THESIS

PERCHING AND THROUGHFLOW IN A LATERITE PROFILE IN RELATION TO THE IMPACT OF *PHYTOPHTHORA CINNAMOMI* IN THE NORTHERN JARRAH FOREST

by

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DECLARATION

This thesis is my own account of work conducted by me.

ABSTRACT

Using throughflow interception trenches located on laterite and piezometers in clay, the development of perching and subsurface throughflow in a laterite profile in the jarrah (*Eucalyptus marginata* Donn ex Sm.) forest, were compared between and within areas of hillslope with different impact following infection by the fungal pathogen *Phytophthora cinnamomi* Rands. In a high impact area, many understorey species and >50% of the overstorey are infected whereas in a moderate impact area many understorey and <10% of the overstorey are infected. Textures of the clay from cores to 6 m and the conformation of the laterite surface determined by probing with a steel rod, were also compared between and within areas.

Perched water tables developed on the sandy clays beneath the laterite more rapidly, were more sustained and more extensive in the high than the moderate impact area, and were related to a reduced infiltration capacity due to fewer cracks and vertical channels passing through the lateritic duricrust and to finer clay textures in the high impact area.

In the high impact area, the perched horizon developed most rapidly in the upper slope position

within the laterite and separate from a perched horizon on the clay. This may be significant in accelerating perching and throughflow in positions downslope.

Following winter rain events of average intensity, throughflow occurred in cracks between duricrust blocks and over the surface of the duricrust in the mid and lower slope positions of the high impact area, following a rapid buildup of a perched horizon through the full thickness of the laterite. In the moderate impact area, the perched horizon is only likely to extend through the full thickness of laterite relatively briefly in the lower slope position following average winter rainfall, and most flow occurs on the clay and at depth between duricrust blocks.

There was a greater soil moisture storage capacity in the moderate area which had a deeper topsoil horizon, and areas of unconsolidated laterite between duricrust blocks, which may have acted to delay the onset and reduce the magnitude of perching.

The difference in vegetation density between the moderate and high impact areas was further exaggerated by the greater loss of canopy in the high impact area. This would result in a larger soil moisture deficit through canopy interception and transpiration and act to delay the onset of perching in the moderate compared with the high impact area.

The earlier onset of perching and throughflow in the upper slope position of the high impact area - an inversion of the typical sequence - and the contribution of throughflow from healthy forest to lower slope positions suggest that soil physical properties are more important than vegetation differences in explaining the different hydrological behaviour of the impact types.

The soil overlying the laterite, in channels passing through the laterite, and in cracks between duricrust blocks, was sufficiently porous to permit dispersal of *P. cinnamomi* by subsurface water.

P. cinnamomi was consistently recovered from throughflow above the laterite high in the landscape in the high impact area and below the laterite mostly in the lower slope position.

Inoculum dispersal occurred throughout winter, at depth in the laterite profile where temperatures appear to be sufficient for low rates of infection. This suggests that the infrequent periods of mass collapse of jarrah that followed summer rain events, may be due to outbreaks of lesion extension in already infected trees and not to single periods of widespread dispersal and infection.

The increasing hardness and continuity of duricrust and finer texture of clay with distance upslope in the high impact area, suggest the influence of dolerite dykes in that area.

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CHAPTER 1

INTRODUCTION

1.1 The Problem

The severity of infection of the jarrah (*Eucalyptus marginata* Donn ex Sm.) forest by the fungus *Phytophthora cinnamomi* Rands is variable and appears to be related to physical conditions which influence the activity of the pathogen and its dispersal at depth within the lateritic soil profile by lateral subsurface flow of water (Shea *et al.*, 1983). However, little is known about the shallow subsurface hydrology of the lateritic soils of the jarrah forest.

This study was initiated to establish first, whether the differences in disease expression between high (many understorey species and >50% of overstorey dead) and moderate (many understorey species and <10% of overstorey dead) impact areas were related to differences in the development of perching and shallow subsurface throughflow in the upper laterite profile; and to relate any differences in hydrological behaviour to physical characteristics of the laterite profile.

1.2 Jarrah Dieback

1.2.1 The Pathogen

Approximately 11% of state forest in the south west of Western Australia, dominated principally by jarrah, is infected by *P. cinnamomi* (Forests Department of W.A., 1982). However, not all areas of the forest are equally infected as the progress of *Phytophthora* diseases is determined by the direct effects of environmental factors, particularly moisture and temperature, on the life cycle of the pathogen (Duniway, 1983).

Wet soil conditions favour sporangial production and zoospore release (Reeves, 1975; Gisi *et al.*, 1980) although the minimum and maximum soil water potentials depend on interactions with other factors including depth in the soil and soil texture which affect aeration. Hence sporangial formation is greatest in soils at field capacity and least in waterlogged soils (Nesbitt *et al.*, 1979). The optimal temperature for sporangial production is 24°C and the minimum 15°C (Nesbitt *et al.*, 1979). These data, however, are mostly derived using media or soil extracts under controlled conditions and there is little information on sporangial production and zoospore release under the physical conditions found in soils *in situ*.

Zoospores of *P. cinnamomi* are considered to be the principal agents of dispersal and root infection by the pathogen especially under wet conditions (Reeves, 1975). Zoospores may be dispersed by actively swimming in water, but typically no further than a few centimetres (Duniway, 1976). The extent of movement of zoospores in soils, and hence probability of infection, is determined by both soil water potential and soil structure which determine the size distribution of water-filled pores (Griffin, 1978). Inoculum can be dispersed passively over much greater distances by the movement of infected soil, e.g. by vehicles or animals (Havel, 1979) or by flowing surface water (Kliejunas and Ko, 1976; Weste and Taylor, 1971). In contrast little is known about long distance dispersal of inoculum by subsurface water movement within the soil profile. In the only reported trial, Shea *et al.* (1983) detected zoospores flowing in water at the interface of a concreted lateritic layer 30 cm below the soil surface and 2 m downslope from a trench that had been filled with a water and zoospore suspension.

1.2.2 Epidemiology

The northern jarrah forest has a Mediterranean climate with cool, wet winters and hot, dry summers.

The environment in moisture-gaining valleys is suitable for fungal survival and activity throughout the year because there is maximum coincidence of warm, moist conditions favourable for disease development (Shea, 1975). In these areas, disease impact is limited due to the presence of resistant species. In contrast, moisture levels of surface soils in upland sites during dry summers are too low for sporulation, and survival of spores outside large roots is limited. During winter, spores can survive but surface soil temperatures are too low for sporangium formation. Hence it is only during brief periods in spring and autumn when there is a coincidence of suitable soil moisture and temperature that the pathogen can emerge from the stumps and large roots of highly susceptible species, particularly *Banksia grandis* Willd., to reproduce (Shea *et al.*, 1980). Dispersal of inoculum in surface soil horizons of upland sites is believed to be restricted and to occur mostly by lateral spread along roots of highly susceptible species. Inoculum transport by surface water is limited since overland flow in the freely draining surface soils is rare (Loh *et al.*, 1984). Yet it is on the laterite-mantled upland sites comprising *ca.* 75% of the landscape (McKinell, 1981), where disease impact is the greatest.

The reasons for this became apparent when it was shown that some upland sites favour the activity of *P. cinnamomi* and the infection of jarrah roots at depth in the soil profile during periods when surface soils are suboptimal for survival and reproduction by the pathogen (Shea *et al.*, 1983). In contrast to the markedly seasonal conditions in surface soil, temperatures at depth remain sufficient for sporangial production throughout the year (Shearer, pers. comm.). The presence of a concreted laterite layer acts to impede infiltration of water following rainfall, favouring the release and dispersal of zoospores in subsurface lateral flow. Sinker roots of jarrah were found to be girdled where they passed through vertical channels in the laterite (Shea *et al.*, 1982), although it is not known where in the profile infection occurs since it was not possible to access the roots deep within the root channel.

The association of specific site characteristics with disease severity suggest that the jarrah forest is composed of a mosaic of site types with differing vulnerability to disease. Second, the behaviour of the pathogen, and hence impact type, is related to the hydrological characteristics of a site which in turn are influenced by the physical properties of the soil profile.

1.3 Regional Geology and Landforms

Factors which determine the properties of a soil profile include the geology of the underlying parent rock and landform development. The northern jarrah forest, synonymous with the Darling Range and the Darling Plateau, occupies the south western extremity of the Archaean Shield of Western Australia (Biggs *et al.*, 1980). The basement rocks of the region are predominantly granites with areas of granitic gneisses and migmatites. These are intruded by numerous mafic dykes, mainly of quartz dolerite and gabbro, typically between 5 m and 50 m wide (Murray, 1979) and comprising about 15% of the basement rock (Biggs *et al.*, 1980).

The mantle of weathered rock overlying the Plateau is generally considered to have been subjected to various cycles of erosional modification (Mulcahy, 1960). The resulting landscape consists of soils in patterns which depend partly on the degree of stripping of the weathered mantle, on the geology of the underlying rocks and partly on the spread of weathered and erosional products across the slope elements (Churchward and Gunn, 1983).

The degree of dissection of the Plateau was greatest along the Darling Scarp where uplift rejuvenated drainage. However, despite the deep incision by the main rivers in the vicinity of the Scarp, the lateritic duricrust capping the weathered mantle has helped preserve broad areas of minimal stripping. Eastwards the thinner and less cemented ferruginous zone may have been less effective in limiting stripping resulting in valleys that are broad and shallow with low gradients (Mulcahy and Hingston, 1961). Dykes represent an important topographic control since due to their resistance to weathering they often remain prominent as ridges and spurs (McArthur *et al.*, 1977).

1.4 The Laterite Profile

1.4.1 Morphology

Ferruginous and aluminous horizons have developed in the upper part of the weathered mantle on the Plateau and, together with either the mottled or pallid clay zone, is the minimum expression of the laterite profile (Hubble *et al.*, 1983). The standard laterite profile (Fig. 1.1) consists of 6 more or less distinct zones (Bettenay *et al.*, 1980):

A Relict or derived soil; mainly sands, loams and pisolitic gravels.

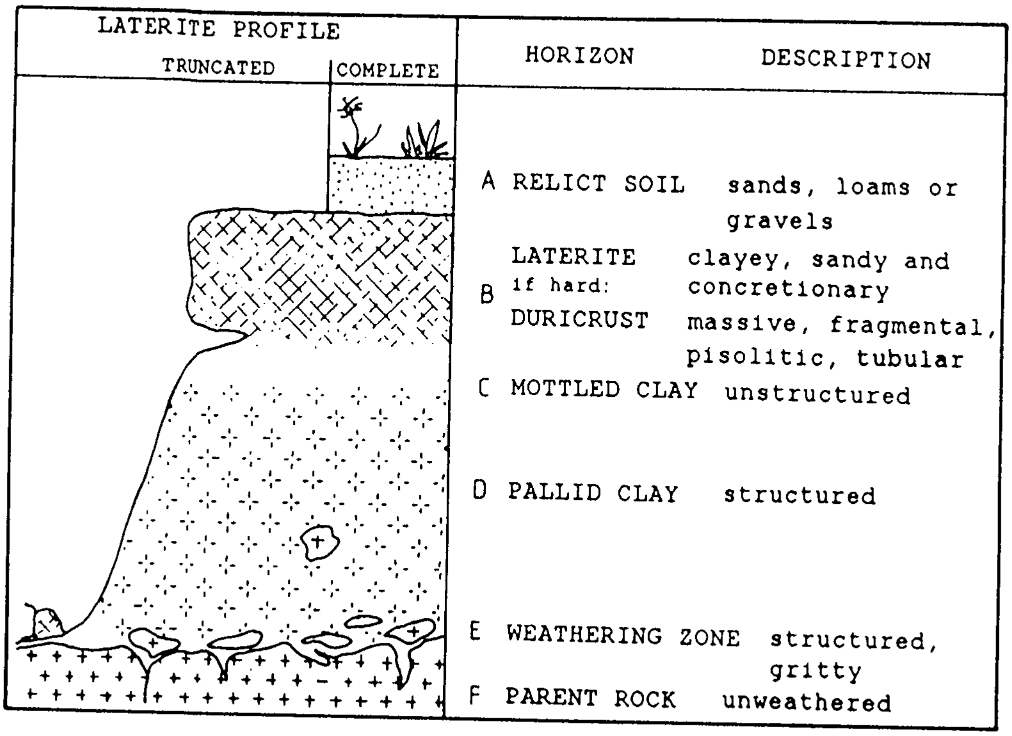

Fig. 1.1. Morphological zones of a laterite profile (after Millot, 1970; Bettenay *et al.*, 1980).

B Laterite; usually a concretionary zone (duricrust), typically ferruginous, massive, fragmental, pisolitic or tubular, overlying an earthy often porous and friable zone.

C Mottled clay; unstructured whitish kaolinitic clay with coarse yellow, brown and red mottles.

D Pallid clay; near-white kaolinitic clay with few mottles; frequently the fabric of the parent rock is preserved as a skeletal quartz matrix.

E Weathering zone; zone of decomposition of parent rock; mineralogy and texture of parent rock is partially preserved in a matrix of red and brown clay minerals.

F Parent rock; unweathered rock.

In the Darling Range the laterite weathering profile has an average thickness of 30 m (Bettenay, *et al.*, 1980), however, the form of the laterite and the dimensions vary greatly. The duricrust in particular, varies in texture and composition (Geidans, 1973). Whereas the boundary between the top of the laterite and the overlying soils is typically sharp (Hubble *et al.*, 1983; Owens, 1954), reports on the transition between the lower zones vary. Hence Hubble *et al.* (1983) state that all zone boundaries are merging ones and in some profiles there is a continual change from the laterite down to the parent rock. In contrast Peck *et al.* (1980) observed that there is usually a fairly sharp transition from the coarser to the finer-textured material in the soil profile. Bettenay *et al.* (1980) also found that a characteristic common to most soil profiles in catchments near Collie was their duplex nature.

1.4.2 Formation

Laterites are widely distributed throughout the world and are not unique to Western Australia. Hence the literature on laterites is extensive but elements of their genesis remain controversial. Laterite is formed by the intensive weathering of silicate rocks under the influence of abundant rainfall. Conditions favouring the greater mobility of silica, alkalis and alkali earths result in the relative accumulation of the more stable secondary minerals newly developed during weathering, i.e. iron and aluminium oxides and hydroxides and the retention of the most resistant primary minerals, e.g. quartz (Norton, 1973). The leaching of primary minerals and regrouping of residua is a continuing process with the mineral progression towards greater stability in situations progressively nearer the surface (McFarlane, 1983). The partial and complete decolourization of the mottled and pallid zones reflect their relative concentration of iron.

Hardening of laterite, a phenomenon distinct from and secondary to lateritisation, has been extensively reviewed by Alexander and Cady (1962) and Sivarajasingham *et al.* (1962). Iron plays a key role in the process although high concentration alone does not ensure hardening. Reducing conditions, high acidity and presence of organic complexing agents contribute to the mobilization and movement of iron to sites where development of crystallinity and dehydration result in hardening.

1.4.3 Genetic Requirements

Lateritisation and hardening are essentially chemical processes, however, since they can take place only under certain physical conditions the relative balance between the physical and chemical conditions are reflected in the variation in the end products (Geidans, 1973). The principal genetic requirements essential for lateritisation have been discussed by Geidans (1973). Critical properties of the parent rock include its chemical composition and texture. In the Darling Range, the finer grained dolerites are less susceptible to weathering than granites and gneisses and their higher iron content is usually evident in the overlying ferruginous duricrust (Baker, 1975). Sufficient relief is necesssary to drain saturated solutions and generally to lower the water table below which laterites do not form. High aluminium to iron ratios in laterite (bauxite) are usually associated with well drained areas (Baker, 1975). Vegetation prevents erosion from slopes and is important in controlling extraction of silica by maintaining lower levels of pH in the groundwater and in the mobilization of iron either as organic complexes or by providing organic decomposition products as reducing agents.

1.4.4 Hydrology of Laterite

Soil moisture is one of the most important factors influencing the life cycle of *P. cinnamomi*, however, little is known about the hydrological behaviour of laterites, the principal soil type in the Darling Range. The saturated hydraulic conductivities of the gravelly surface soils in the Darling Range are in the order of 2 m/day and are unlikely to be exceeded by most rain events (Sharma *et al.*, 1980). No measurements of the permeability of Darling Range laterites are available but based on their morphology, the variation would be expected to be considerable. At one extreme, duricrust is dense with very little pore space and is essentially impermeable (Alexander *et al.*, 1956). Infiltrating water may pass into the underlying horizons via gravel-filled cracks and root channels between massive duricrust blocks (Dell *et al.*, 1983; Johnston *et al.*, 1983). When rainfall exceeds the infiltration capacity of the channels, perching above the laterite may occur (Throssell, 1984). In contrast, unhardened Arkansas bauxite has a porosity between 30 and 40% (Gordon *et al.*, 1958).

Perched water table development in the Darling Range has been more frequently associated with mottled and pallid clays, mostly in lower slope positions (Batini *et al.*, 1977; Bettenay *et al.*, 1980; Stokes and Loh, 1982), but also in mid to upper slopes (Johnston *et al.*, 1983; Throssell, 1984). Darling Range pallid zones have saturated hydraulic conductivities in the order of 0.03 m/day (Peck *et al.*, 1980). However, there is firm evidence that vertical pathways with high infiltration capacity exist within the less permeable clay horizons of some granite-derived laterite profiles, enabling rapid flow to deeper groundwater. In contrast, vertical channels are absent in clays derived from dolerite (Dell *et al.*, 1983.; Johnston *et al.*, 1983).

The hydrological properties of the vertical channels have important implications for disease epidemiology and further investigation is needed. Knowledge of the size and distribution of the channels could help to explain the occurrence of perching and subsurface flow on hillslopes. Because of the coarse textured materials in the vertical channels, a saturated zone is necessary at the top of the channel to conduct appreciable amounts of flow down the pathway. Most channels typically contain tree roots (Dell *et al.*, 1983; Johnston *et al.*, 1983). Where a limited number of vertical channels occur in massive duricrust, they are more likely to be shared by roots of jarrah and the highly susceptible *B. grandis*, and provide one of the few avenues for infiltration of water. Perching of infested water at the top of the root channel and the presence of diseased banksia roots would make the infection of jarrah roots inevitable.

There is circumstantial evidence that the depth and conformation of the surface of the laterite horizon plays an important role in disease development. Shea *et al.* (1983) noted that vertical root channels were frequently formed in depressions in the deeply incised surface of the duricrust and that density of *P. cinnamomi* inoculum was greatest in the depressions. Johnston *et al.* (1983) observed that lateral flow of perched water over mottled clay did not occur in a continuous sheet but in defined lateral preferred paths, however, it is not known whether flow over duricrust is directed by horizontal channels in the microrelief of the duricrust, or whether they coincide with vertical root channels. The depth of soil overlying the laterite would influence the temperature regime at the laterite surface and the proportion of rainfall detained in soil storage. Knowledge of the depth and conformation of the laterite surface is necessary to enable the siting of instrumentation and the interpretation of data, e.g. matric potential at a location within the soil profile will depend not only on depth *per se* but also on the proximity to, and the local topography of, the laterite layer.

1.5 Aims of Study

This study was initiated to establish whether there were differences between high and moderate impact areas, and the upper, mid and lower hillslopes within them, with respect to:

1. Soil profile characteristics.

2. Perching of water and subsurface flow in the laterite profile.

3. Dispersal of *Phytophthora cinnamomi* by subsurface flow over laterite.

Chapter 2

METHODOLOGY

2.1 Introduction

The observations of the hydrological characteristics of the surface of the laterite layer, made by Shea *et al.* (1983), were of a qualitative nature and at a single severely diseased site. Hence to establish the importance of size and frequency of subsurface flows in relation to impact of *P. cinnamomi*, it is necessary to quantify these flow characteristics at sites of different impact types and in relation to a wide range of rainfall patterns. There have been no comparative studies of subsurface flow over laterite, at different elevations of a hillslope and in relation to different disease impact types, in the forested areas of the Darling Range and hence no guide was available to suggest the range of throughflow that may occur. Furthermore there has been no quantitative description of the volumes, rates or duration of flows that may be functionally significant in disease epidemiology. The loss in vegetation due to the impact of *P. cinnamomi* may induce changes, that may be subtle, in the hydrological behaviour of a site. Hence it was important to select a means of measuring throughflow with minimal disturbance to the flow characteristics of a site and with maximal accuracy and resolution. Due to the unpredictable nature of the occurrence, intensity and duration of rainfall, an automated throughflow monitoring system is desirable.

