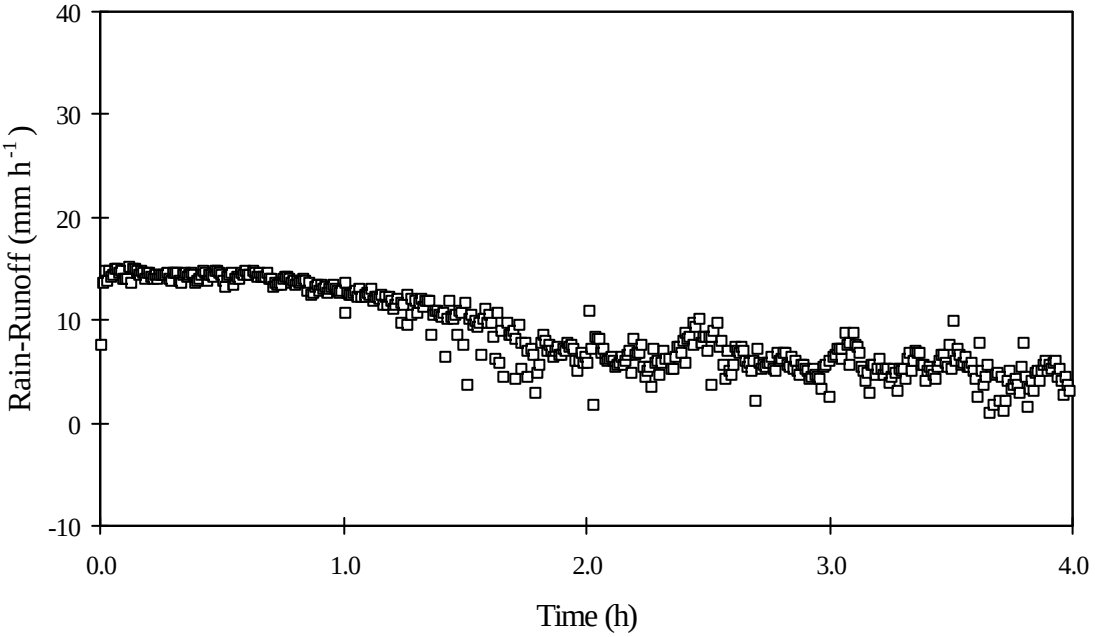
Infiltration rate as a function of time for R35 Condobolin BC Dry under 33 mm h^{-1} rainfall with high kinetic energy



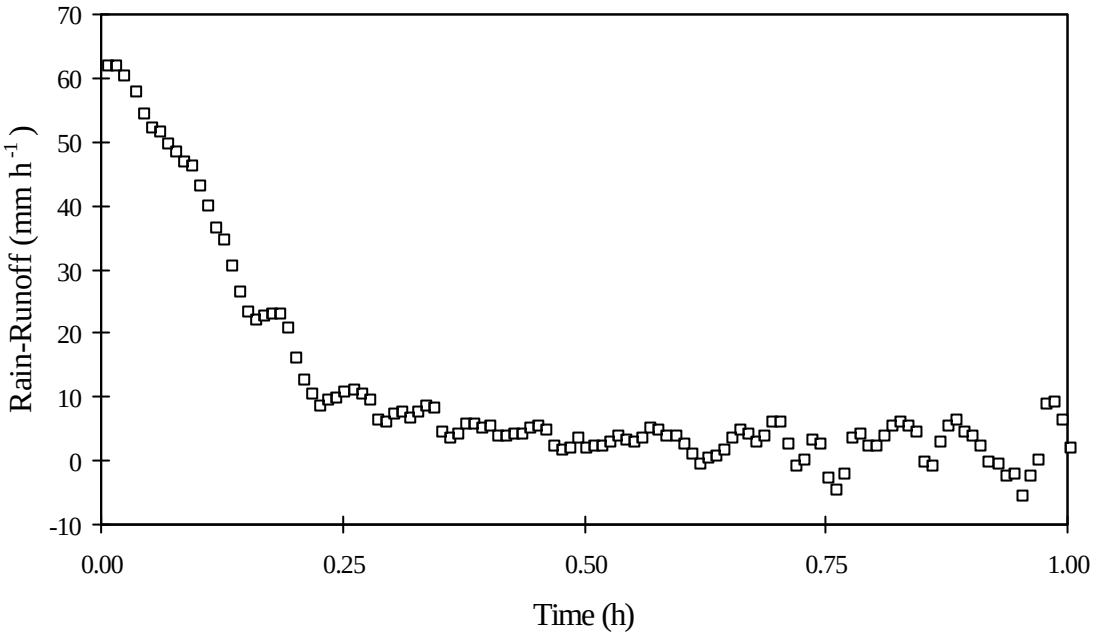
Infiltration rate as a function of time for R50 Condobolin RH Tension pre-wet under 16.5 mm h^{-1} rainfall with high kinetic energy



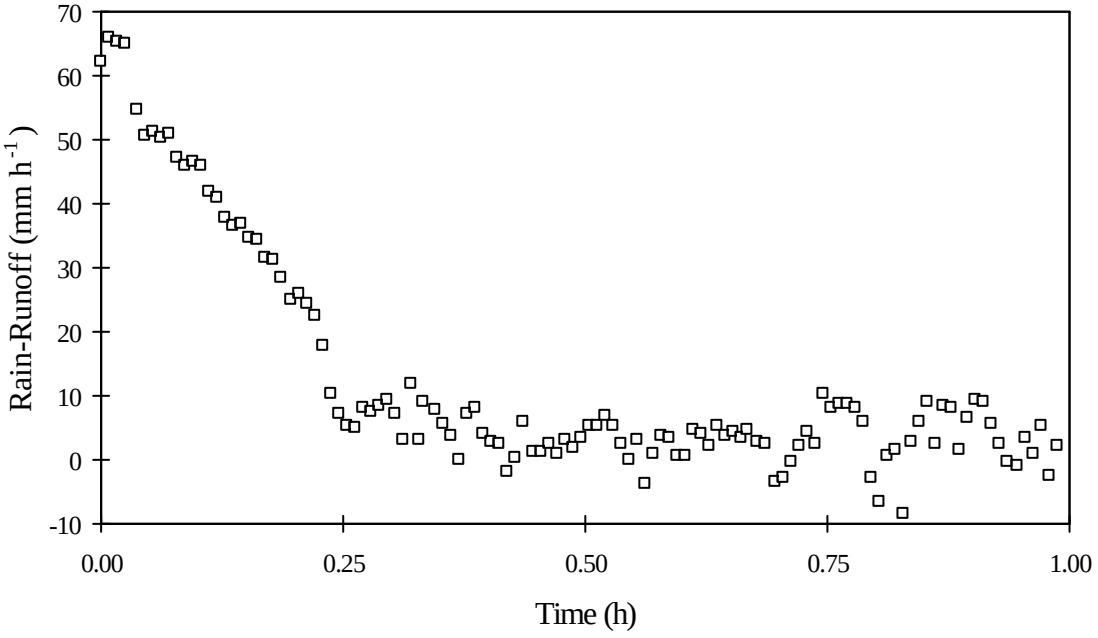
Infiltration rate as a function of time for R52 Condobolin RH Tension pre-wet under 16.5 mm h^{-1} rainfall with high kinetic energy



Infiltration rate as a function of time for R51 Condobolin RH Tension pre-wet under 66 mm h^{-1} rainfall with high kinetic energy



Infiltration rate as a function of time for R53 Condobolin RH Tension pre-wet under 66 mm h^{-1} rainfall with high kinetic energy



Appendix B

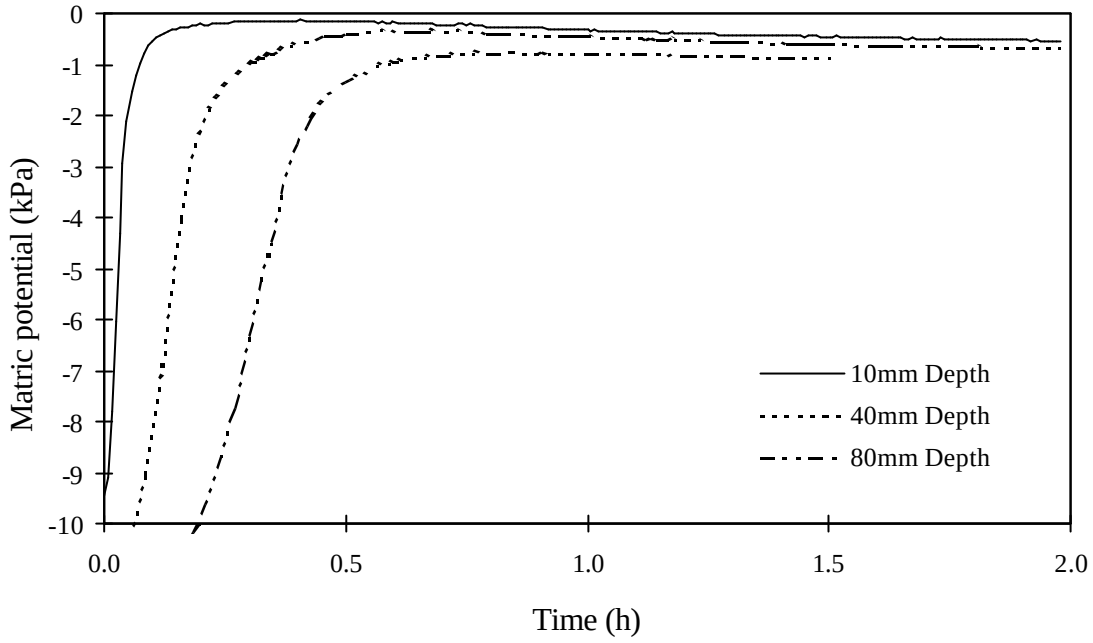
SUB-SEAL MATRIC POTENTIAL AS A FUNCTION OF TIME UNDER SIMULATED RAINFALL

This appendix contains graphs of sub-seal matric potential as a function of time for all R series rainfall simulations (referred to in section 4.4) as follows -

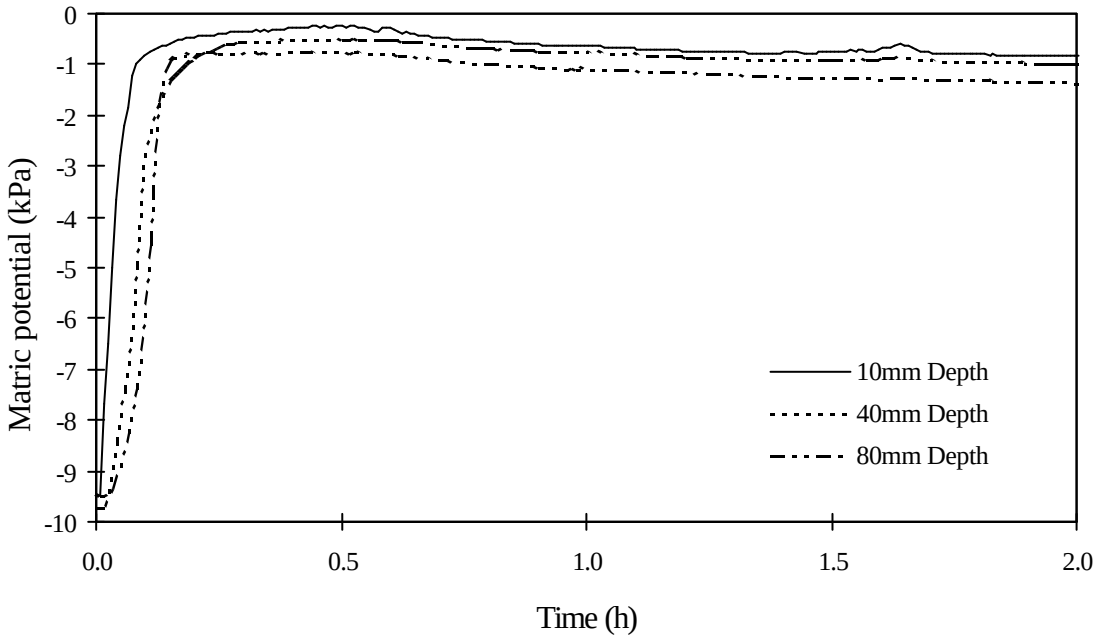
pp.	Run	Soil	Tillage Treatment	Rainfall Energy	Rainfall Intensity ($mm\ h^{-1}$)	Wetting Pre-treatment
B3	R14, R15	Cowra	DD	High	33	Tension
B4	R21, R23	Cowra	DD	Low	33	Tension
B5	R16, R17	Cowra	DD	High	33	Rapid
B6	R22, R24	Cowra	DD	Low	33	Rapid
B7	R18, R19	Cowra	DD	High	33	Dry
B8	R20, R25	Cowra	DD	Low	33	Dry
B9	R9, R7	Cowra	TT	High	33	Tension
B10	R11, R12	Cowra	TT	Low	33	Tension
B11	R2, R8	Cowra	TT	High	33	Rapid
B12	R4, R3	Cowra	TT	Low	33	Rapid
B13	R6, R10	Cowra	TT	High	33	Dry
B14	R5, R13	Cowra	TT	Low	33	Dry
B15	R30, R31	Condobolin	RH	High	33	Tension
B16	R48, R49	Condobolin	RH	Low	33	Tension
B17	R26, R27	Condobolin	RH	High	33	Rapid
B18	R45, R46	Condobolin	RH	Low	33	Rapid
B19	R28, R29	Condobolin	RH	High	33	Dry
B20	R44, R47	Condobolin	RH	Low	33	Dry
B21	R33, R36	Condobolin	BC	High	33	Tension
B22	R42, R43	Condobolin	BC	Low	33	Tension
B23	R34, R37	Condobolin	BC	High	33	Rapid
B24	R38, R39	Condobolin	BC	Low	33	Rapid

B25	R32, R35	Condobolin	BC	High	33	Dry
B26	R40, R41	Condobolin	BC	Low	33	Dry
B27	R50, R52	Condobolin	RH	High	16.5	Tension
B28	R51, R53	Condobolin	RH	High	66	Tension

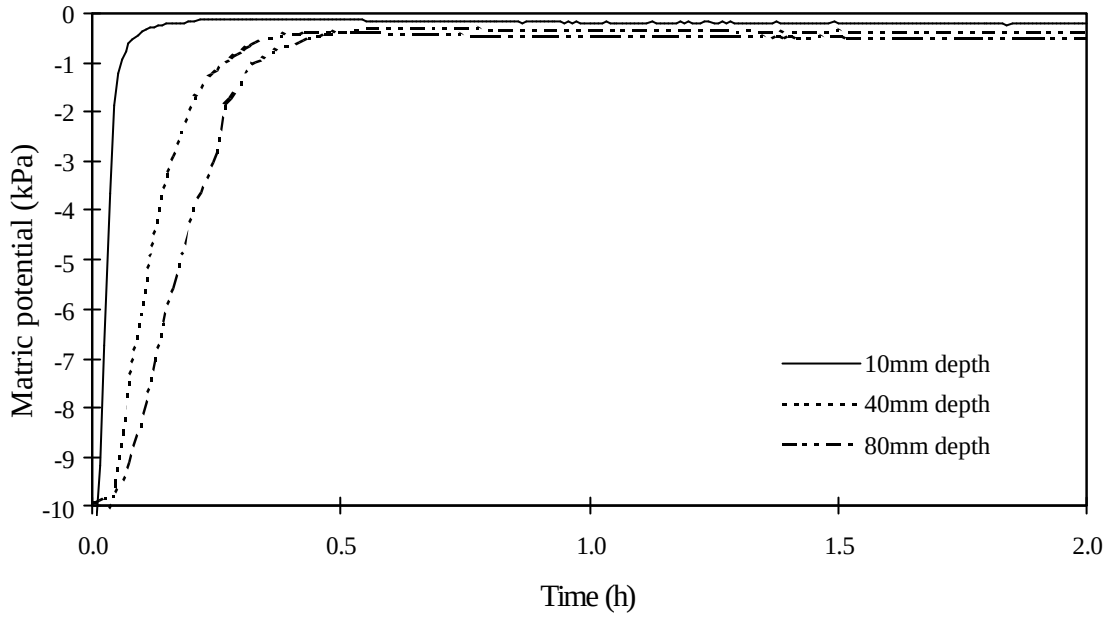
Sub-seal matric potential as a function of time for R15 Cowra DD Tension prewet under 33 mm h^{-1} rainfall with high kinetic energy



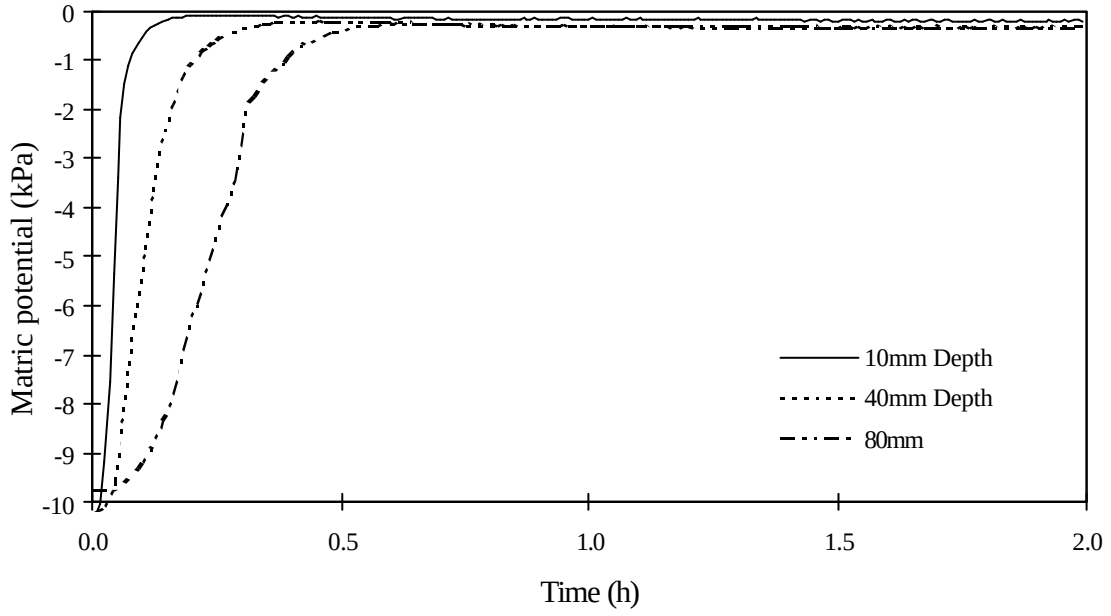
Sub-seal matric potential as a function of time for R14 Cowra DD Tension prewet under 33 mm h^{-1} rainfall with high kinetic energy



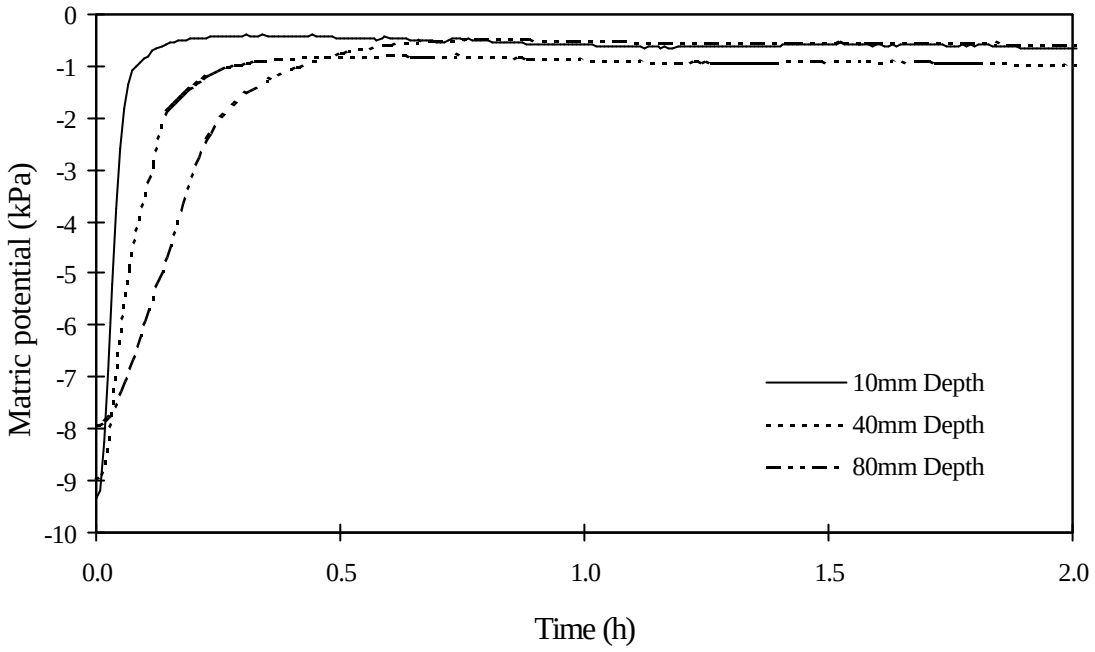
Sub-seal matric potential as a function of time for R21 Cowra DD Tension prewet under 33 mm h^{-1} rainfall with low kinetic energy



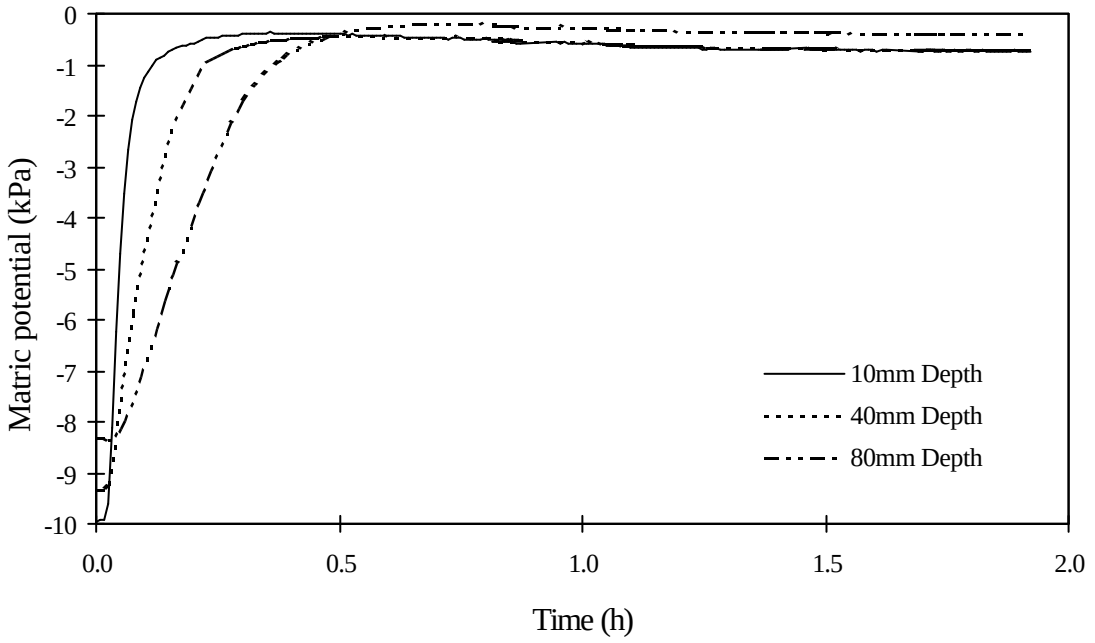
Sub-seal matric potential as a function of time for R23 Cowra DD Tension prewet under 33 mm h^{-1} rainfall with low kinetic energy



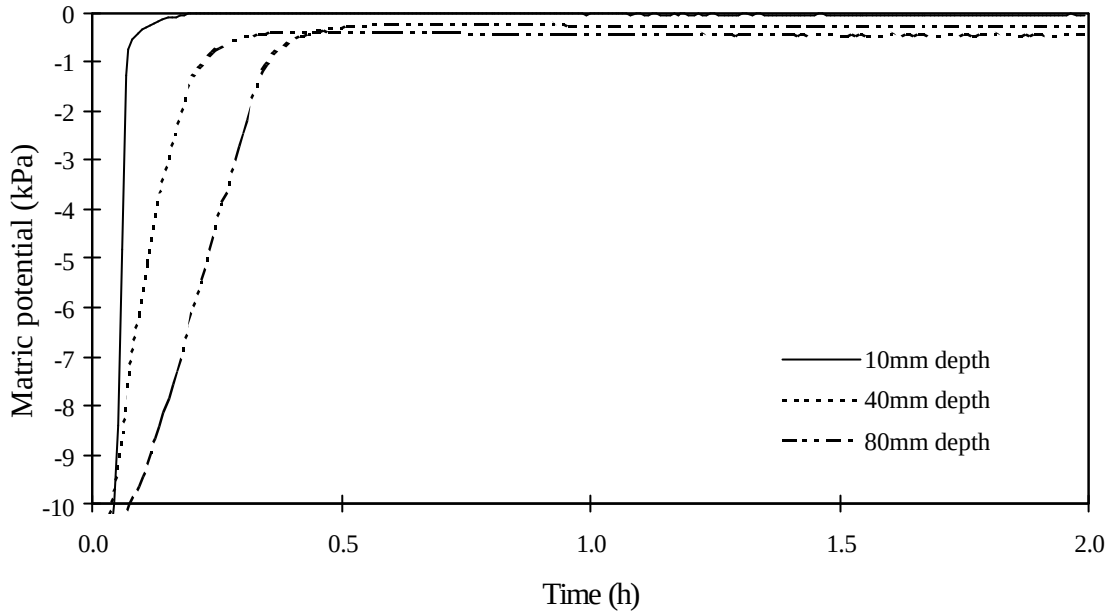
Sub-seal matric potential as a function of time for R16 Cowra DD Rapid prewet under 33 mm h^{-1} rainfall with high kinetic energy



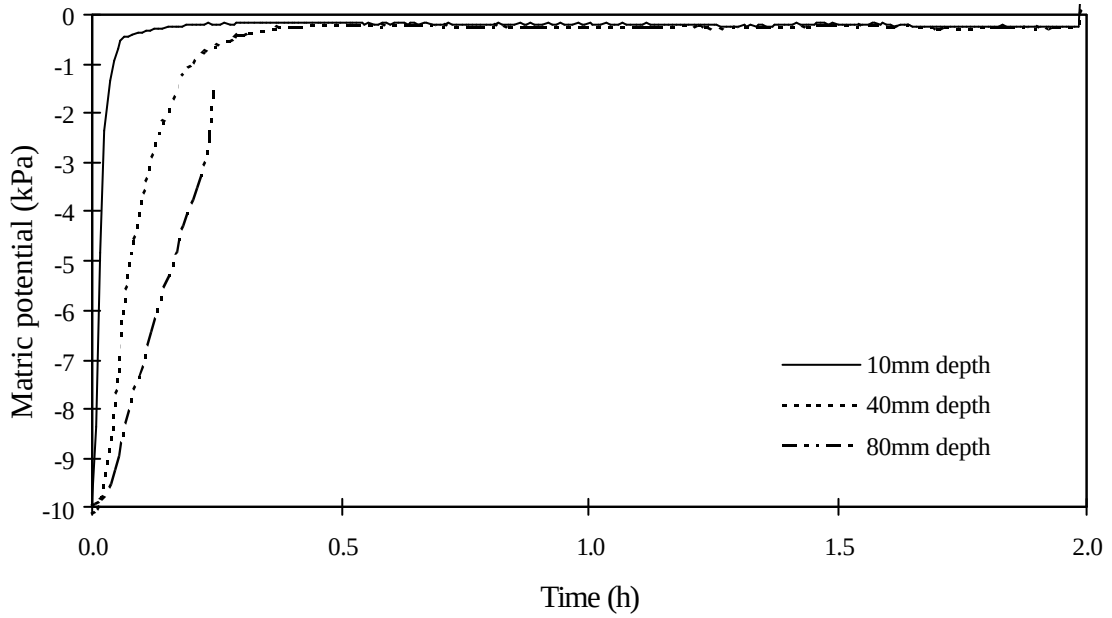
Sub-seal matric potential as a function of time for R17 Cowra DD Rapid prewet under 33 mm h^{-1} rainfall with high kinetic energy



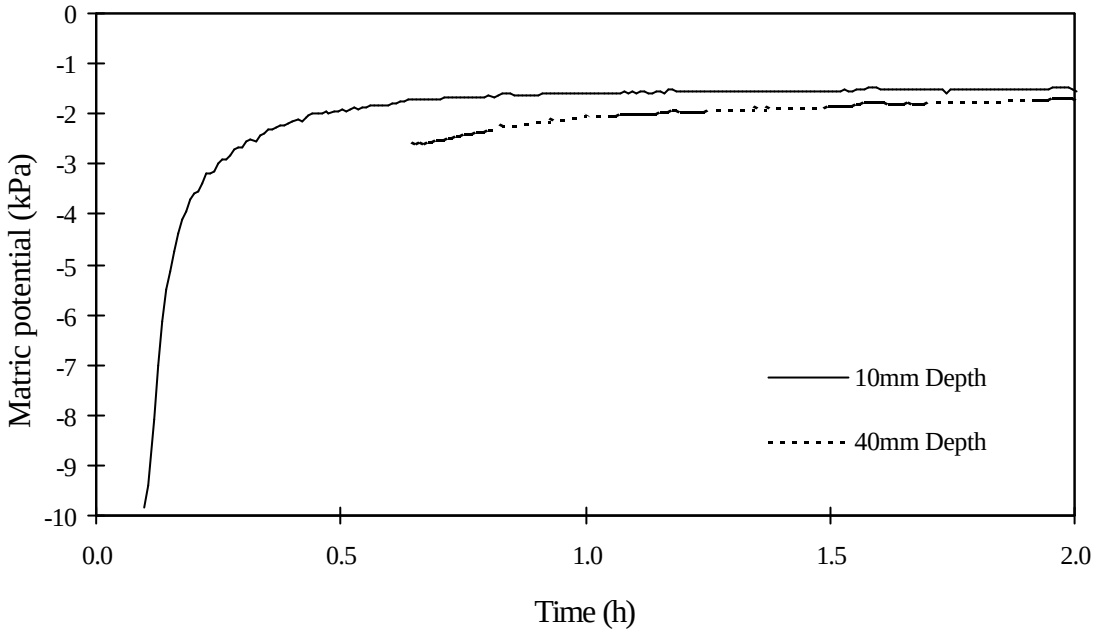
Sub-seal matric potential as a function of time for R22 Cowra DD Rapid prewet under 33 mm h^{-1} rainfall with low kinetic energy