Saturated subsurface flow may be measured directly by either tracer methods or throughflow interception (Atkinson, 1978). Interception trenches were chosen for this study since they enable a more accurate estimate of total volumes and rates of discharge, they more readily integrate the variation in flow over an area and are more easily automated.

The presence of throughflow interception trenches in a hillslope, however, may affect the movement of water that it is intended to measure, resulting in distortion of both the throughflow hydrograph and the contributing area (Knapp, 1973; Atkinson, 1978). In order for water at an open trench face to leave the pore system of the soil and flow away, the water must be at atmospheric pressure. Thus the soil at the face must be saturated. Inevitably under such conditions a wedge of saturated soil extends upslope from the trench face, possibly into soil which would not otherwise be saturated had the artificial free face not been constructed. The extent and thickness of the wedge may depend on the flux of moisture from upslope and hence change as the flux changes (Atkinson, 1978). Also, the net of hydraulic potential upslope from the trench varies according to the extent of saturation near the pit and upslope so that the trenches may receive drainage from areas not directly upslope from them (Knapp, 1973). However, there are corrective treatments that will minimize the impact of trenches on throughflow. Backfilling a trench may provide hydraulic continuity between trench face and collecting drain and hence essentially reduce the area of open face from that of the contributing face of the trench to that of the open cross section of the outflow pipes draining the trench. The question of backfill has been addressed to only a limited extent by other workers. Whipkey (1965) and Beasley (1976) used 'pea gravel' and Dunne and Black (1970) and Knapp (1973) used soil. However, natural soil backfill varies widely in permeability and may become compacted if installed under wet conditions (Fausey and Hundal, 1980). End effects may be eliminated by sandwiching the monitored sections of the trench between sections of ungauged trench (Dunne and Black, 1970; Mosley 1979, 1982).

Throughflow has been measured by stopwatch and measuring cylinder (Weyman, 1973), weir and stage height (Dunne and Black, 1970), and tipping buckets (Bonell and Gilmour, 1978). The stopwatch-bucket method is labour intensive, can provide only an estimate of total volume of throughflow, and is wholly unsuited to continuous, long-term monitoring. Since tipping buckets are more suited than V-notch weirs for measuring low flow rates (i.e. <36 l/min; Edwards *et al.*, 1974), and since they are readily monitored with data loggers, tipping buckets were chosen for this study.

Throughflow interception systems typically consist of a tile drain or a rigid trough embedded in a recess in the impeding horizon, below a textural junction (e.g. Dunne and Black, 1970). Usually the impeding layer was sufficiently soft or the trenches relatively short, enabling excavation to collect water seeping over the layer, and to achieve sufficient gradient in the troughs to collect the water from a single outflow at one end of the trough. Knapp (1973) resorted to a pneumatic drill to excavate shale and mudstone for a trench only 1 m long. Mosley (1982) was forced to concrete a 1 m long trough directly onto bedrock. Apparently only Whipkey (1965) deliberately sought a section of hillslope where the depth to the textural change was uniform. In most cases selection of trench length appeared to be somewhat arbitrary. An exception was the study by Dunne and Black (1970) where contiguous trenches of length 38 m, 15 m and 15 m were used to gauge throughflow from convex, concave and straight sections of hillslope respectively.

The highly variable microrelief of the laterite layer, its extreme hardness in places, and the uncertainty about the size and frequency of throughflow and their significance to disease epidemiology influenced the design and construction of throughflow interception trenches in this study.

To evaluate the aims of this study, measurement of the following variables was needed:

Dependent:
1. Soil profile characteristics.
2. Perching of water in laterite.
3. Subsurface flow over laterite.
4. *P. cinnamomi* inoculum in subsurface water.

in relation to

Independent:
1. Location in high or moderate impact areas.
2. Location in upper, mid or lower positions of the landscape.
3. Rainfall.
4. Time.

Subsurface flow over laterite was measured by throughflow interception trenches located in low, middle and upper positions of both a moderately diseased (Mod) and a severely diseased (Hi) area. Piezometers were located within the laterite to register the presence of perched aquifers. Samples of perched water and throughflow were taken and analysed for presence of *P. cinnamomi*, throughout the year. Soil cores were taken from the holes drilled for piezometers. Rainfall was monitored continuously for a year, however, only the responses of the piezometers and throughflow trenches to 2 rain events in winter 1985, 1 event during summer 1986 and 1 event during autumn 1986 are described because they represent the range of events observed.

2.2 Site Description

The study site was located adjacent to Dawn Creek Road approximately 20 km south-east of Dwellingup at Australian Map Grid reference N636500, E415500 (Fig. 2.1). The site provided an opportunity for a comparative study since both Hi and Mod areas occurred along the same hillslope and experienced the same weather patterns. The hillslope was on the western side of a first order catchment with a slope of *ca*. 14%.
The Havel (1975) vegetation type of the Hi area was w-S. S sites are characterized by moderately tall, dense stands dominated by jarrah and found on mid and upper slopes, plateaus and ridges with heavy gravel soils with a sandy loam matrix. The w-S area had predominantly S characteristics but with an understorey vegetation that indicated a tendency to excessive wetness in winter, a characteristic more typical of W

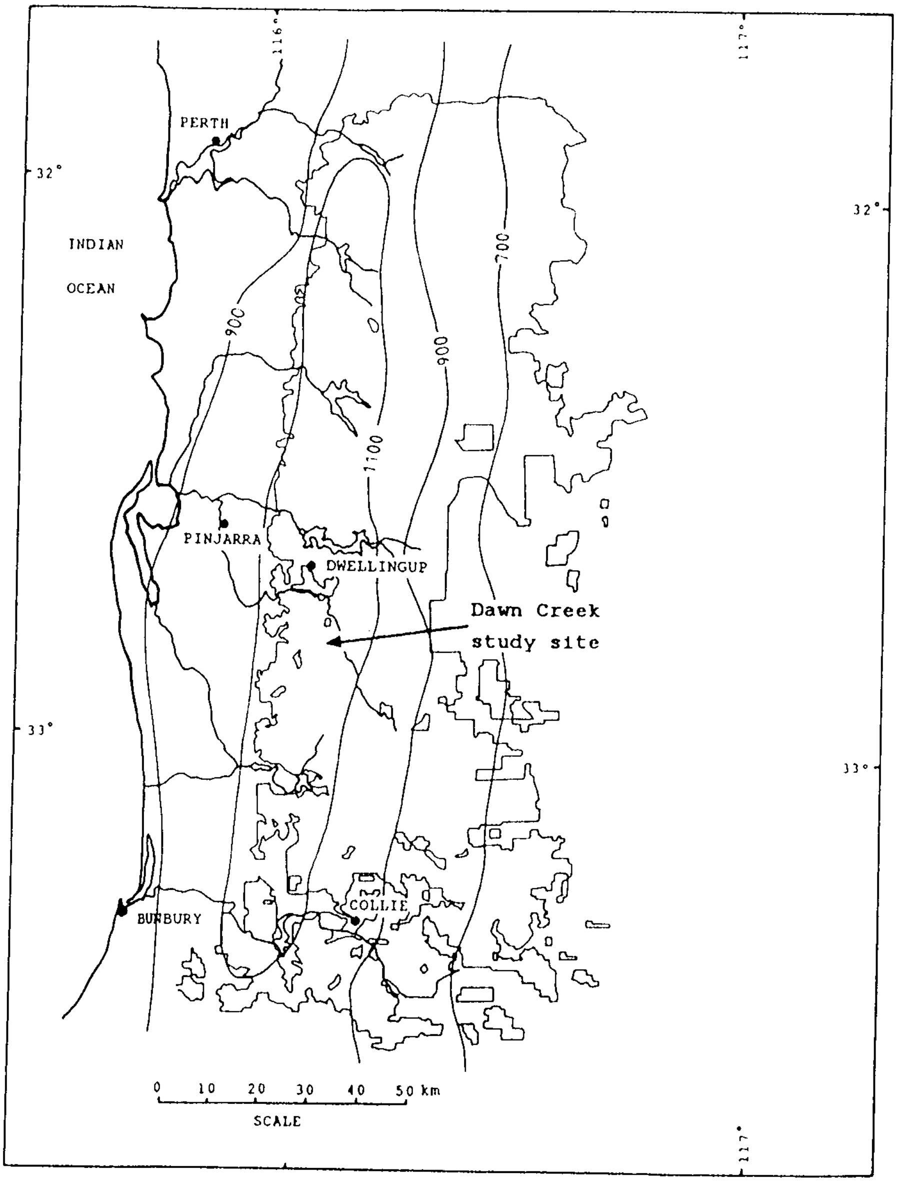

Fig. 2.1. Distribution of the northern jarrah forest (shaded) and rainfall isohyets (mm) in south Western Australia and location of the Dawn Creek study site.

sites found on lower slopes and valley floors. The Mod area was a t-S site type which was predominantly an S type but with understorey species that reflected the higher fertility of the T sites. In the Hi area, many of the overstorey trees were dead, and the range of canopy cover through the area, according to visual estimate, varied from 0 to 30%, and the ground cover from 20 to 40%. In the Mod area the canopy cover varied between 30 and 50%, and the ground cover from 40 to 60%. The study site is part of the Dwellingup landform-soils unit which is a gently undulating surface dominated by duricrust, gravels and sands (McArthur *et al.*, 1977). In this unit the soil profile typically consists of a laterite layer over mottled and pallid clays formed from *in situ* weathering to a depth in excess of 30 m.

Throughflow interception trenches located above the laterite horizon, and piezometers located within the laterite, were situated in upper, mid and lower topographic positions of the Hi and Mod areas (Fig. 2.2). The trench positions were offset so that trenches at higher elevations did not intercept flow to those below.

2.3 Mapping Laterite Microtopography

Sites proposed for throughflow interception trenches were gridded at 25 cm intervals. At each grid point a 12 mm-diameter steel probe, 110 cm long, was driven through the soil until a resisting layer was met. The depths below ground level were corrected for

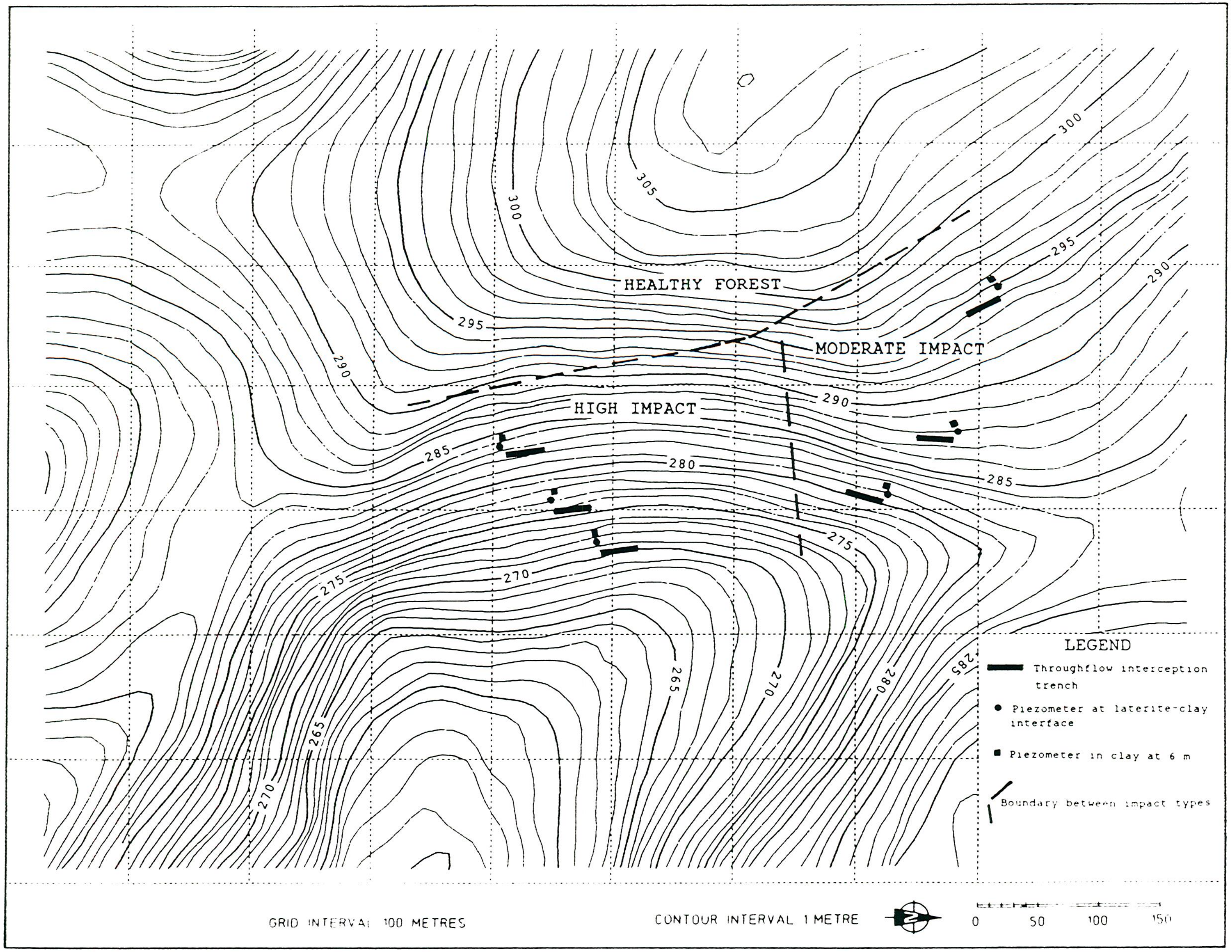

Fig. 2.2. Plan of study site at Dawn Creek showing position of throughflow interception trenches and piezometers in relation to areas of high and moderate impact infected with *Phytophthora cinnamomi*.

irregularities from a plane surface. The resulting maps (Fig. 2.3) depict the conformation of the laterite layer in relation to a flat ground surface.

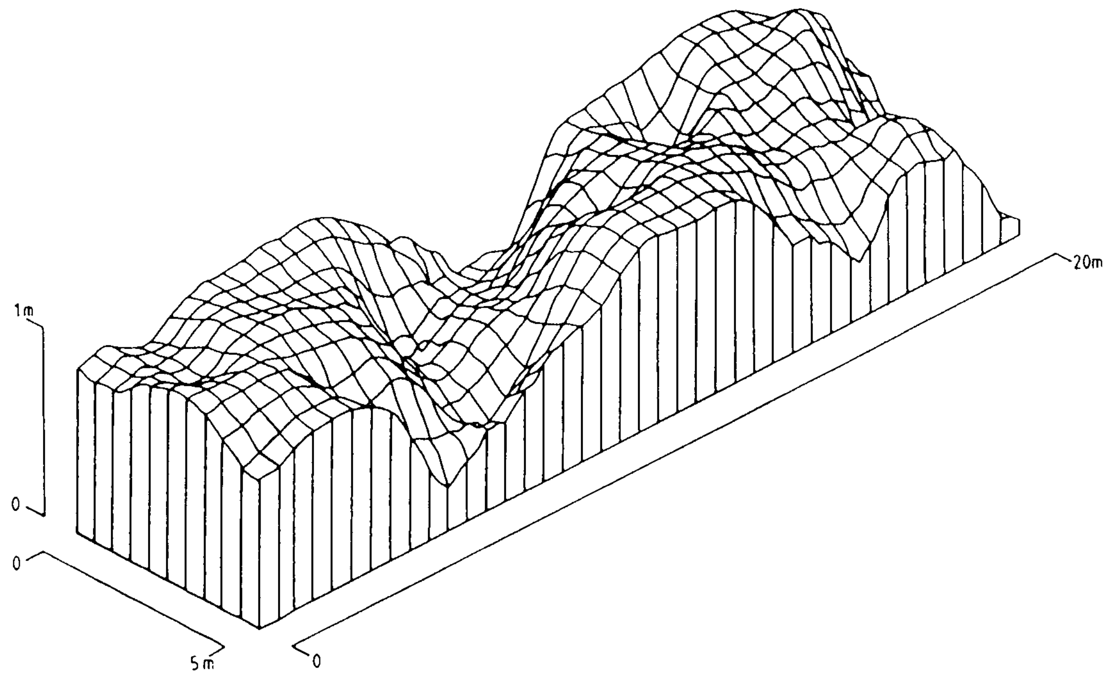

Fig. 2.3 Map of the surface of laterite in the mid slope position of the moderate impact area at Dawn Creek, determined by probing on a 25 cm grid within a 20 m x 5 m area. Depth of topsoil varied from 0 cm to over 1 m.

Anomalies that may have occurred arose from rock floaters or tree roots suspended in the soil above the laterite. However, when plotted, these points were usually obvious irregularities when viewed against the background trend. The choice of length of probe (110 cm) was a compromise between a length that catered for the depth of laterite in most preliminary trials and a practical length as judged by operators of different stature. The effect of the hole, created by driving the probe into the soil profile, on the hydrological behaviour of the site is unknown. However, the relative effect should be less significant in a comparative study where all sites are treated similarly.

2.4 Throughflow Interception Trenches

Construction

Observations of subsurface flow following storms, across laterite exposed by excavation, revealed localized seeps (Fig. 2.4) in the contributing face and flowpaths that were not always downslope but followed tortuous channels in the deeply incised laterite layer (Fig. 2.5). Some water was detained in local depressions. Ideally, in such a location, throughflow trenches should be sufficiently long to integrate the spatial variation in flow and, if possible, have the facility to monitor separate sections of each trench to quantify the extent of variation. The laterite layer exposed at Dawn Creek was, in parts, so hard that it resisted all but superficial excavation by pneumatic jackhammer. Evidently, embedding a trough in the floor of a trench over hardened laterite would be impossible.

Fig 2.4. Upper slope face in throughflow interception trench showing scouring of soil at seep. Note flow of water along tree root (arrowed).

Fig. 2.5. Flow of water in valleys in microrelief of exposed laterite surface.

The method of construction of throughflow trenches 30 m long and 1.5 m wide at Dawn Creek entailed sealing the trench floor and lining the downslope face so that the trench itself would function as a drain. Multiple outlows were used to drain the trench, their positions determined by the local microtopography of the laterite.

Prior to excavating the trench a contour map (Fig. 2.3) of the surface of the laterite layer was obtained by probing. The map enabled:

1. Judgement of an appropriate size of trench in relation to the microrelief of the laterite.
2. Prior indication of the extent of excavation necessary.
3. Positioning of the trench to optimise water collection whilst minimizing the amount of modification of the trench floor needed to prevent retention of water in depressions.
4. Prior location of outflows to drain the trench.

A backhoe was used to excavate the bulk of the soil from the trenches and outflows, dumping the spoil on the downslope side of the trench. The final cleaning of the trench floor was done by hand. All potential paths for vertical infiltration through the trench floor (e.g. root channels, fissures, and depressions which would detain water) were sealed with concrete. Areas of concreted floor were coated with 'Bondcrete' sealant. A pneumatic jackhammer was used to excavate parts of the trench floor to facilitate the movement and minimize the pooling of water. Rainfall during construction was a valuable aid in checking for the movement and detention of water. The downslope face of the trench was lined with 0.15 mm polythene film (Fig. 2.6) which was cemented to the trench floor.

Fig. 2.6. Throughflow interception trench without roof following installation of graded filter and soil backfill. Black polythene film lines lower slope face of trench and divides subsections of trench.

Throughflow into the open trenches following storms, gave an indication of both the variation in discharge across the contributing face and the subsurface flowpaths across the floor. Natural barriers existing in the trench floor were built up and the intervening sections drained by separate outflow pipes sealed to the polythene film. The outflows could be monitored independently to determine the variation in throughflow along the trench as well as collectively for total discharge.

Backfilling the trenches was necessary to minimize disturbance to subsurface flow by ensuring hydraulic continuity between contributing face and trench. However, it was also necessary to consider a material for backfill whose properties were suitable for preventing the backward erosion of the contributing face through scouring of the finer material (Fig. 2.4) which would otherwise limit the life of the installation. Furthermore, an open trench could be damaged by or prove hazardous to wildlife and would collect litter hence requiring ongoing maintenance.

The procedure adopted for trench backfill followed the standards for the design of graded filter materials for subsoil drainage trenches (DSIR, 1952). By the appropriate selection of filter material sizes it was possible to ensure sufficient permeability to water yet resist the passage of silt and hence prevent the clogging or internal erosion of the backfill. The filters used, 7 mm and 20 mm nominal crushed granite, were standard size classes and readily available from

Table 2.1. Piping and permeability ratios for soil from upperslope face of throughflow interception trench at high impact mid slope position at Dawn Creek, and graded filters where filter 1 is adjacent to the trench face (after DSIR, 1952).

	filter 1 / trench face[c]	filter 2 / filter 1[c]
Piping ratio[a]	0.4	2.3
Permeability ratio[b]	6.8	4.4

[a] Piping ratio = $\frac{\text{15\% size of filter material}}{\text{85\% size of subgrade}}$ should be < 5.

[b] Permeability ratio = $\frac{\text{15\% size of filter material}}{\text{15\% size of subgrade}}$ should be > 5.

[c] Subgrade.

quarries since they were manufactured to meet road-making specifications. The particle size distributions were close to the requirement of the DSIR standards (Table 2.1). The filters were layered against the contributing face (Fig. 2.7) using formwork. Soil previously excavated from the trench was returned to support the filter (Fig. 2.6). To reduce end effects, barriers were installed 5 m from each end of the trenches and those sections drained separately to the inner 20 m. However, they could potentially be pooled with the remainder of the trench should their discharge be within the variation found over the inner trench sections. In this study, only the flow from the inner 20 m was monitored.

Each trench was covered from rainfall by a roof draining to the downslope side (Fig. 2.7).

Throughflow measurement

Throughflow was monitored using tipping buckets monitored continuously by data loggers. The tipping buckets, commercially produced by Deltameter, incorporated a water inlet manifold that distributed incoming water over a progressively greater length of the bucket as flows increased, so reducing the errors due to turbulence (Schrale, 1981). A moving magnet-reed switch arrangement on the buckets enabled each tip to be recorded by a digital event recorder. The buckets were

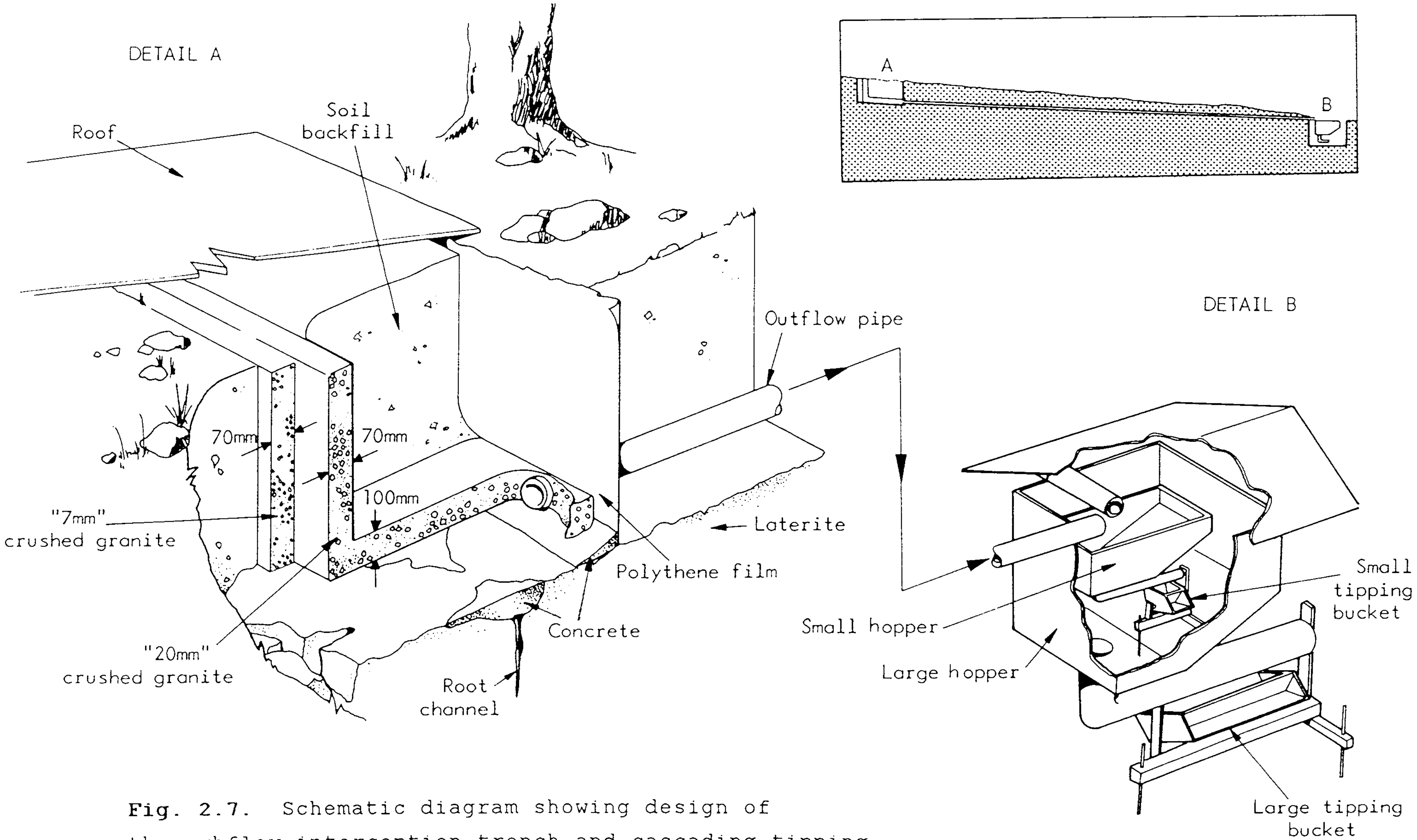

Fig. 2.7. Schematic diagram showing design of throughflow interception trench and cascading tipping buckets.

available in two sizes of 200 ml and 1.7 L capacity and an upper flow limit of *ca.* 10 L/minute and 70 L/min respectively.

Discharge was measured by either a single small or a cascading small and large tipping bucket combination (Fig. 2.7) according to the discharge anticipated from observations of throughflow made during trench construction. Water was directed firstly into a galvanized sheet metal hopper which fed the small tipping buckets. In a cascading arrangement the small hopper was contained within a large hopper which in turn fed the large buckets. At low flow rates all water was measured firstly by the small buckets then again by the large. At low flows or during both the initial stage and the receding limb of the hydrograph, the small buckets had a better time resolution. There was also a relatively smaller error due to the retention of water in a bucket following the last tip - a volume that is added to the flow for the next event. At flows greater than 10 L/min the response of the small buckets quickly plateaued and the additional water spilled over the small hopper into the large so that the large buckets were measuring water passing through the small buckets as well as the overflow from the small hopper. Tests using outflow pipes set at a gradient of 1% showed that water flowing at 0.3 L/min would take less than 1 minute to travel from the trench to the buckets.

The tipping buckets were supplied with a 'universal' calibration curve, however, a check showed that individual curves were warranted. A constant pressure head was assured by using gravity-fed water from an automatically recharging water tower. By this method it was possible to establish a tightly fitting linear regression. The lowest coefficient of determination (R^2) for 10 tipping buckets of both sizes was 0.994 (n = 35).

Solid-state electronic data loggers accumulated the number of tips occurring within a 10 minute interval. A logger with a 16 Kbyte memory and logging two channels each 10 minutes would exhaust its memory capacity after 24 days.

Flow rate was determined by using the counts from the small bucket at low flows and from the larger bucket at high flows.

2.5 Piezometers

Piezometers were located in pairs, 20 m upslope from one end of each of the trenches, to register the presence of aquifers beneath the laterite layer. One hole was terminated 50 cm into the clay horizon and the other at a depth of 6 m. The holes were drilled, using a 150 mm hollow-stem auger, on topographic highpoints of the laterite profile determined by probing, to minimize the entry of water perched on the laterite. The piezometers were screened over the lower 50 cm and packed with sand over a distance of 25 cm either side of the screened section. The remainder of the annulus was filled with bentonite with a cement collar in the upper 30 cm of laterite.

During and following rain events, the piezometers were monitored manually using a Nordmeyer acoustic water level meter at intervals illustrated in Fig. 3.5 (mostly hourly but at times up to 3 days).

2.6 Soil Cores

Soil cores (5 cm-diameter) were taken and logged to determine the morphology and texture of the profile, while drilling holes for the piezometers.

2.7 Inoculum in Water Samples

Daily water samples (500 ml) were taken, when available during and following rain, from throughflow passing through the tipping buckets and by sucking water up through a PVC tube from piezometers, whenever either source of water was available. Between samples the tubes and sample bottles were sterilised with alcohol and rinsed thoroughly with distilled water. Within a day of sampling, the water was distributed into styrofoam cups in 50 ml lots together with about 6 *Eucalyptus sieberi* cotyledons (Marks and Kassaby, 1974) and kept for 10 days at 25℃. Infected cotyledons show a colour change on their underside from a normal reddish hue to green. Suspect cotyledons were plated onto half strength potato dextrose agar with added pimaricin, vancomycin, petrachloro- nitrobenzene and hymexazol (Tsao and Guy, 1977), to confirm the presence of *P. cinnamomi* by visual inspection of hyphal morphology.

2.8 Rainfall

Rainfall was monitored continuously using a ground level 0.2 mm-tipping bucket rain gauge connected to a data logger recording the number of tips occurring within a 5 minute interval.

2.9 Data Analysis

A series of parameters, detailed in Table 2.2 and Fig. 2.8, was determined for each rain event. A rain

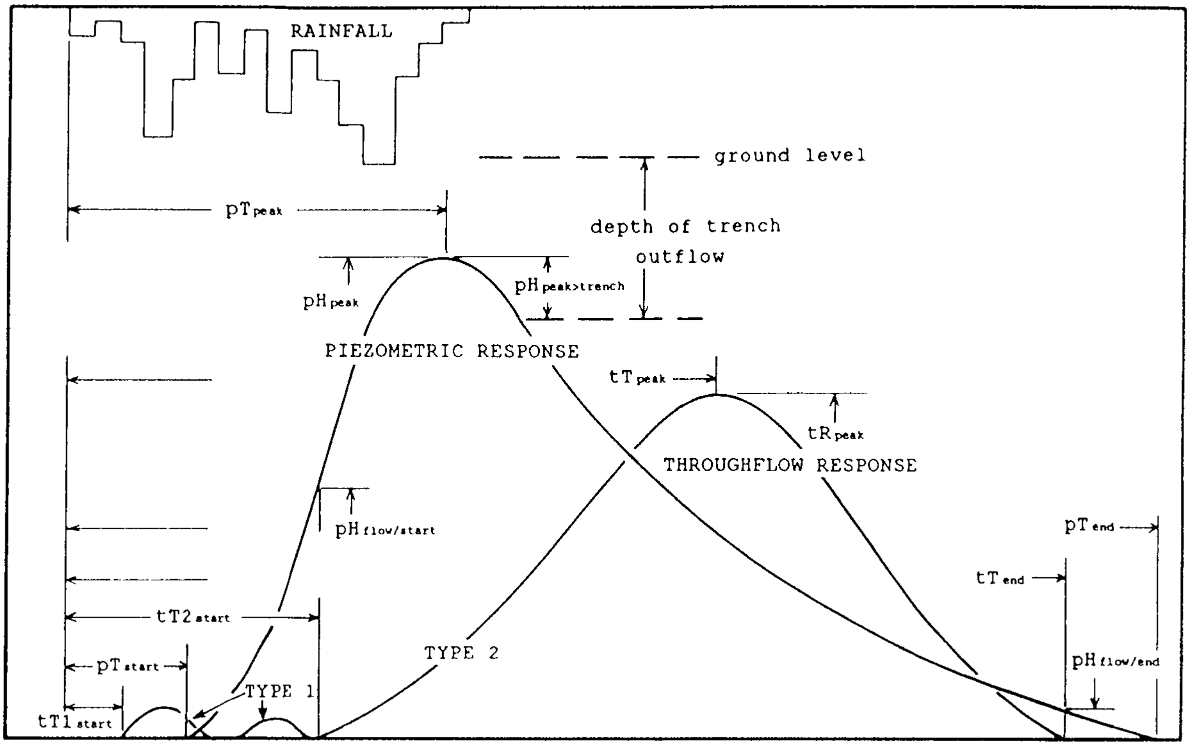

Fig. 2.8. Illustration of throughflow and piezometric parameters defined in Table 2.2 and §2.9.

event was defined by the first and last bucket tip of a period of rain delimited by a rainfree period of at least 6 hours. Daily rainfall was determined according to calendar days.

In all piezometer locations, the shallower of the two piezometers was located with the screened section straddling the laterite-clay interface. The response of these piezometers has been presented, on the same figure, as the height of water above the piezometer tip and hence as the relative thickness of the aquifer perched above the laterite-clay interface. This differs from the conventional method of representing piezometric water level as a depth below ground.

Table 2.2. Definition of rainfall, piezometric and throughflow parameters.

	Parameter	Description
Rainfall	Rainfall	Total rainfall (mm).
	Duration	Duration of rain event (hours).
	R.I.I.	Rainfall intensity index = Rainfall/duration.
	A.R.I.	Antecedent rainfall index $=\sum_{n=1}^{30} R_n/n$ where R_n is the rainfall on the n^{th} day beforehand (after Mosley, 1979).
Piezometers	pT_{start}	Time from start of rain to start of rise of piezometer.
	pT_{peak}	Time from start of rain to peak piezometer height.
	pT_{end}	Time from start of rain to zero piezometer height.
	pH_{peak}	Peak piezometer height.
	$pH_{peak>trench}$	Height by which the peak piezometer height was above the level of the deepest outflow draining the throughflow trench in the same slope position.
	$pH_{flow/start}$	Piezometer height when Type 2 throughflow in the trench in the same slope position has started.
	$pH_{flow/end}$	Piezometer height when throughflow in the trench in the same slope position has ceased.
Throughflow	$tT1_{start}$	Time from start of rain to start of Type 1* throughflow.
	tT_{start}	Time from start of rain to start of Type 2* throughflow.
	tT_{peak}	Time from start of rain to peak flow rate.
	tT_{end}	Time from start of rain to when throughflow has ceased.
	tR_{peak}	Peak throughflow rate.
	tV	Total throughflow volume.

* Defined in §2.9.

The throughflow hydrographs were divided into two major components: Type 1 and Type 2. The magnitude of Type 1 throughflow was closely related to the timing and intensity of rainfall, could be discontinuous, and was relatively small in relation to Type 2 flow which peaked after most rain had fallen.

A series of parameters was derived to compare the effects of rainfall intensity and antecedent soil moisture on the throughflow generated by sections of a hillslope (Fig. 2.9).

$$C_{total}(m^2) = \frac{\text{Volume throughflow (kl)}}{\text{Rainfall (m)}}$$

$$= D_{total}\ (m) \times \text{Trench length (m)}$$

where C_{total} is equivalent to that area of catchment directly upslope from a trench and contributing 100% runoff to a trench for an entire rain event. C_{total} is determined by expressing total throughflow as a volume contained in a flat sheet with depth = total rainfall, width of upper face = trench length, and length of upper face = D_{total}.

$C_{slope/mid}\ (m^2)$

$$= D_{slope/mid}\ (m) \times \text{Trench length (m)}$$

where $D_{slope/mid}$ is the distance directly upslope and between the mid slope and upper slope trenches. $C_{slope/mid}$ defines that area of catchment which contributes an increment of throughflow additional to that received by the upper slope trench.

$C_{slope/lower}$ (m^2)

$$= D_{slope/lower} (m) \times \text{Trench length} (m)$$

where $D_{slope/lower}$ is the distance directly upslope and between the lower slope and mid slope trenches. $C_{slope/lower}$ defines that area of catchment which contributes an increment of throughflow additional to that received by the mid slope trench.

$C_{yield/mid}$(m^2)

$$= C_{total/mid}(m^2) - C_{total/upper}(m^2)$$

corresponds to that portion of the mid slope that contributes throughflow to the mid slope trench.

$C_{yield/lower}$(m^2)

$$= C_{total/lower}(m^2) - C_{total/mid}(m^2)$$

corresponds to that portion of the lower slope that contributes throughflow to the lower slope trench.

Since all throughflow trenches are 20 m long, the C parameters are directly related to their respective D parameters and hence correspond with a distance upslope from each trench. They are represented this way in Fig. 2.9.

Typically, $C_{yield} < C_{slope}$ since rainfall will be partitioned, at least, among soil storage and infiltration. Otherwise, if

(i) $C_{yield} = 0$, no throughflow occurred.

(ii) $C_{yield} < 0$, more throughflow occurred in the adjacent higher trench.

(iii) $C_{yield} = C_{slope}$, there was 100% yield of rainfall over C_{slope}.

(iv) $C_{yield} > C_{slope}$, there was a greater volume of throughflow than could be generated by rain falling on that section of hillslope.

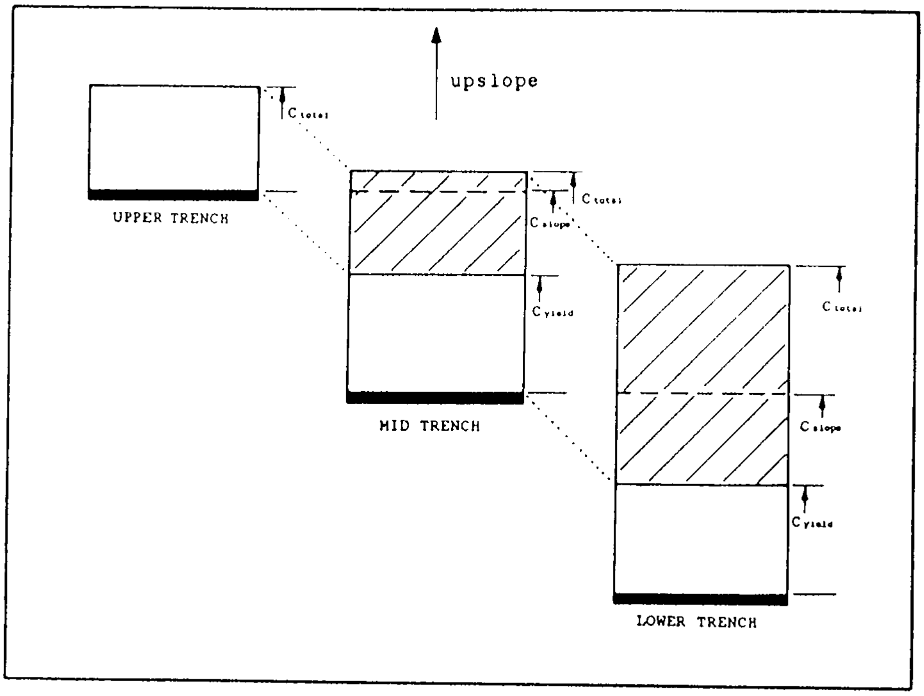

Fig. 2.9. Schematic representation of catchment parameters for throughflow over laterite at lower, mid and upper slope positions

Recovery of *P. cinnamomi* from each water sample was presented as the proportion of 10 subsamples that were positive.

Chapter 3

RESULTS

3.1 Laterite Profile

In all topographic positions of both Hi and Mod areas, there were abrupt textural changes at each of the topsoil-laterite and laterite-clay junctions (Fig. 3.1).

The topsoil in all slope positions consisted of *ca.* 10 cm loamy sandy gravel overlying a clayey sandy gravel horizon. The volume of soil overlying the laterite was greater in the mid and upper slope positions of the Mod area than in the comparable positions in the Hi area (Fig. 3.2). However, the volume estimates for the Mod area are conservative since, in computing volumes, an arbitrary depth of 105 cm was substituted for all depths greater than 1 m.