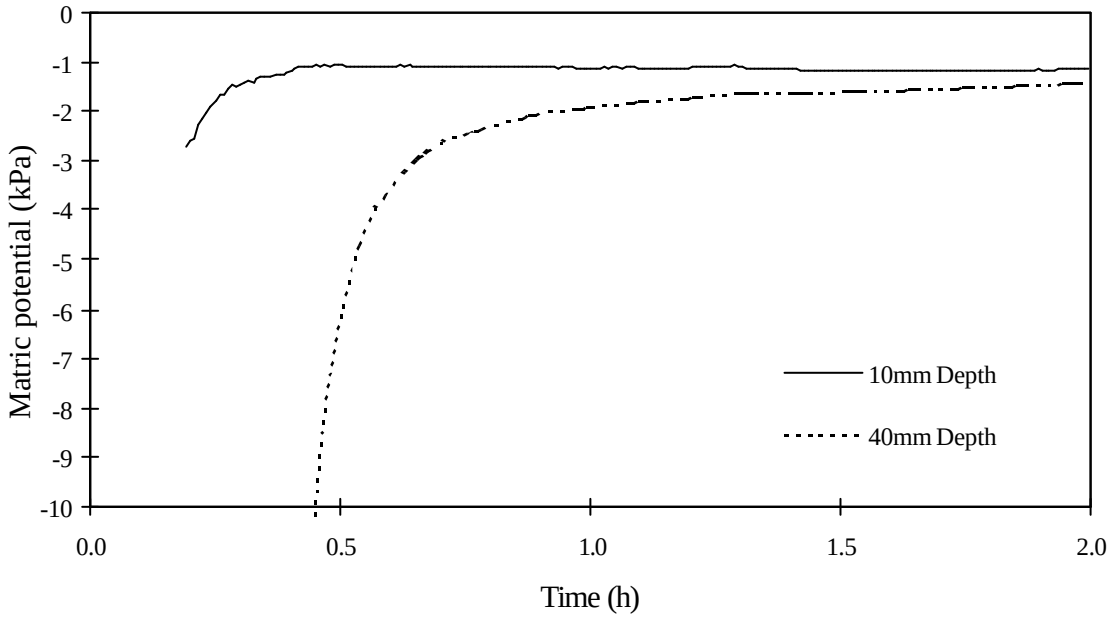
Sub-seal matric potential as a function of time for R24 Cowra DD Rapid prewet under 33 mm h^{-1} rainfall with low kinetic energy



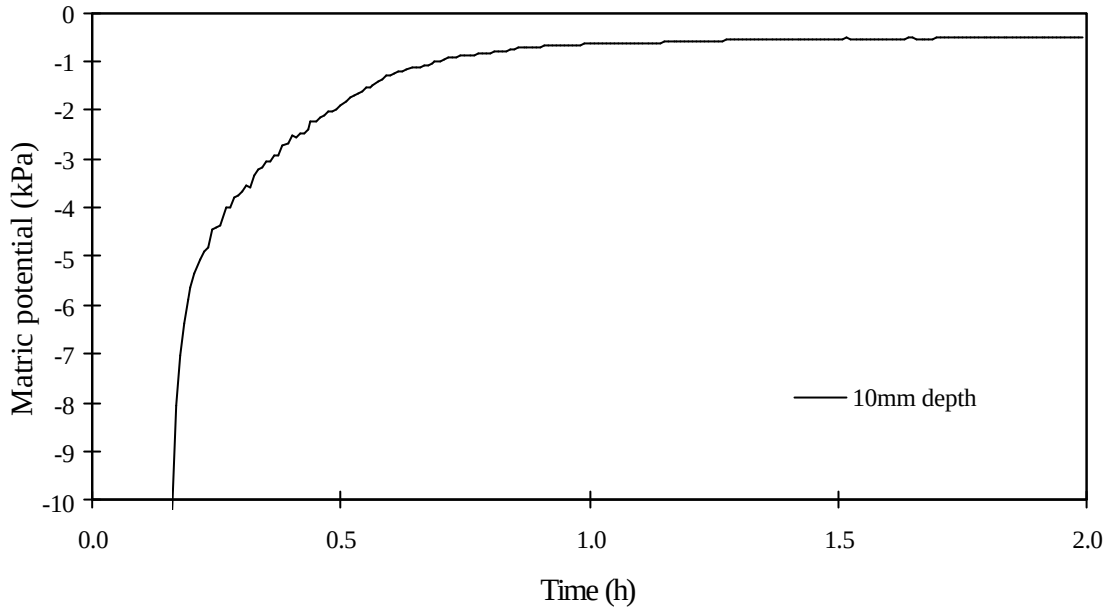
Sub-seal matric potential as a function of time for R18 Cowra DD Dry under 33 mm h^{-1} rainfall with high kinetic energy



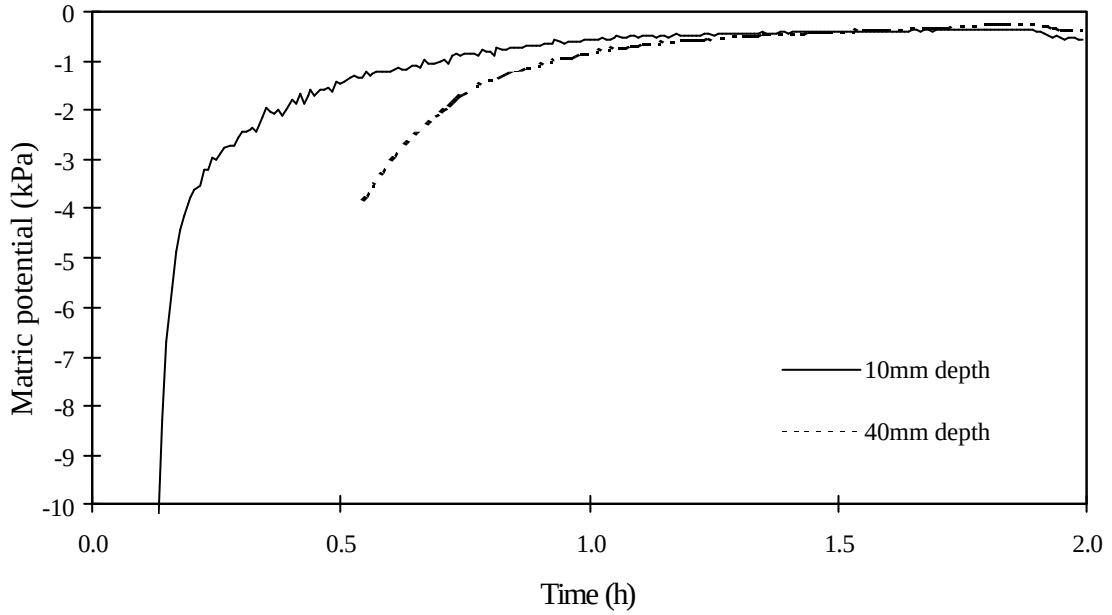
Sub-seal matric potential as a function of time for R19 Cowra DD Dry under 33 mm h^{-1} rainfall with high kinetic energy



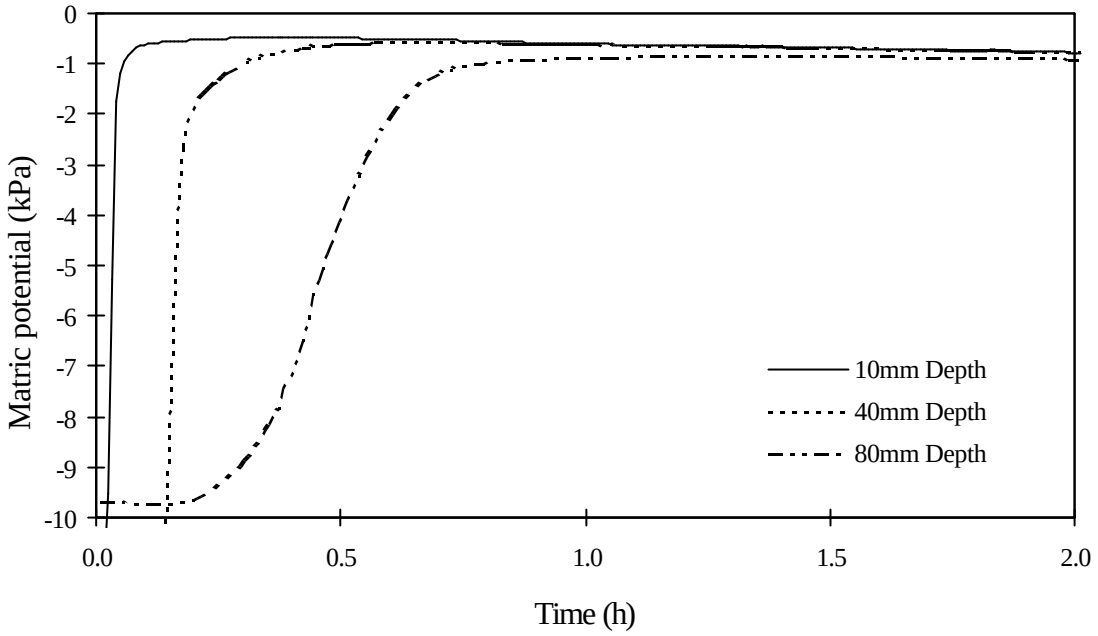
Sub-seal matric potential as a function of time for R20 Cowra DD Dry under 33 mm h^{-1} rainfall with low kinetic energy



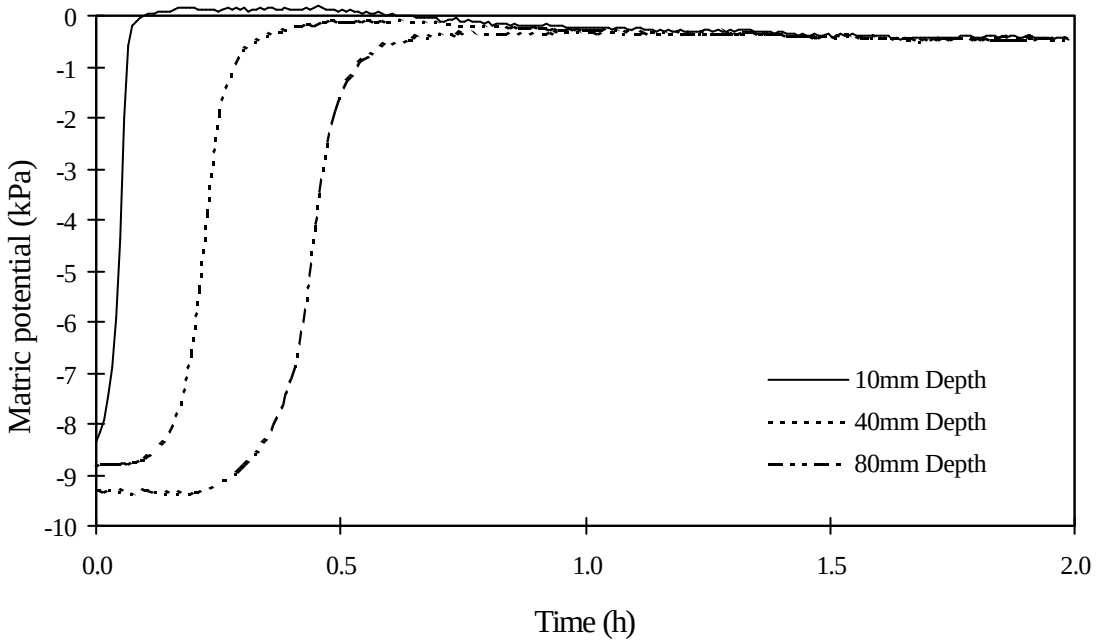
Sub-seal matric potential as a function of time for R25 Cowra DD Dry under 33 mm h^{-1} rainfall with low kinetic energy



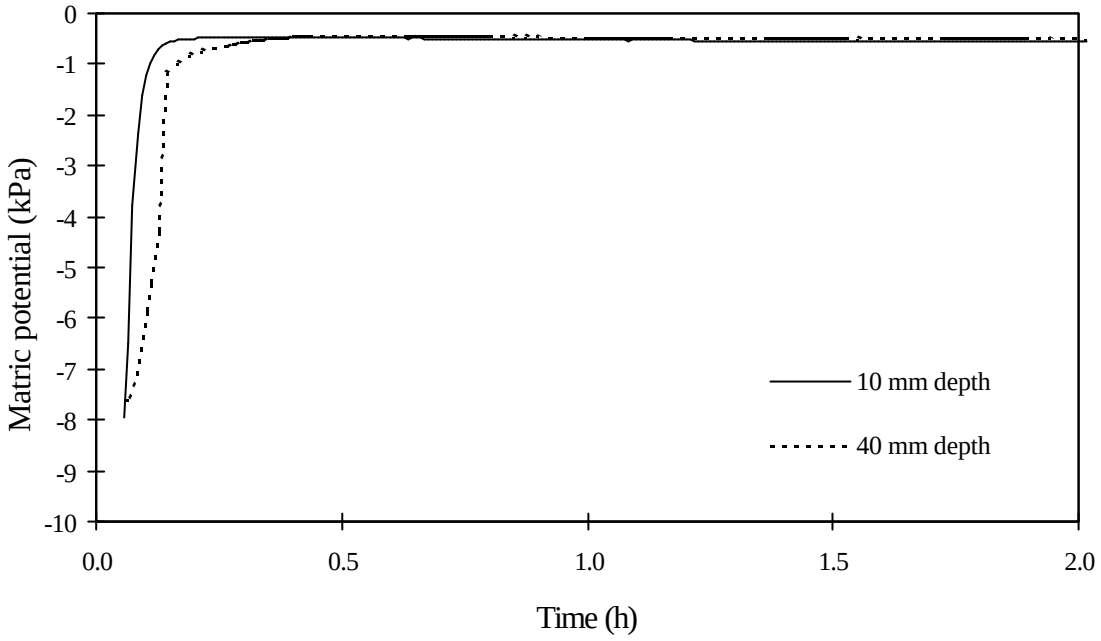
Sub-seal matric potential as a function of time for R9 Cowra TT Tension prewet under 33 mm h^{-1} rainfall with high kinetic energy



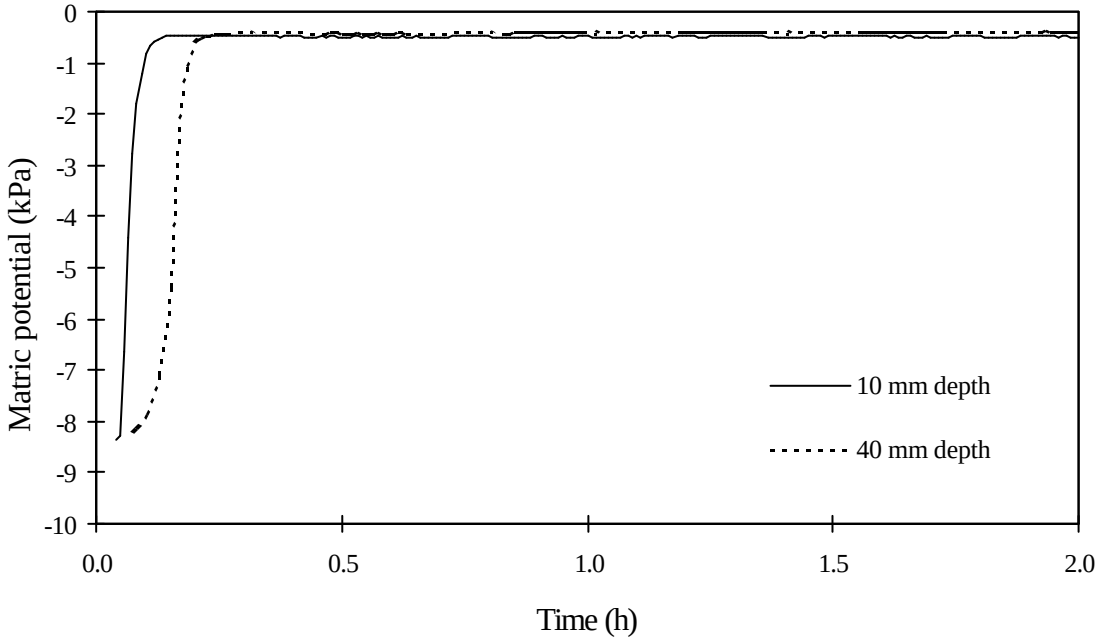
Sub-seal matric potential as a function of time for R7 Cowra TT Tension prewet under 33 mm h^{-1} rainfall with high kinetic energy



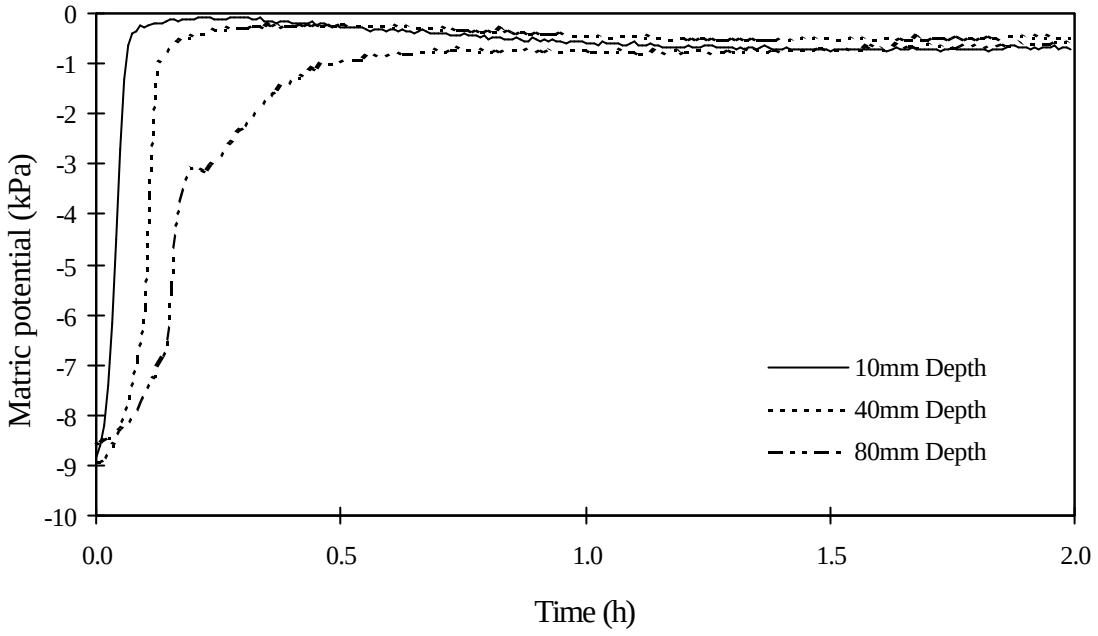
Sub-seal matric potential as a function of time for R11 Cowra TT Tension prewet under 33 mm h^{-1} rainfall with low kinetic energy



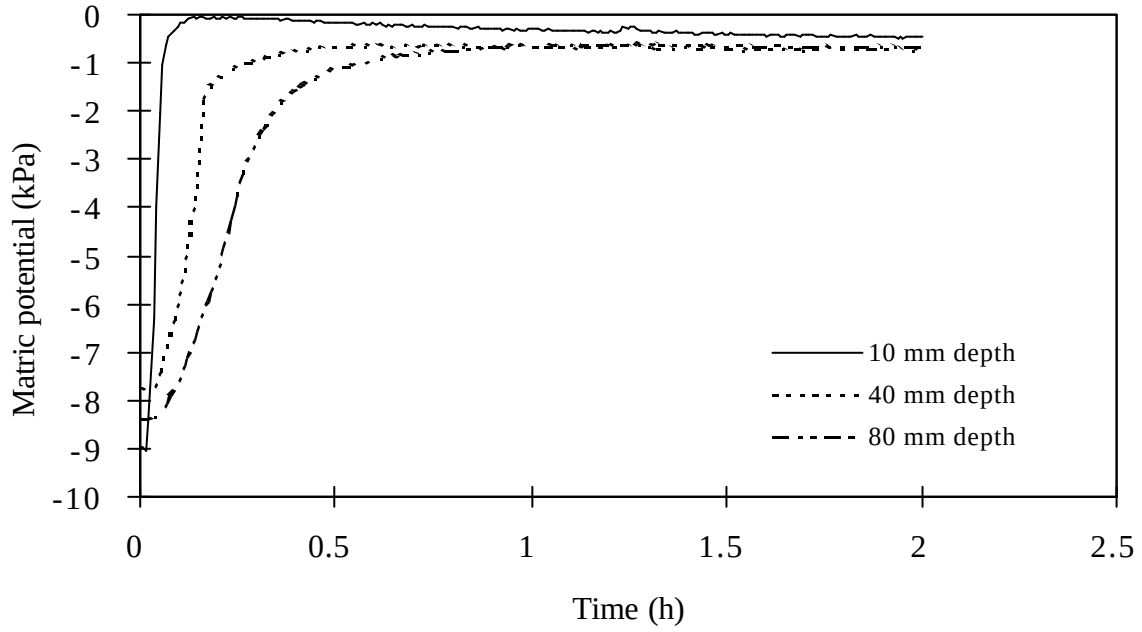
Sub-seal matric potential as a function of time for R12 Cowra TT Tension prewet under 33 mm h^{-1} rainfall with low kinetic energy



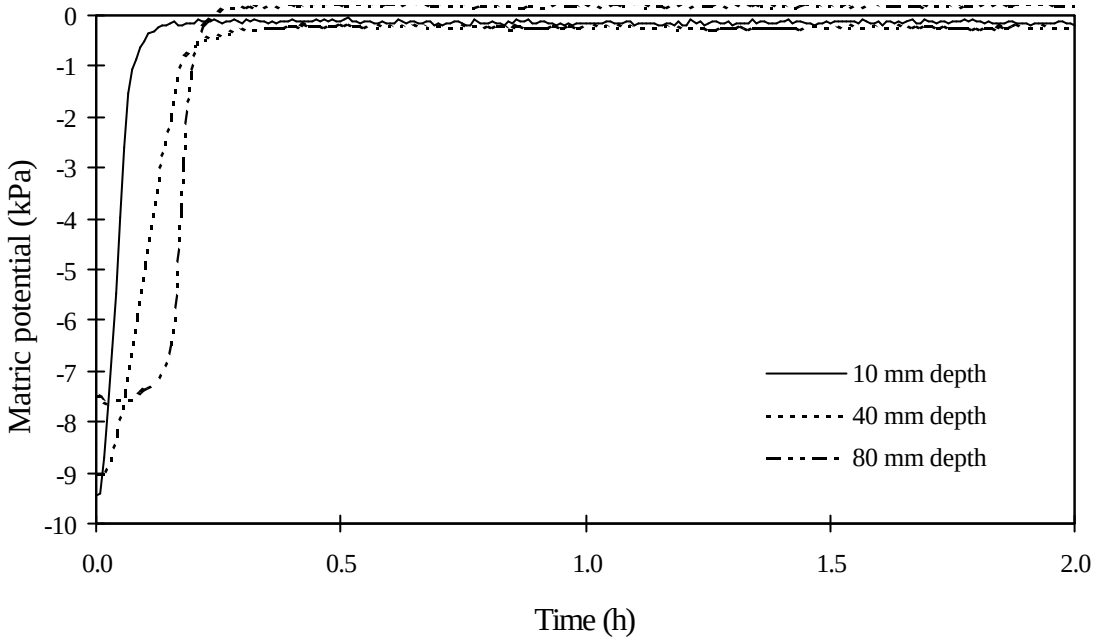
Sub-seal matric potential as a function of time for R2 Cowra TT Rapid prewet under 33 mm h^{-1} rainfall with high kinetic energy



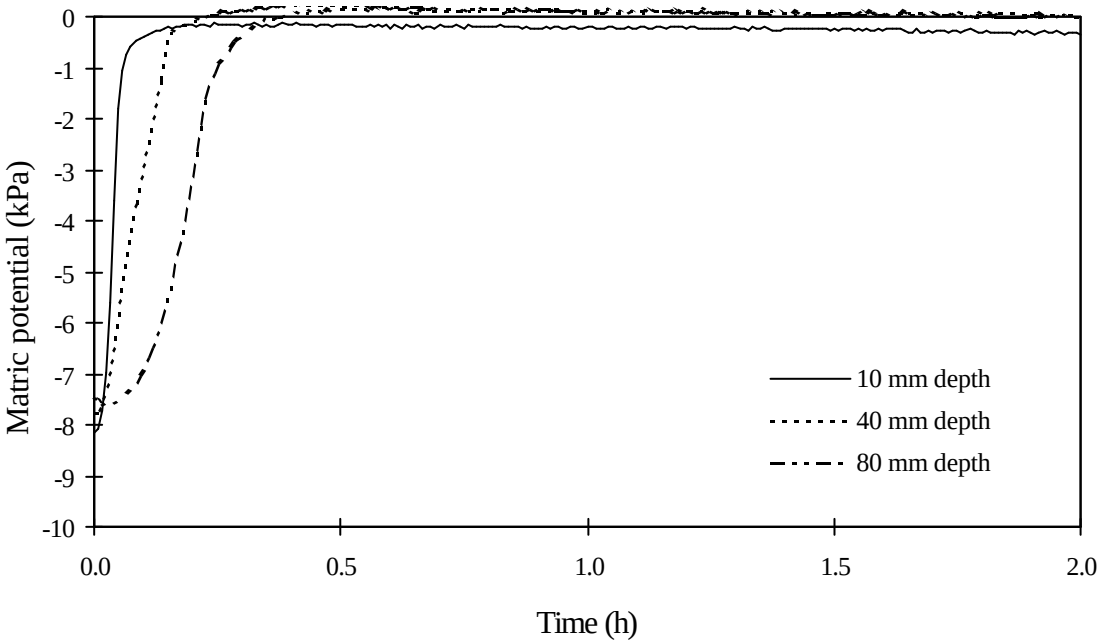
Sub-seal matric potential as a function of time for R8 Cowra TT Rapid prewet under 33 mm h^{-1} rainfall with high kinetic energy



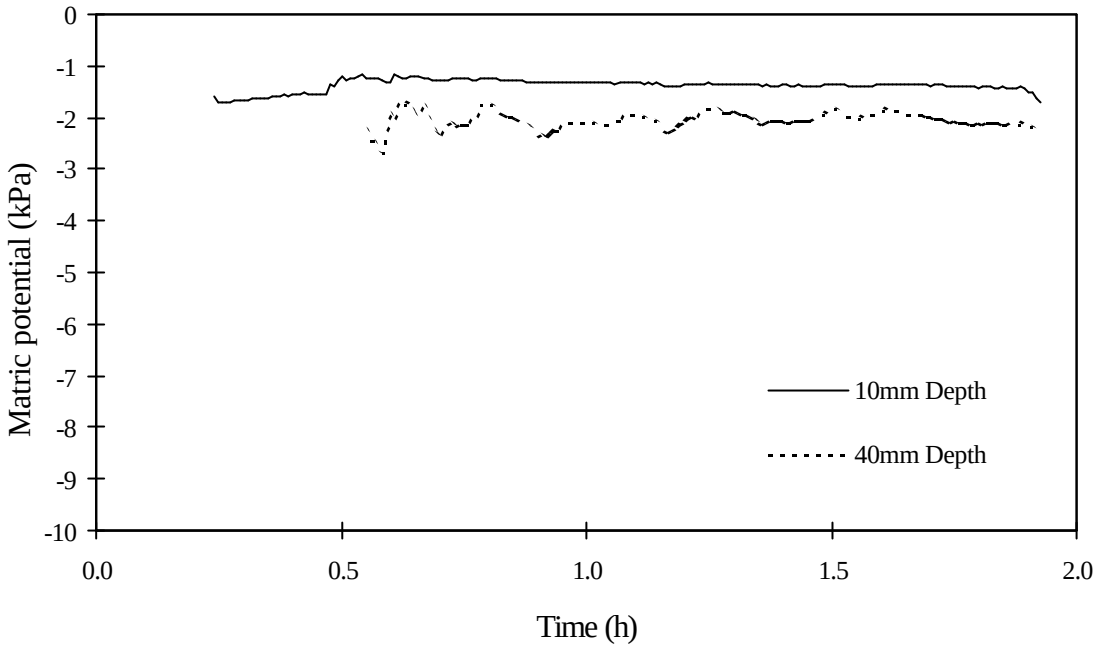
Sub-seal matric potential as a function of time for R4 Cowra TT Rapid prewet under 33 mm h^{-1} rainfall with low kinetic energy



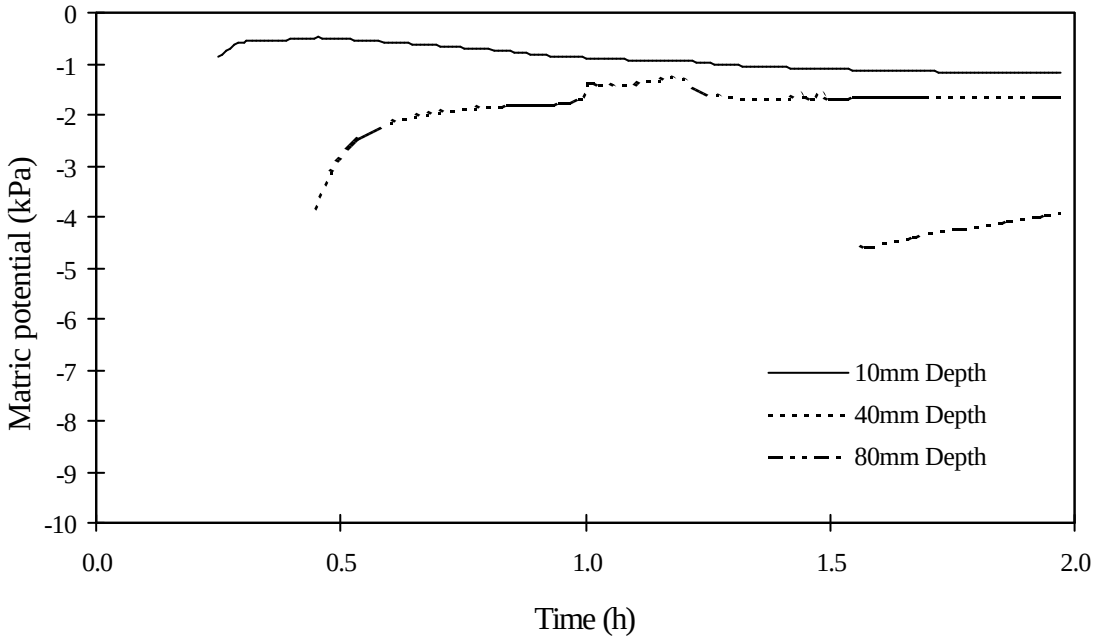
Sub-seal matric potential as a function of time for R3 Cowra TT Rapid prewet under 33 mm h^{-1} rainfall with low kinetic energy