The laterite horizon varied more in morphology than the topsoil and clay horizons. Laterite thickness and hardness increased with elevation in both impact areas but was generally harder and 50-70 cm thicker in the Hi area than in the Mod area (Fig. 3.1). Massive duricrust was more extensive in the Hi than in the Mod area and

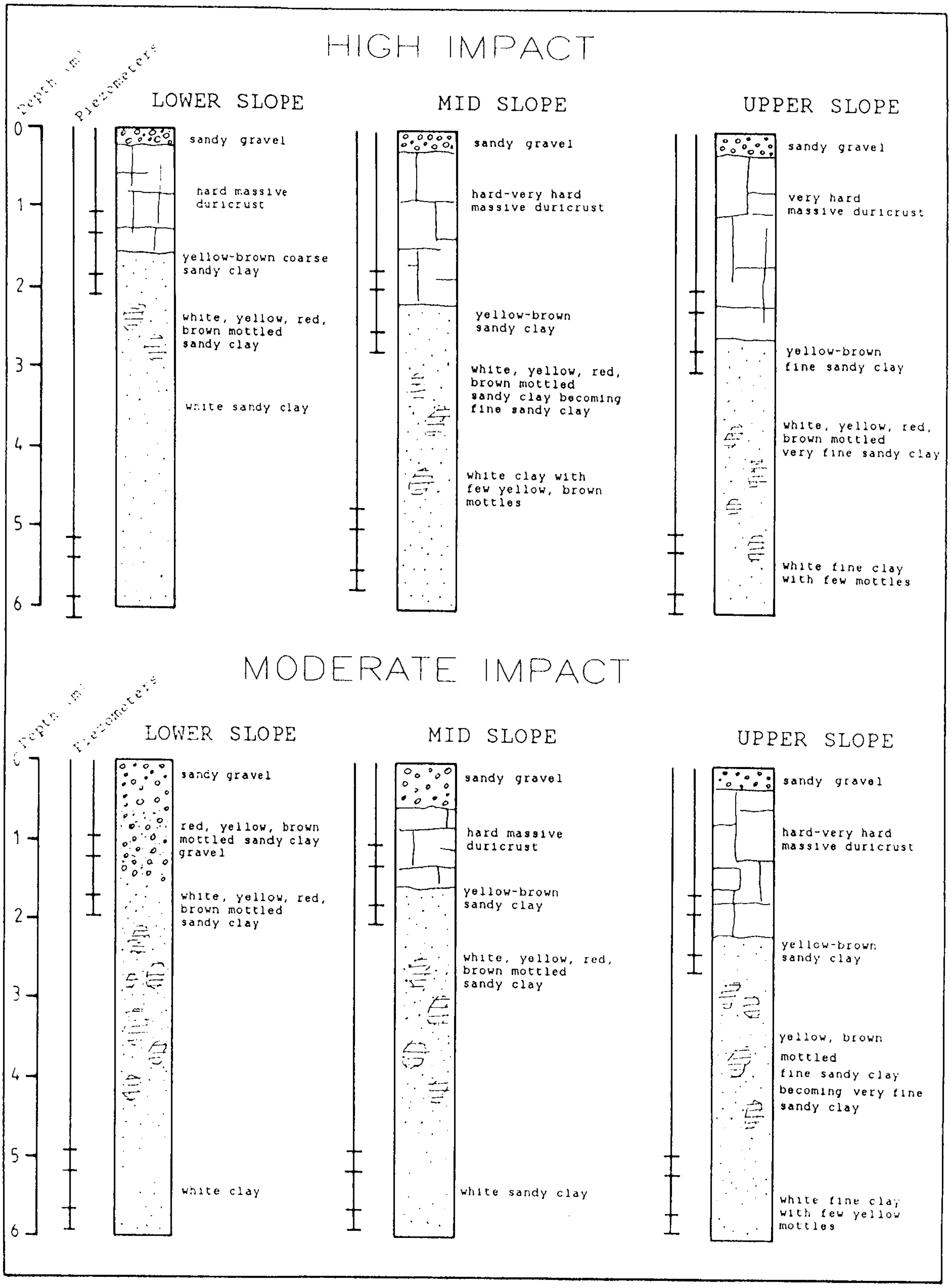

Fig. 3.1. Soil profiles at piezometer locations at upper, mid and lower slope positions of high and moderate impact areas infected with *Phytophthora cinnamomi* at Dawn Creek. Vertical lines represent piezometers; inner bars indicate screened section, outer bars indicate sand pack

comprised the full thickness of the laterite layer. The laterite in the Mod area consisted of duricrust blocks and unconsolidated sandy clayey gravel. At the Mod-mid and upper positions the duricrust blocks extended laterally for several metres and contained smaller areas of unconsolidated laterite. At the Mod-lower position, the laterite consisted of boulders, mostly less than 1 m in diameter, interspersed in an unconsolidated matrix and the soil cores taken in this area, passed between duricrust boulders (Fig. 3.1). Because of the difficulty in removing the overlying soil without disturbing the smaller laterite boulders and surrounding friable laterite, the laterite in some sections was removed during trench construction. Thus 80% of the Mod-lower trench was located on clay and 20% on laterite and throughflow over both clay and laterite was collected.

The depth of the laterite surface below ground varied considerably between 10 and 90 cm (Fig. 3.2). However, depth to the laterite surface does not fully describe the microrelief of the trench floors which varied according to slope position. In both the Hi and Mod areas, the laterite surface at the upper and mid slope positions was deeply textured with a network of valleys and ridges (Fig. 2.5). At the Hi-lower slope position, the laterite surface was relatively flat. The laterite surface at Mod-lower was characterized by irregular protrusions, possibly small boulders <1 m

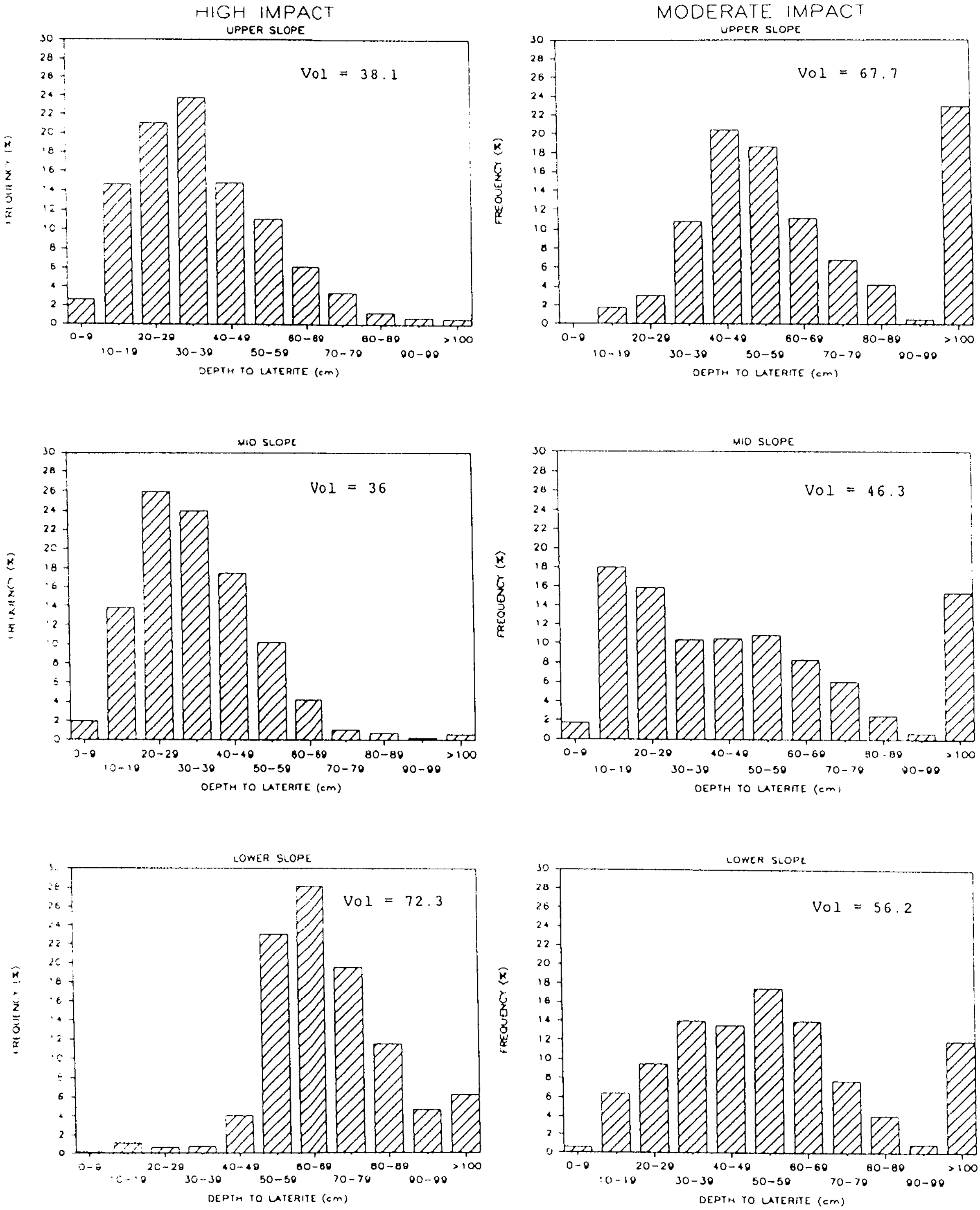

Fig. 3.2. Frequency distributions of depths of laterite surface below ground at upper, mid and lower slope positions of high and moderate impact areas infected with *Phytophthora cinnamomi* at Dawn Creek. Depths were determined on a 25 cm grid within a 20 m x 5 m area at each trench position. Vol = volume (m^3) of soil overlying the laterite at each plot.

in diameter.

There was a marked contrast between Hi and Mod areas in the frequency of depths to laterite greater than 1 m (Fig. 3.2). In the Mod area, the relatively high frequency of depths greater than 1 m, indicate locations of vertical breaks in continuity of the laterite layer corresponding with the gravel-filled cracks and vertical channels (Fig. 3.3), occasionally containing roots, observed in trench floors. In the Mod area, the frequency of the vertical channels increased with elevation, whereas in the Hi area, there were most vertical channels in the lower slope position. Where the laterite was unconsolidated, excavation showed that the gravel-filled channels were continuous between the laterite and the mottled clay.

In all topographic positions of both impact types, the clay horizons followed a progression from yellow-brown or mottled sandy clay immediately beneath the laterite, becoming mottled variously white, yellow, red and brown with depth and changing to predominantly white clay at a depth of 5 m or less (Fig. 3.1). In the Mod area, the clay textures were finest in the upper slope position and most coarse in the mid slope position. In Mod-upper and lower, the clay textures became finer with decreasing quartz content with increasing depth, whereas in Mod-mid there was no change in clay texture with depth. In the Hi area, clay

Fig. 3.3. Gravel-filled channel passing through laterite. Arrows indicate channel boundary.

textures became finer with decreasing coarse quartz content with increasing depth although there was a trend towards increasingly coarse textures in the upper clay horizons, with distance downslope. The clay textures were finer in the upper and mid slope positions of the Hi area than in the Mod area, and finer at Mod-lower than in Hi-lower.

3.2 Rainfall

Perching and throughflow responses to four rain events were compared between lower, mid and upper slope positions of the Hi and Mod areas (Fig. 3.4). Rain event 1 in mid winter was the most intense and occurred on the wettest soil (RII, ARI, Table 3.1). Most rain fell in event 2 in late winter, however, the soils were drier and the intensity of rainfall was less than in event 1. Rain event 3 in late summer, fell on the driest soil but the total and intensity were similar to event 1. Event 4 in late autumn was the least intense but occurred when soils had a moisture content intermediate between events 2 and 3.

The rainfall at Dwellingup for the months preceding and including the rain events 1 to 4 and the long term averages, are shown in Table 3.2. The February rain event was atypically heavy (RII = 3.3, Table 3.1) and the May event was preceded by a month of well below

Table 3.1. Rainfall statistics for four rain events at Dawn Creek.

Rain event	Period	Rainfall (mm)	Duration (hours)	R.I.I.[a]	A.R.I.[b]
1	13 Jul 85	64.6	17.7	3.6	21.6
2	18-19 Aug 85	95.4	42.7	2.2	13
3	21 Feb 86	60.2	18.4	3.3	3.9
4	19-21 May 86	77.6	61.5	1.3	5.5

[a] Rainfall intensity index = Rainfall/duration.

[b] Antecedent rainfall index = $\sum_{n=1}^{30} R_n/n$ where R_n is the rainfall on the n^{th} day beforehand (after Mosley, 1979).

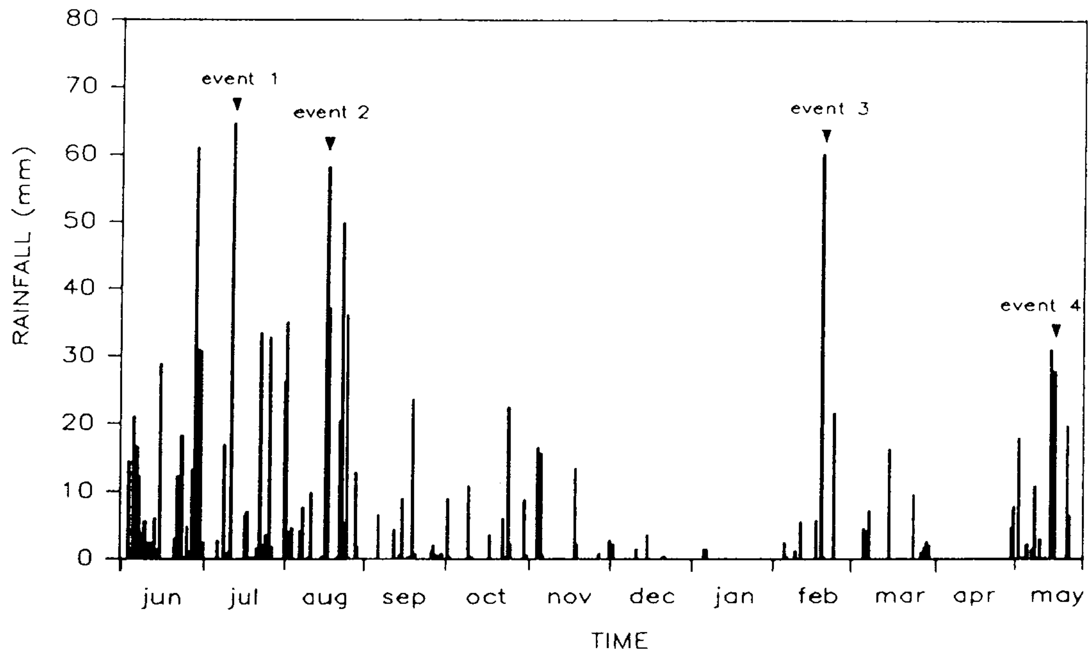

Fig. 3.4. Daily rainfall at Dawn Creek for the period June 1985 to May 1986.

average rainfall (ARI = 5.5).

Table 3.2. Comparison of rainfall totals and distribution at Dwellingup, with long term averages (Hall *et al*, 1981).

	1985/86		Long term average	
	Rainfall[a] (mm)	Number of rain days	Rainfall (mm)	Number of rain days
1985 Jun	223	22	280	19
Jul	249	17	254	20
Aug	270	19	206	17
1986 Jan	7	2	13	4
Feb	108	10	18	3
Apr	13	5	71	9
May	164	16	167	15

[a] To the nearest mm.

3.3 Hydrological Response

3.3.1 Rain event 1

Piezometers in laterite-clay

All piezometers showed water within hours of the start of rain, with those in the Hi area responding about 4 hours earlier than those in the Mod area (pT_{start}, Table 3.3)

Within both impact types the upper and mid-slope piezometers responded earlier than those at the lower slope (pT_{start}, Table 3.3). Hi-mid and upper piezometers already had high levels of water from a

Table 3.3. Response of piezometers at the laterite-clay interface, at upper, mid and lower slope positions of high and moderate impact areas infected with *Phytophthora cinnamomi*, to 2 rain events at Dawn Creek. Parameters are defined in Table 2.2 and Fig. 2.8.

Rain event	Parameter	High impact Upper	High impact Mid	High impact Lower	Moderate impact Upper	Moderate impact Mid	Moderate impact Lower
	pT_{start}(h)	3	3	7	7	7	11
	pT_{peak}(h)	14	15	38	17	9	27
	pT_{end}(days)	>5[a]	>5[a]	>5[a]	2	1	2
1	pH_{peak}(cm)	235	221	131	68	40	105
	$pT_{peak>trench}$(cm)	44	44	41	0	0	85
	$pH_{flow/start}$(cm)	185	185	47	[b]	26	0
	$pH_{flow/end}$(cm)	168	138	[c]		7	0[c]
	pT_{start}(h)	35	35	57	57	No response	
	pT_{peak}(h)	60	63	68	63		
	pT_{end} (days)	>5[c]	>5[c]	5	1		
4	pH_{peak}(cm)	204	50	35	24		
	$pH_{peak>trench}$(cm)	13	0	0	0		
	$pH_{flow/start}$(cm)	no throughflow					

[a] Perched water still present at start of next rain event. [c] Still flowing at start of next rain event. [b] No Type 2 throughflow.

previous rain event (Fig. 3.5) and began to rise about three hours after rain began, followed by the lower site about four hours later. A similar but delayed pattern occurred in the Mod area; upper and mid piezometers responded about seven hours after rain began followed by the lower piezometer about four hours later (Table 3.3).

The amplitude of the change in piezometer levels was greater in the Hi area than in the Mod (Fig. 3.5). In the Hi area, height of peak level was directly related to elevation. In contrast, there was no systematic relationship between pH_{peak} and slope position in the Mod area (Table 3.3). The lowest peak occurred at the mid slope and the highest peak at the lower slope position.

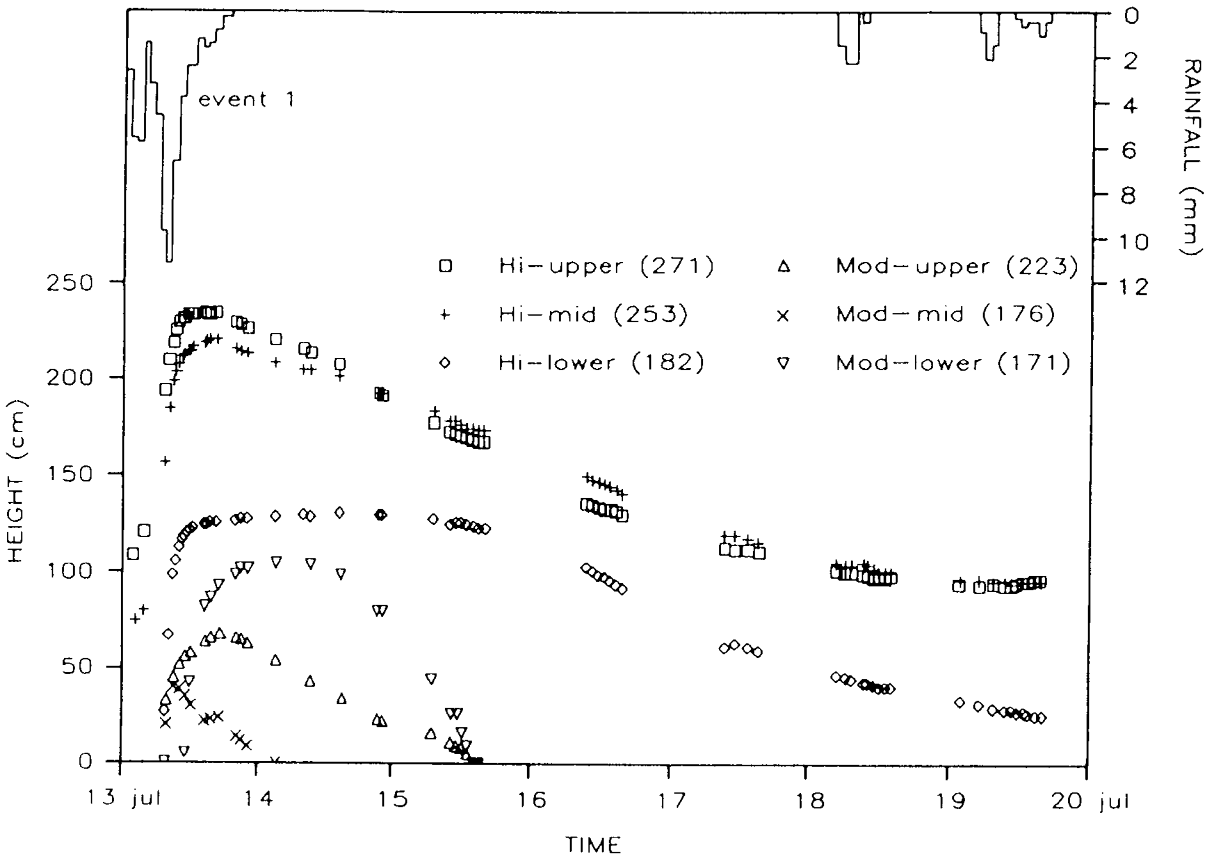

Fig. 3.5. Hourly rainfall distribution (bars) and responses of piezometers (symbols) located at the laterite-clay interface at upper, mid and lower slope positions of high and moderate impact areas infected with *Phytophthora cinnamomi* at Dawn Creek, for the period 13 - 20 July 1985. Number in parenthesis is the depth of each piezometer below ground.

Perching was more prolonged in the Hi than in the Mod area (pT_{end}, Table 3.3). In the Hi area, the piezometer levels were more sustained in the upper and mid slopes than on the lower slope. Duration of perching in the Mod area unlike the Hi, was not related to elevation. Piezometric levels were more prolonged in Mod-upper and lower positions and very transient in the mid slope. Piezometer levels were still raised in the Hi area when a subsequent rain event occurred.

Throughflow

Type 1 throughflow commenced from all trenches about 2 hours after rain had begun when *ca.* 12 mm had fallen; it began earlier than the piezometric response over the sub-laterite clay horizon ($tT1_{start}$, pT_{start}, Tables 3.3,3.4). Type 2 throughflow commenced, after the piezometric response, from all trenches except the one at the Mod-lower position; in the Mod-lower trench throughflow preceded perching by about 2 hours ($tT2_{start}$, Tables 3.3, 3.4). In the Mod area, minor peaks Type 1 in flow occurred at 3:00, 6:00 and 8:00 h when hourly rainfall exceeded about 4 mm (Fig 3.6c).
Similarly in the Hi area, a minor flow peak occurred at *ca.* 3:00 h (Fig. 3.6d). A second and disproportionately larger throughflow component occurred in Mod-lower and all trenches in the Hi area, commencing between 6:00 and 9:00 h ($tT2_{start}$, Table 3.4). The Mod-mid trench had a relatively less pronounced response. In all trenches, Type 2 peak flow occurred after at least 98% of rain had fallen.

Table 3.4. Response of throughflow trenches at upper, mid and lower slope positions in high and moderate impact areas infected with *Phytophthora cinnamomi*, to three rain events at Dawn Creek. Parameters defined in Table 2.2 and Fig. 2.8

Rain event	Parameter	High impact			Moderate impact		
		Upper	Mid	Lower	Upper	Mid	Lower
	$tT1_{start}$(h)	1.7	2	2	2	2.3	1.5
	$tT2_{start}$(h)	6.8	8.2	7.8	-	13.3	7.8
	tT_{peak}(h)	16.5	24.8	34.7	8.5	15	15
1	tT_{end}(days)	2.6	3.3	>5[a]	1.6	1	>5[a]
	tR_{peak}(L/min)	9.3	41.4	48.3	0.2	1.2	11.1
	tV (L)	13,409	115,232	157,520[a,b]	37	441	26,605[a,b]
	$tT1_{start}$(h)	8.5	13	6.5	8.5	8.5	6
	$tT2_{start}$(h)	12.5	16.8	15	-	-	16.7
	tT_{peak}(h)	42.5	48	42.3	11.8	37.5	45.7
2	tT_{end}(days)	3.7	4.4	>5[a]	2.8	2	>5[a]
	tR_{peak}(L/min)	10.8	44	52.6	0.1	0.5	12.8
	tV (L)	13,128	127,659	181,200[a]	23	253	32,980[a]
	$tT1_{start}$(h)	9.3	9.3	9.3	5.8	4.3	4.3
	tT_{peak}(h)	13.7	13.6	9.7	14.7	13.7	13.9
3	tT_{end}(days)	0.9	0.9	0.9	0.9	0.9	0.9
	tR_{peak}(L/min)	2.7	1.5	5.8	0.1	1.5	2.1
	tV (L)	168	80	366	24	180	332

[a] Still flowing at start of next storm. [b] Flowing at start of storm

Type 2 throughflow began in the Hi area at the same time as or sooner than in the Mod sites ($tT2_{start}$, Table 3.4). In the Hi area, $tT2_{start}$ was shortest in the upper slope and longest in the mid slope position. In the Mod area, $tT2_{start}$ was also less in the lower slope than in the mid slope ($tT2_{start}$, Table 3.4).

The magnitude of throughflow was considerably greater in the Hi than in the Mod areas (Fig. 3.6a,b). The ratios between the Hi and Mod areas for corresponding upper, mid and lower slope positions were, for total throughflow: 360, 260 and 5.9, and for peak flow rate: 46, 39 and 3.9 respectively (Table 3.4). In both Hi and Mod areas, total discharge and peak flow were greatest in the lower slope and least in the upper slope positions (tV, tR_{peak}, Table 3.4).

In all trenches including Mod-upper which did not have a Type 2 response, flow continued after rain had ceased (Fig. 3.6a,b). The trenches in the Hi- and Mod-lower slope positions were flowing when this rain event began, and when a subsequent rain event occurred. The duration of flow from trenches in the high impact area was greater than in the Mod area (tT_{end}, Table 3.4). In the Hi area, the duration of throughflow was greatest in the lower slope and least in the upper slope. In the Mod area there was no systematic relationship with elevation. Flow was most sustained in the lower slope and least in the mid slope.

Piezometer levels in the Hi area and in the Mod-lower position, peaked above the level of the deepest outflow draining the corresponding throughflow trench ($pH_{peak>outflow}$, Table 3.3). Although throughflow occurred from trenches at the Mod-upper and mid slopes, pH_{peak} levels were below the level of the trench floors.

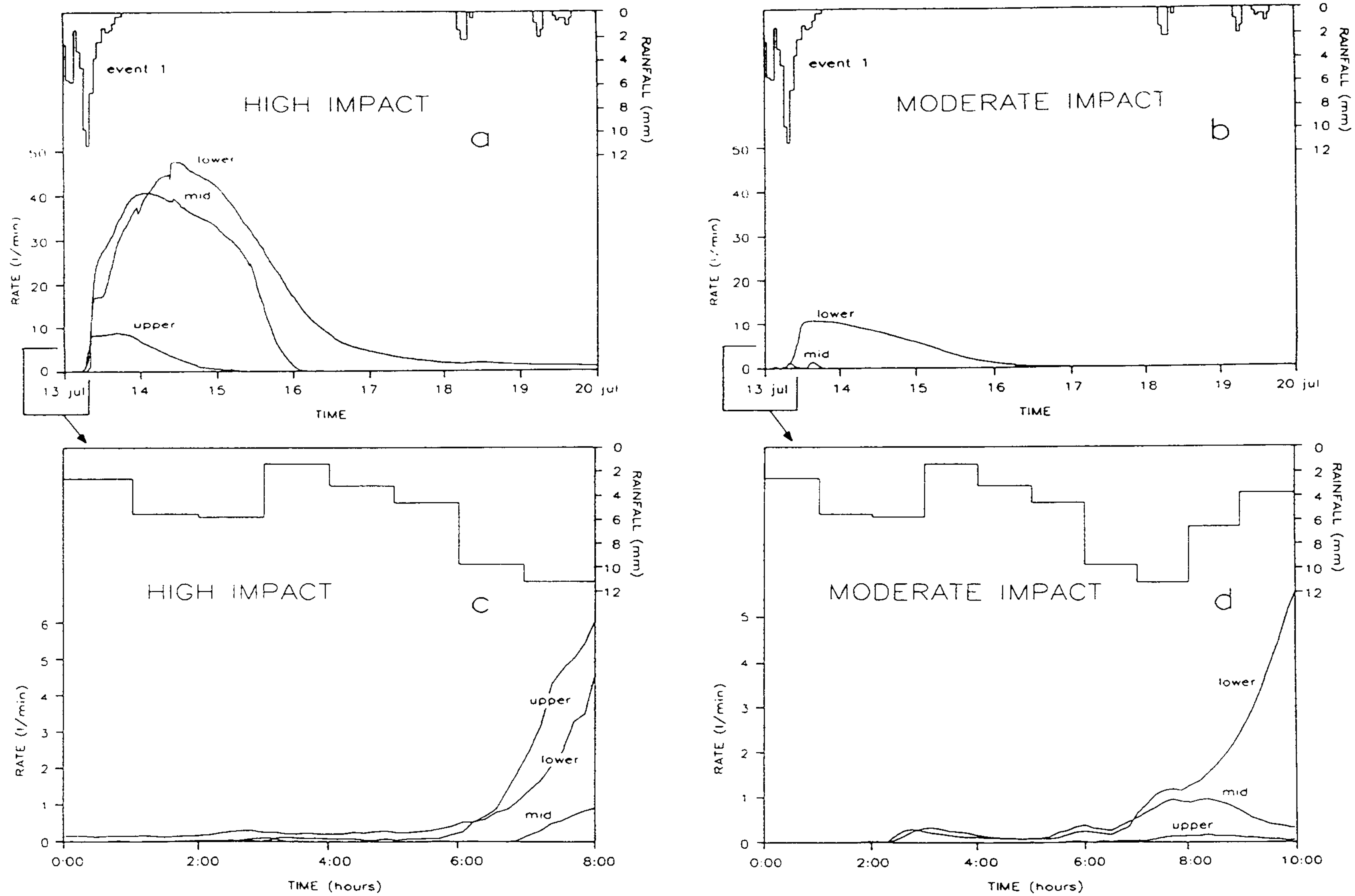

Fig. 3.6. Hourly rainfall distribution (bars) and throughflow (lines) over laterite at upper, mid and lower slope positions of high and moderate impact areas infected with *Phytophthora cinnamomi* at Dawn Creek (throughflow over laterite and clay in mod-lower slope position) for the period 13 - 20 July 1985. Note difference in vertical scales of enlargements (c,d).

There were no consistent relationships between start and end of throughflow, and piezometer levels (tT_{start}, $pH_{flow/start}$, tT_{end}, $pH_{flow/end}$, Tables 3.3, 3.4). Peak throughflow rates and peak piezometer levels did not coincide in time (tR_{peak}, pH_{peak}, Tables 3.3, 3.4). In the Hi area, the duration of throughflow over laterite was longest in the lower slope where throughflow continued after no perched water was evident, in contrast to the upper and mid slope positions where water continued to perch over clay after throughflow had ceased (tT_{end}, pT_{end}, Tables 3.3, 3.4). At Mod-upper, water perched over clay for a few hours after throughflow had ceased. Perching and throughfow were of the same duration at Mod-mid. At Mod-lower, throughflow continued for several days after perched water was no longer evident (Figs 3.5 and 3.6).

C_{total} extended tens of metres above the trenches in the Hi area whereas in the Mod-upper and mid positions, C_{total} extended centimetres from the trench face (Fig. 3.7). In the Hi area, $C_{total/mid}$ and $C_{total/lower}$ were at similar elevations and within 25 metres of the boundary between diseased and healthy forest, however, both extended further upslope than $C_{total/upper}$. In the Mod area $C_{total/lower}$ extended less than half of the distance to the adjacent mid trench position. At the Hi-mid slope there was a greater influx of water as throughflow than had fallen in rain on the catchment area, i.e. $C_{yield/mid}$ > $C_{slope/mid}$. At the Hi-lower slope, $C_{yield/lower}$ was slightly less than $C_{slope/lower}$. In the Mod area, $C_{yield/lower}$ was less than half of $C_{slope/lower}$, and $C_{yield/mid}$ was close to zero.

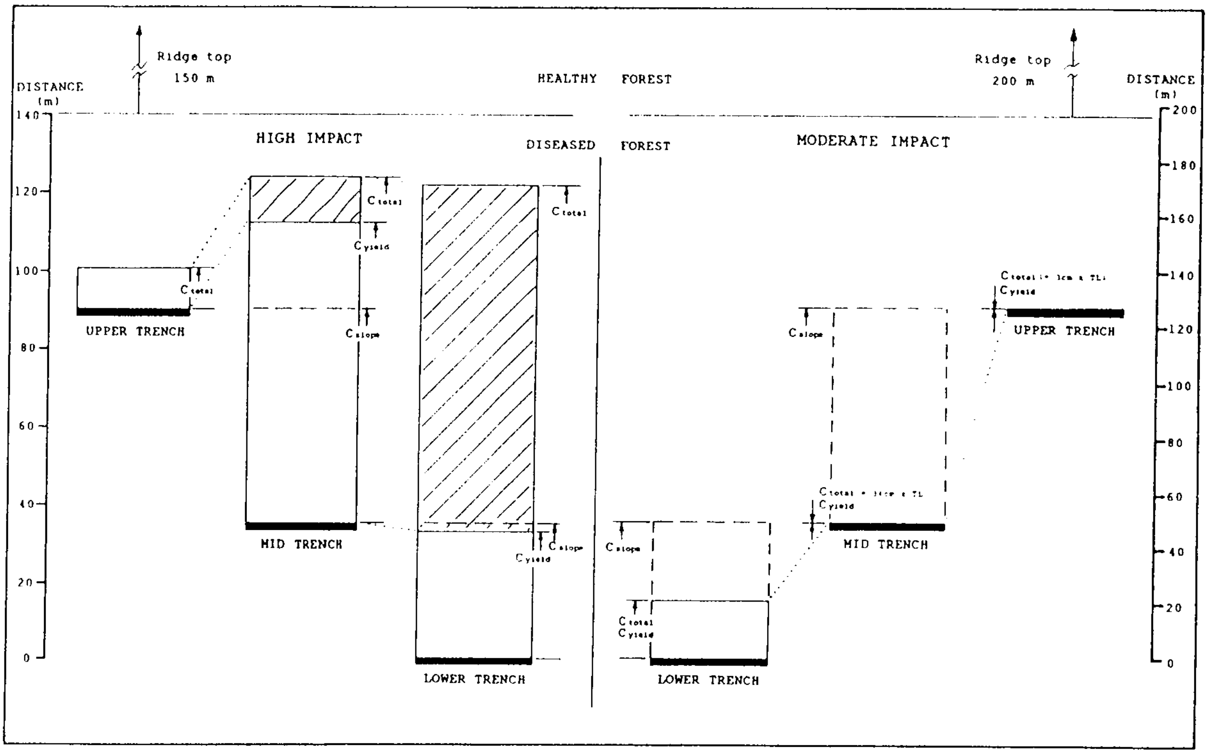

Fig. 3.7. Schematic representation of catchment parameters for throughflow over laterite at upper, mid and lower slope positions of high and moderate impact areas infected with *Phytophthora cinnamomi* at Dawn Creek (throughflow over laterite and clay in mod-lower position), following rain event 1 commencing 13 July 1985. Vertical distances are to scale; horizontal distances not to scale. TL (trench length) = 20 m.

3.3.2 Rain event 2

Piezometers in laterite-clay

Piezometric levels were monitored once daily following rain event 2, allowing only a qualitative assessment of responses. The pattern of relative levels was similar to rain event 1 (Fig. 3.5, 3.8);

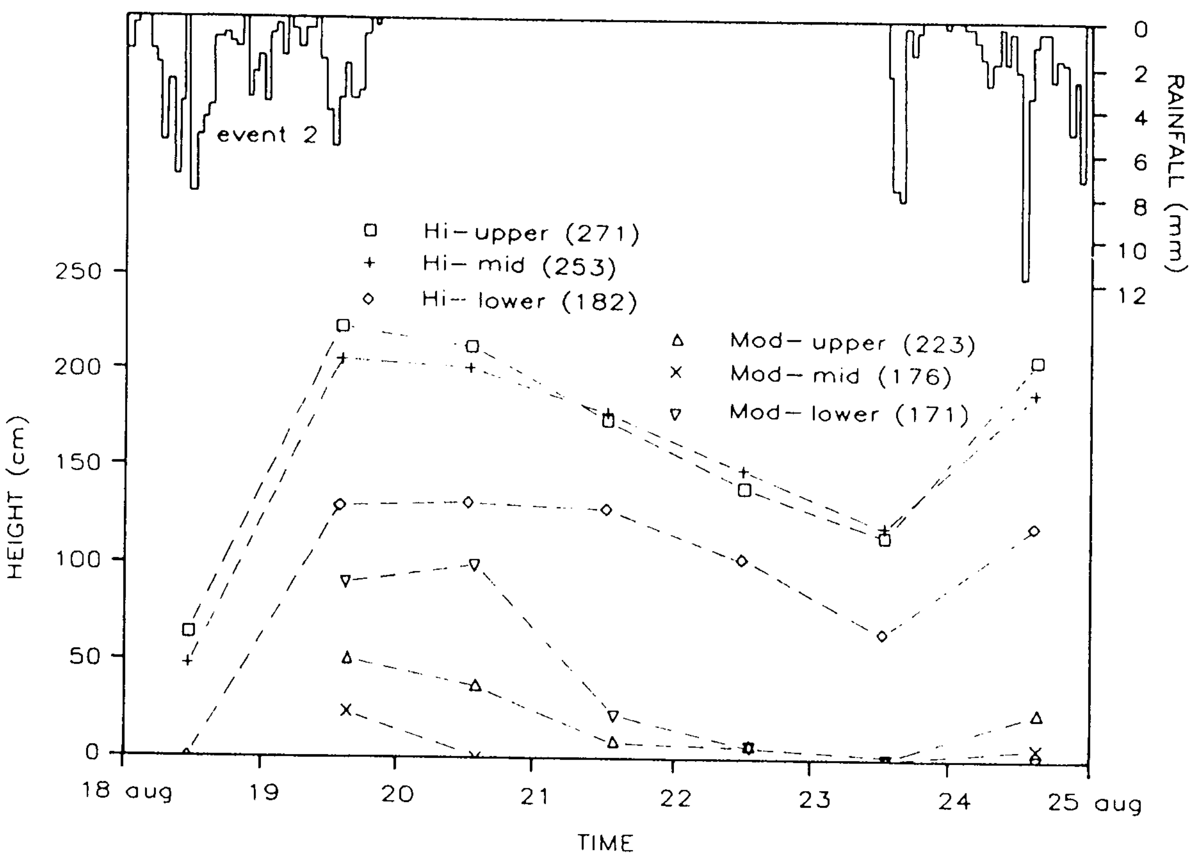

Fig. 3.8. Hourly rainfall distribution (bars) and responses of piezometers (symbols) located at the laterite-clay interface at upper, mid and lower slope positions of high and moderate impact areas infected with *Phytophthora cinnamomi* at Dawn Creek, for the period 18 - 25 August 1985. Number in parenthesis is the depth of each piezometer below ground.

levels were higher and more sustained in the Hi area than in the Mod. In the Hi area, height and duration of perching were directly related to elevation, whereas in the Mod area the lowest and most transient levels occurred at the mid slope position, the highest levels at the lower slope and duration of perching were equal at Mod-upper and lower slope positions.

Throughflow

Types 1 and 2 throughflow occurred from all trenches in response to rain event 2 (Fig. 3.9). At all trenches except Hi-mid, Type 1 throughflow peaked at *ca.* 9:30 and 12:30 h, and coincided with hourly peaks in rainfall exceeding 7mm. Type 2 throughflow commenced at all trenches except Mod-upper and mid, at times between *ca.* 12:30 and 17:00 h ($tT2_{start}$, Table 3.4), and peaked after 99% rain had fallen (Fig. 3.9). Individual flow peaks at Mod-mid occurred at 23:00 (18/8), 2:00, 13:00 and 17:00 h (19/8), however, since they all coincided with periods of intense rainfall and their peak values were in the same range as those occurring earlier, they are considered to be predominantly Type 1 flow.

Type 1 throughflow had commenced at all sites, except Hi-mid, within 8½ h after rain began and after 15 mm of rain had fallen ($tT1_{start}$, Table 3.4).

The lag time to Type 2 throughflow was less in the Hi-lower than in the Mod-lower slope positions ($tT2_{start}$, Table 3.4). In the Hi area, Type 2 flow began first in the upper slope, followed in order by the lower slope and the mid slope - the same pattern that occurred for rain event 1.

The magnitude of throughflow was greater in the Hi than in the corresponding trenches in the Mod area (Fig. 3.9). Ratios of total discharge and peak flow rate between the corresponding upper, mid and lower slopes were: 570, 504 and 5.5, and 108, 88 and 4.1 respectively (Table 3.4). Although more rain fell in event 2 than event 1, there was not a proportionate increase in peak flow rates or total discharge. In Mod-mid and upper, and Hi-upper trenches, there was less throughflow from rain event 2 than from event 1.