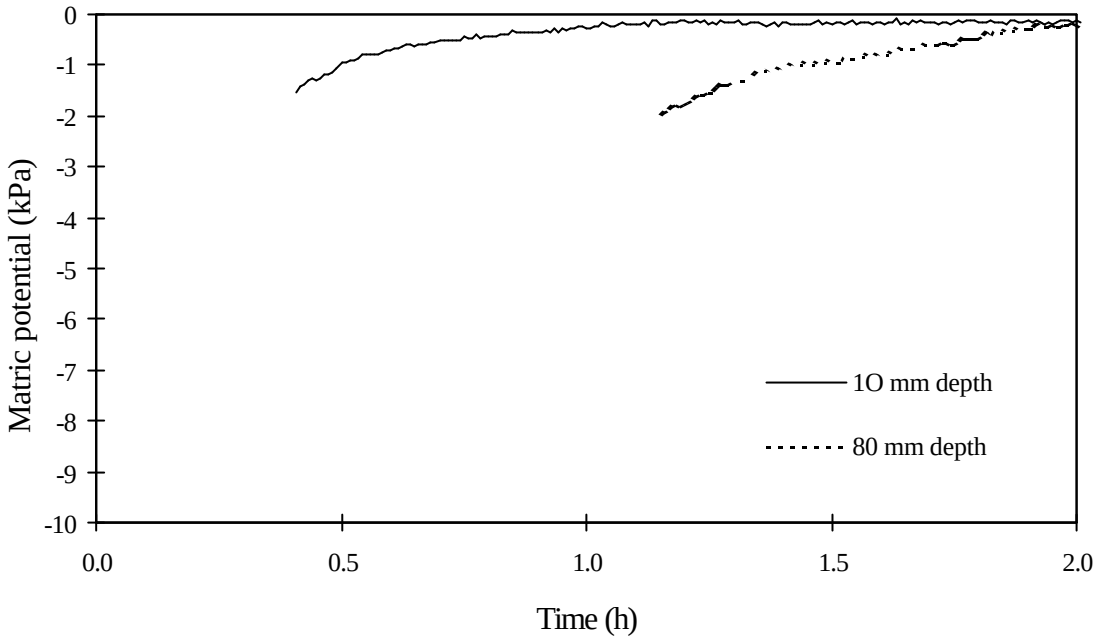
Sub-seal matric potential as a function of time for R6 Cowra TT Dry under 33 mm h^{-1} rainfall with high kinetic eoergy



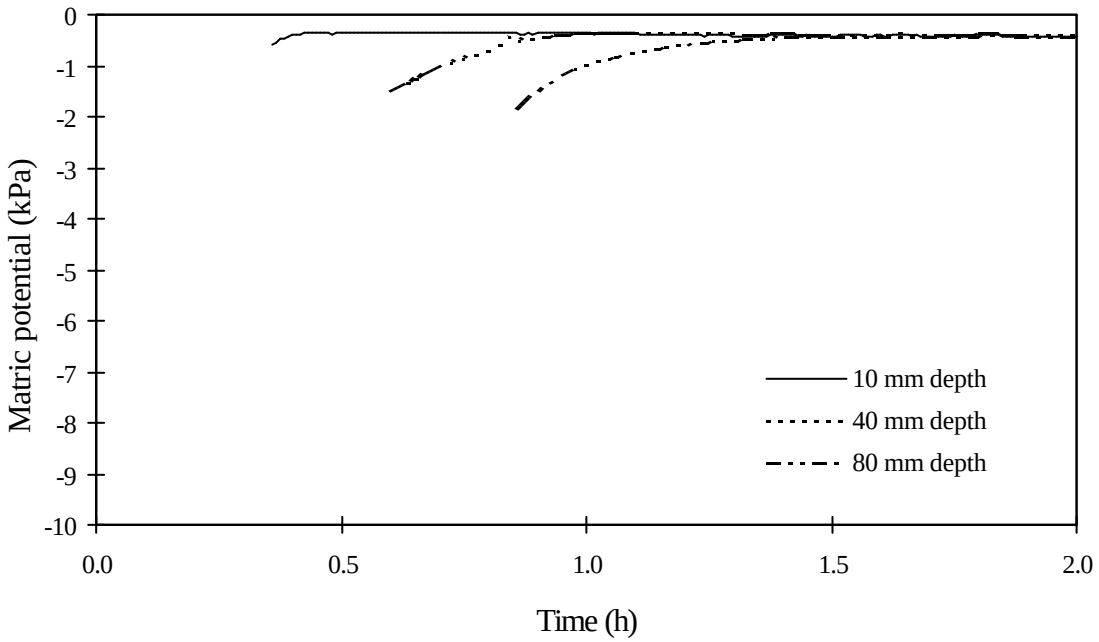
Sub-seal matric potential as a function of time for R10 Cowra TT Dry under 33 mm h^{-1} rainfall with high kinetic energy



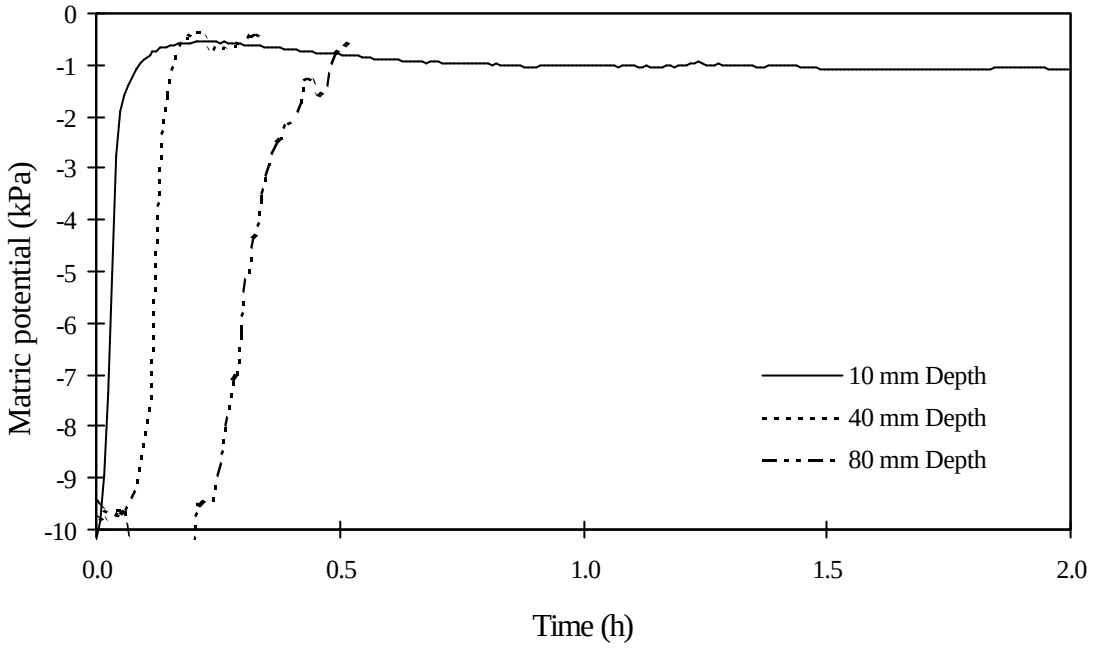
Sub-seal matric potential as a function of time for R5 Cowra TT Dry under 33 mm h^{-1} rainfall with low kinetic energy



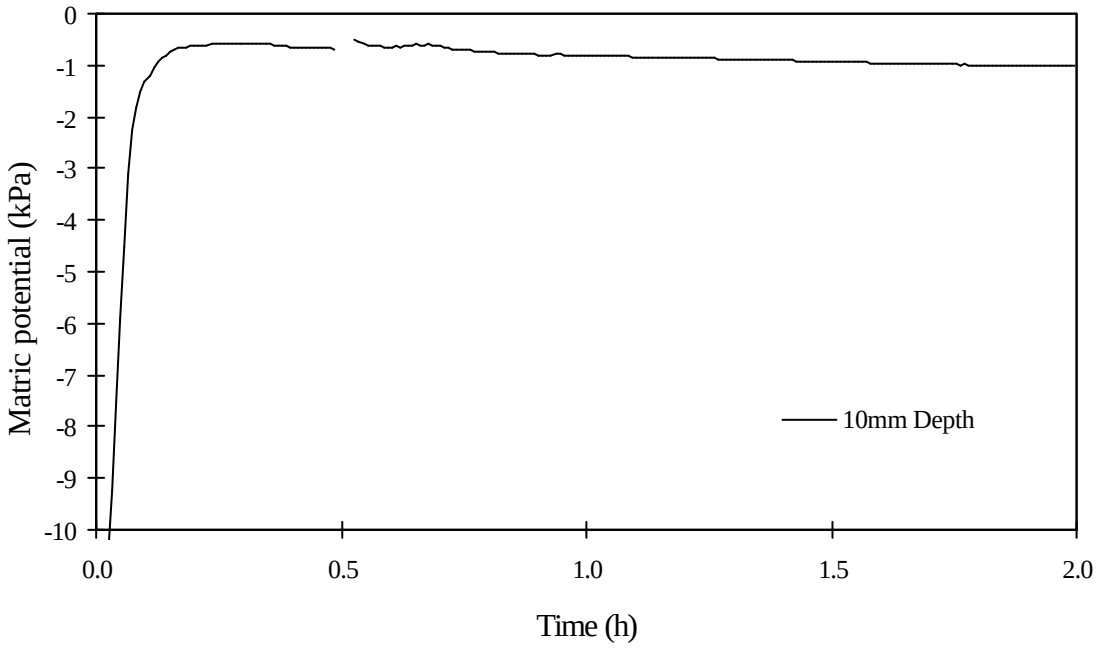
Sub-seal matric potential as a function of time for R13 Cowra TT Dry under 33 mm h^{-1} rainfall with low kinetic energy



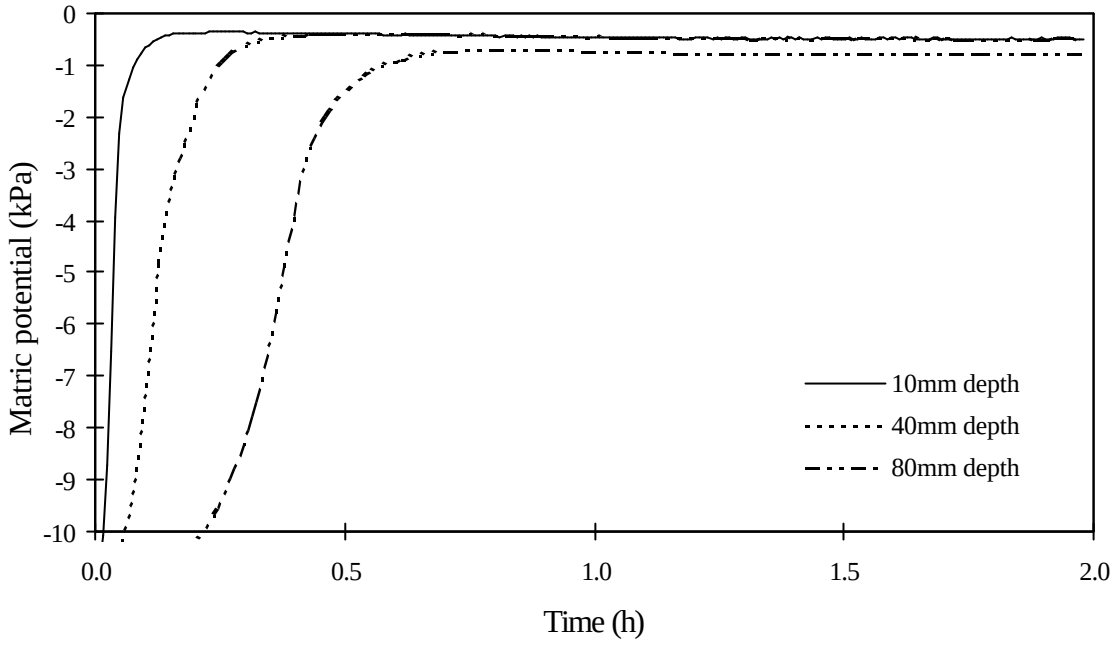
Sub-seal matric potential as a function of time for R30 Condobolin RH Tension prewet under 33 mm h^{-1} rainfall with high kinetic energy



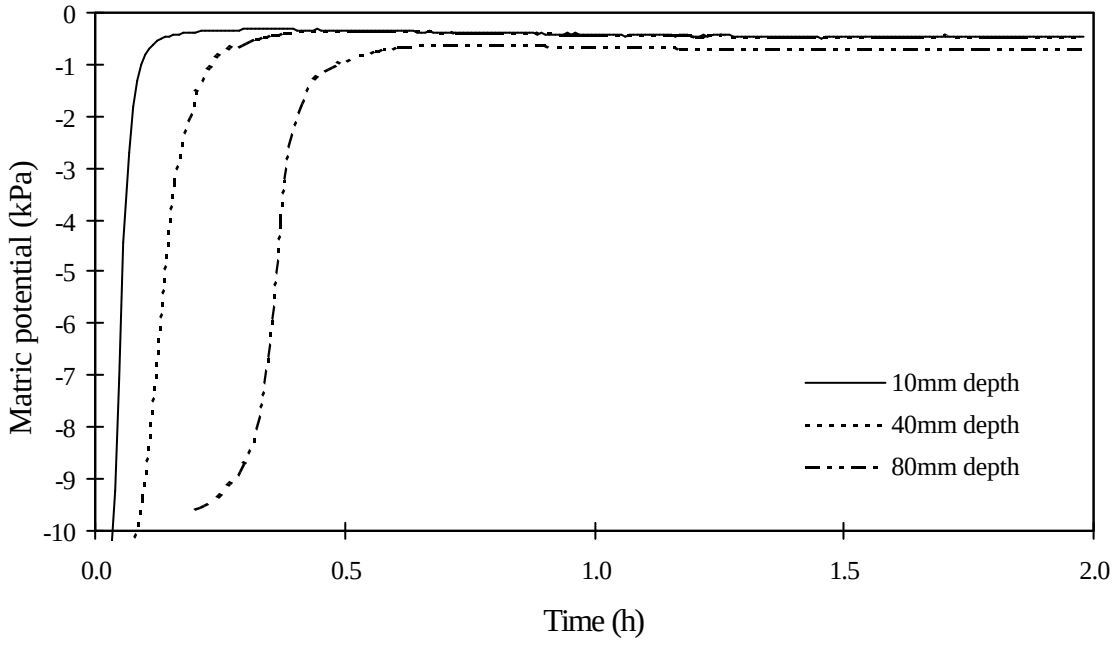
Sub-seal matric potential as a function of time for R31 Condobolin RH Tension prewet under 33 mm h^{-1} rainfall with high kinetic energy



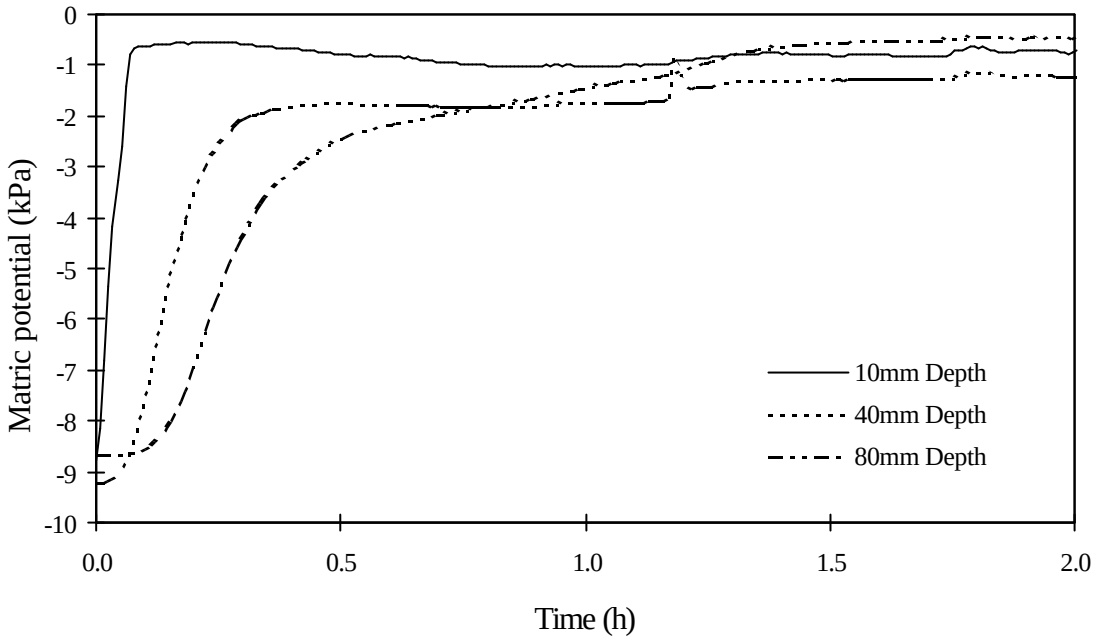
Sub-seal matric potential as a function of time for R48 Condobolin RH Tension prewet under 33 mm h^{-1} rainfall with low kinetic energy



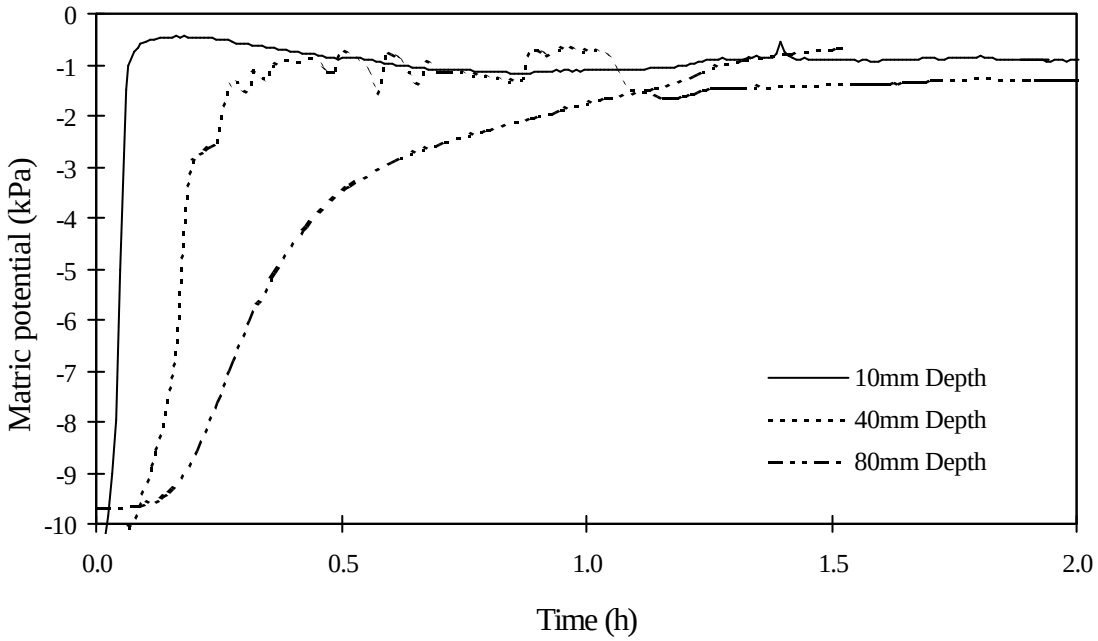
Sub-seal matric potential as a function of time for R49 Condobolin RH Tension prewet under 33 mm h^{-1} rainfall with low kinetic energy



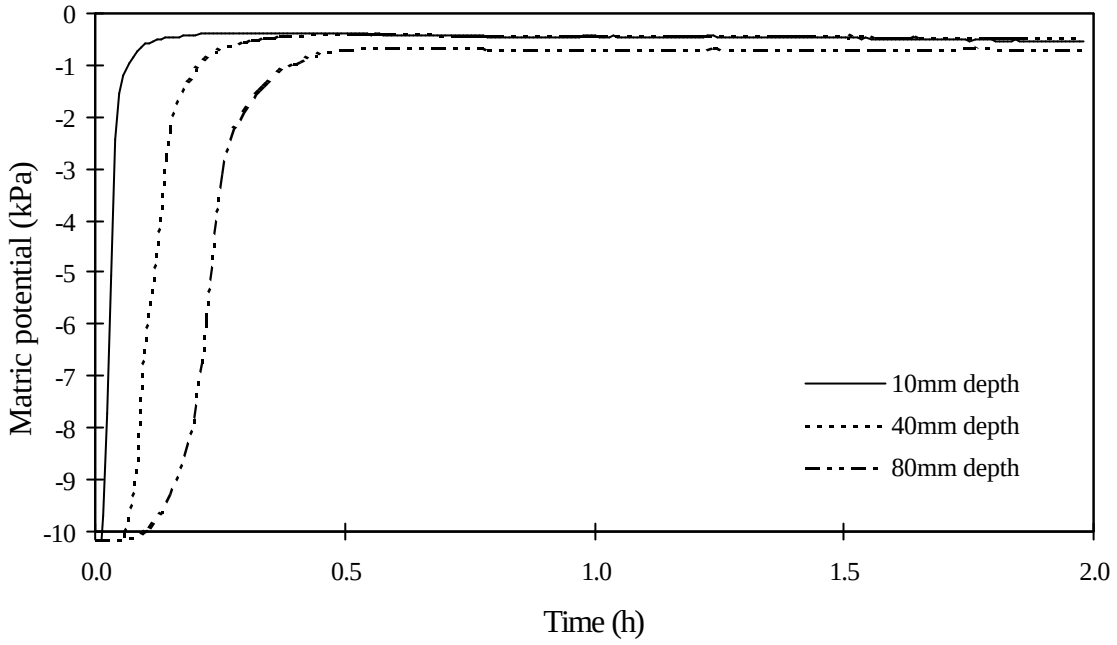
Sub-seal matric potential as a function of time for R26 Condobolin RH Rapid prewet under 33 mm h^{-1} rainfall with high kinetic energy



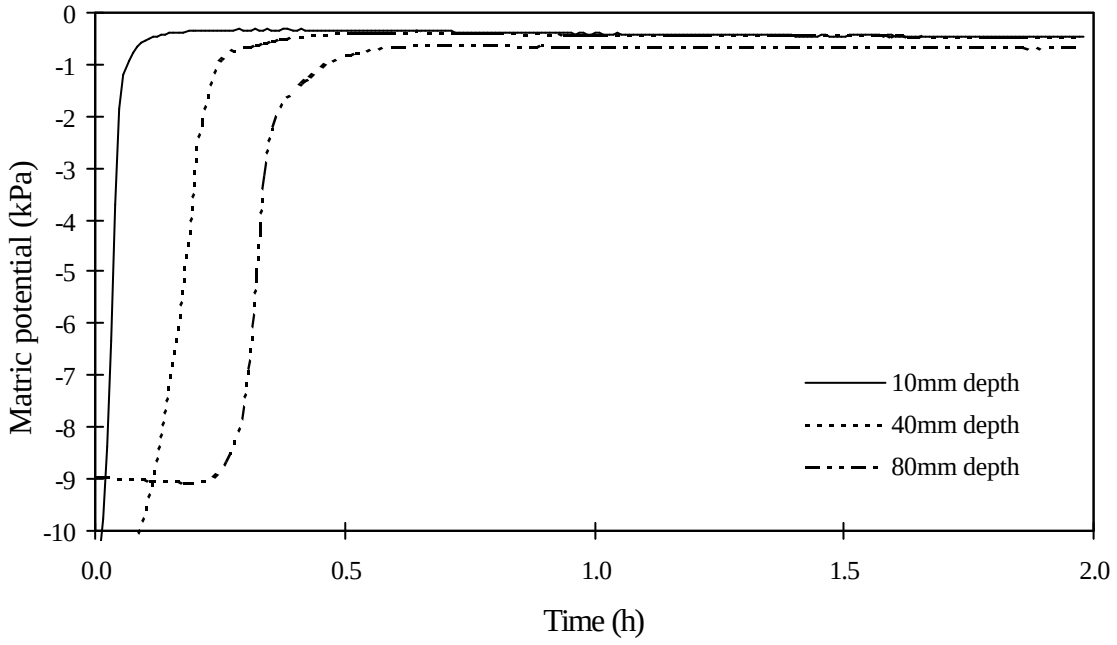
Sub-seal matric potential as a function of time for R27 Condobolin RH Rapid prewet under 33 mm h^{-1} rainfall with high kinetic energy



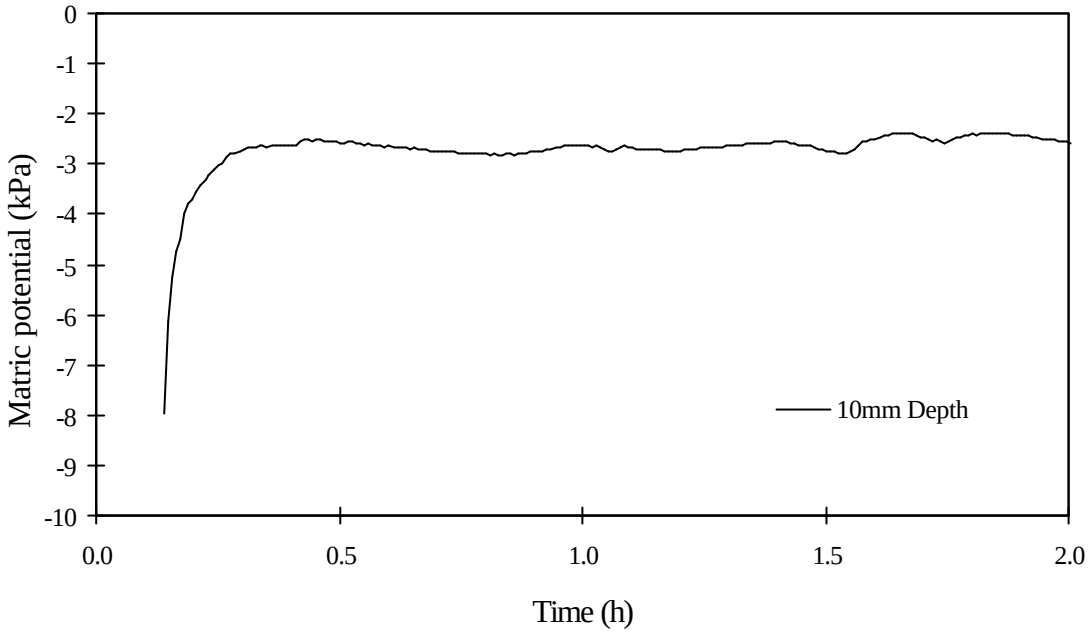
Sub-seal matric potential as a function of time for R45 Condobolin RH Rapid prewet under 33 mm h^{-1} rainfall with low kinetic energy



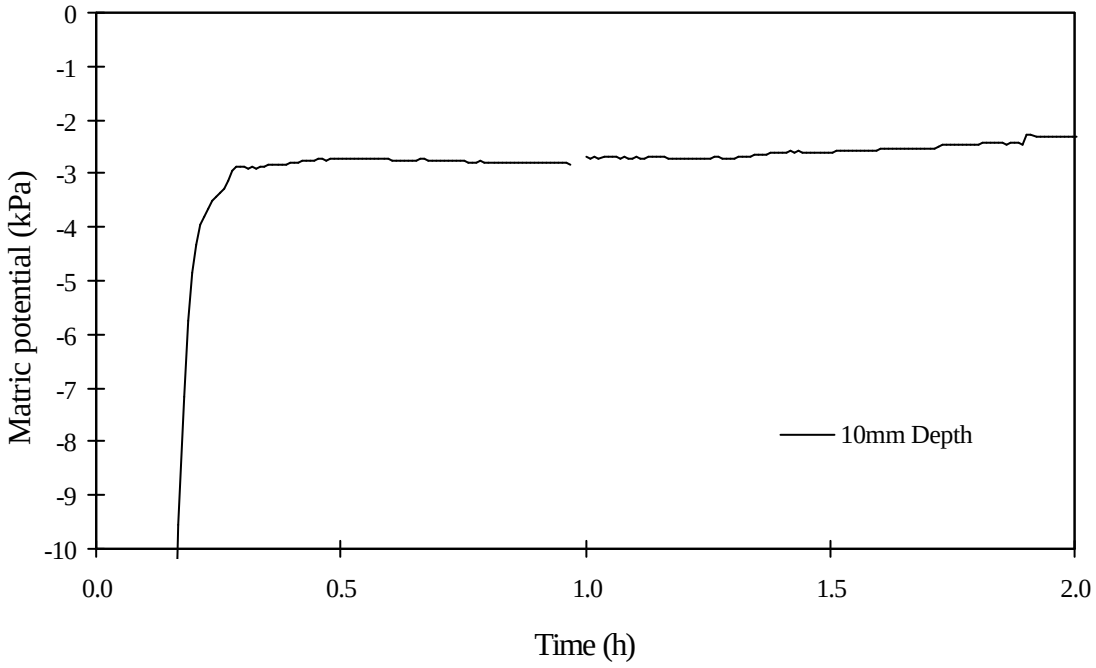
Sub-seal matric potential as a function of time for R46 Condobolin RH Rapid prewet under 33 mm h^{-1} rainfall with low kinetic energy