In both Hi and Mod areas, total discharge and peak flow were inversely related to elevation as they were for event 1 (tV, tR_{peak}, Table 3.4).

Flow continued from all trenches after rain had ceased (Fig. 3.9). The duration of throughflow following event 2 was longer than for event 1 (tT_{end}, Table 3.4). Hi- and Mod-lower trenches were still flowing at the start of a subsequent storm, 5 days later.

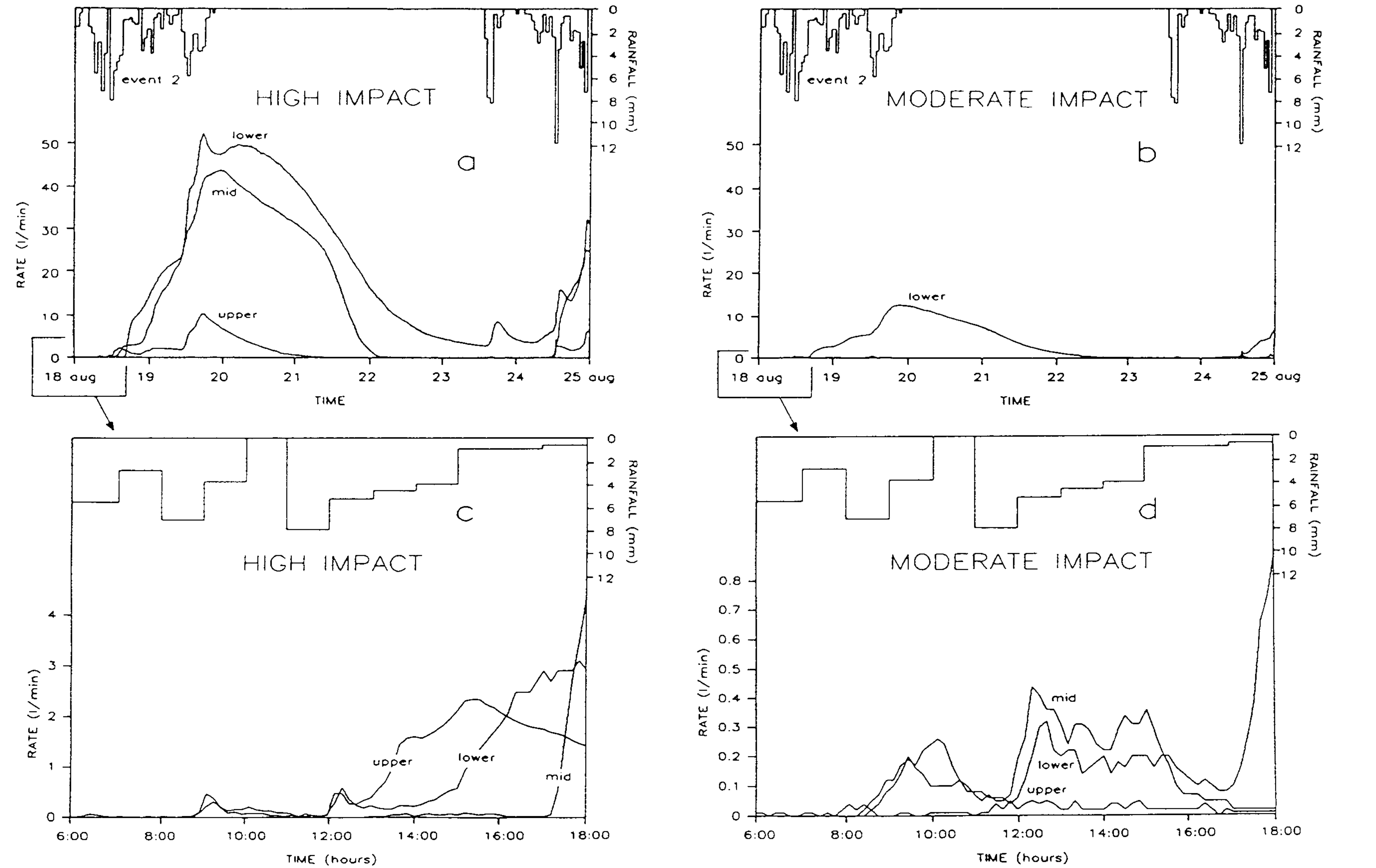

Fig. 3.9. Hourly rainfall distribution (bars) and throughflow (lines) over laterite at upper, mid and lower slope positions of high and moderate impact areas infected with *Phytophthora cinnamomi* at Dawn Creek (throughflow over laterite and clay in mod-lower slope position) for the period 18 - 25 August 1985. Note difference in vertical scales of enlargements (c,d).

The relative size of C_{total} between all trench positions was similar to event 1, however, C_{total} and C_{yield} for event 2 were less than for event 1 (Fig. 3.10). As for event 1, the $C_{yield/mid} > C_{slope/mid}$ and $C_{yield/lower}$ was slightly less than $C_{slope/lower}$.

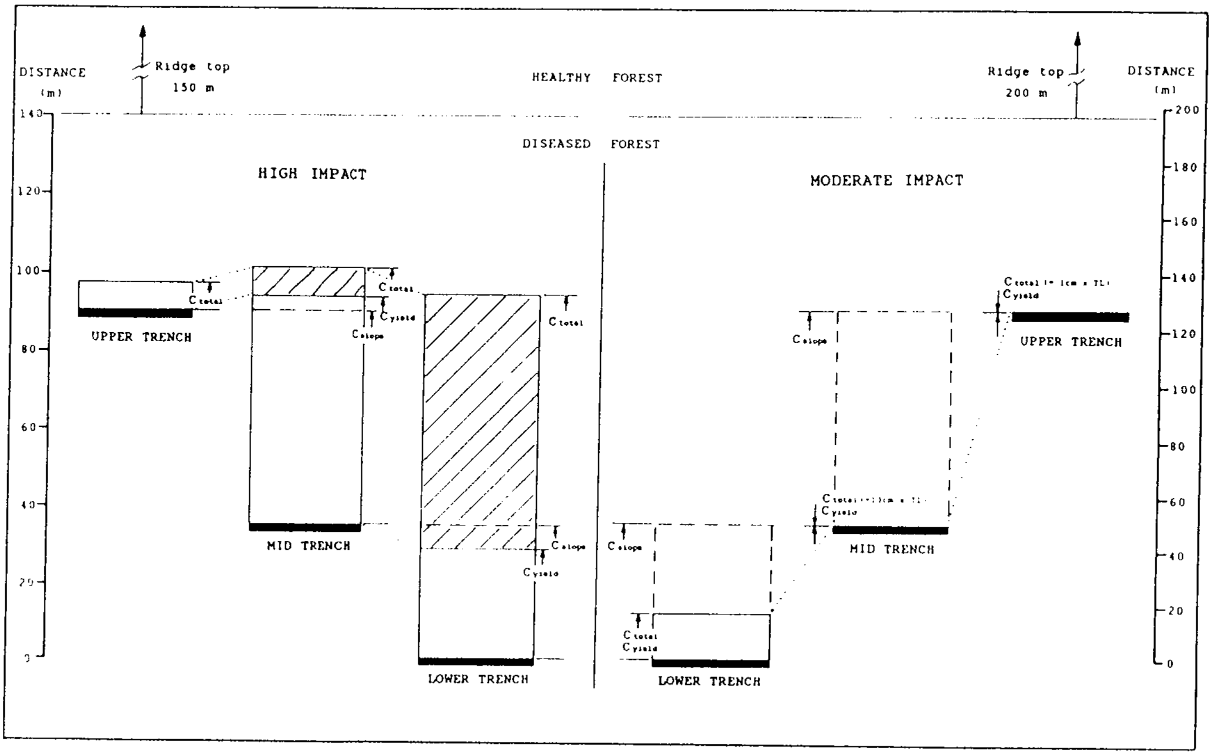

Fig. 3.10. Schematic representation of catchment parameters for throughflow over laterite at upper, mid and lower slope positions of high and moderate impact areas infected with *Phytophthora cinnamomi* at Dawn Creek (throughflow over laterite and clay in mod-lower position), following rain event 2 commencing 18 August 1985. Vertical distances are to scale; horizontal distances not to scale. TL (trench length) = 20 m.

3.3.3 Rain event 3

Piezometers in laterite-clay

There was no piezometric response immediately following rain event 3, but Hi-upper rose to a peak of 35 cm two days after 21 mm of rain had fallen and seven days after event 3.

Throughflow

Throughflow occurred at all trenches in response to rain event 3, (Fig. 3.11), however, unlike the response to rain event 1 which was of similar duration and total rainfall (Table 3.1), all hydrographs were dominated by the Type 1 response. Peaks in flow corresponded with periods of intense rainfall and flow from all trenches had ceased within 3 hours after rain had stopped (Fig. 3.11). However, peak flow rates were greater than for the Type 1 peaks in events 1 and 2 (Figs 3.6c,d, 3.9c,d, 3.11c,d).

Peak flow rates and total discharge were mostly greater in the Hi than in the Mod areas (tR_{peak}, Table 3.4). However, the relative difference between Hi and Mod was much less than for events 1 and 2. Ratios between Hi and Mod sites for corresponding upper, mid and lower slope positions were, for volume: 7, 0.4 and 1.1, and for peak flow rate: 27, 1 and 2.8.

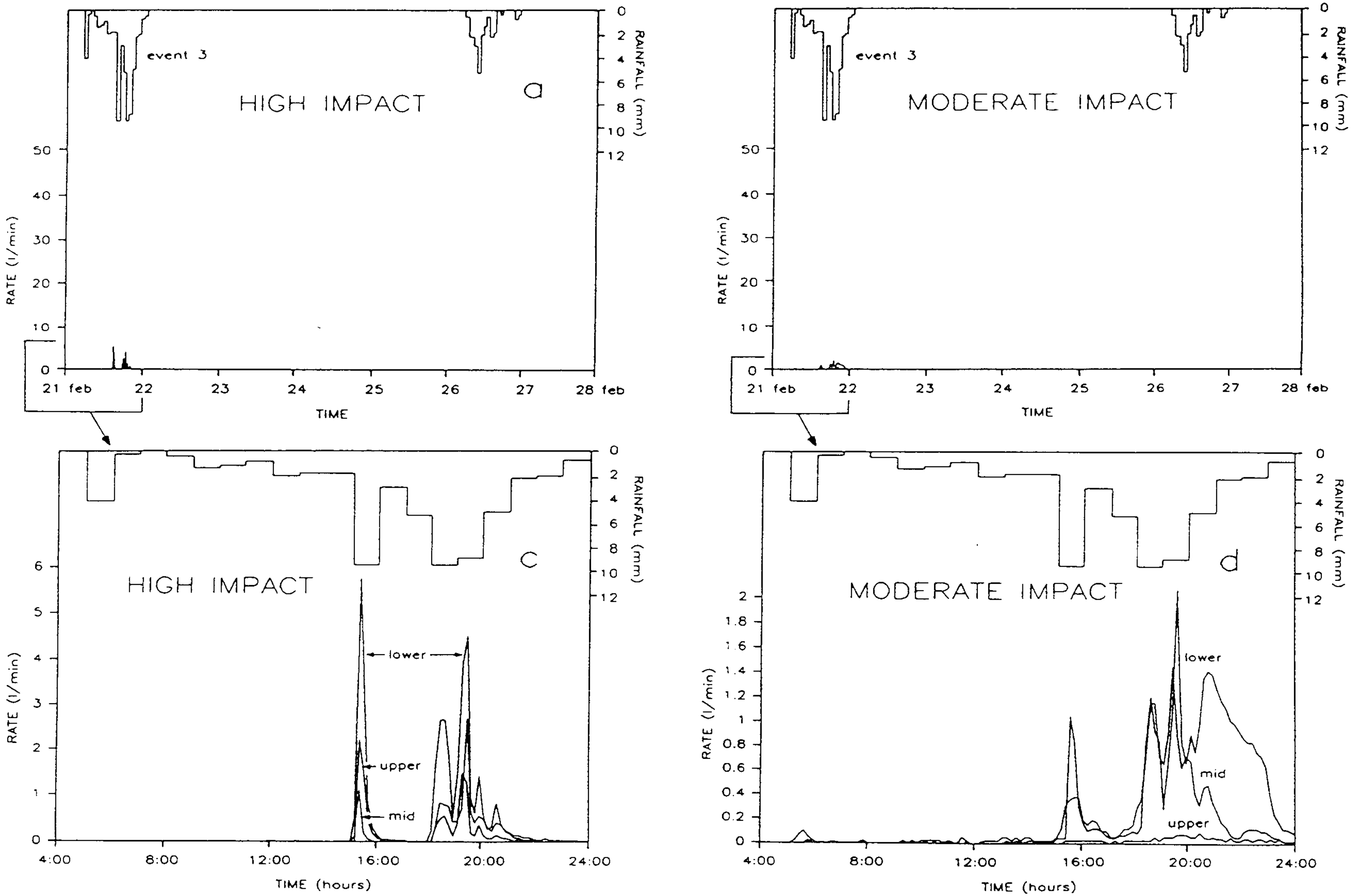

Fig. 3.11. Hourly rainfall distribution (bars) and throughflow (lines) over laterite at upper, mid and lower slope positions of high and moderate impact areas infected with *Phytophthora cinnamomi* at Dawn Creek (throughflow over laterite and clay in mod-lower slope position) for the period 21 - 28 February 1986. Note difference in vertical scales of enlargements (c,d).

Unlike events 1 and 2, C_{total} extended centimetres from all trenches and hence C_{yield} was close to zero relative to C_{slope} (Fig. 3.12). For Mod-mid and upper, C_{total} was similar for all three rain events (Figs 3.7, 3.10, 3.12).

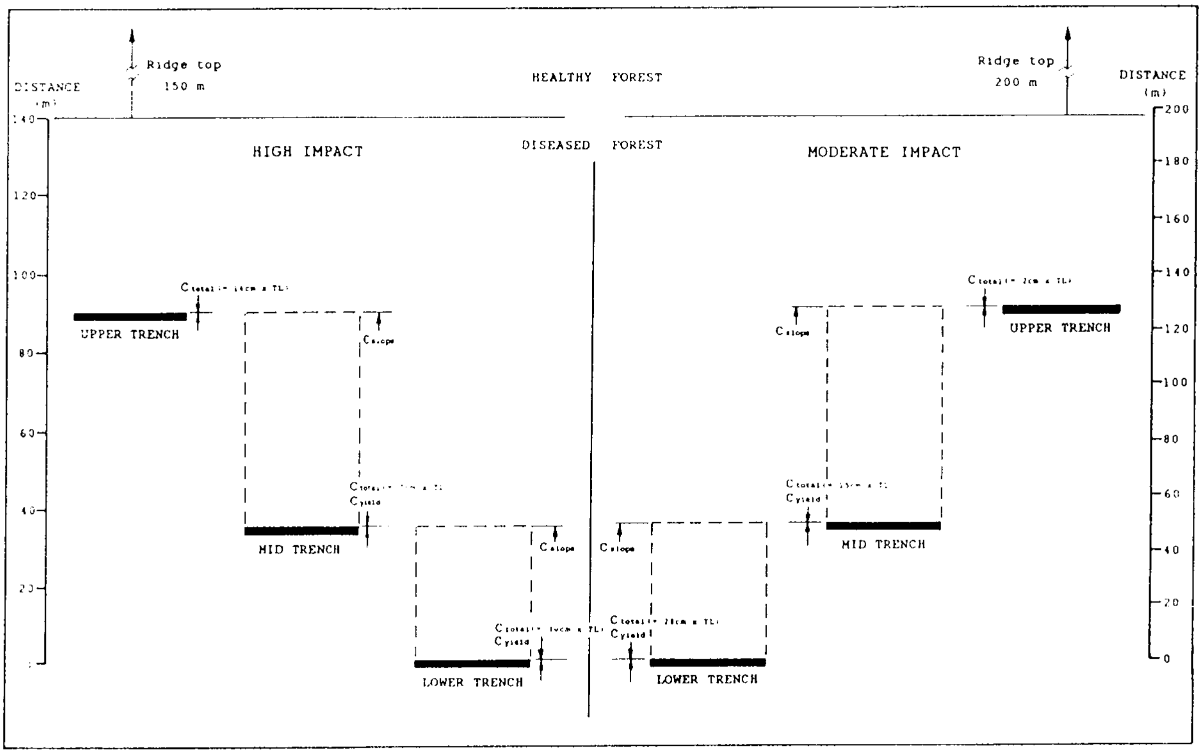

Fig. 3.12. Schematic representation of catchment parameters for throughflow over laterite at upper, mid and lower slope positions of high and moderate impact areas infected with *Phytophthora cinnamomi* at Dawn Creek (throughflow over laterite and clay in mod-lower position), following rain event 3 commencing 21 February 1986. Vertical distances are to scale; horizontal distances not to scale. TL (trench length) = 20 m.

3.3.4 Rain event 4

Piezometers in laterite-clay

In this event, ARI was lower than for events 1 and 2, rainfall was the least intense of all rain events and lag time to start and peak piezometric responses were longer than for events 1 and 2 (Tables 3.1, 3.3). No perching was evident at the mid and lower slopes of the Mod area. As for event 1, Hi-upper and mid piezometers responded sooner than Hi-lower (pT_{start}, Table 3.3).

As for rain event 1, peak levels in the Hi area were directly related to elevation (pH_{peak}, Table 3.3). pH_{peak} was greater in the Hi than in the Mod area. The size of all responses was less than for event 1, but disproportionately more so in all piezometers except that at the Hi-upper position.

The peizometer levels in the Hi areas were sustained for over 3 days after which further rain again increased the levels (Fig. 3.13). In the Mod-upper slope position, water remained in the piezometer for one day.

Throughflow

No throughflow occurred in response to event 4 even though pH_{peak} at Hi-upper was, at 204 cm, above the level of the deepest outflow draining the throughflow trench for about 9 hours. The rate of throughflow from the Hi-upper trench in event 1 when the piezometer level was at 204 cm, was 3.2 L/min.

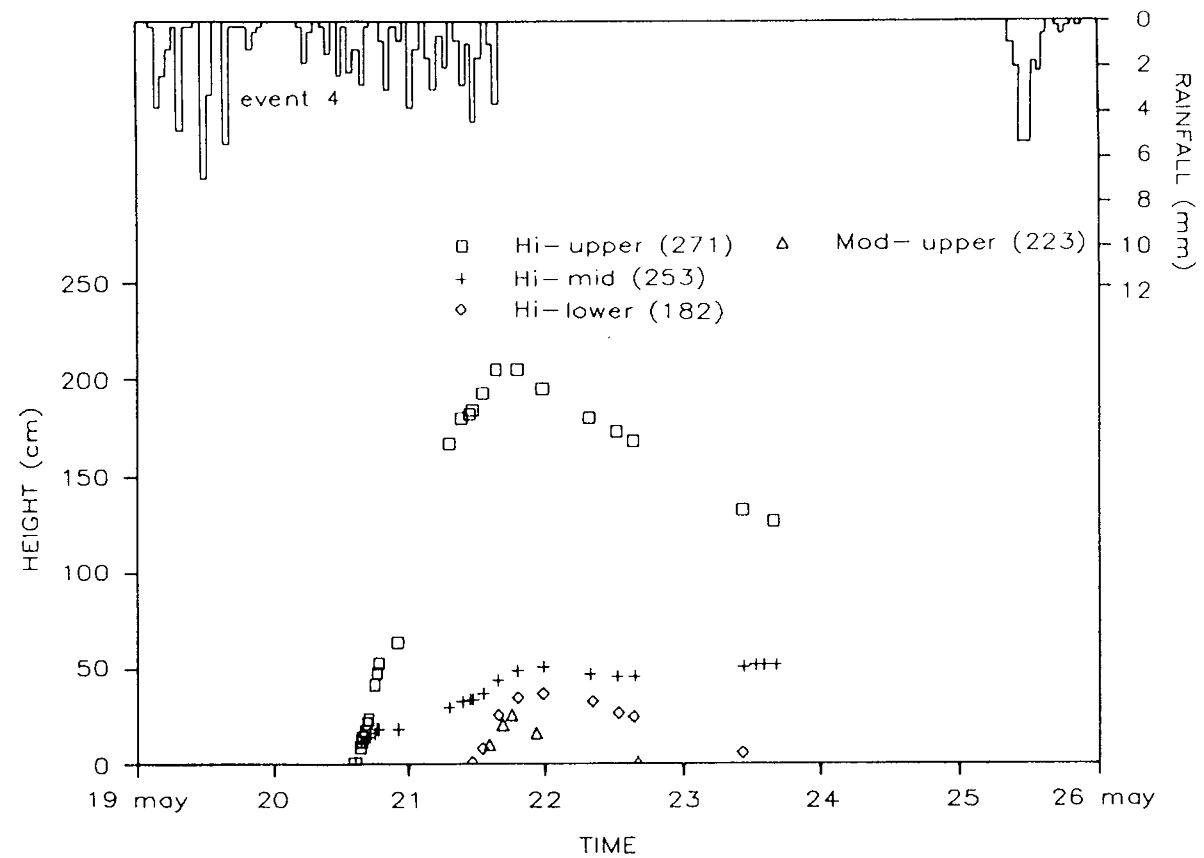

Fig. 3.13. Hourly rainfall distribution (bars) and responses of piezometers (symbols) located at the laterite-clay interface at upper, mid and lower slope positions of high and moderate impact areas infected with *Phytophthora cinnamomi* at Dawn Creek, for the period 19 - 26 May 1986. Number in parenthesis is the depth of each piezometer below ground.

3.3.5 Piezometers in Clay

On no occasion during the four rain events, was any water present in the deep piezometers. However, from early September to late October the water level in the Hi-lower piezometer remained at around 30 $\pm$ 10 cm.

3.4 Inoculum in Water Samples

Phytophthora cinnamomi was present in subsurface water in winter, autumn and summer (Fig. 3.14). Inoculum was recovered from throughflow above the laterite and in water perched on the clay horizon, but was more prevalent in the Hi than in the Mod area and above the laterite compared with above the clay horizon.

In the Hi areas, inoculum was present at most times that throughflow over laterite occurred. Less throughflow occurred in the Mod area and proportionately less inoculum was recovered. Recoveries of *P. cinnamomi* in throughflow were consistently high at all slope positions in the Hi area, whereas in the Mod area, recoveries increased with distance downslope.

During winter, from water samples collected above the laterite-clay interface, there were no recoveries of inoculum from Hi-upper and mid slopes and Mod-mid slope

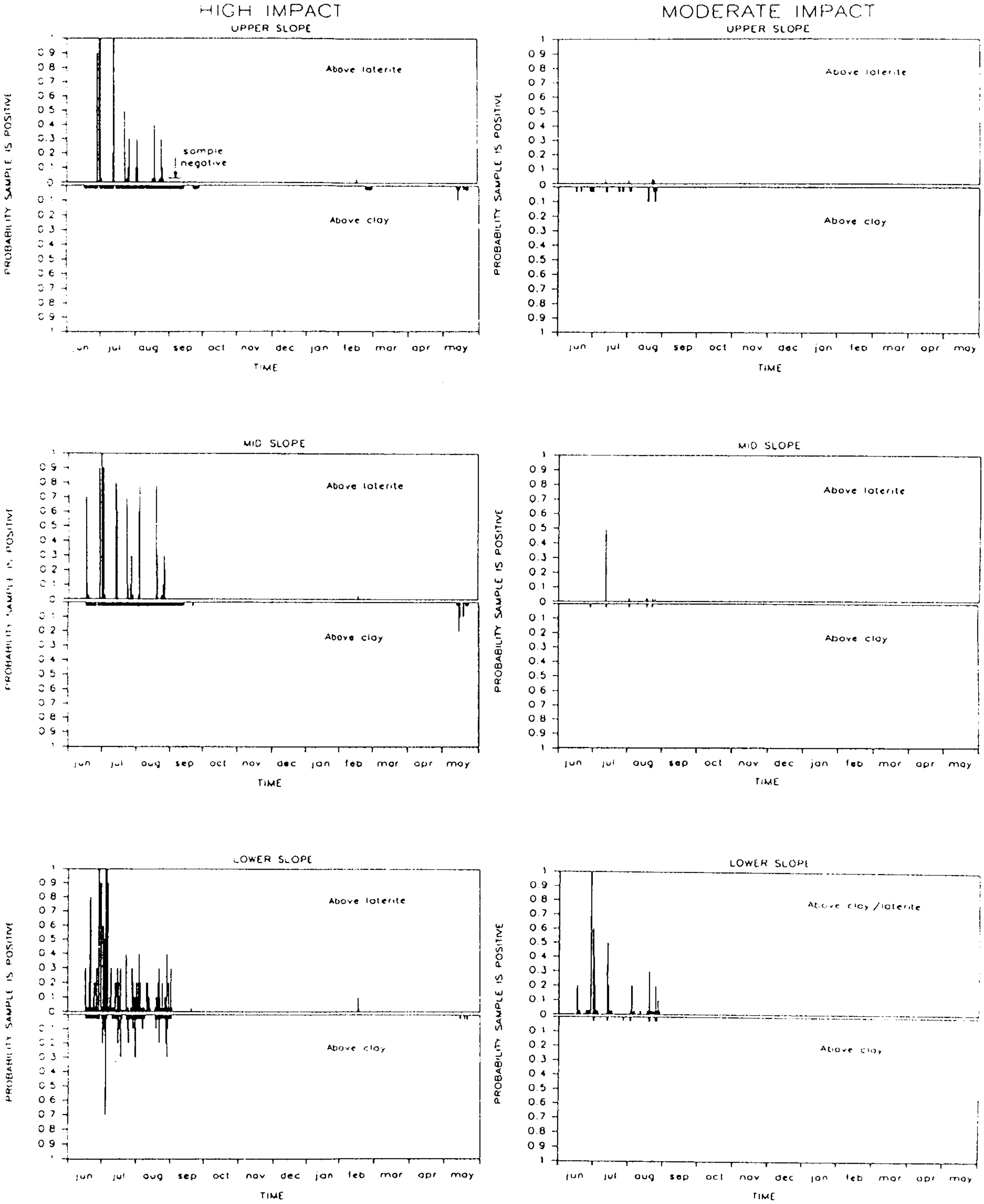

Fig. 3.14. Recovery of inoculum of *Phytophthora cinnamomi* from subsurface water above laterite and at the laterite-clay interface at upper, mid and lower slope positions of high and moderate impact areas at Dawn Creek for the period June 1985 to May 1986. A bar with height 0.02 indicates that a water sample was negative.

positions; about half of the samples from Hi-lower and Mod-lower, at up to 1.8 m in depth, were positive; and a very low frequency from the Hi-upper were positive. In May, water was sampled from above the clay only in the Hi area. There was a low recovery of inoculum from Hi-upper and mid and none from Hi-lower.

Chapter 4

DISCUSSION

4.1 Introduction

Ideally, the comparisons should be made between areas of healthy forest which, if they were to become infected with *P. cinnamomi*, would be high (Hi) and moderate (Mod) impact respectively. The areas of forest chosen for comparison were already affected by disease since at the time of starting the project it was not possible to accurately predict the potential impact of *P. cinnamomi* on healthy forest. There is potentially a problem in separating the confounding influence of disease impact from the influence of physical characteristics, on the hydrological behaviour of the site. However, very large differences in hydrological behaviour between the Hi and Mod areas have been observed and are due in part to the physical characteristics of the laterite profile which are clearly independent of the influence of the disease. This is discussed in detail in the following sections.

4.2 Perching and Throughflow

Within both Hi and Mod areas, the volume of throughflow increased with distance downslope indicating a cumulative effect of distance on throughflow. However, the relative timing of perching on sandy clay and throughflow over laterite between slope positions within each impact area, were not consistent with studies of throughflow on other hillslopes. For example, Weyman (1973) and Mosley (1979) observed that throughflow on a hillslope with a shallow, relatively impervious layer was accompanied by a saturated wedge, increasing in depth at the base of the slope as it received flow from upslope. If throughflow at Dawn Creek developed similarly, the piezometric response and the rising limb of the main throughflow hydrograph would commence first at the slope base and last at the upper slope position as the saturated wedge extended upslope. When the zone of saturation had reached its maximum distance upslope, maximum discharge from each trench should occur simultaneously and piezometer height would be at its greatest, but with height proportional to discharge. Clearly, the hydrological responses at Dawn Creek were not as simple as the pattern above and indicate that the permeability of the laterite profile is not uniform over the landscape.

The variation in hydrological response between and within impact types may be explained by differences in the infiltration capacity of the laterite profile. At Dawn Creek, the discontinuities in the laterite, determined by probing, corresponded with cracks between duricrust boulders or gravel-filled channels passing through the laterite in the trench floors exposed by excavation, and suggest pathways for rapid preferred flow through the laterite (Dell *et al.*, 1983). The most rapid, most sustained and highest piezometric levels occurred in the Hi area which had markedly fewer vertical breaks in continuity of the laterite than the Mod area. Water percolating through a laterite profile moves rapidly through the soil overlying the laterite (Loh *et al.*, 1984) and follows gravel-filled vertical cracks or channels between massive duricrust boulders. (Dell *et al.*, 1983; Johnston *et al.*, 1983).

Within both Hi and Mod areas, the piezometers that were the earliest to respond and were the most sustained, were in the upper slope position where the clay textures were the finest. The most delayed in onset and the most transient piezometric responses were in the Hi-lower and Mod-mid positions where the clay textures were most coarse. The infiltration capacity of a soil is partly determined by its porosity (texture and structure) hence a fine-textured soil has a lower infiltration capacity than a coarse-textured soil (Hewlett, 1982).

Water percolating through the laterite may pass rapidly down to the permanent table table through vertical gravel-filled channels, bypassing the relatively impermeable clays. Excavation through unconsolidated laterite revealed gravel-filled channels passing through the laterite and continuing into the mottled clays and support similar observations by Dell *et al.* (1983). The greater frequency of discontinuities in the laterite surface in the Mod area than in the Hi, may represent a greater number of vertical channels continuing through the laterite and into the clay and acting as paths for rapid preferred flow through the clay.

The time to onset and the size of the piezometric responses in both Hi and Mod areas to all four rain events was directly related to the antecedent rainfall index. The infiltration capacity of a soil is determined, in part, by its antecedent water content and decreases with an increase in soil water content (Hewlett, 1982). Since the moisture retention characteristic of a soil is influenced by texture, a fine-textured soil will drain less freely following rain than a coarse-textured soil. The presence of a sustained perched aquifer in the Hi area increased the probability that moderately intense rain events would result in throughflow over laterite.

Rainfall intensity was not consistently related to the magnitude of perching and throughflow between seasons and may possibly be more important for very intense events. Even though event 3 in summer was atypically intense, no perching on clay was evident. However, throughflow over clay and laterite occurred following event 1 in winter which was of similar total and intensity to event 3 but when antecedent soil moisture was higher.

There was a greater potential for storage of infiltrating water in the Mod area where there was a larger volume of porous laterite and of soil overlying the laterite, than in the Hi area. This would delay the onset and reduce the extent of perching in the Mod area. However, since saturated flow may occur through macropores, thus bypassing an either dry or moist soil matrix (Beasley, 1976; Bonell *et al.*, 1982), it is possible that the antecedent moisture status of the clay profile is more important than the topsoil in initiating perching.

At all trench locations, the timing and intensity of Type 1 flow corresponded very closely with rainfall and commenced earlier than the response of the piezometers at the laterite-clay interface. Type 1 flow is probably derived from flow over the ground surface and subsurface flow on the surface of relatively shallow, broad areas of duricrust upslope from and continuous with the trenches. Type 1 flow peaks were highest in event 3 in summer when surface soils were driest and hence unsaturated hydraulic conductivity was least. To establish the extent of overland flow, a shallow gutter installed immediately upslope from the trenches would separate the contributions of flow over the ground surface from subsurface flow. The effective contributing area for Type 1 flows, however, was relatively small, extending less than a metre from the trenches.

The presence of a zone of saturation within the profile is an indication that the infiltration capacity of the clay has been exceeded. The saturated zone flows downslope over the sandy clay or through cracks between duricrust blocks and is evident as Type 2 throughflow when the thickness of the zone of saturation rises through the laterite above the level of the trench floor.

There is evidence that the aquifer perched on the clay in the upperslope position was confined between relatively impermeable clay and duricrust horizons and hence separate from the aquifer in the duricrust. The piezometric response in the Hi-upper position was earliest and most sustained and, following rain event 4 when the piezometric level was above the level of the trench floor, no throughflow occurred in the upper trench. Type 2 throughflow in the Hi-upper position may occur following the development, and rapid increase in thickness, of a saturated zone within the laterite in a relatively small number of narrow cracks between duricrust blocks. This supports the role of areas of massive duricrust high in the landscape in initiating perching and throughflow, suggested by Shea *et al.* (1982) and Dell *et al.* (1983). At lower elevations in the Hi area and throughout the Mod area, it appears that the sandy clay horizon is most important in initiating perching and throughflow. The early onset of perching in the Hi-upper slope position may increase the probability of perching downslope where perching is delayed.

The trenches in all positions except Mod-lower were located above the laterite and did not intercept throughflow that occurred above the sandy clay and in cracks between duricrust blocks. The further upslope extent of $C_{total/mid}$ and $C_{total/lower}$ than $C_{total/upper}$ in the Hi area, suggests that throughflow passed beneath the level of the upper slope trench floor. The steep rising limb of the Hi-mid throughflow hydrograph indicates rapid flow beneath the trench floor before the saturated zone rose in level above the trench floor. Throughflow occurred over the sandy clay in the Mod-lower slope position and probably also in the Mod-upper and mid positions when the piezometers showed a saturated zone. Throughflow in the Hi area, over the sandy clay or within the laterite, is also likely to occur in response to rain events less intense than events 1 and 2, and where the saturated zone does not extend through the full thickness of the laterite. Clearly, the difference between the throughflow responses in Hi-lower and Mod-lower trenches would be far greater if the Mod-lower trench was located over laterite. The relative contribution of throughflow over the sandy clay beneath the laterite and within and over the laterite would be more readily determined by constructing a throughflow trench on the sandy clay. However, this would require a rock-cutting device that could excavate through duricrust to a depth of at least 2.5 m. No such machine was available at a realistic cost.

Piezometers are more easily installed below laterite than are throughflow trenches, however, they are less able to register the presence of a thin saturated zone than a trench which integrates flow over a larger distance. Throughflow over the sandy clay continued into the Mod-lower trench for several days after there was no water evident in the lower slope piezometer. This difference could also be due partly to the difference in elevation between piezometer and trench.

The laterite-clay interface was unlikely to conform exactly with the ground surface and variation in depth would result in differences in piezometric response. An irregular conformation of the clay surface is suggested by the flow of water over the clay in lateral preferred paths, observed by Johnston *et al.* (1983). A larger number of piezometers in a transect up the slope in each impact type would overcome local variation in soil physical properties. The difficulty in continuously monitoring a large number of piezometers and in detecting shallow, transient piezometric levels, suggest that perching and throughflow in the upper landscape of the Darling Range may be more common than the few published accounts indicate.

The high $C_{yield/mid}$ values in the Hi area may also have resulted from convergent flow to the trench. However, this is unlikely for several reasons: the trench design would be expected to minimize distortion of the throughflow hydrograph; flow occurred in distinctive paths over the laterite surface and from localized seeps in the upper slope trench face; the highest rates of throughflow did not always come from both outer subsections of the trenches. The use of tracers and tensiometer arrays would help to clarify this in future studies.

Vegetation density can affect antecedent soil moisture content. Differences in stand density between the areas may be related to differences in fertility. The Mod area is situated at the more fertile end of the continuum of forest site types, rated by Havel (1975) according to vegetation species which reflect site physical characteristics including fertility. The site-type differences are further exaggerated by the loss of canopy from disease impact. A lower antecedent soil moisture content could be expected in the more fertile Mod area where the denser canopy would result in a reduced net rainfall through interception and a greater soil moisture deficit from transpiration between rain events (Rutter, 1968). Stoneman (pers. comm.) measured a difference in canopy interception of 19% of winter rainfall between a thinned and an unthinned jarrah stand.

In the Hi area, the upper extent at which throughflow was generated is underestimated by $C_{total/mid}$ and $C_{total/lower}$ since flow occurred along lateral preferred paths and since some water would have been lost by infiltration deeper into the profile. It is highly likely that throughflow to the Hi-mid and lower slope trenches originated within healthy forest upslope from the infected area. This suggests that differences in the physical characteristics of the laterite profile may be more important than differences in vegetation density between Hi and Mod areas in initiating perching and throughflow.

4.3 Laterite Profile

The differences in physical characteristics of the laterite profile and in stand density between the Hi and Mod areas at Dawn Creek may have resulted from the influence of two factors on soil profile development: dolerite dykes and soil fertility.

Dolerite dykes

The increasing thickness, hardness and continuity of the lateritic duricrust with distance upslope in the Hi area, suggest a source of iron high in the landscape. The iron content of dolerite (14-18%) is significantly greater than that of granite (2-5%) (Bettenay *et al.*, 1980). Dolerite outcrops and ferruginous laterite above dolerite parent rock may provide iron in solution by lateral movement to contribute to cementation of the laterite in adjacent profiles. Sadleir and Gilkes (1976) attributed the ferruginous duricrust at their study site in Jarrahdale to this process.

The low frequency of channels passing through the laterite at the Hi-upper and mid trench locations suggests that these soil profiles may be derived from dolerite (Dell *et al.*, 1983). The finer clay profiles in the Hi-upper and mid piezometer locations also suggest a possible doleritic origin. Weathering of parent rock occurs around the rigid framework of the relatively resistant quartz grains. Consequently dolerite, with less abundant and finer quartz content (*ca.* 8%), weathers to a clay with finer texture than granitic clay (*ca.* 20% quartz) (Bettenay *et al.*, 1980). This property is reflected in the water retention capacity of the two clay types. Maximum water content of dolerite saprolite (54% by volume) is considerably greater than that of granite saprolite (36%) (Johnston *et al.*, 1983). A more detailed analysis of the soil cores should identify their origin.

Soil fertility

Soil weathering, fertility and vegetation are interrelated. Gravel-filled root channels, passing through the laterite and into lower horizons, apparently result from dissolution of the soil by humic acid produced by roots (Plumb and Gostin, 1973). Downwasting of channel material is followed by backfill from topsoil (Gilkes, pers. comm.). Forest sites at the more fertile end of the continuum recognized by Havel (1975) would be expected to have greater potential for root channel erosion through greater turnover of biomass.

Vegetation may also influence the extent of hardening of laterite. The association between removal or thinning of vegetation and subsequent hardening of laterite is widely documented (Alexander and Cady, 1962). Under reducing conditions the solubility, and hence the extent of leaching, of iron is increased (Petersen, 1971). The most likely source of reducing agents is organic decomposition products; or the iron may be mobilized by the formation of complexes with soil organic matter (Taylor *et al.*, 1983). Jarrah leaf extract was found to be particularly active in solubilizing iron oxides (Bloomfield, 1955). Differences in vegetation density and in turnover of organic matter between Hi and Mod areas over a long time, may be sufficient to ensure different rates of hardening of laterite.

4.4 Inoculum dispersal

The early onset of perching and throughflow in the laterite profile at the upper slope position of the Hi area is significant to the dispersal of *P. cinnamomi*. The probability of inoculum dispersal is increased since even small throughflow events may contribute to ongoing cumulative downslope movement.

The higher levels of *P. cinnamomi* in subsurface water in the Hi area than in the Mod area, reflect both the greater intensity of disease and the more extensive perching and throughflow that occurred in the Hi area. In the Mod-upper and mid slope positions, throughflow was principally Type 1 and hence from a relatively small and shallow catchment area. In the Mod area, the larger number and area of channels passing through the laterite probably lessen the likelihood that individual channels will be shared by roots of jarrah and *B. grandis*. Where both species share root channels, infection of the highly susceptible banksia guarantees a food base for the pathogen and increases the probability of infection of the more resistant jarrah roots.