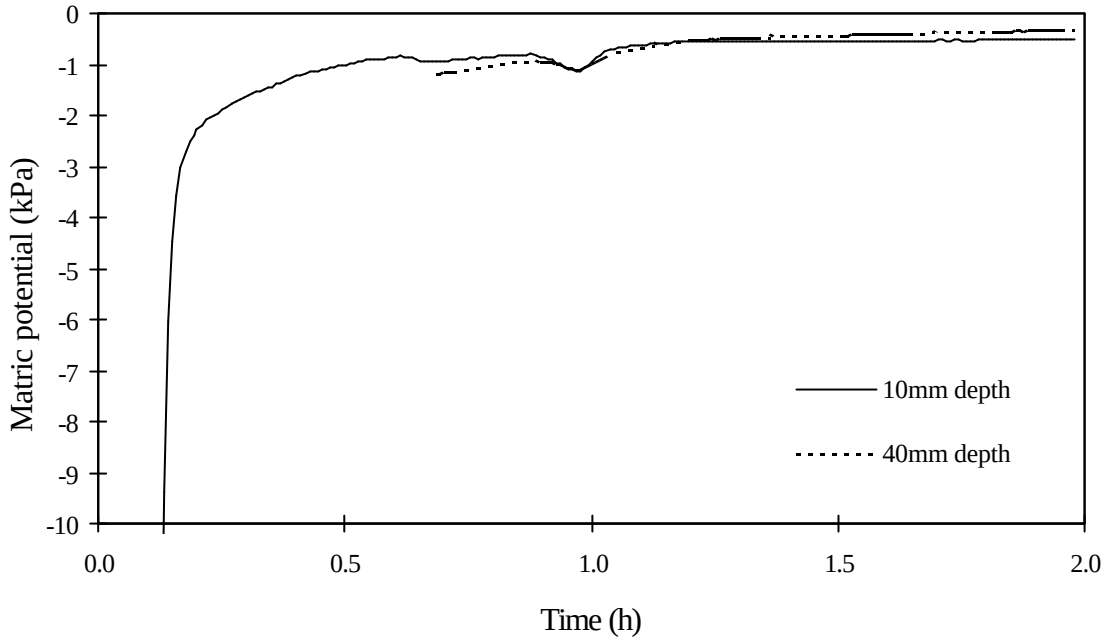
Sub-seal matric potential as a function of time for R28 Condobolin RH Dry under 33 mm h^{-1} rainfall with high kinetic energy



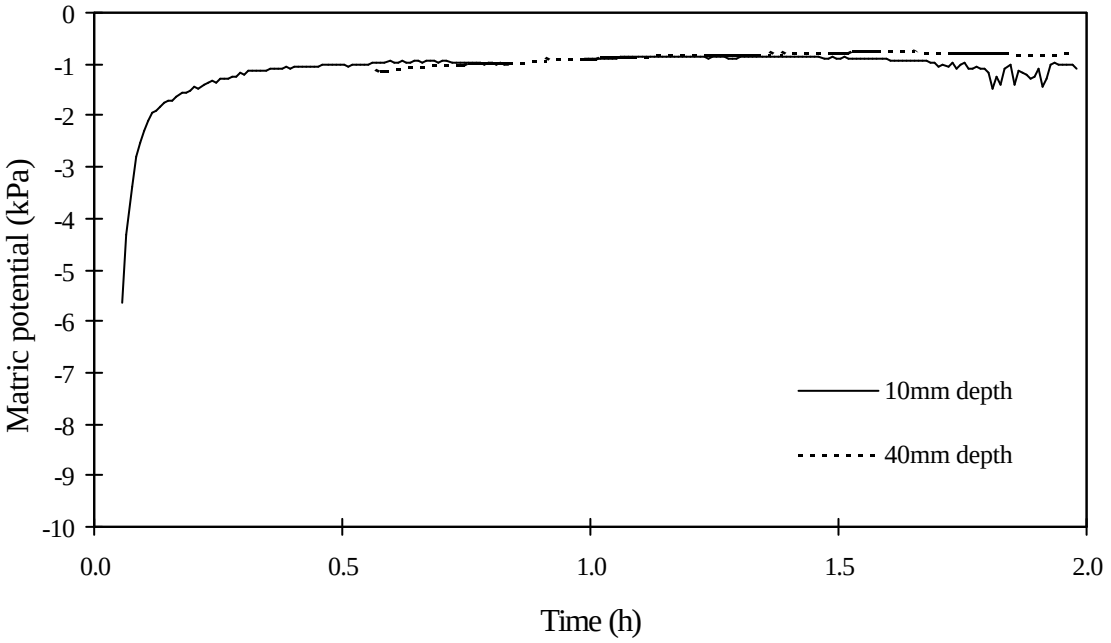
Sub-seal matric potential as a function of time for R29 Condobolin RH Dry under 33 mm h^{-1} rainfall with high kinetic energy



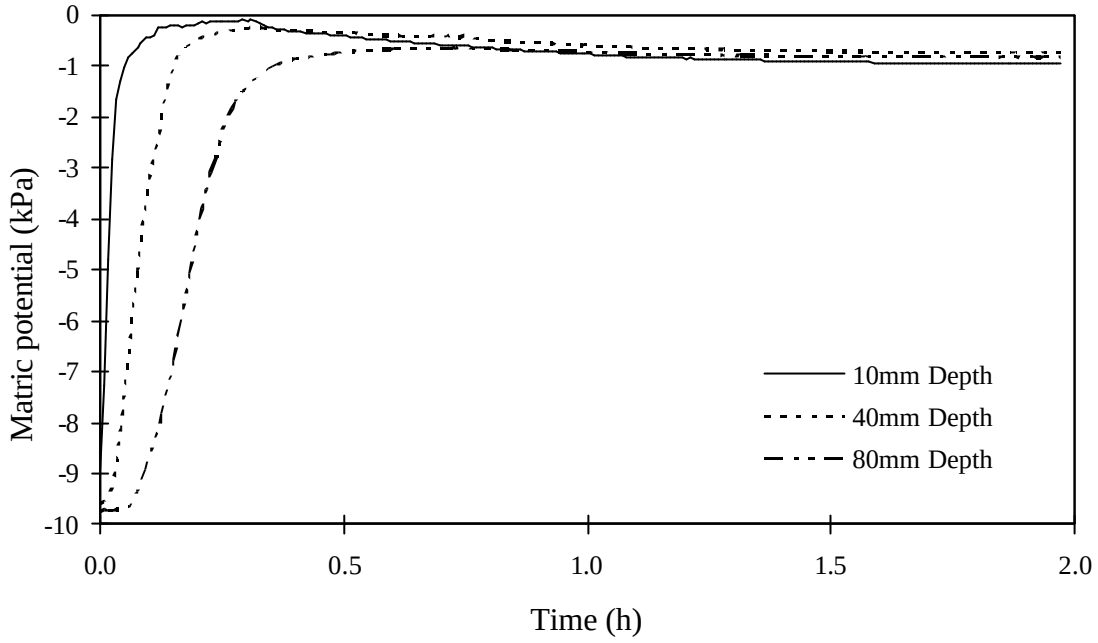
Sub-seal matric potential as a function of time for R44 Condobolin RH Dry under 33 mm h^{-1} rainfall with low kinetic energy



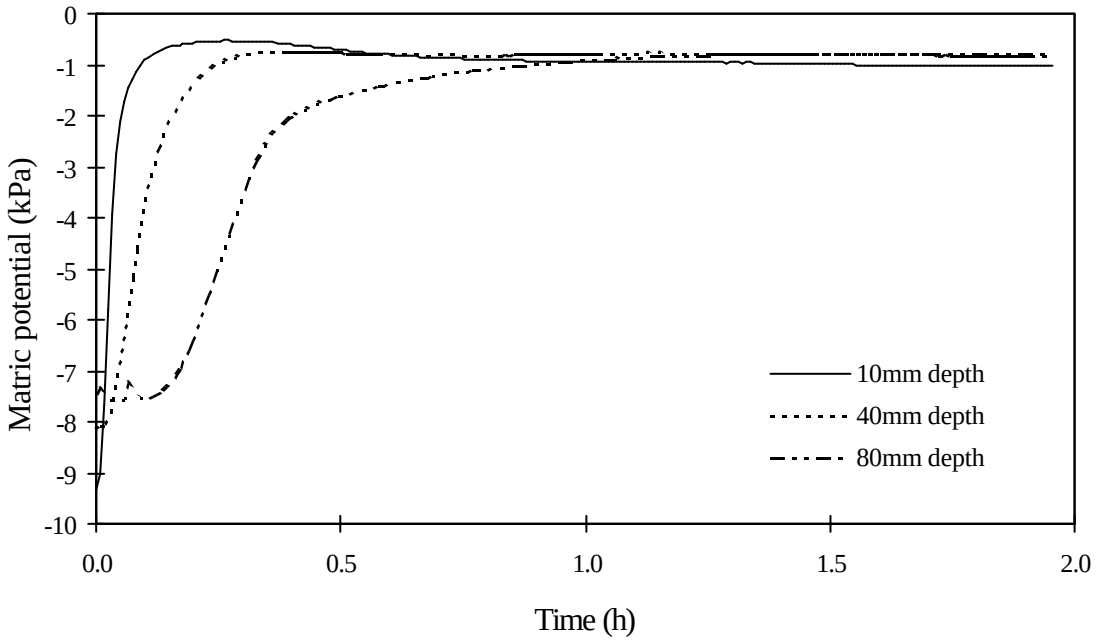
Sub-seal matric potential as a function of time for R47 Condobolin RH Dry under 33 mm h^{-1} rainfall with low kinetic energy



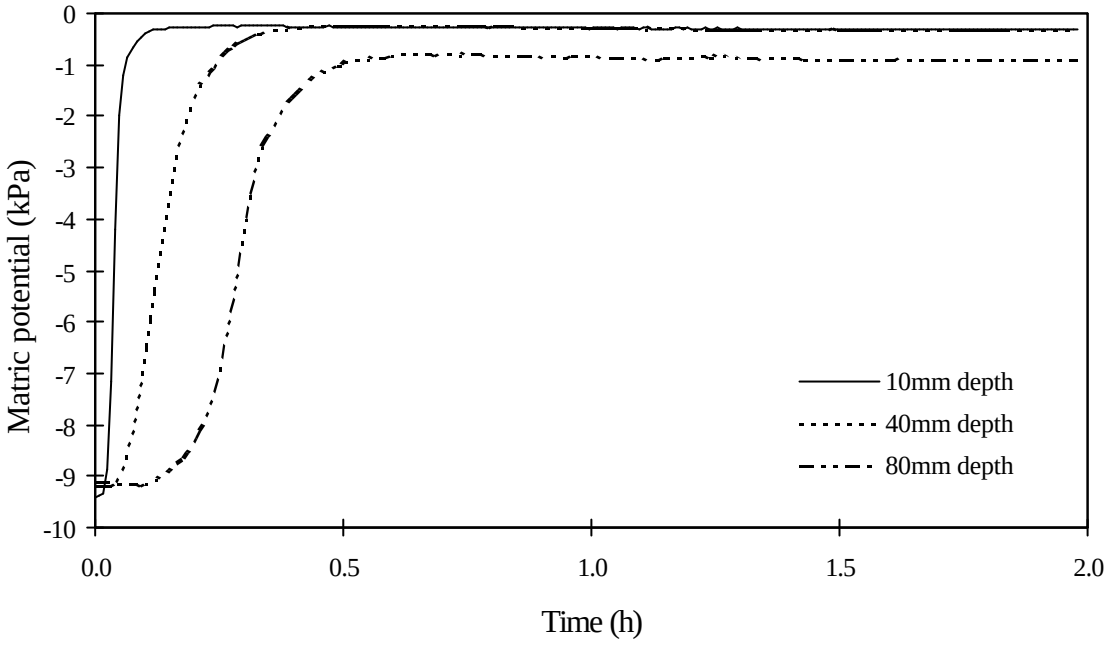
Sub-seal matric potential as a function of time for R33 Condobolin BC Tension prewet under 33 mm h^{-1} rainfall with high kinetic energy



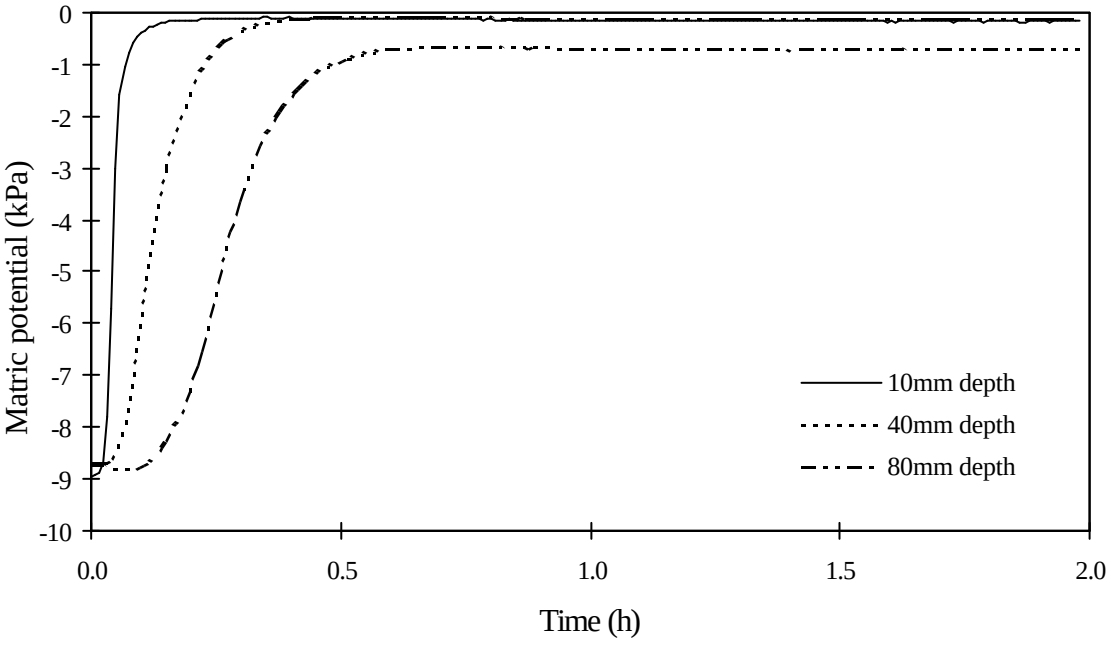
Sub-seal matric potential as a function of time for R36 Condobolin BC Tension prewet under 33 mm h^{-1} rainfall with high kinetic energy



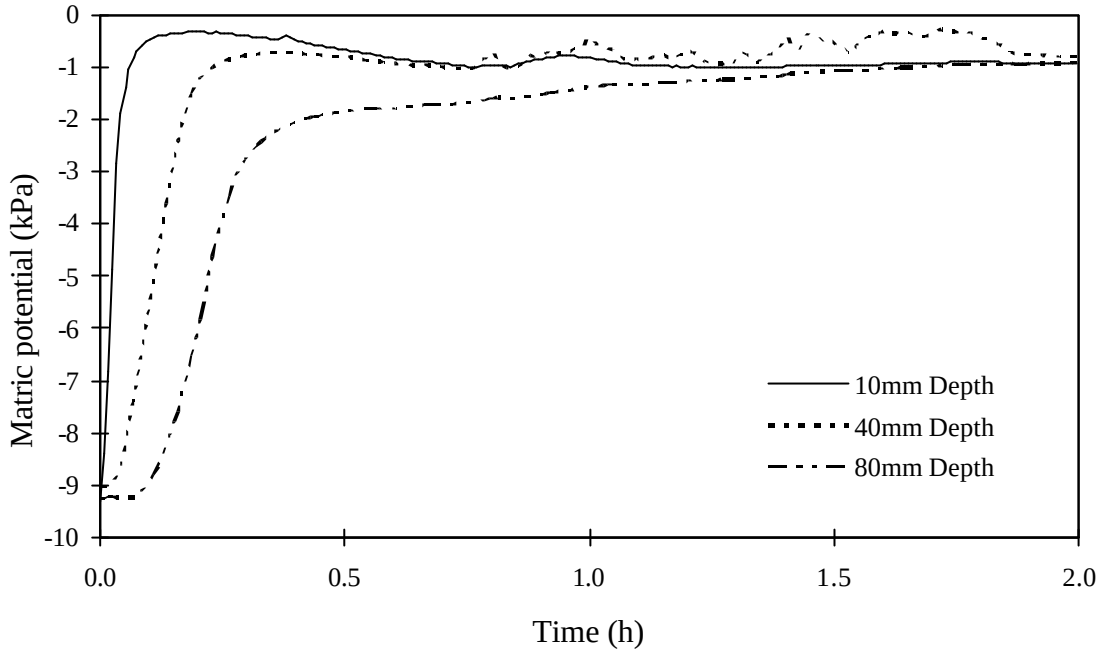
Sub-seal matric potential as a function of time for R42 Condobolin BC Tension prewet under 33 mm h^{-1} rainfall with low kinetic energy



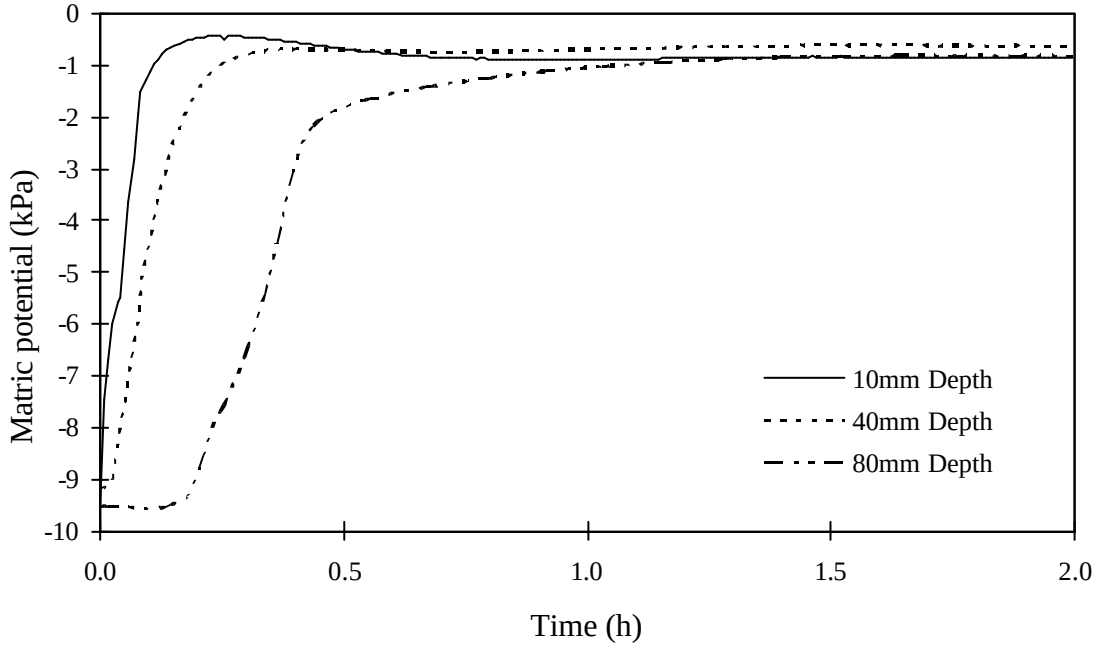
Sub-seal matric potential as a function of time for R43 Condobolin BC Tension prewet under 33 mm h^{-1} rainfall with low kinetic energy



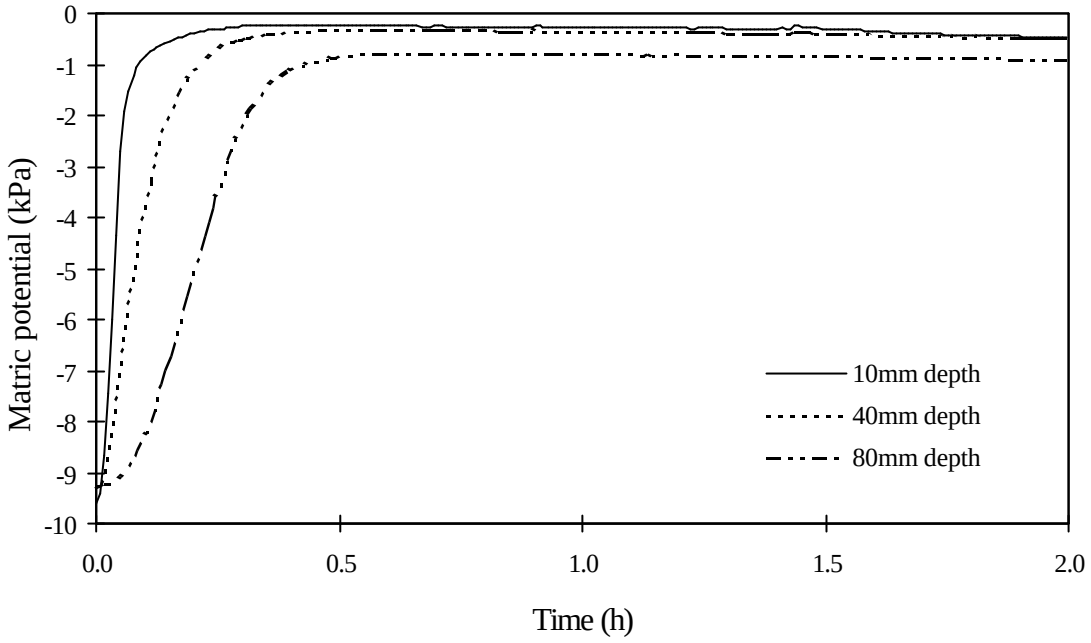
Sub-seal matric potential as a function of time for R34 Condobolin BC Rapid prewet under 33 mm h^{-1} rainfall with high kinetic energy



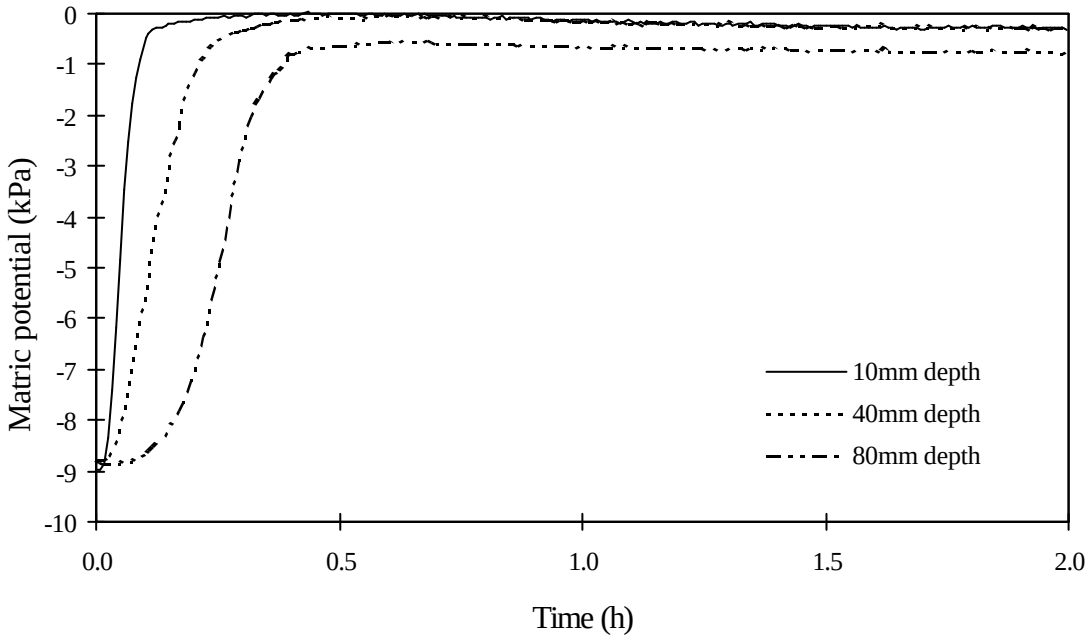
Sub-seal matric potential as a function of time for R37 Condobolin BC Rapid prewet under 33 mm h^{-1} rainfall with high kinetic energy



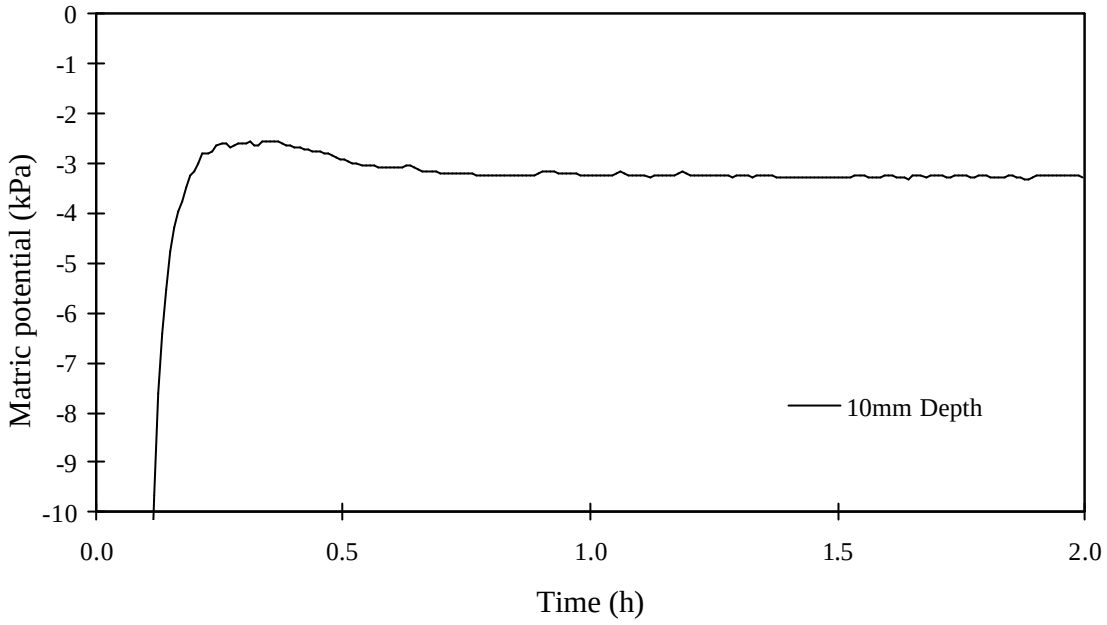
Sub-seal matric potential as a function of time for R38 Condobolin BC Rapid prewet under 33 mm h^{-1} rainfall with low kinetic energy



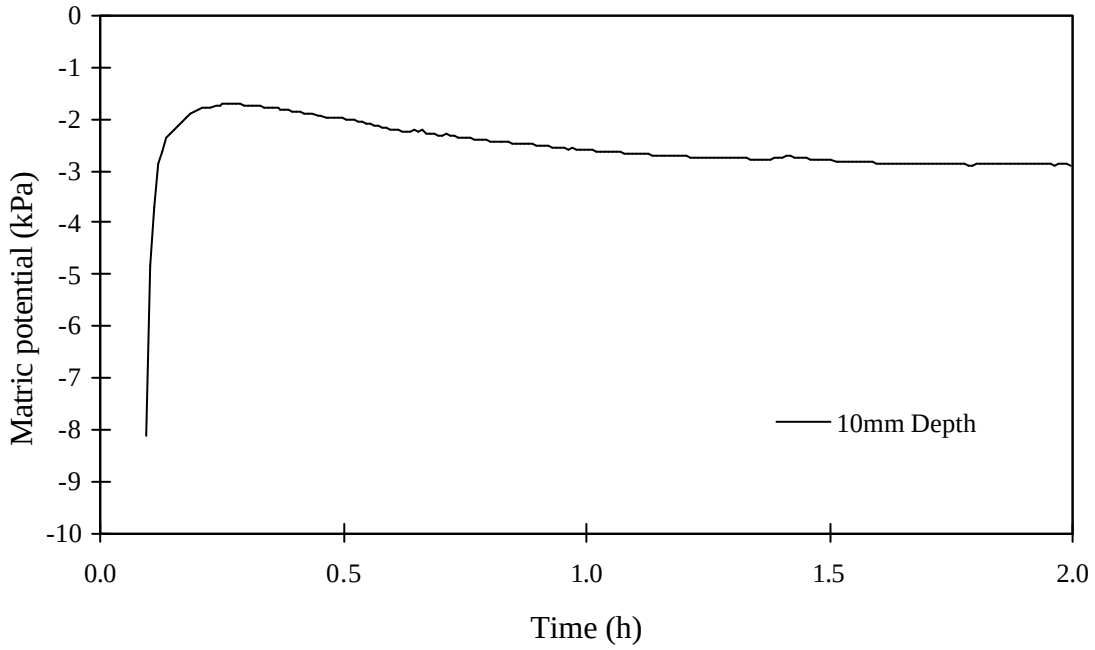
Sub-seal matric potential as a function of time for R39 Condobolin BC Rapid prewet under 33 mm h^{-1} rainfall with low kinetic energy



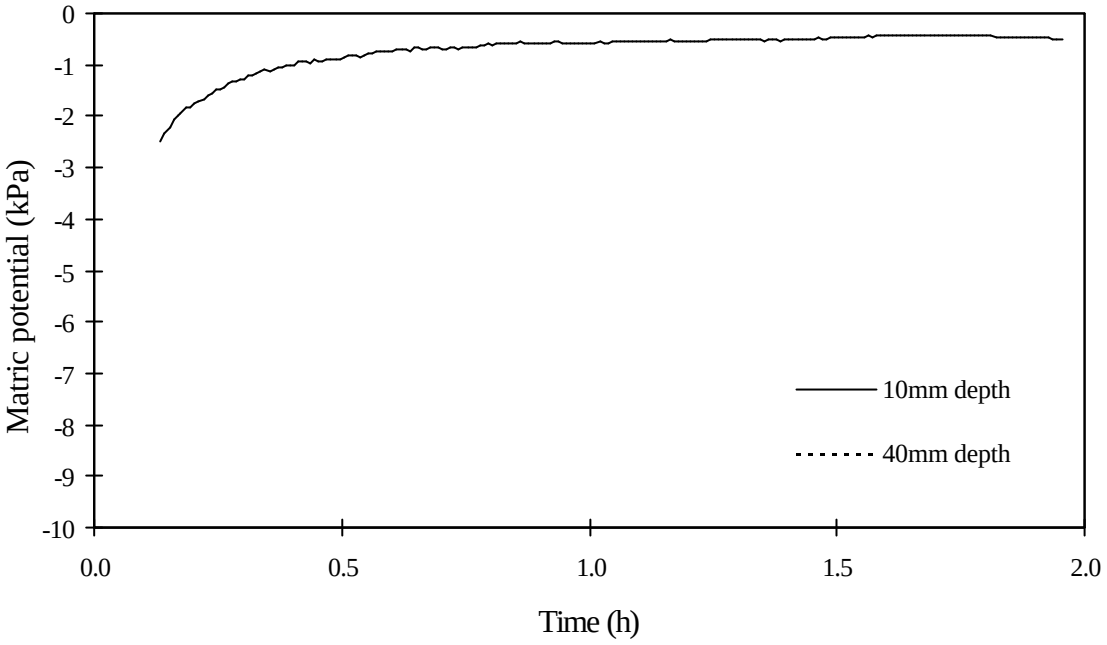
Sub-seal matric potential as a function of time for R32 Condobolin BC Dry under 33 mm h^{-1} rainfall with high kinetic energy



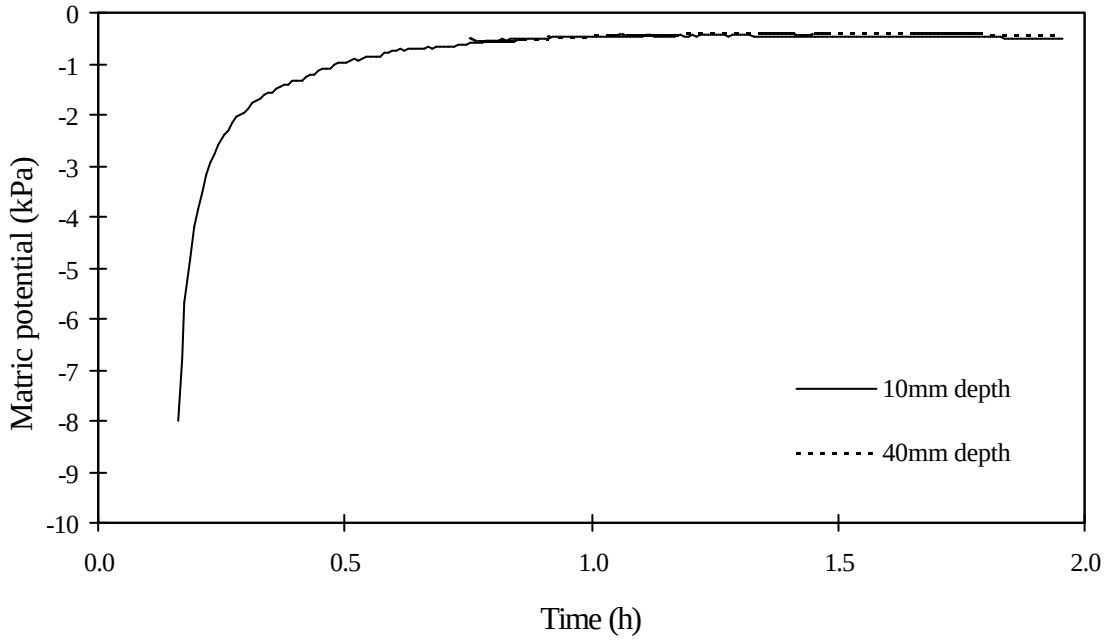
Sub-seal matric potential as a function of time for R35 Condobolin BC Dry under 33 mm h^{-1} rainfall with high kinetic energy



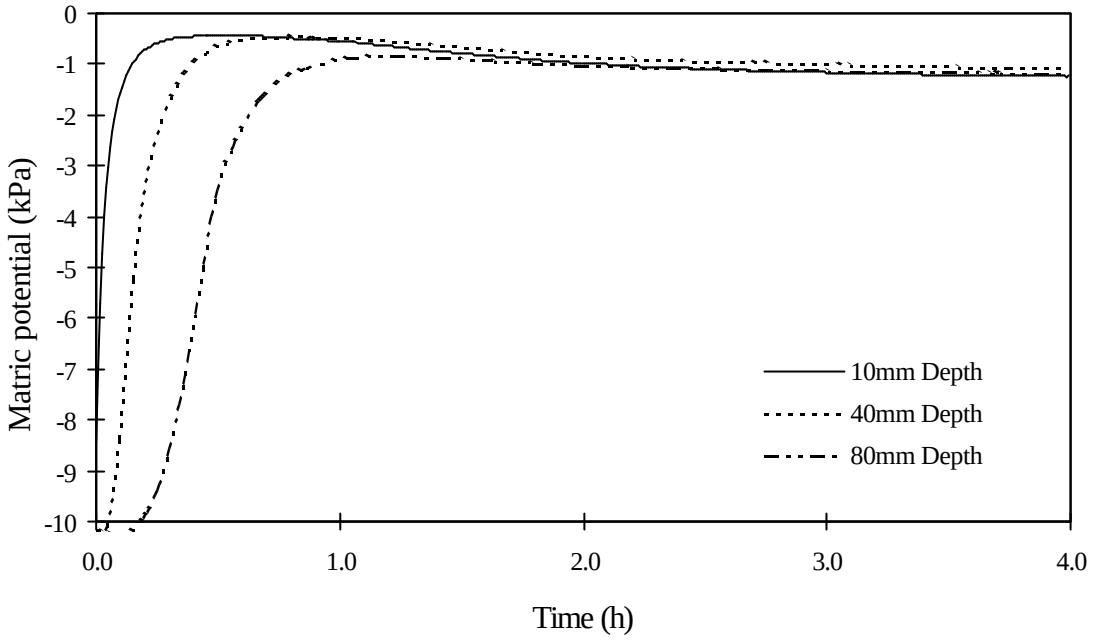
Sub-seal matric potential as a function of time for R40 Condobolin BC Dry under 33 mm h^{-1} rainfall with low kinetic energy



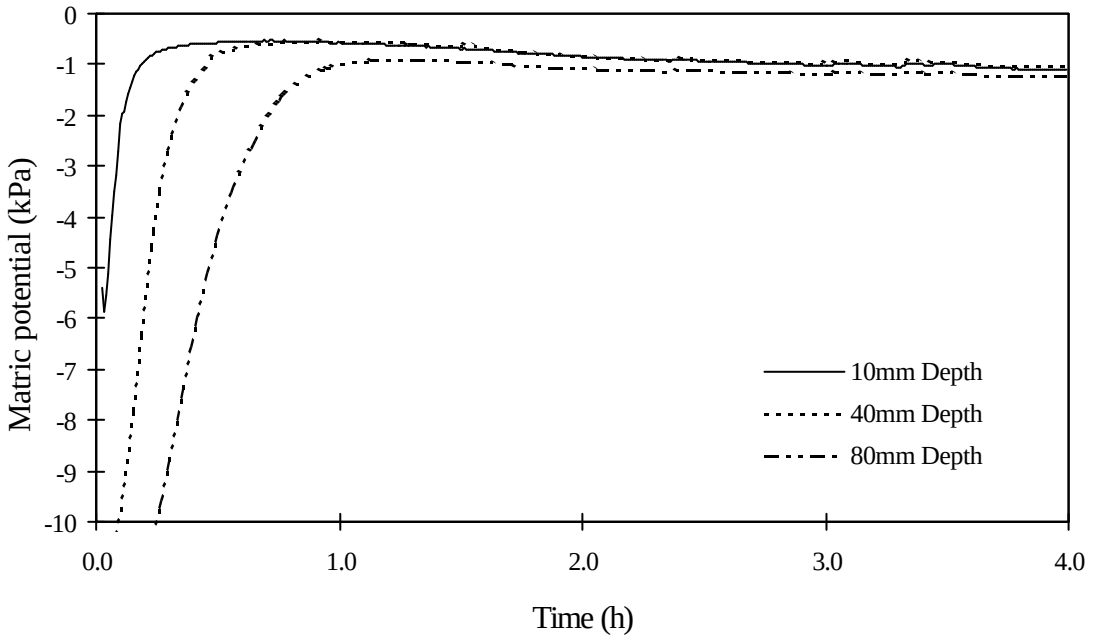
Sub-seal matric potential as a function of time for R41 Condobolin BC Dry under 33 mm h^{-1} rainfall with low kinetic energy



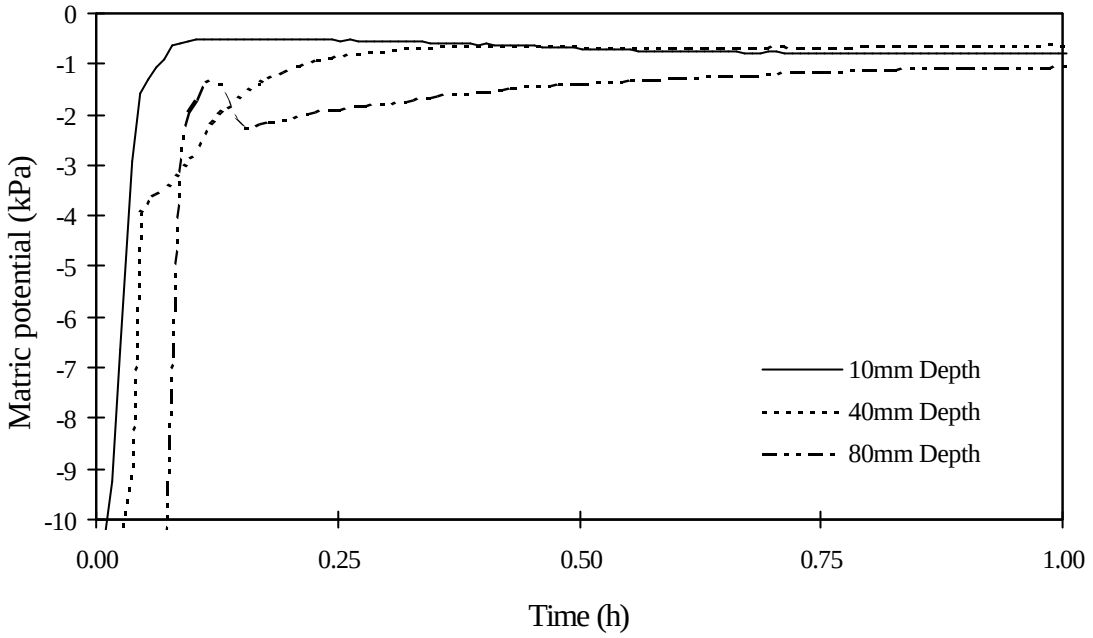
Sub-seal matric potential as a function of time for R50 Condobolin RH Tension prewet under 16.5 mm h^{-1} rainfall with high kinetic energy



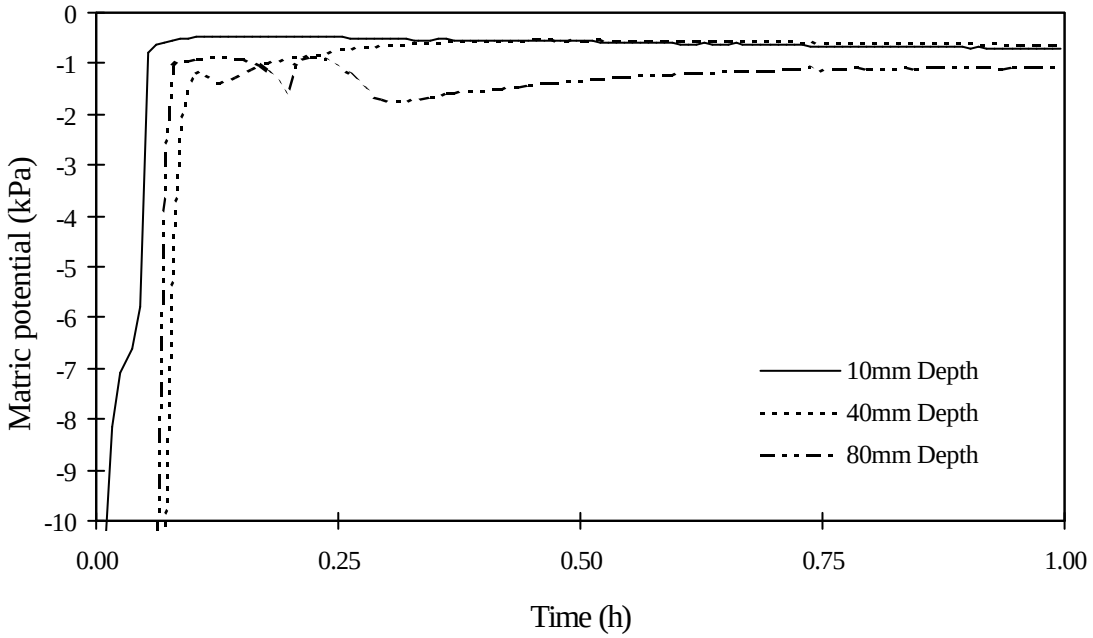
Sub-seal matric potential as a function of time for R52 Condobolin RH Tension prewet under 16.5 mm h^{-1} rainfall with high kinetic energy



Sub-seal matric potential as a function of time for R51 Condobolin RH Tension prewet under 66 mm h^{-1} rainfall with high kinetic energy



Sub-seal matric potential as a function of time for R53 Condobolin RH Tension prewet under 66 mm h^{-1} rainfall with high kinetic energy



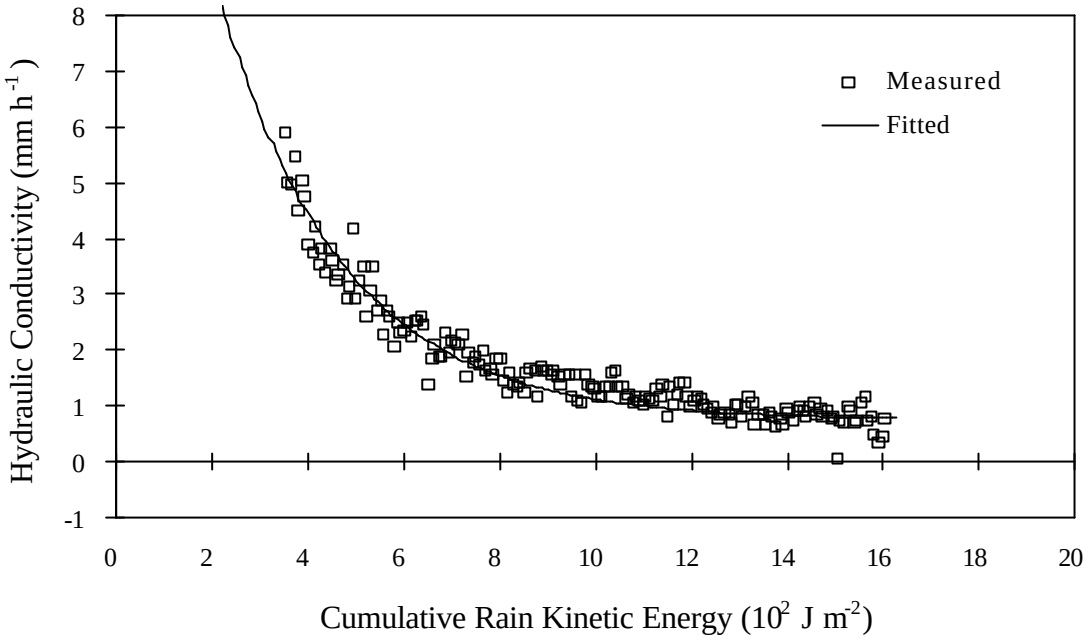
Appendix C

SURFACE HYDRAULIC CONDUCTIVITY UNDER SIMULATED RAINFALL

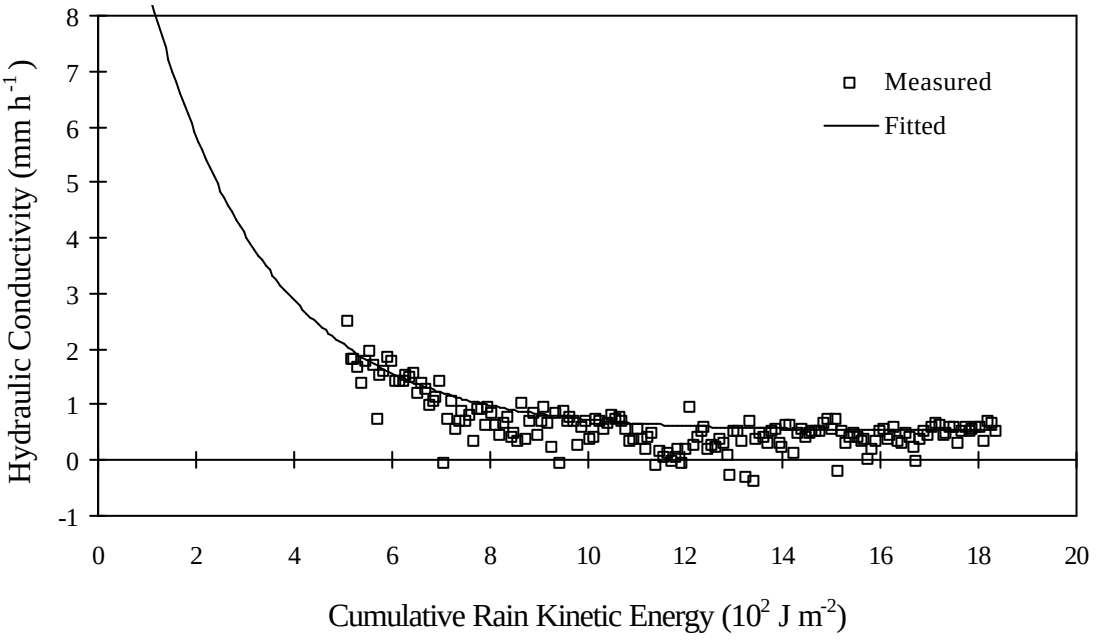
This appendix presents graphs of surface hydraulic conductivity as a function of time for all R series rainfall simulations that resulted in runoff (referred to in section 4.5) as follows -

pp.	Run	Soil	Tillage Treatment	Rainfall Energy	Rainfall Intensity ($mm\ h^{-1}$)	Wetting Pre-treatment
C2	R14, R15	Cowra	DD	High	33	Tension
C3	R16, R17	Cowra	DD	High	33	Rapid
C4	R18, R19	Cowra	DD	High	33	Dry
C5	R9, R7	Cowra	TT	High	33	Tension
C6	R2, R8	Cowra	TT	High	33	Rapid
C7	R6, R10	Cowra	TT	High	33	Dry
C8	R30, R31	Condobolin	RH	High	33	Tension
C9	R26, R27	Condobolin	RH	High	33	Rapid
C10	R28, R29	Condobolin	RH	High	33	Dry
C11	R33, R36	Condobolin	BC	High	33	Tension
C12	R34, R37	Condobolin	BC	High	33	Rapid
C13	R38, R39	Condobolin	BC	Low	33	Rapid
C14	R32, R35	Condobolin	BC	High	33	Dry
C15	R50, R52	Condobolin	RH	High	16.5	Tension
C16	R51, R53	Condobolin	RH	High	66	Tension

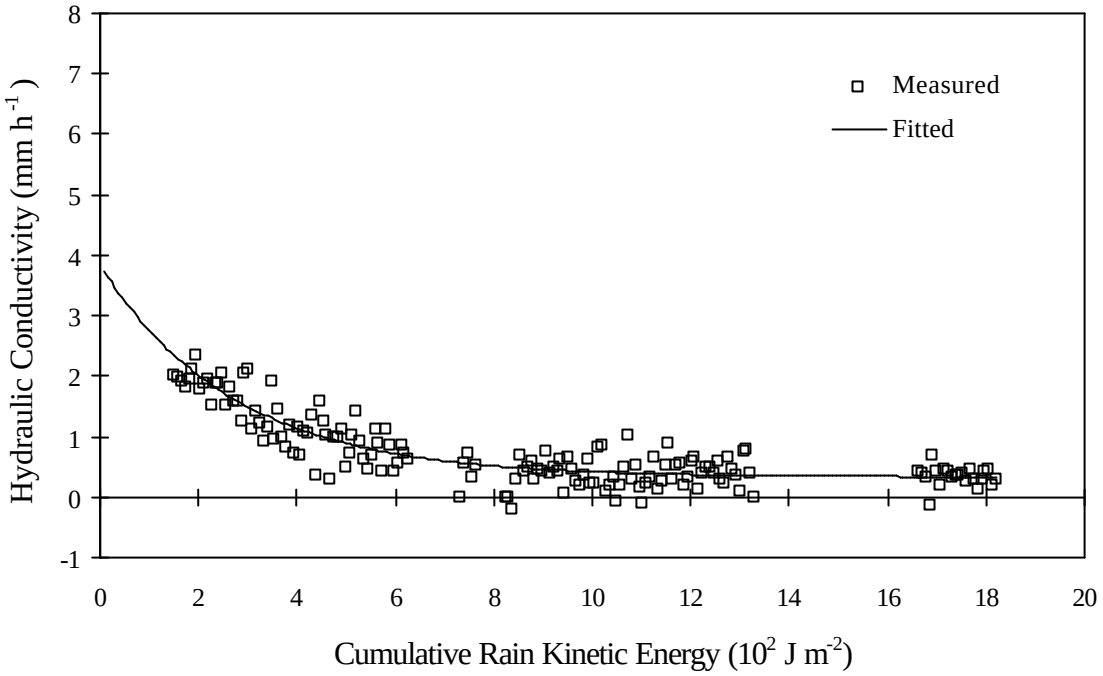
Surface hydraulic conductivity for R15 Cowra DD Tension pre-wet under 33 mm h^{-1} rainfall with high kinetic energy



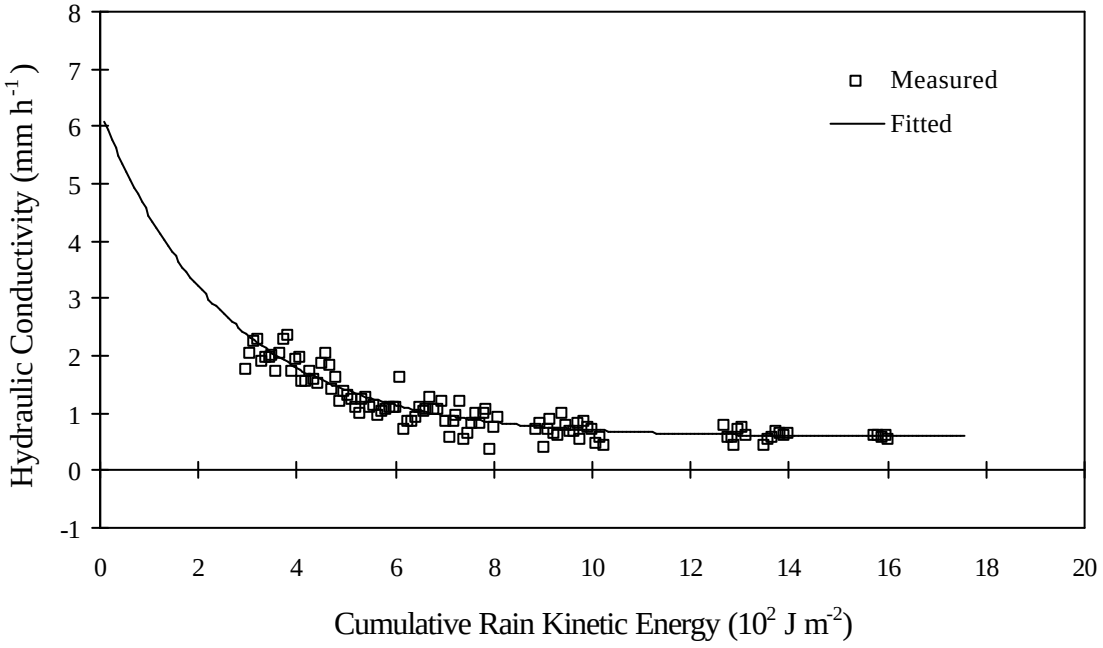
Surface hydraulic conductivity for R14 Cowra DD Tension pre-wet under 33 mm h^{-1} rainfall with high kinetic energy



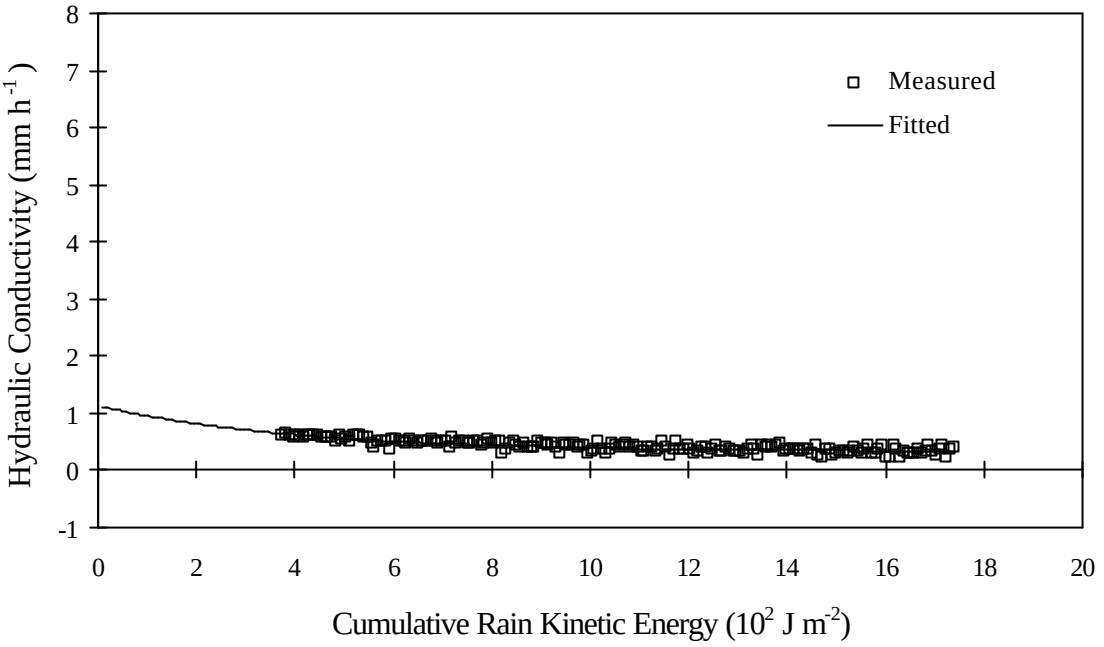
Surface hydraulic conductivity for R16 Cowra DD Rapid pre-wet under 33 mm h^{-1} rainfall with high kinetic energy



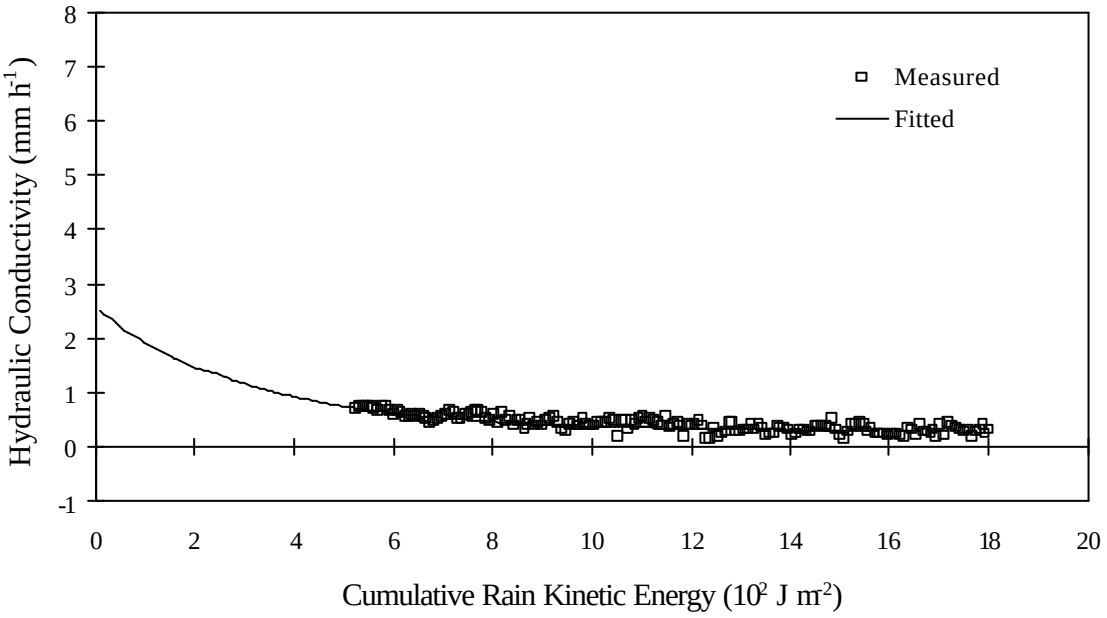
Surface hydraulic conductivity for R17 Cowra DD Rapid pre-wet under 33 mm h^{-1} rainfall with high kinetic energy



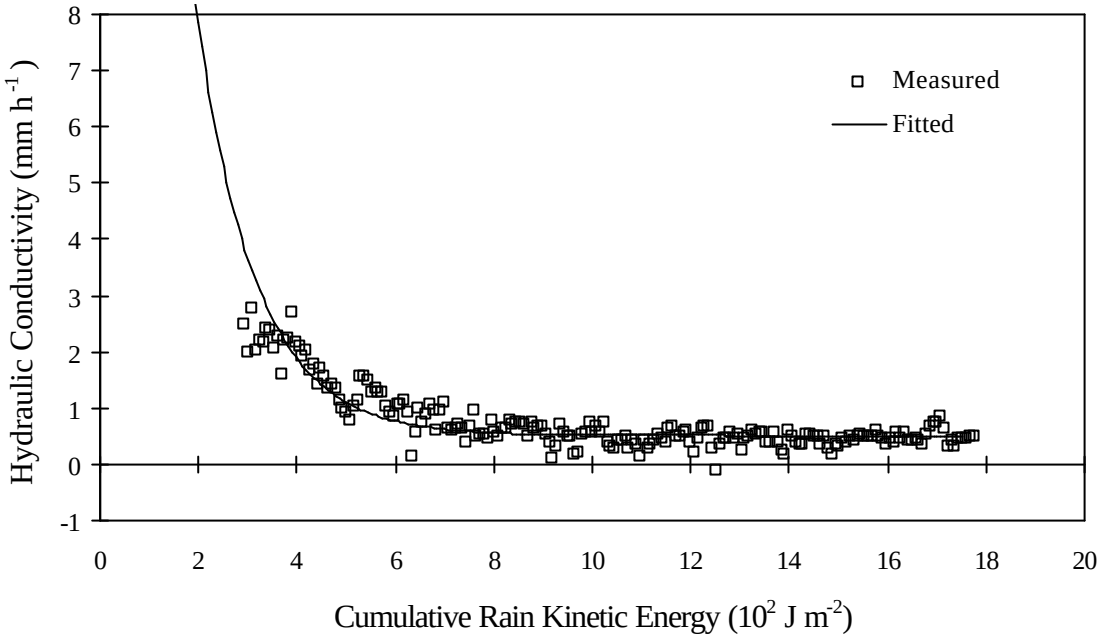
Surface hydraulic conductivity for R18 Cowra DD Dry under 33 mm h^{-1} rainfall with high kinetic energy



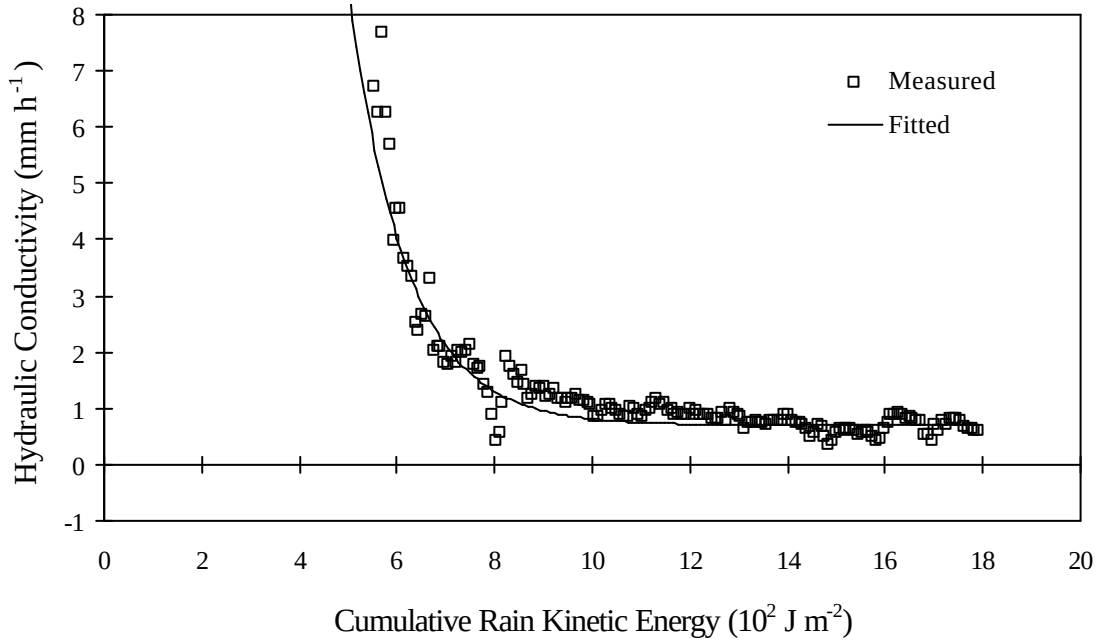
Surface hydraulic conductivity for R19 Cowra DD Dry under 33 mm h^{-1} rainfall with high kinetic energy



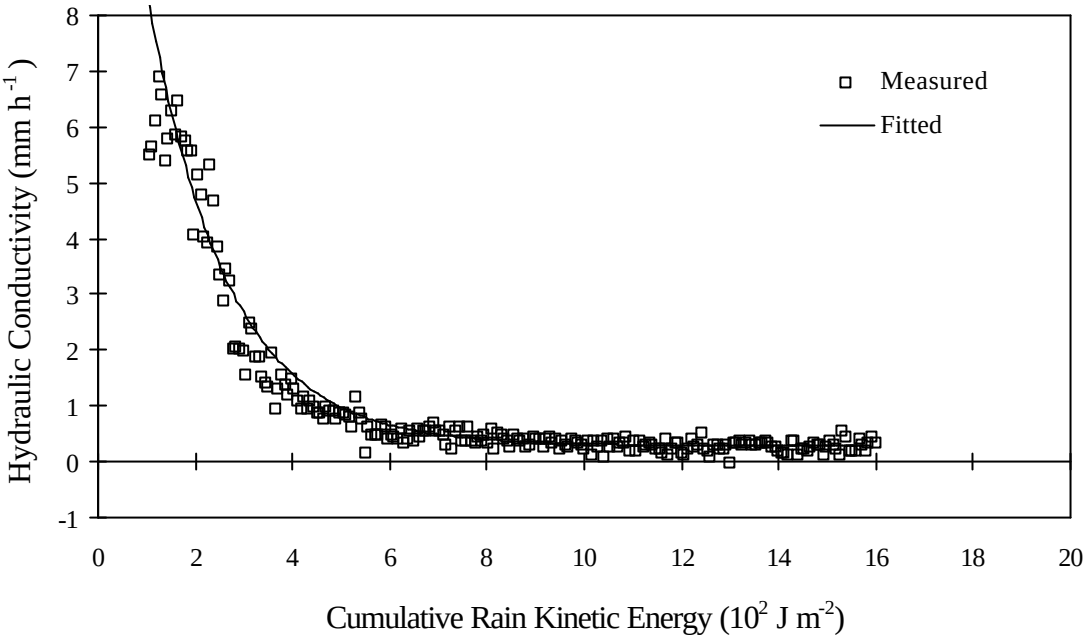
Surface hydraulic conductivity for R9 Cowra TT Tension pre-wet under 33 mm h^{-1} rainfall with high kinetic energy



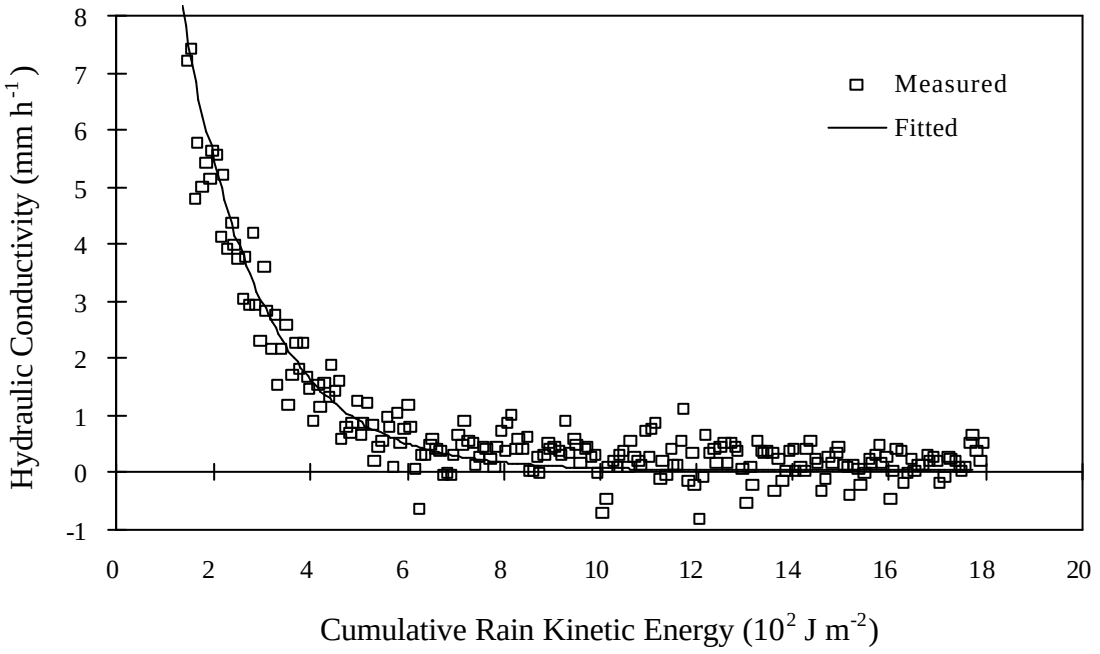
Surface hydraulic conductivity for R7 Cowra TT Tension pre-wet under 33 mm h^{-1} rainfall with high kinetic energy



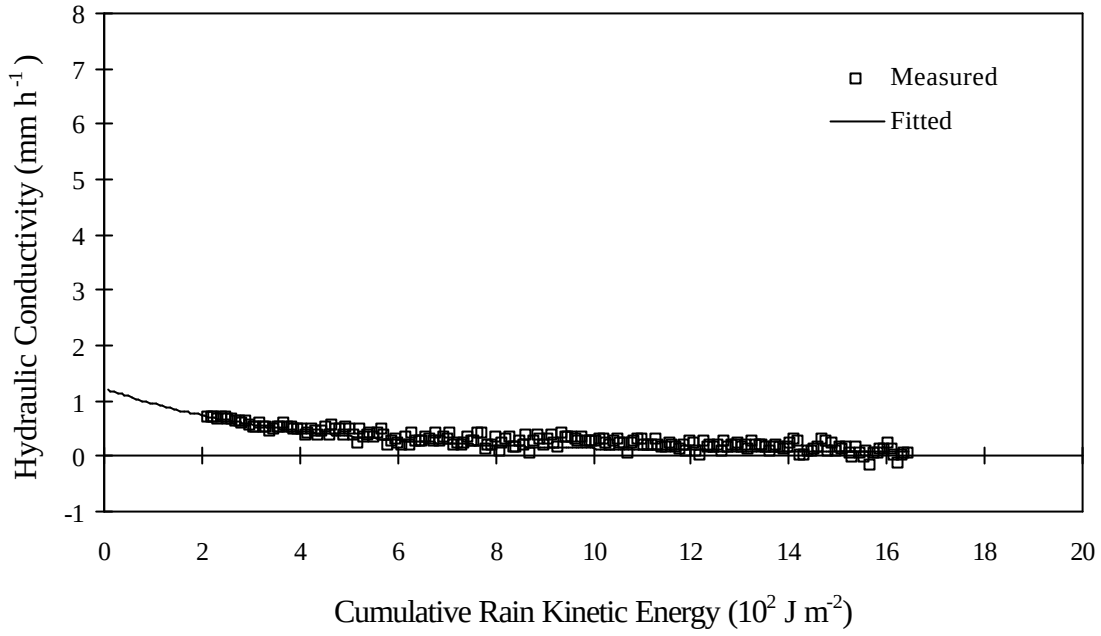
Surface hydraulic conductivity for R2 Cowra TT Rapid pre-wet under 33 mm h^{-1} rainfall with high kinetic energy



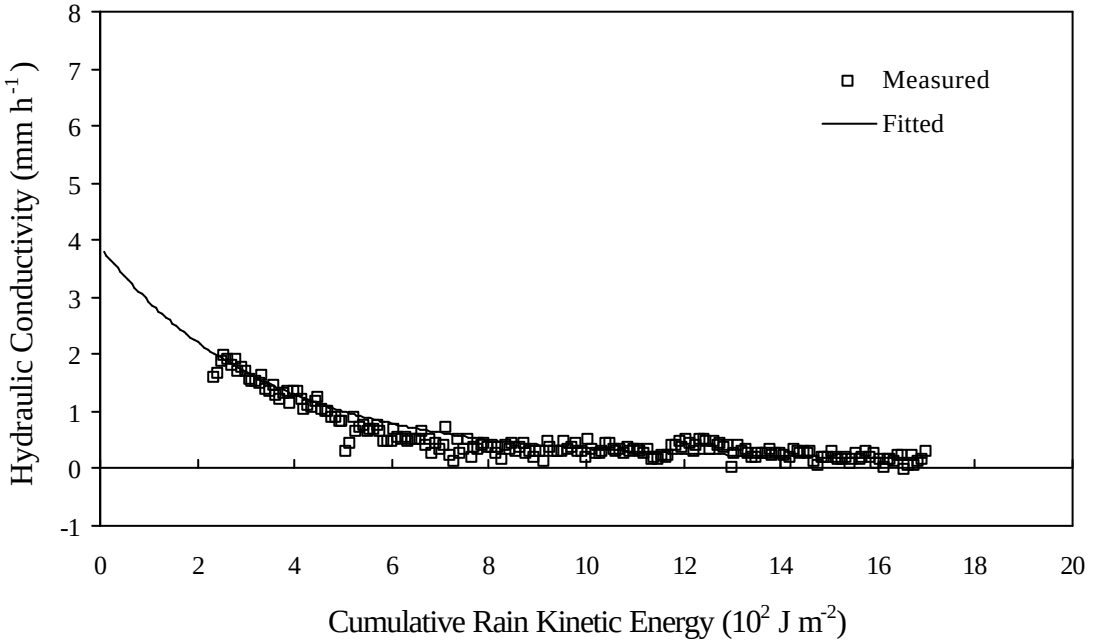
Surface hydraulic conductivity for R8 Cowra TT Rapid pre-wet under 33 mm h^{-1} rainfall with high kinetic energy



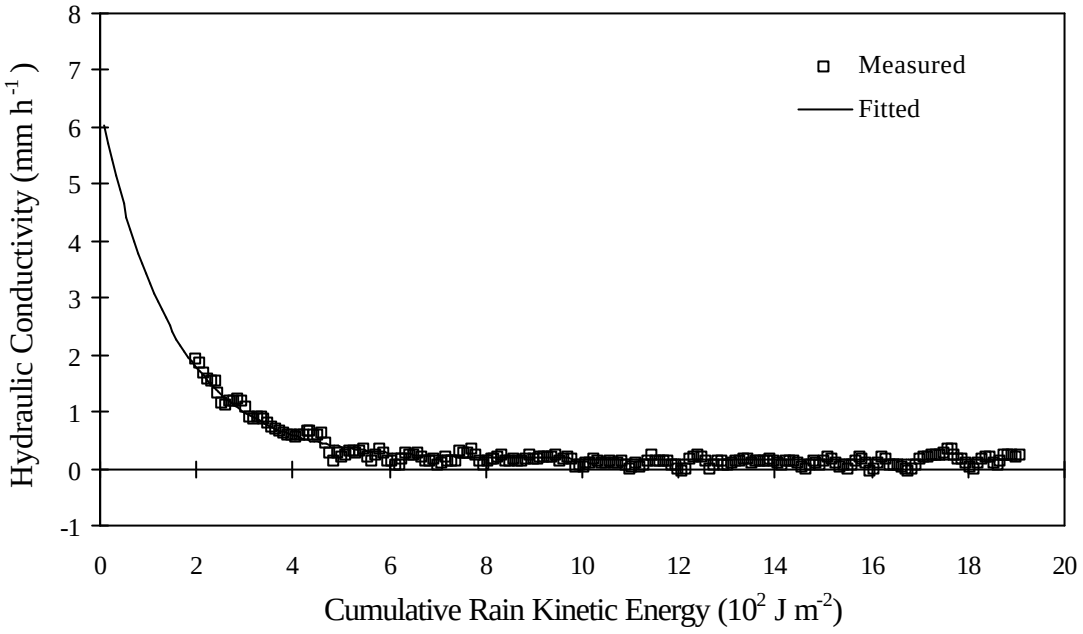
Surface hydraulic conductivity for R6 Cowra TT Dry under 33 mm h^{-1} rainfall with high kinetic energy



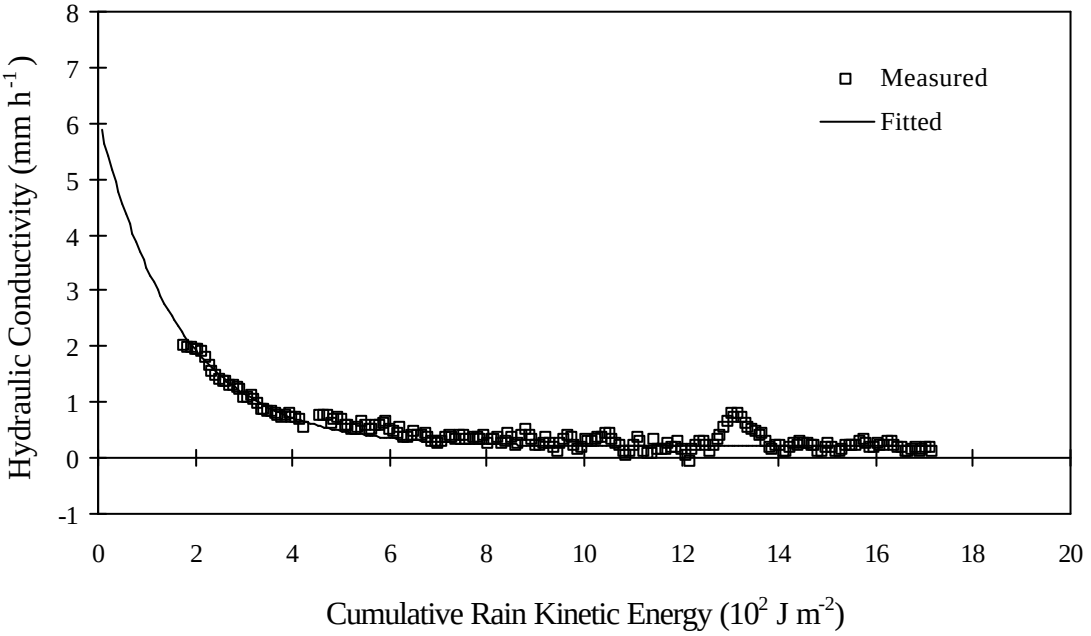
Surface hydraulic conductivity for R10 Cowra TT Dry under 33 mm h^{-1} rainfall with high kinetic energy



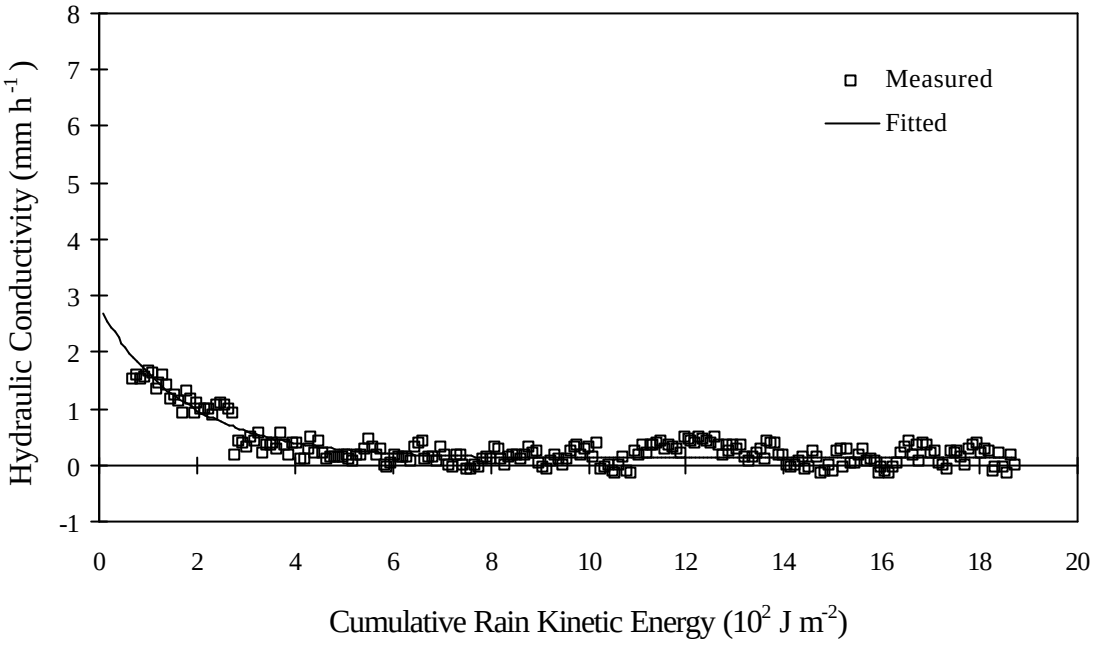
Surface hydraulic conductivity for R30 Condobolin RH Tension pre-wet under 33 mm h^{-1} rainfall with high kinetic energy



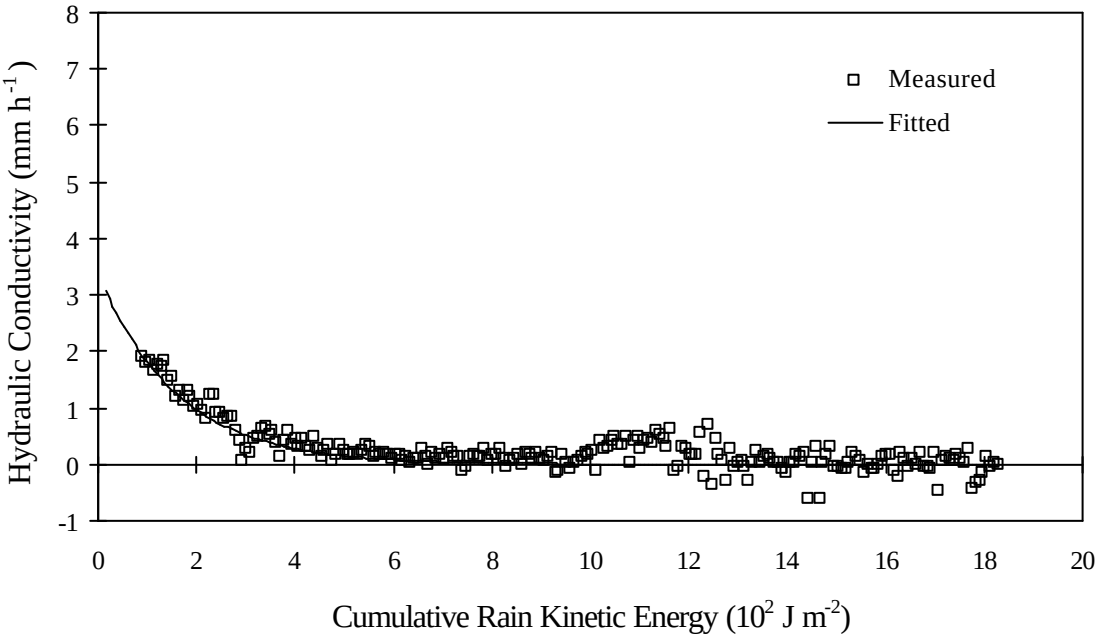
Surface hydraulic conductivity for R31 Condobolin RH Tension under 33 mm h^{-1} rainfall with high kinetic energy



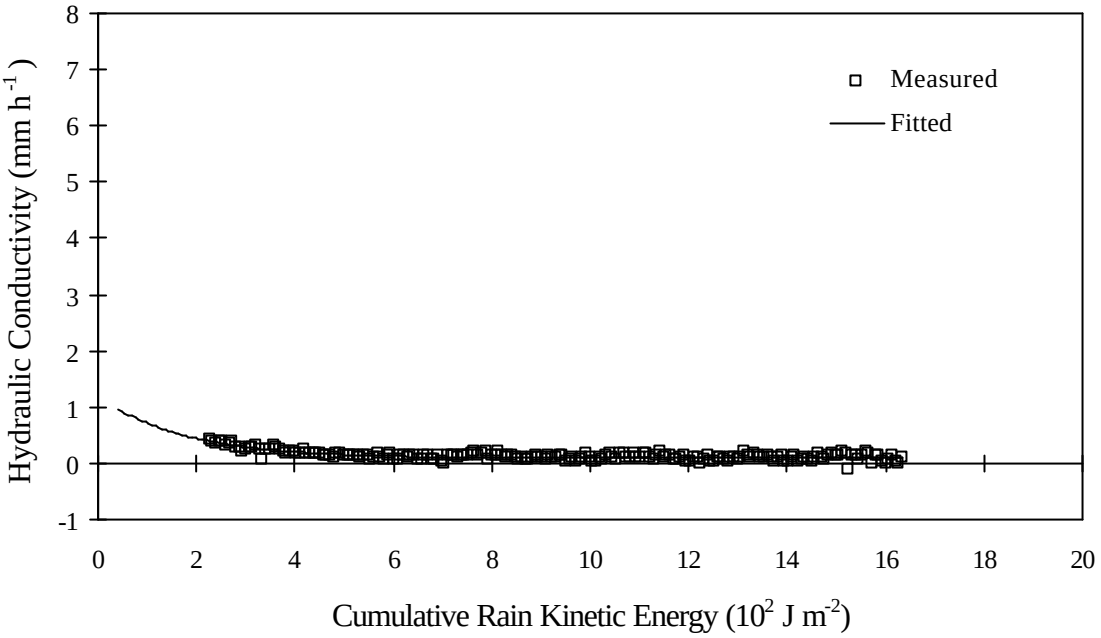
Surface hydraulic conductivity for R26 Condobolin RH Rapid pre-wet under 33 mm h^{-1} rainfall with high kinetic energy



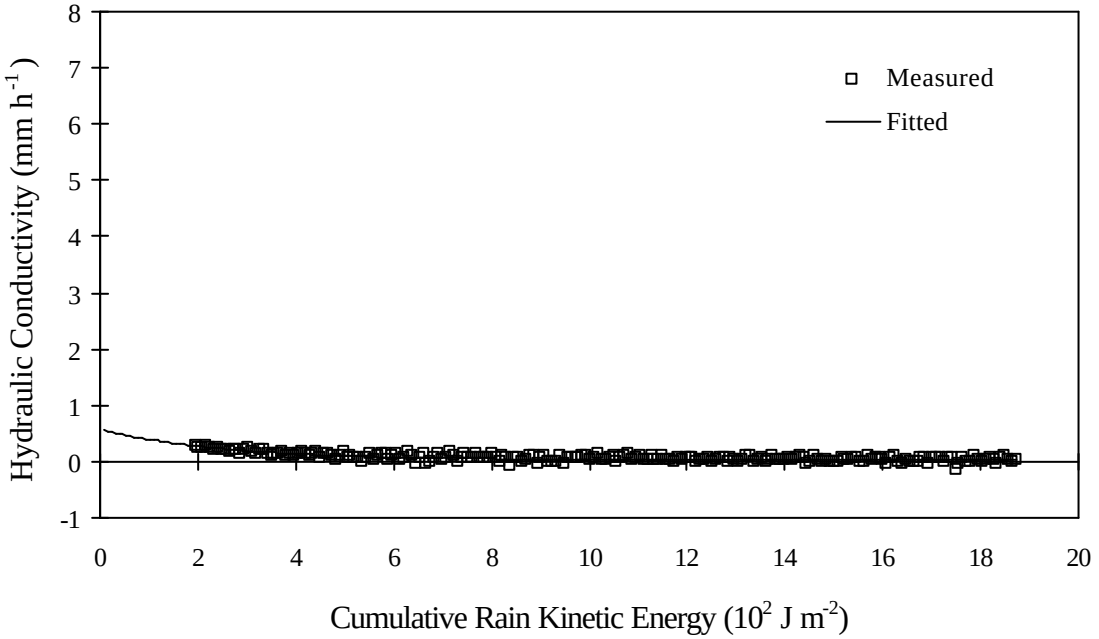
Surface hydraulic conductivity for R27 Condobolin RH Rapid pre-wet under 33 mm h^{-1} rainfall with high kinetic energy



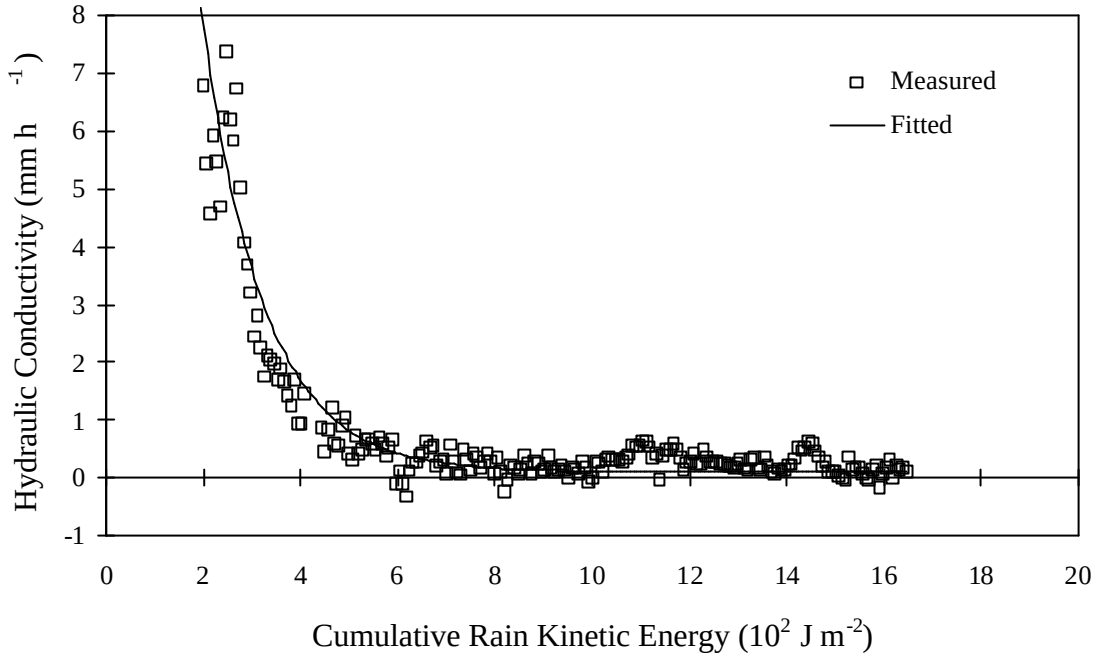
Surface hydraulic conductivity for R28 Condobolin RH Dry under 33 mm h^{-1} rainfall with high kinetic energy



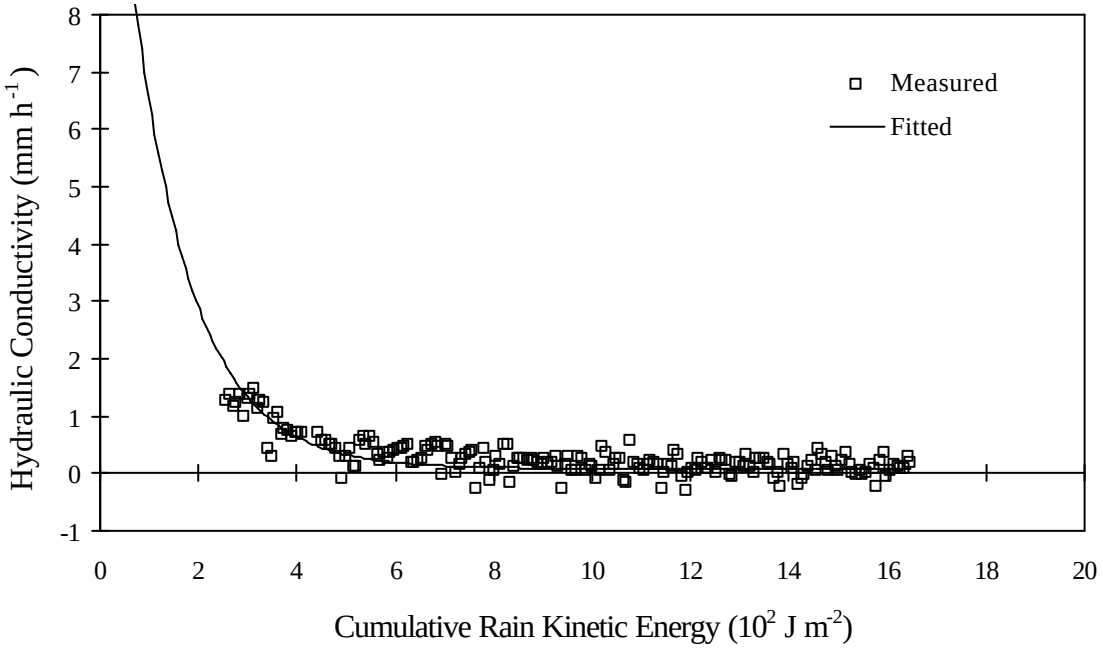
Surface hydraulic conductivity for R29 Condobolin RH Dry under 33 mm h^{-1} rainfall with high kinetic energy



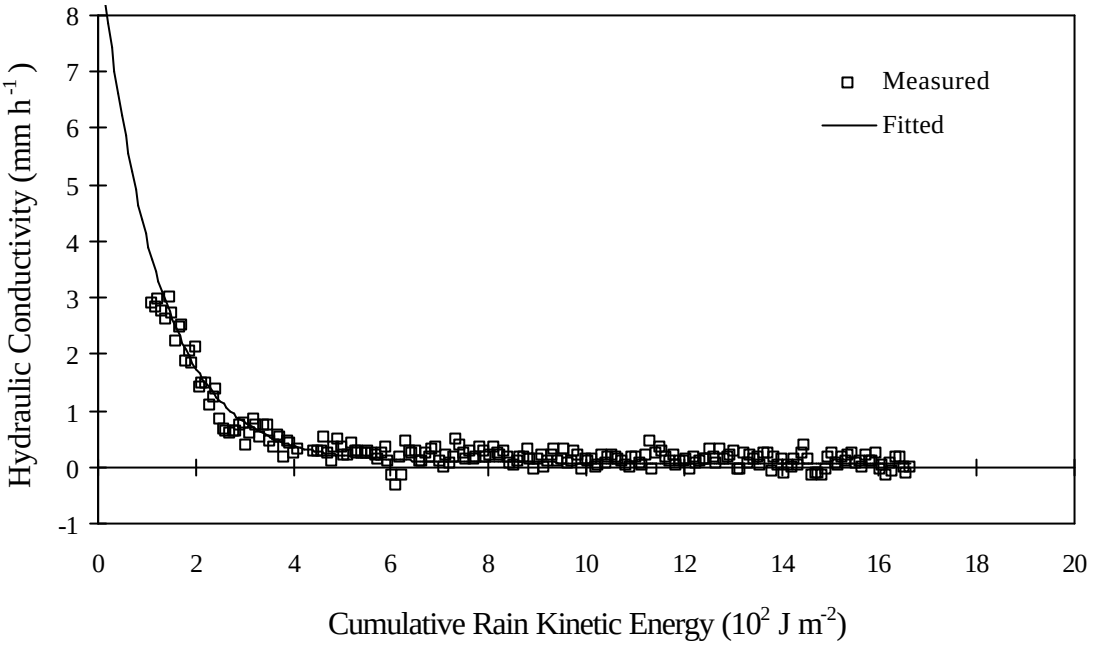
Surface hydraulic conductivity for R33 Condobolin BC Tension pre-wet under 33 mm h^{-1} rainfall with high kinetic energy



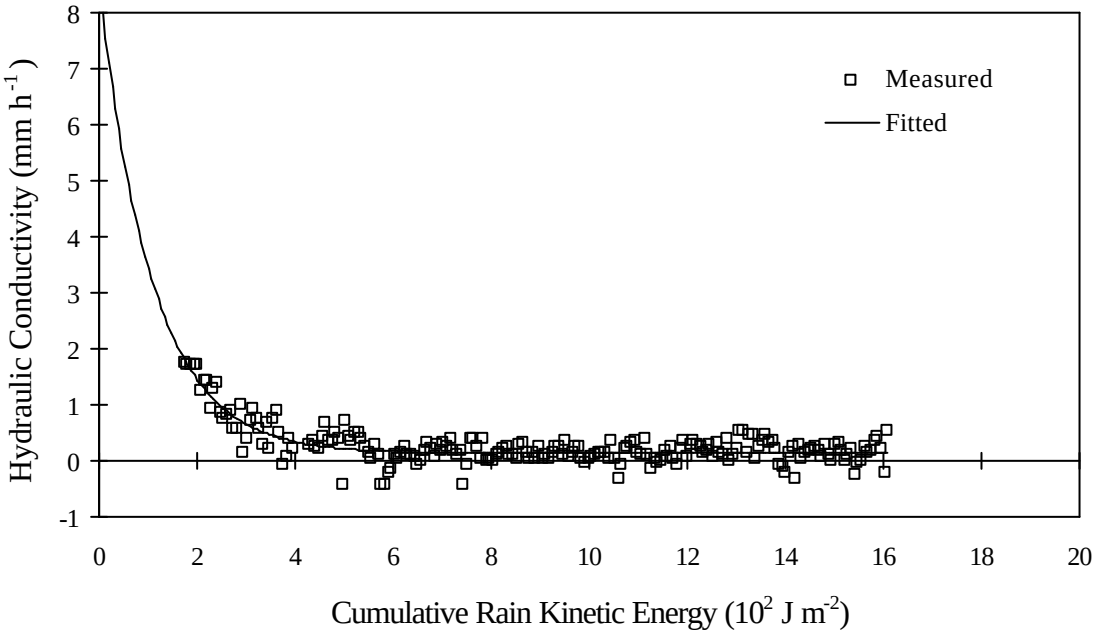
Surface hydraulic conductivity for R36 Condobolin BC Tension pre-wet under 33 mm h^{-1} rainfall with high kinetic energy



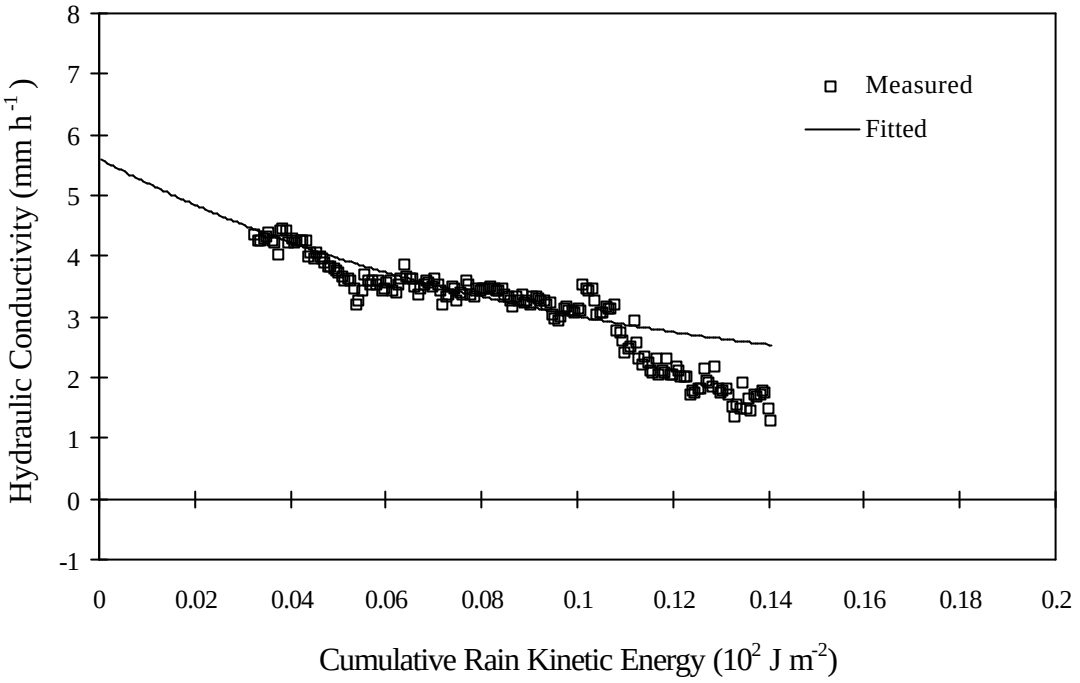
Surface hydraulic conductivity for R34 Condobolin BC Rapid pre-wet under 33 mm h^{-1} rainfall with high kinetic energy



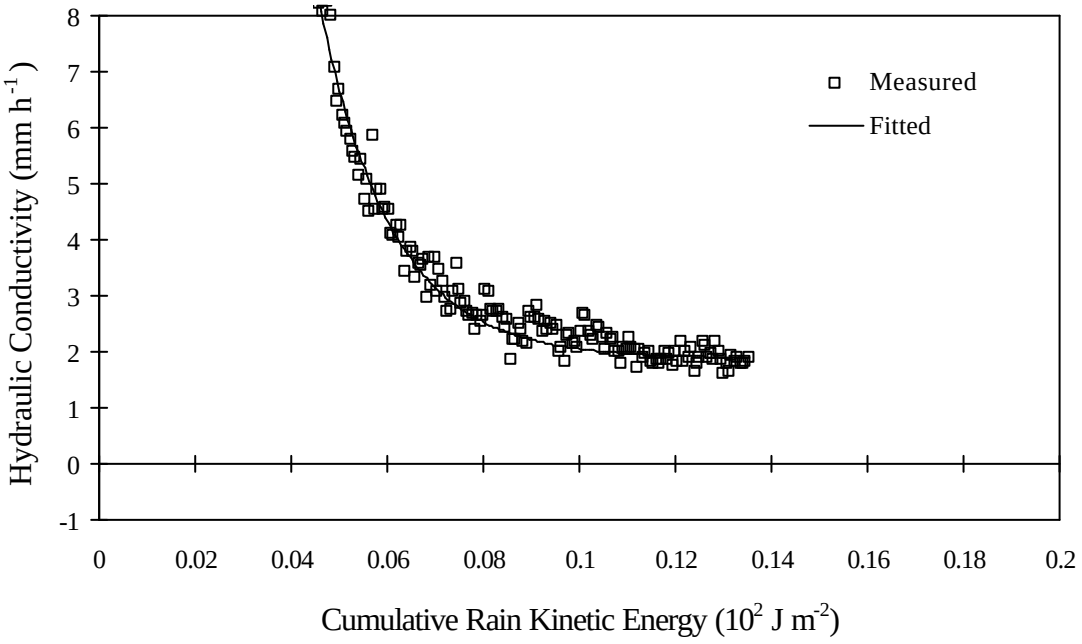
Surface hydraulic conductivity for R37 Condobolin BC Rapid pre-wet under 33 mm h^{-1} rainfall with high kinetic energy



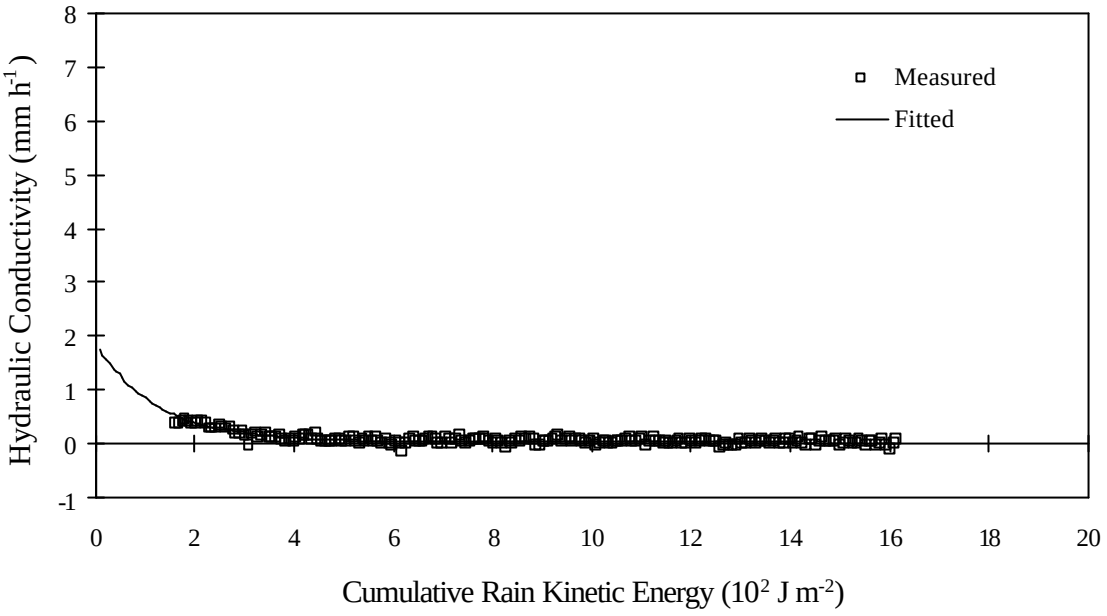
Surface hydraulic conductivity for R38 Condobolin BC Rapid pre-wet under 33 mm h^{-1} rainfall with low kinetic energy



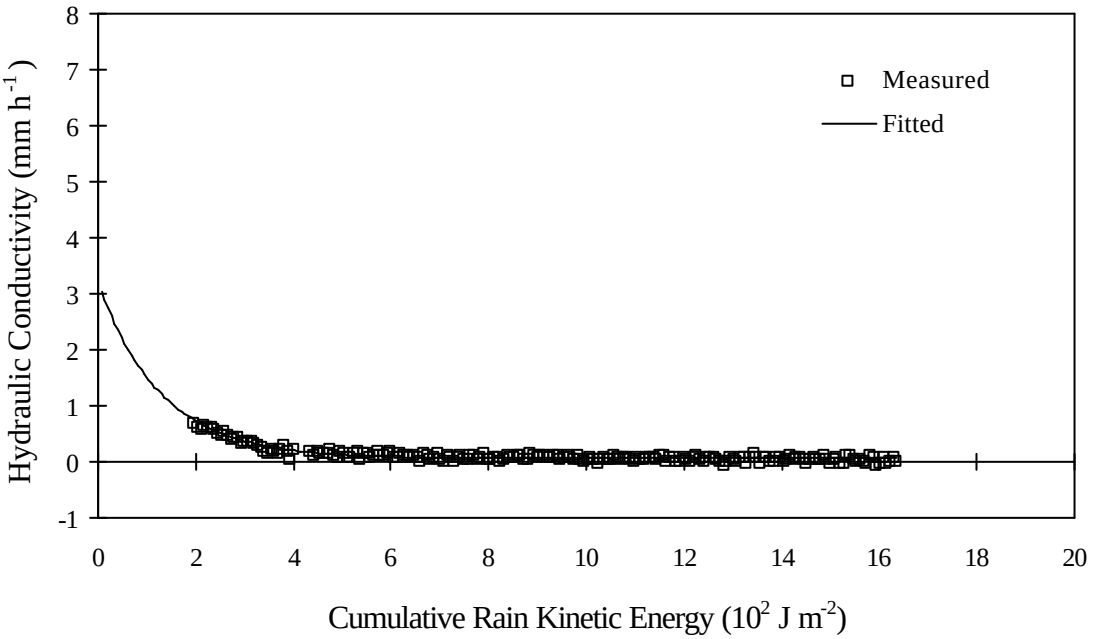
Surface hydraulic conductivity for R39 Condobolin BC Rapid pre-wet under 33 mm h^{-1} rainfall with low kinetic energy



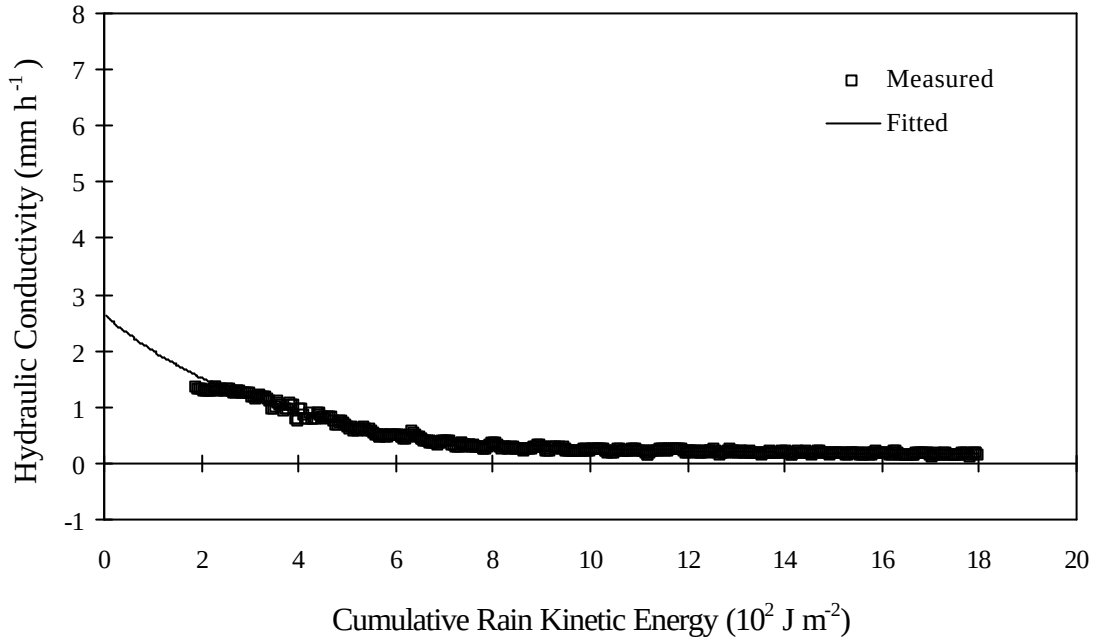
Surface hydraulic conductivity for R32 Condobolin BC Dry under 33 mm h^{-1} rainfall with high kinetic energy



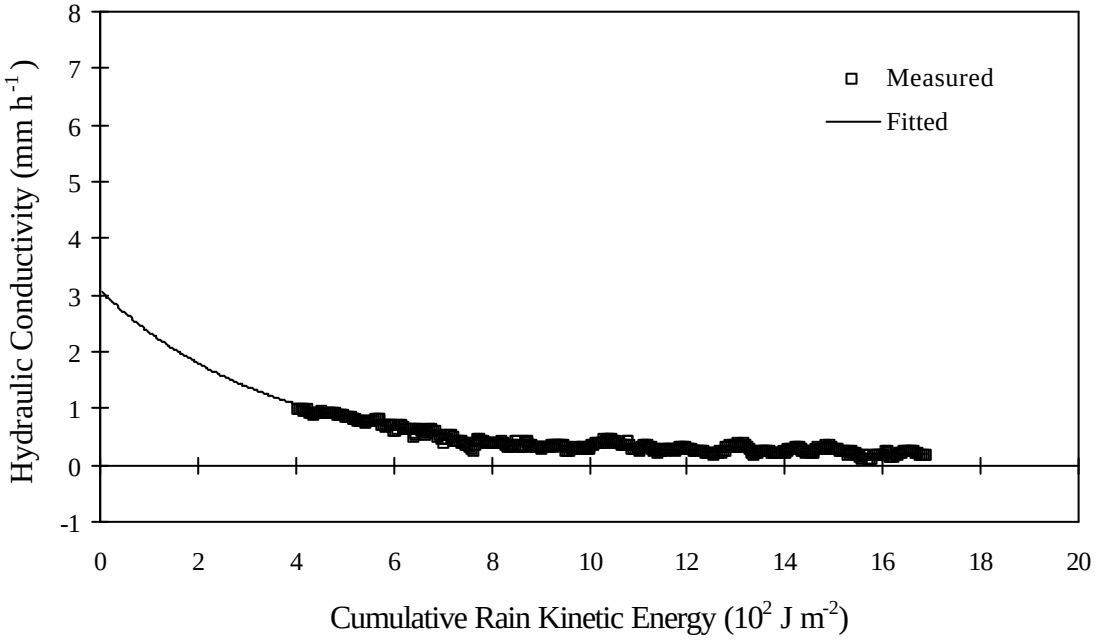
Surface hydraulic conductivity for R35 Condobolin BC Dry under 33 mm h^{-1} rainfall with high kinetic energy



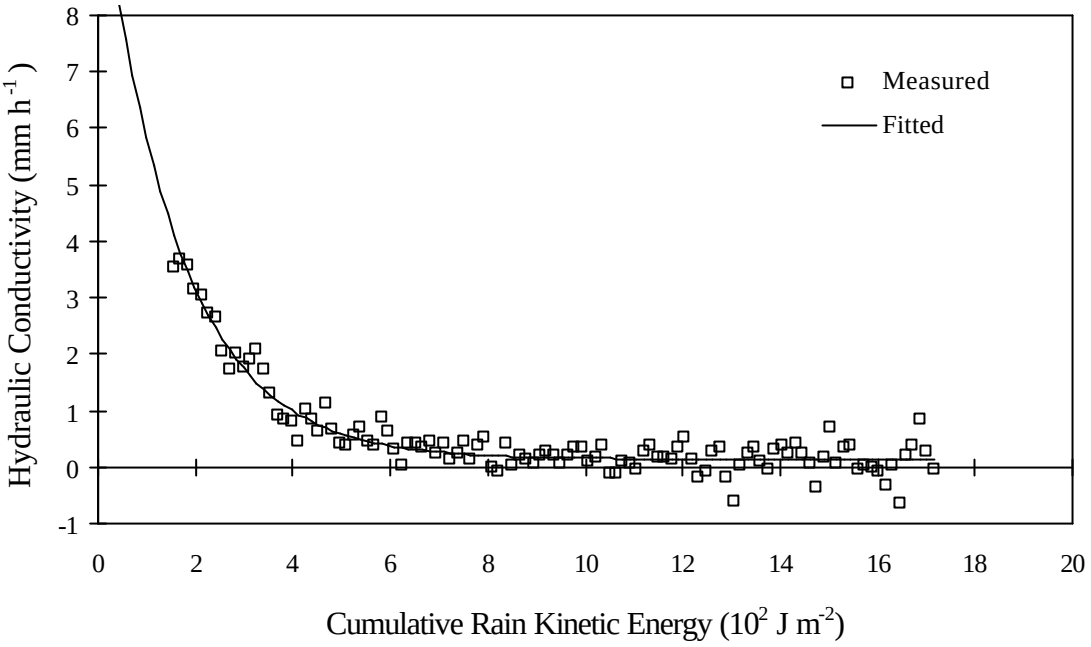
Surface hydraulic conductivity for R50 Condobolin RH Tension pre-wet under 16.5 mm h^{-1} rainfall with high kinetic energy



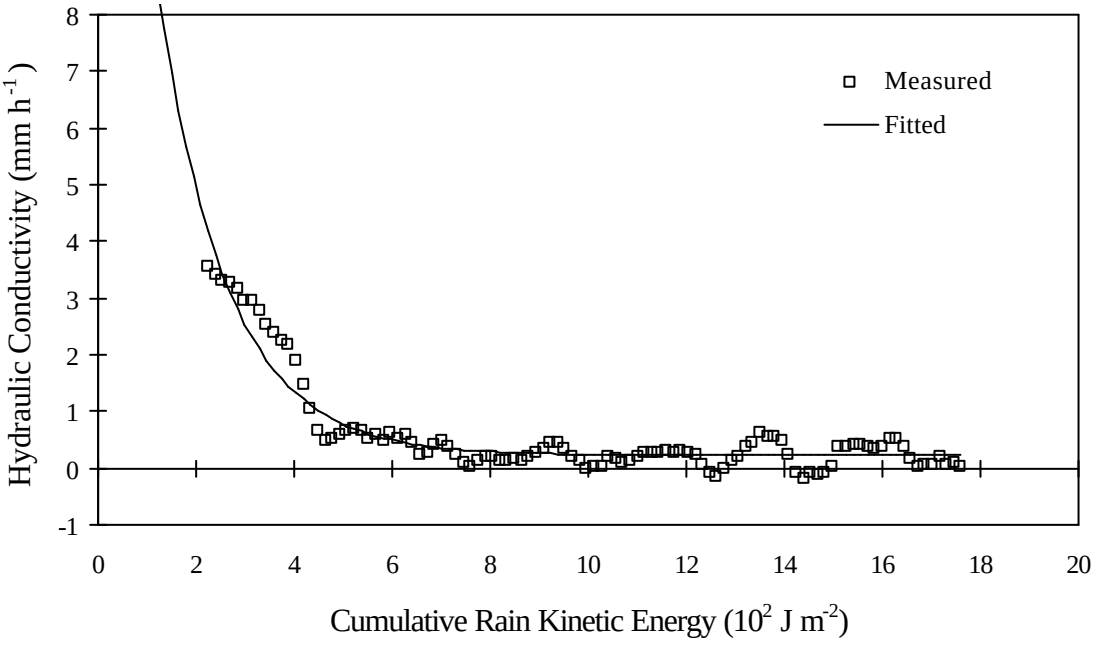
Surface hydraulic conductivity for R52 Condobolin RH Tension pre-wet under 16.5 mm h^{-1} rainfall with high kinetic energy



Surface hydraulic conductivity for R51 Condobolin RH Tension pre-wet under 66 mm h^{-1} rainfall with high kinetic energy



Surface hydraulic conductivity for R53 Condobolin RH Tension pre-wet under 66 mm h^{-1} rainfall with high kinetic energy



Appendix D

OUTPUT FROM SIMULATIONS DEMONSTRATING POSSIBLE EFFECTS OF SUB-SEAL DE-SATURATION ON MEASURED HYDRAULIC CONDUCTIVITY

This appendix presents information on the SWIM simulations used in section 4.6.7 to illustrate the potential effects of sub-seal desaturation on measured hydraulic conductivity. Section D.1 presents input parameters for each of the SWIM simulations S1 to S6. Section D.2 presents predicted water potential profiles, steady flow rates and volumetric soil water content profiles for each of the SWIÍ simulations. Section D.3 presents an annotated example of the SWIM v1.02 input files for simulation S1.

D.1 Input parameters for simulations S1 to S6

The following SWIM input parameters were common to all simulations -

Duration of simulation = 4 h
Water increment determining simulation integration step = 0.01 cm
Vegetation types = 0
Evaporation = 0 mm h^{-1}
Precipitation = 20 mm h^{-1}
Initial surface storage (I) = 5 mm (Surface storage is effectively depressional storage Final surface storage (M) = 5 mm as runoff only occurs when surface storage is full)
Precipitation constant (P) = 100 (rainfall required for 63% reduction in surface storage)
Runoff rate factor (R) = 100 (where runoff = R x (surface water - surface storage)^{P})
Runoff rate power (P) = 1
Initial surface conductance = 20 h^{-1}
Final surface conductance = 20 h^{-1}
Precipitation constant (P) = 100 (rainfall required for 63% reduction in surface conductance)
Sealed layer - K_{sat} = 0.2 mm h^{-1}, θ_s = 0.2, Campbell b = 4.81, initial potential = 0 kPa
Unsealed soil - K_{sat} = 20 mm h^{-1}, θ_s = 0.3, Campbell b = 4.81, initial potential = 0 kPa

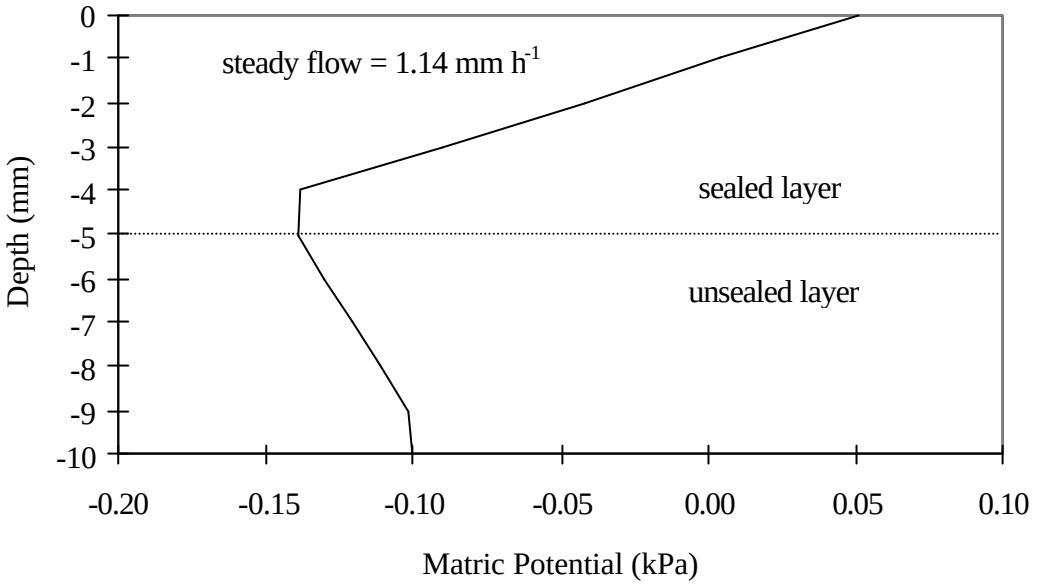
Lower boundary condition = 1 (specifies constant potential at the lower boundary)
Cosine of angle between depth and gravity = 1

Lower boundary potential and seal air entry potential were varied between simulations as follows -

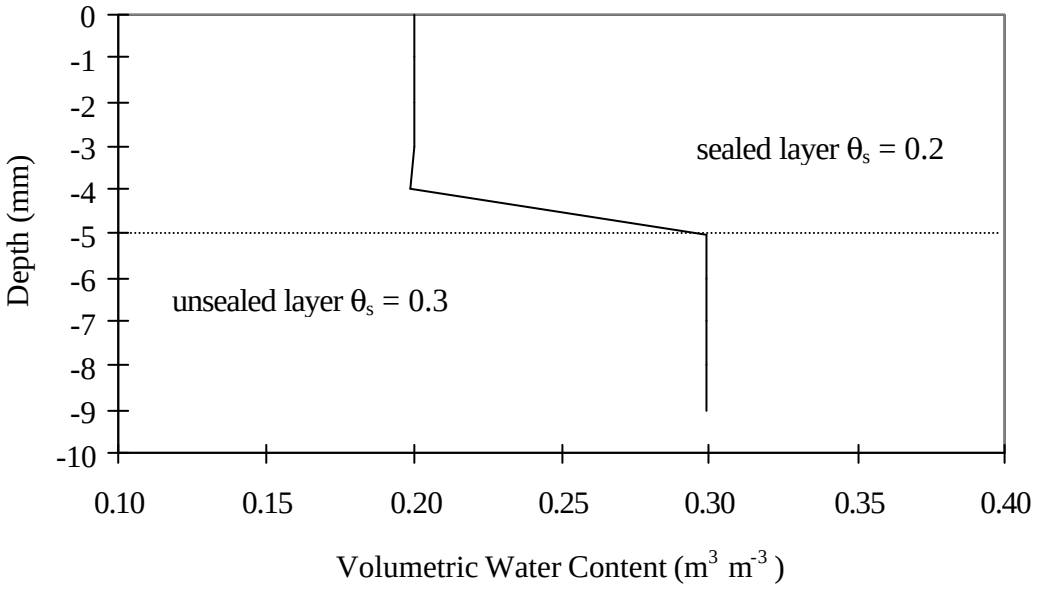
Simulation	Lower boundary potential (kPa)	Seal Air entry potential (kPa)
S1	-0.10	-0.48
S2	-0.50	-0.48
S3	-1.00	-0.48
S4	-0.10	-2.08
S5	-0.50	-2.08
S6	-1.00	-2.08

D.2 Water potential profiles, steady flow rates and volumetric soil water content profiles for each SWIM simulation at 4 hours.

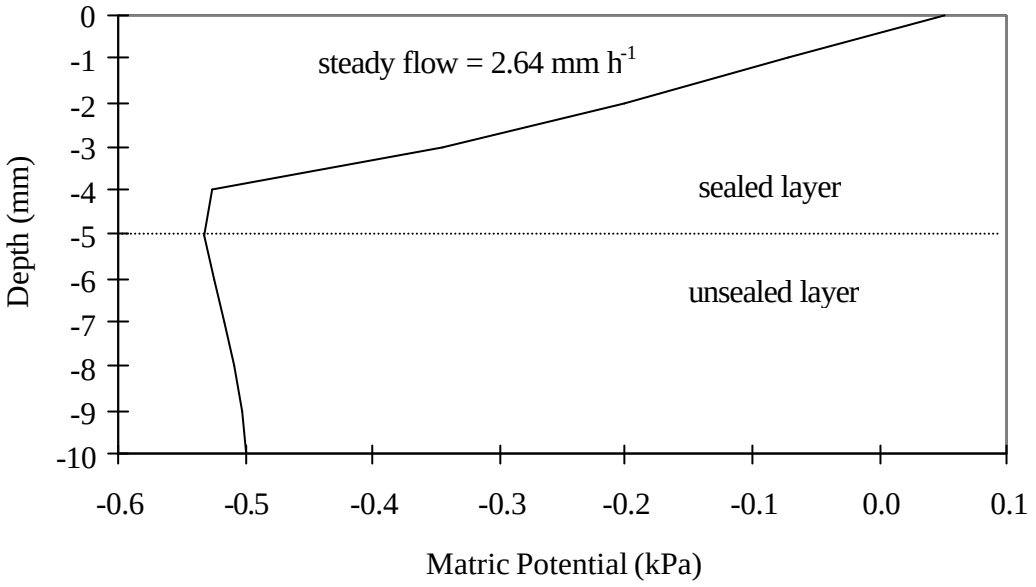
The soil matric potential profile and steady flow rate for SWIM simulation S1 at 4 h.



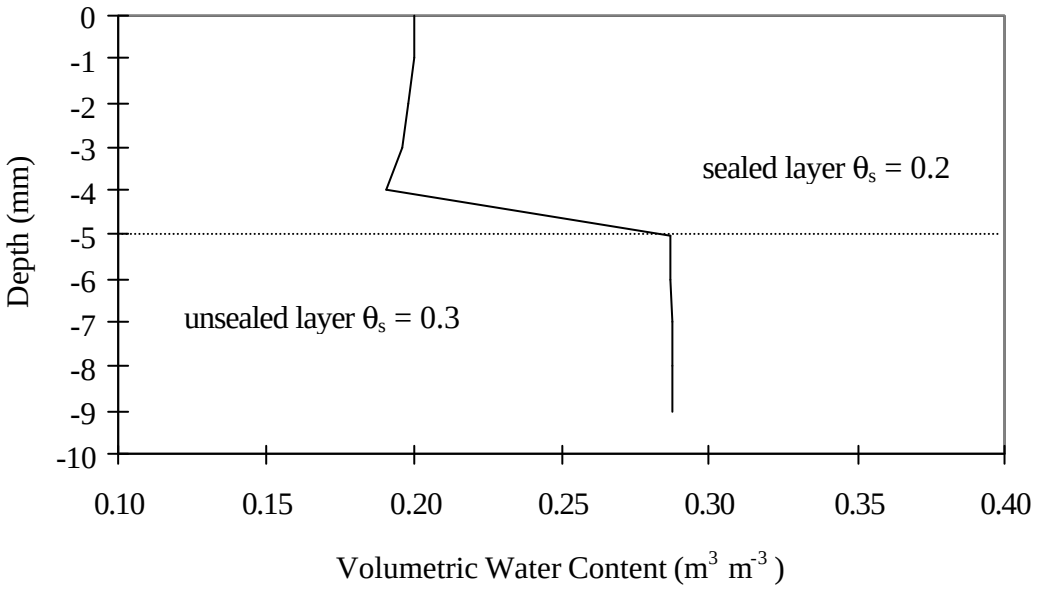
The volumetric soil water content profile and steady flow rate for SWIM simulation S1 at 4 h.



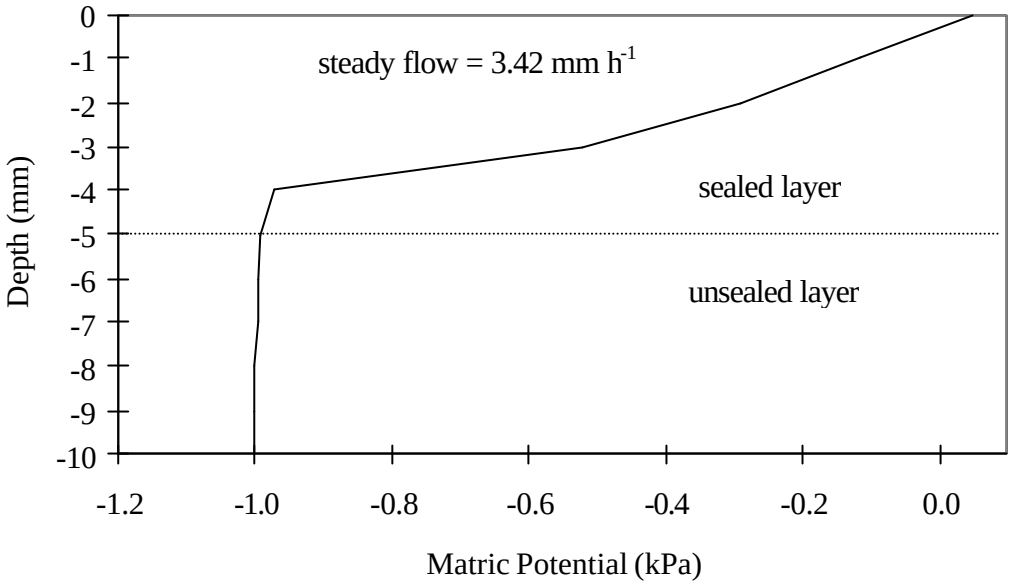
The soil matric potential profile and steady flow rate for SWIM simulation S2 at 4 h.



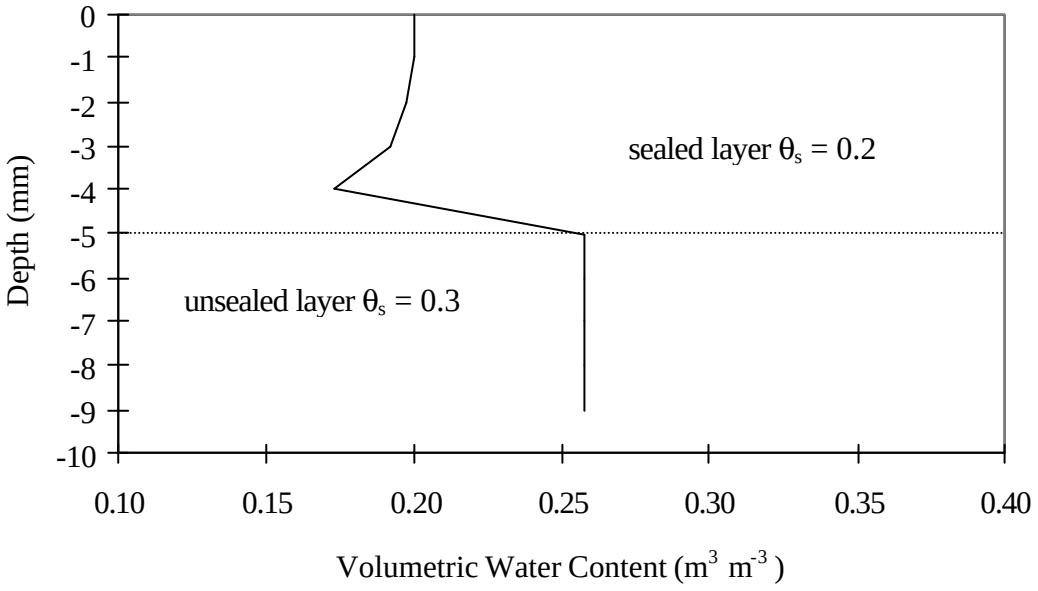
The volumetric soil water content profile and steady flow rate for SWIM simulation S2 at 4 h.



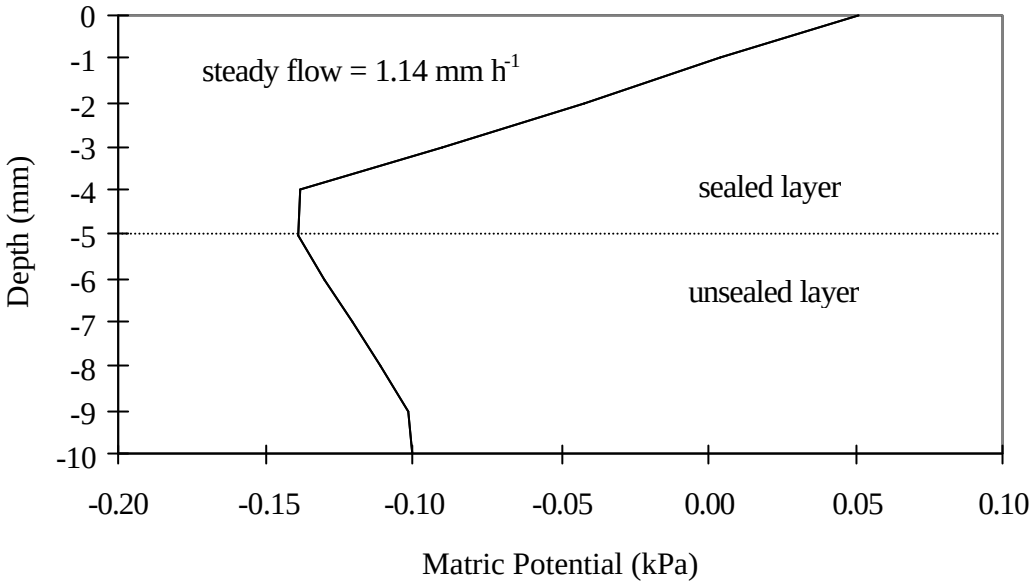
The soil matric potential profile and steady flow rate for SWIM simulation S3 at 4 h.



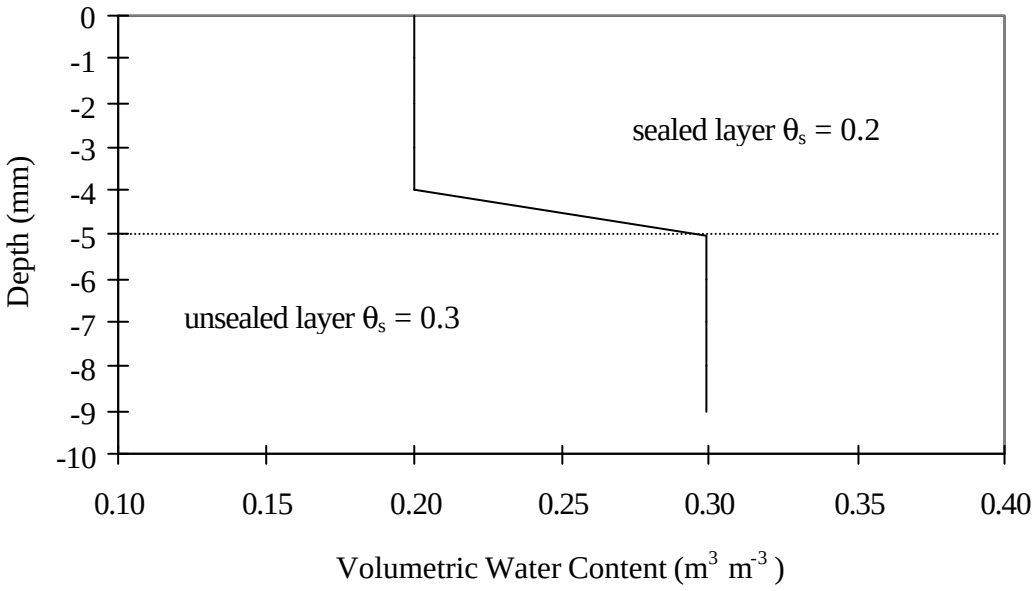
The volumetric soil water content profile and steady flow rate for SWIM simulation S3 at 4 h.



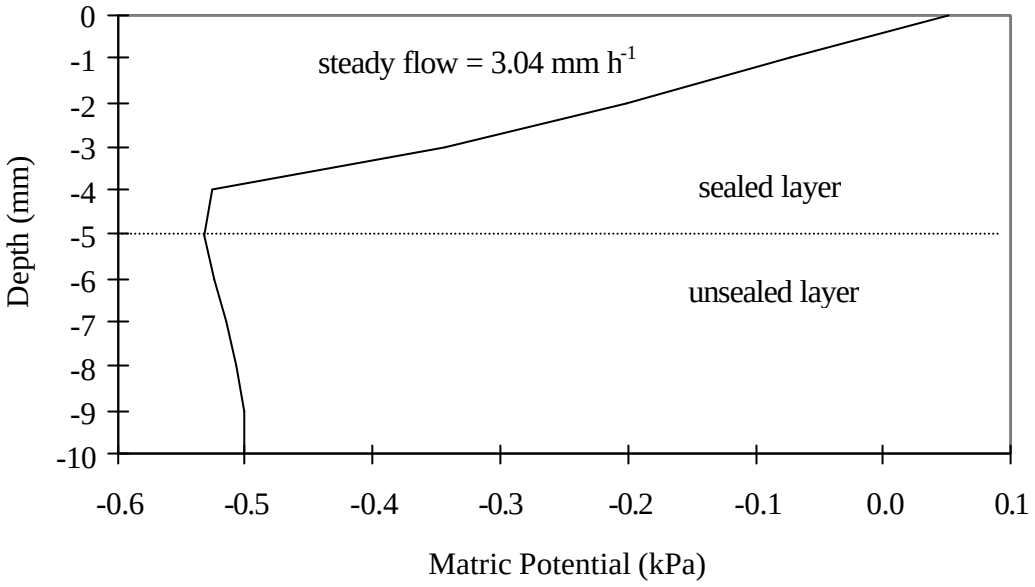
The soil matric potential profile and steady flow rate for SWIM simulation S4 at 4 h.



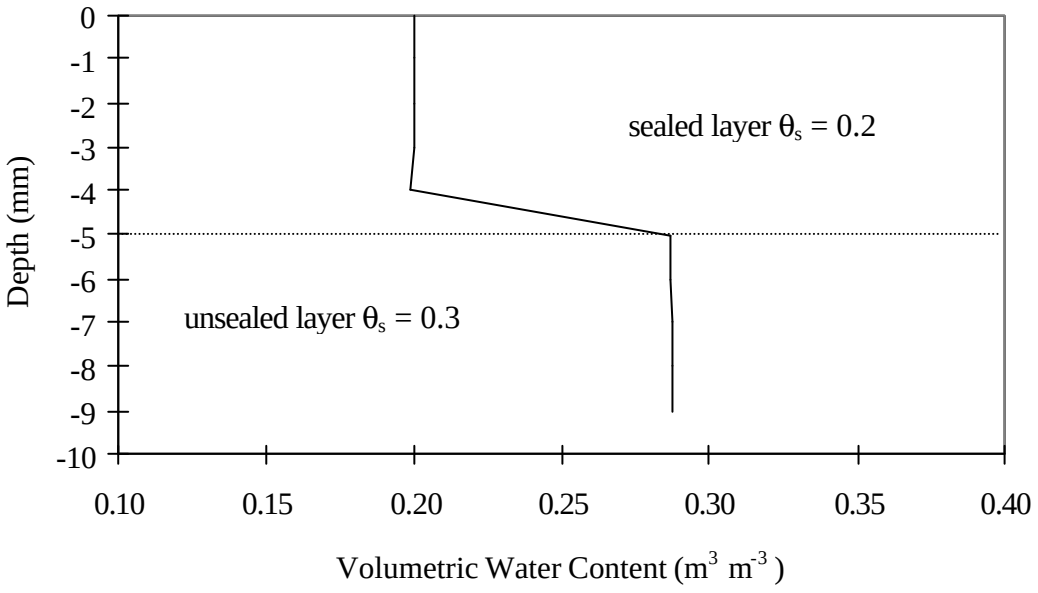
The volumetric soil water content profile and steady flow rate for SWIM simulation S4 at 4 h.



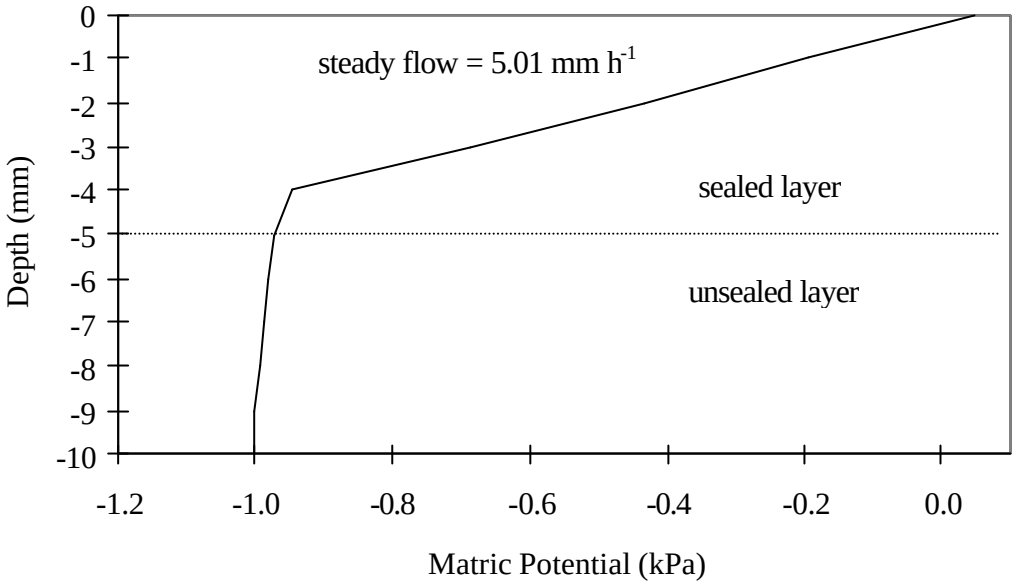
The soil matric potential profile and steady flow rate for SWIM simulation S5 at 4 h.



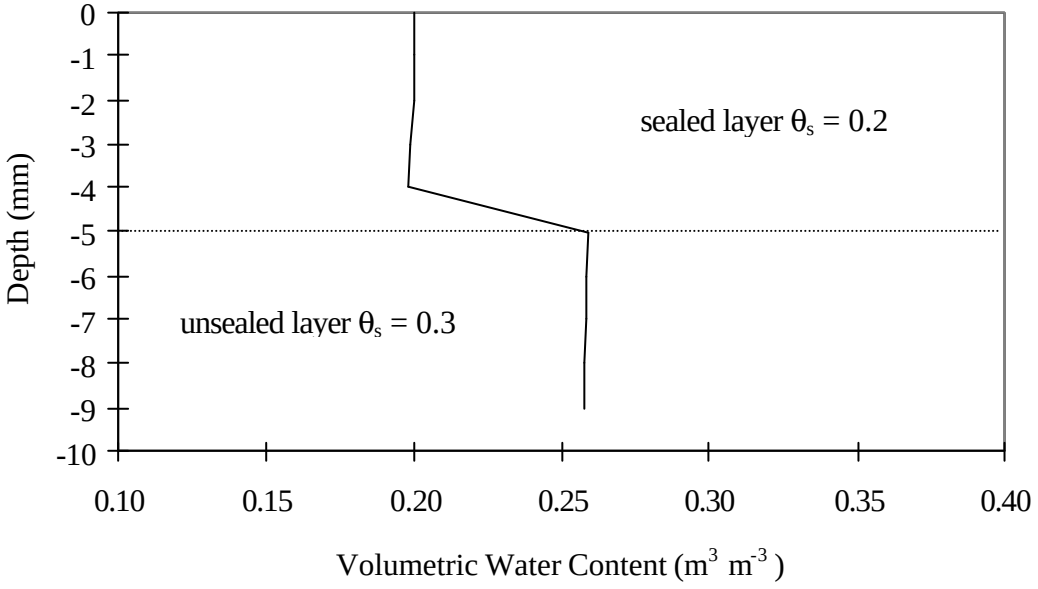
The volumetric soil water content profile and steady flow rate for SWIM simulation S5 at 4 h.



The soil matric potential profile and steady flow rate for SWIM simulation S6 at 4 h.



The volumetric soil water content profile and steady flow rate for SWIM simulation S6 at 4 h.



D.3 Annotated input file for SWIM simulation S1 using SWIM v1.02 (Ross, 1990)

```
0 4 .2 .01
```
(start and finish time, print interval, water increment)

```
0
```
(no vegetation)

```
11
```
(11 soil depths)

```
0     0   0.2   -4.81    4.81 .02 2.62370   0   0
0.1   0   0.2   -4.81    4.81 .02 2.62370   0   0
0.2   0   0.2   -4.81    4.81 .02  2.62370   0   0
0.3   0   0.2   -4.81    4.81 .02  2.62370   0   0
0.4   0   0.2   -4.81    4.81 .02  2.62370   0   0
0.5   0   0.3   -4.81    4.81 2  2.62370   0   0
0.6   0   0.3   -4.81    4.81 2  2.62370   0   0
0.7   0   0.3   -4.81    4.81 2  2.62370   0   0
0.8   0   0.3   -4.81    4.81 2  2.62370   0   0
0.9   0   0.3   -4.81    4.81 2  2.62370   0   0
1.0 -1   0.5   -100   5  20  2.6       0   0
```
(depth, initial matric potential, saturated volumetric water content, air entry potential, Campbell b, K_{sat},, n and macroporosity parameters for each soil depth)

```
1
```
(constant potential at lower boundary)

```
1
```
(depth parallel to gravity)

```
20        20        100       0.18
```
(constant and very high surface conductance of 20 h^{-1})

```
.5        .5        100       100       1
```
(constant surface storage of 5 mm with rapid runoff of water in excess of this storage)

```
0.5
```
(initial surface water depth of 5 mm)

2
(2 cumulative precipitation pairs specifying time in h and precipitation in cm)

0 0.00
10 20
(cumulative precipitation pairs specifying excess rainfall)

2
(2 cumulative evaporation pairs specifying time in h and evaporation in cm)

0 0
4 0
(cumulative evaporation pairs specifying no evaporation)

Appendix E

OUTPUT FROM SIMULATIONS DEMONSTRATING POSSIBLE EFFECTS OF TILLAGE TREATMENT ON THE SOIL WATER BALANCE AT COWRA

This appendix presents the SWIM simulations used in section 4.7.3. to demonstrate the potential effects of tillage treatments on the soil water balance at Cowra. Section E.1 presents the input parameters used for each of the SWIM simulations. Section E.2 summarises the predicted runoff for tillage treatment/surface storage combinations and section E.3 presents an annotated example of the SWIM v1.02 (Ross, 1990b) input files for these simulations.

E.1 Input parameters for simulations.

The rationale behind the selection of input parameters is presented in section 4.7.3. The following input parameters and conditions were common to all simulations -

Duration of simulation = 30 days
Water increment determining simulation integration step = 0.1 cm
Lower boundary condition = 0 (specifies gravitational drainage through lower boundary)
Vegetation types = 0
Runoff rate factor (R) = 100
Runoff rate power (P) = 1
(Runoff rate = R x (depth surface water - surface storage)^{P})Hence these parameter values specify almost immediate removal of surface water in excess of surface storage to simulate point runoff)
Initial surface water depth = 0 mm
Cosine of angle between depth and gravity = 1 (depth is measured parallel to gravity)

Eight soil depths with the following parameters

soil depth (mm)	θ_{sat}	air entry potential (kPa)	Campbell b	K_{sat}, (mm h^{-1})	n
0	0.342	-0.1	7.69	64.8	2.390
10	0.342	-0.1	7.69	64.8	2.390
50	0.342	-0.1	7.69	11.4	2.390
180	0.333	-0.187	20.24	13.2	2.148
300	0.333	-0.187	20.24	13.2	2.148
450	0.333	-0.187	20.24	13.2	2.148
600	0.333	-0.187	20.24	13.2	2.148
800	0.333	-0.187	20.24	13.2	2.148

The following surface sealing parameters differed between sealing scenarios -

Parameter	Sealing scenario		
	Cowra TT sealing	Cowra DD sealing	No sealing
initial conductance (h^{-1})	11.8	28	11.8
final conductance (h^{-1})	0.022	0.064	11.8
precipitation parameter	0.53	0.52	0.53
effectiveness parameter	0.184	0.184	0.184

The following parameters differed between simulations for each sealing scenario -

Initial and minimum surface storage = 0, 1, 2, 4, 6, 8, and 10 mm
(Surface storage is effectively depressional storage as runoff only occurs when surface storage is full)

The following inputs and parameters differed between years -

June rainfall and evaporation as measured
Antecedant soil water potential

E.2 Predicted runoff for June over the period 1949-1988 at Cowra under various surface sealing scenarios

Surface storage	Sealing scenario		
	Cowra TT sealing	Cowra DD sealing	No sealing
(mm)	runoff (mm)	runoff (mm)	runoff (mm)
0	6.0	2.9	0.6
1	4.0	1.9	0.5
2	3.1	1.4	0.4
4	1.9	0.9	0.3
6	1.2	0.7	0.2
8	0.9	0.6	0.1
10	0.7	0.5	0.0

E.3 Annotated example input file simulating Cowra DD during June 1984 using SWIM v1.02 (Ross, 1990b)

3648 4368 24 0.1
(start and finish time in h, print interval in h, water increment in cm)
0
(no vegetation)
8
(eight soil depths specified)

0	-0.779326E+06	0.342	-1	7.69	6.47753	2.390117	0 0
1	-0.197612E+04	0.342	-1	7.69	6.47753	2.390117	0 0
5	-0.121896E+03	0.342	-1	7.69	1.138568	2.390117	0 0
18	-0.108137E+03	0.333	-1.87	20.24	1.313945	2.148221	0 0
30	-0.997867E+02	0.333	-1.87	20.24	1.313945	2.148221	0 0
45	-0.949045E+02	0.333	-1.87	20.24	1.313945	2.148221	0 0
60	-0.927163E+02	0.333	-1.87	20.24	1.313945	2.148221	0 0
80	-0.919547E+02	0.333	-1.87	20.24	1.313945	2.148221	0 0

(depth, initial matric potential, saturated vol. water content, air entry, Campbell b, K_{sat},, n and macroporosity parameters for each depth as presented in E.1 above)
0
(zero potential gradient for lower boundary, ie., gravitational drainage)
1
(cosine of angle between depth and gravity, ie. depth is measured parallel to gravity)

28 0.064 0.520 0.184

(surface hydraulic conductance parameters calculated to match the decline in surface hydraulic conductivity presented in section 4.5 for Cowra DD Dry)

0 0 100 2000 1

(surface storage parameters specifying constant surface storage of 0 mm and runoff parameters specifying rapid rate of removal of water in excess of surface storage)

0

(initial surface water depth is 0 mm)

7

(seven cumulative precipitation pairs for June 1984)

4091.33 0

4093.83 0.16

4094.5 0.3

4095.58 0.46

4096.5 0.5

4097.17 0.5

4097.5 0.52

(cumulative precipitation pairs showing time in h and cumulative precipitation in cm)

62

(no. cumulative evaporation pairs)

3642 9.937435

3654 9.937435

3666 10.01061

3678 10.01061

3690 10.08378

3702 10.08378

3714 10.15695

3726 10.15695

3738 10.23013

3750 10.23013

3762 10.3033

3774 10.3033

3786 10.37647

3798 10.37647

3810 10.44965

3822	10.44965
3834	10.52282
3846	10.52282
3858	10.59599
3870	10.59599
3882	10.66917
3894	10.66917
3906	10.74234
3918	10.74234
3930	10.81551
3942	10.81551
3954	10.88869
3966	10.88869
3978	10.96186
3990	10.96186
4002	11.03503
4014	11.03503
4026	11.10821
4038	11.10821
4050	11.18138
4062	11.18138
4074	11.25455
4086	11.25455
4098	11.32773
4110	11.32773
4122	11.4009
4134	11.4009
4146	11.47407
4158	11.47407
4170	11.54725
4182	11.54725
4194	11.62042
4206	11.62042
4218	11.69359
4230	11.69359
4242	11.76677
4254	11.76677
4266	11.83994
4278	11.83994

4290 11.91311
4302 11.91311
4314 11.98629
4326 11.98629
4338 12.05946
4350 12.05946
4362 12.13263
4344 12.13263
(cumulative evaporation pairs showing time in h and cumulative evaporation in cm)