The recovery of inoculum from subsurface water over clay and laterite suggest that the soil in cracks between duricrust blocks and within vertical channels passing through the laterite is sufficiently porous to permit the passage of *P. cinnamomi*. The absence of inoculum from the laterite clay interface at Hi-upper and mid piezometers throughout winter, when most recoveries above the laterite were positive, is further evidence that the aquifer is relatively confined and that the sandy clay is not sufficiently porous for zoospore movement. It is important to recognize that the water sampled from the piezometer is from a considerably smaller catchment compared with the trenches which integrate flow over a length of 20 m. Mosley (1979) concluded that at a forested site in New Zealand, eluviation along the interface between relatively impermeable gravels and the overlying soil has increased the porosity there. Similarly at Dawn Creek it is likely that the flow paths between and over duricrust blocks in the Hi area are relatively more permeable to fungal propagules than in the Mod area.

Potentially, inoculum may be dispersed over the distance that saturated throughflow occurred. In the Hi area, the upper extent at which throughflow was generated is underestimated by $C_{total/mid}$ and $C_{total/lower}$ since flow occurred along lateral preferred paths and since some water would have been lost by infiltration deeper into the profile. Throughflow occurred over a distance of at least 130 m in the Hi area. The actual extent of movement of inoculum at Dawn Creek is not known and could be determined using labelled zoospores. The rates of peak throughflow in the Hi area reflect a considerable force for propelling propagules through the soil. It is unlikely that throughflow was contaminated by trench soil backfill; the trenches were covered from rain and the graded filters were probably too thick to enable wetting up of the backfill.

The consistent recovery of *P. cinnamomi* at depths up to 1.8 m (and rarely as deep as 2.7 m) in the soil profile means that infection of tree roots is possible at these depths. Oxygen tensions at depth in the soil profile are not known, however, germination of zoospores and initial germ tube growth is unaffected by anoxic conditions (Davison and Tay, 1986). In mid winter, the temperature of the soil profile in the Hi area increased with depth to *ca.* 15°C at 2 m (Shearer pers. comm.). It has generally been assumed that because 15°C was the limit below which sporulation of *P. cinnamomi* does not occur, that disease development in the jarrah forest was limited at lower temperatures (Shea, 1975). However, below 15°C, infection by *P. cinnamomi* is possible (Zentmyer, 1981; Shew and Benson, 1983; Halsall and Williams, 1984) and establishment and growth in host tissues does occur (Shearer *et al.*, 1986). More information is needed on the effect of low temperatures on rates of infection of jarrah in the soil profile.

The fungal propagules are probably either zoospores, encysted from continuous contact with soil particles or chlamydospores. Shea *et al.* (1980) detected very few chlamydospores in jarrah forest soils, however, they only sampled the top 10 cm of soil. The type of propagule recovered in subsurface water at Dawn Creek could possibly be identified by its growth characteristics on agar. The spores may have survived in the profile for several months following rain events in summer or early autumn when soil temperatures were higher. More information is needed on the longevity of spores at depth in the soil in the jarrah forest. If the spores resulted from sporangium production, then it occurred during winter at temperatures lower than previously thought possible (Nesbitt *et al.*, 1979). Studies on sporulation have not investigated the effect of temperatures *in situ* or on the effect of low temperature with time, on rate of sporulation.

Sporangium production is reduced by hypoxic conditions as occur in water, static in pots (Davison and Tay, 1985). However, the oxygen tensions of water perched and moving laterally through a laterite profile is unknown. Unlike static water, it is possible that the action of subsurface throughflow, predominantly through preferred paths, may oxygenate the water sufficiently for sporangium production to occur. The use of the term waterlogged for soils within a perched aquifer on a hillslope (Davison and Tay, 1985, 1986), may be inappropriate and misleading. The term waterlogged is more appropriate to those situations where the water table is close to the ground surface and hence where tree roots are entirely submerged, permanently or for most of the year, and where soil moisture is relatively static. At Dawn Creek, the aquifer above the clay was clearly perched; there was no evidence of a deeper water table within 6 m of the ground surface when perching above clay occurred and hence the root systems of trees on the hillslope were not entirely submerged at any time.

The dispersal of inoculum by Type 2 throughflow over laterite at most times that flow occurred, has important implications in disease epidemiology. Because of their infrequent and unpredictable occurrence, periods of mass collapse of the dominant eucalypt overstorey within a short time span in Western Australia (Shea *et al.*, 1984) and Victoria, have been associated with above average late spring or summer rainfall (Marks and Idczak, 1977; Tregonning and Fagg, 1984). This has led to two alternative hypotheses that seek to explain disease epidemiology in terms of the controlling influence of the environment on either the behaviour of the pathogen or on host physiology. In the first, Weste and Ruppin (1975, 1977) hypothesize that the coincidence of suitable moisture and temperature conditions, following heavy summer rainfall, result in a rapid buildup in soil inoculum potential and thus increased probability of root infection. In the second (Tippett *et al.*, 1986), the increased availability of soil water following summer rainfall on sites with specific hydrological characteristics permits trees to maintain a high tissue water potential. The coincidence of warm temperatures and high inner bark moisture enable fungal lesion extension to outstrip jarrah resistance mechanisms. These results show that above average unseasonal rainfall is not necessary for sustained sporulation and dispersal of *P. cinnamomi* in the laterite profile. The probability of infection of tree roots in the laterite of the Hi area was high throughout an average winter and would be expected to recur each year. The results support the second hypothesis, that mass collapse of jarrah occurs as a result of unrestrained lesion extension triggered by high summer soil moisture status.

4.5 Concluding Remarks

This study has shown the significance of the physical and hydrological properties of the laterite profile to the epidemiology of *Phytophthora cinnamomi* and subsequently to the impact of the pathogen on the jarrah forest. It is important that these properties are quantified at Dawn Creek so that they may be used as diagnostic tools in predicting the impact of *P. cinnamomi* on healthy forest.

The ongoing monitoring of *P. cinnamomi* poulations and of subsurface hydrology at Dawn Creek is highly desirable to determine the behaviour of the pathogen over time and in relation to a wide range of rainfall patterns. Further work is needed to establish the rates of sporulation and infection by *P. cinnamomi* in the soil profile over time.

The important role of the upper slope position in the high impact area in initiating subsurface throughflow emphasizes the need to restrict the potential infection of areas high in the landscape by vehicles, and to minimize activities that would change the hydrologic behaviour of those areas to reduce vertical infiltration of water.

The relative importance of soil physical characteristics and vegetation may be determined by modelling the hydrologic cycle within both impact areas. This has important implications to the management of forest as water catchments.

BIBLIOGRAPHY

Alexander, L.T., Cady, J.G., Whittig, L.D. and Dever, R.F. (1956). Mineralogical and chemical changes in the hardening of laterite. International Congress of Soil Science (6th) Transactions, pp. 67-72.

Alexander, L.T. and Cady, R.J. (1962). Genesis and hardening of laterite in soils. Tech. Bull. U.S. Dep. Agric. No. 1282.,

Atkinson, T.C. (1978). Techniques for measuring subsurface flow on hillslopes. *In*: 'Hillslope Hydrology'. (Ed. M.J. Kirkby.) pp. 73-120. (Wiley: New York.)

Baker, G.F.U. (1975). Darling Range bauxite deposits, W.A. *In* 'Economic Geology of Australia and Papua New Guinea - 1. Metals'. (Ed. C.L. Knight.) Australas. Inst. Min. Metall. Monogr. Ser. 5, pp. 980-986.

Batini, F.E., Hatch, A.B. and Selkirk, A.B. (1977). Variations in level and salinity of perched and semi-confined groundwater tables, Hutt and Wellbucket experimental catchments. Res. Pap. For. Dept. West. Aust. No. 33.

Beasley, R.S. (1976). Contribution of subsurface flow from the upper slopes of forested watersheds to channel flow. *Soil Sci. Soc. Am. J.* **40**, 955-957.

Bettenay, E., Russell, W.G.R., Hudson, D.R., Gilkes, R.J. and Edmiston, R.J. (1980). A description of experimental catchments in the Collie area, Western Australia. CSIRO Aust. Land Manage. Tech. Paper No. 7.

Biggs, E.R., Leech, R.E.J. and Wilde, S.A. (1980). Geology, mineral resources and hydrogeology of the Darling System, Western Australia. *In* 'Atlas of Natural Resources Darling System Western Australia'. Department of Conservation and Environment, pp. 3-20.

Bloomfield, C. (1955). Experimental production of podzolization. *Chem.& Ind. (Rev.)*. **1596**.

Bonell, M., Cassells, D.S. and Gilmour, D.A. (1982). Vertical and lateral soil water movement in a tropical rainforest catchment. First National Symposium on Forest Hydrology, Melbourne, 11-13 May, pp. 30-38.

Churchward, H.M. and Gunn, R.H. (1983). Stripping of deep weathered mantles and its significance to soil patterns. *In* 'Soils: an Australian Viewpoint'. Division of Soils, CSIRO, pp. 73-81. (CSIRO: Melbourne/Academic Press: London).

Davison, E.M. and Tay, F.C.S. (1985). The effect of waterlogging on seedlings of *Eucalyptus marginata*. *New Phytologist* **101**, 743-753.

Davison, E.M. and Tay, F.C.S. (1986). The effect of aeration on colony diameter, sporangium production and zoospore germination of *Phytophthora cinnamomi*. In press.

Dell, B., Bartle, J.R. and Tacey, W.H. (1983). Root occupation and root channels of jarrah forest subsoils. *Aust. J. Bot.* **31**, 615-627.

DSIR (1968). Soil Mechanics for Road Engineers. Dept of Scientific and Industrial Research, Road Research Lab. Her Majesty's Stationery Office, Harmondsworth, Middlesex.

Duniway, J.M. (1976). Movement of zoospores of *Phytophthora cryptogea* in soils of various textures and matric potentials. *Phytopathology*, **66**, 877-882.

Duniway, J.M. (1983). Role of physical factors in the development of *Phytophthora* diseases. *In* 'Phytophthora: its Biology, Taxonomy, Ecology and Pathology'. (Eds. D.C. Erwin., S. Bartnicki-Garcia and P.H. Tsao.) pp. 175-187. (The American Phytopathological Society: St Paul, Minnesota.)

Dunne, T. and Black, R.D. (1970). An experimental investigation of runoff production in permeable soils. *Water Resour. Res.*, **6**, 365-382.

Edwards, I.J., Jackson, W.D. and Fleming, P.M. (1974). Tipping bucket gauges for measuring runoff from experimental plots. *Agric. Meteorol.* **13**, 189-201.

Fausey, N.R. and Hundal, S.S. (1980). Role of trench backfill in subsurface drainage - a review. *Trans. ASAE.* 1197-1200.

Forests Department of W.A. (1982). General Working Plan for State Forests in Western Australia. Working Plan No. 87.

Geidans, L. (1973). Bauxitic laterites of the south western part of Western Australia. *In* 'Pap. W. Aust. Conf. 1973', Australas Inst. Min. Metall. 173-182.

Gisi, U., Zentmyer, G.A. and Klure, L.J. (1980). Production of sporangia by *Phytophthora cinnamomi* and *P. palmivora* in soils at different matric potentials. *Phytopathology*, **70**, 301-306.

Gordon, M., Tracey, J. and Ellis, M.W. (1958). Geology of the Arkansas bauxite region. Geological Survey Professional Paper 259.

Griffin, D.M. (1978). Effect of soil moisture on survival and spread of pathogens. *In* 'Water Deficits and Plant Growth. Vol. V, Water and Plant Disease'. (Ed. T.T. Kozlowski.) pp. 175-197. (Academic Press: New York)

Halsall, D.M. and Williams, J.D. (1984). Effect of root temperature on the development of *Phytophthora cinnamomi* root rot in *Eucalyptus* seedlings. *Aust. J. Bot.* **32**, 521-528.

Havel, J.J. (1975). Site vegetation mapping in the northern jarrah forest (Darling Range). I. Definition of site-vegetation types. Bull. For. Dep. W. Aust. 86.

Havel, J.J. (1979). Identification of vulnerable communities and prediction of disease spread. *In* 'Phytophthora and Forest Management in Australia'. (Ed. K.M. Old.) pp. 64-72. (CSIRO: Melbourne.)

Hewlett, J.D. (1982). 'Principles of Forest Hydrology.' (The University of Georgia Press: Athens, Georgia.)

Hubble, G.D., Isbell, R.F. and Northcote, K.H. (1983). Features of Australian soils. *In* 'Soils: an Australian viewpoint'. Division Soils, CSIRO, pp. 64-72. (CSIRO: Melbourne/Academic Press: London).

Johnston, C.D., Hurle, D.H., Hudson, D.R. and Height, M.I. (1983). Water movement through preferred paths in lateritic profiles of the Darling Plateau, Western Australia. CSIRO, Australia Division of Groundwater Research, Technical Paper No. 1.

Kliejunas, J.T. and Ko, W.H. (1976). Dispersal of *Phytophthora cinnamomi* on the island of Hawaii. *Phytopathology*, **66**, 4457-460.

Knapp, B.J. (1973). A system for the field measurement of soil water movement. Tech. Bull. Brit. Geomorph. Res. Gp. No. 9, 26p.

Loh, I.C., Hookey, G.R. and Barrett, K.L. (1984). The effect of bauxite mining on the forest hydrology of the Darling Range, Western Australia. Water

Resources Branch, Engineering Division, P.W.D. Western Australia. Report No. W.R.B. 73, April, 1984.

McArthur, W.M., Churchward, H.M., Hick, P.T. (1977). Landforms and soils of the Murray River catchment area of Western Australia. CSIRO Aust. Div. Land. Resour. Mgmt Ser. No. 3, pp. 1-23.

McFarlane, M.J. (1983). Laterites. *In*: 'Chemical Sediments and Geomorphology'. (Eds A. Goudie and K.Pye.) pp. 7-58. (Academic Press: New York.)

McKinnell, F.H. (1981). Review of the dieback disease situation 1981. Technical Paper No. 2, Forests Department of Western Australia.

Marks, G.C. and Idczak, R.M. (1977). *Phytophthora cinnamomi* root rot investigations in Victoria: a review with special reference to forestry. Forestry Technical Paper No. 26, December 1977.

Marks, G.C. and Kassaby, F.Y. (1974). Detection of *Phytophthora cinnamomi* in soils. *Aust. For.* **36**(3), 198-203.

Millot, G. (1970). 'Geology of Clays.' (Chapman and Hall: London.)

Mosley, M.P. (1979). Streamflow generation in a forested watershed, New Zealand. *Water Resour. Res.* **15**, 795-806.

Mosley, M.P. (1982). Subsurface flow velocities through selected forest soils, South Island, New Zealand. *J. Hydrol.* **55**, 65-92.

Mulcahy, M.J. (1960). Laterites and lateritic soils in south-western Australia. J. *Soil Sci.* **11**, 206-226.

Mulcahy, M.J. and Hingston, F.J. (1961). The development and distribution of the soils of the York-Quairading area, Western Australia, in relation to landscape evolution. CSIRO Aust. Div. Soils, Soil Publ. No. 7.

Murray, A.M. (1979). Bauxite. *In* 'Mining in Western Australia'. (Ed. R. Prider.) pp. 101-110. (University of W.A. Press: Nedlands, Western Australia.)

Nesbitt, H.J., Malajczuk, N. and Glenn, A.R. (1979). Effect of soil moisture and temperature on the survival of *Phytophthora cinnamomi* Rands in soil. *Soil Biol. Biochem.* **11**, 137-140.

Norton, S.A. (1973). Laterite and bauxite formation. *Econ. Geol.* **68**, 353-361.

Owen, H.B. (1954). Bauxite in Australia, Commonwealth of Australia, Dept. of National Development, Bureau of Mineral Resources, Geology and Geophysics, Bulletin No. 24.

Peck, A.J., Yendle, P.A. and Batini, F.E. (1980). Hydraulic conductivity of deeply weathered materials in the Darling Range, Western Australia. *Aust. J. Soil Res.* **18**, 129-138.

Petersen, U. (1971). Laterite and bauxite formation. *Econ. Geol.* **66**, 1070-1082.

Plumb, K.A. and Gostin, V.A. (1973). Origin of Australian bauxite deposits. Bureau of Mineral Resources, Geology and Geophysics. Aust. Dept. Minerals and Energy. Record 1973/156.

Reeves, R.J. (1975). Behaviour of *Phytophthora cinnamomi* Rands in different soils and water regimes. *Soil Biol. Biochem.* 7, 19-24.

Rutter, A.J. (1968). Water consumption by forests. *In:* 'Water Deficits and Plant Growth, Vol. II, Plant Water Consumption and Response'. (Ed. T.T. Kozlowski.) pp. 23-84. (Academic Press: New York.)

Sadleir, S.B. and Gilkes, R.J. (1976). Development of bauxite in relation to parent material near Jarrahdale, Western Australia. *Geol. Soc. Aust. Jour.* **24**(4), 333-344.

Schrale, G., 1981. The Delta Meter Mk 3: An improved tipping bucket gauge for monitoring tile drain flows. Division of Land Use and Protection, Soil and Water Management Report 11/81. Dept. Agric., South Australia.

Sharma, M.L., Williamson, D.R. and Peck, A.J. (1980). Characterization of soil hydraulic properties of a catchment. *In* 'Land and Stream Salinity Seminar Proc.' Public Works Department of W.A. pp. 23.1-23.3.

Shea, S.R. (1975). Environmental factors of the northern jarrah forest in relation to pathogenicity and survival of *Phytophthora cinnamomi*. West. Aust. For. Dept. Bull. 85.

Shea, S.R., Gillen, K.J. and Leppard, W.I. (1980). Seasonal variation in population levels of *Phytophthora cinnamomi* Rands in soil in diseased, freely drained *Eucalyptus marginata* Sm. sites in the northern jarrah forest of south-western Australia. *Prot. Ecol.* **2**, 135-156.

Shea, S.R., Shearer, B. and Tippett, J. (1982). Recovery of *Phytophthora cinnamomi* Rands from vertical roots of jarrah (*Eucalyptus marginata* Sm). *Aust. Plant Pathol.* **11**(3), 25-28.

Shea, S.R., Shearer, B.L., Tippett, J.T. and Deegan, P.M. (1983). Distribution, reproduction, and movement of *Phytophthora cinnamomi* on sites highly conducive to jarrah dieback in south Western Australia. *Plant Disease*, **67**, 970-973.

Shea, S.R., Shearer, B.L., Tippett, J.T. and Deegan, P.M. (1984). A new perspective on jarrah dieback. Forest Focus, No. 31, July, pp. 3-11. Forests Department of Western Australia.

Shearer, B.L., Shea, S.R. and Deegan, P.M. (1986). Temperature-growth relationships of *Phytophthora cinnamomi* in the secondary phloem of roots of *Banksia grandis* and *Eucalyptus marginata*. *Phytopathology.* In Press.

Shew, H.D. and Benson, D.M. (1983). Influence of soil temperature and inoculum density of *Phytophthora cinnamomi* on root rot of Fraser fir. *Plant Disease* **67**, 522-524.

Sivarajasingham, S., Alexander, L.T., Cady, J.G. and Cline, M.G. (1962). Laterite. *Advan. Agron.* **14**, 1-60.

Stokes, R.A. and Loh, I.C. (1982). Streamflow and solute characteristics of a forested and deforested catchment pair in south-western Australia. First National Symposium on Forest Hydrology, Melbourne, 11-13 May. (Eds E.M. O'Loughlin and L.J. Bren.) Nat. Conf. Publ. No. 82/6, Institution of Engineers, Australia, pp. 60-66.

Taylor, R.M., McKenzie, R.M., Fordham, A.W. and Gillman, G.P. (1983). Oxide minerals. In 'Soils: an Australian Viewpoint'. Division of Soils, CSIRO, pp. 309-334. (CSIRO: Melbourne/Academic Press: London.)

Tippett, J.T., Crombie, D.S. and Hill, T.C. (1986). The effect of phloem water relations on the growth of *Phytophthora cinnamomi* in *Eucalyptus marginata*. In press.

Tregonning, K.C. and Fagg, P.C. (1984). Seasonal rainfall and *Eucalyptus* dieback epidemics associated with *Phytophthora cinnamomi* in Gippsland, Victoria. *Aust. For. Res.* **14**, 219-234.

Tsao, P.H. and Guy, S.O. (1977). Inhibition of *Mortierella* and *Pythium* in a *Phytophthora*-isolation medium containing hymexazol. *Phytopatology* **67**, 796-801.

Weste, G. and Ruppin, P. (1977). *Phytophthora cinnamomi*: population densities in forest soils. *Aust. J. Bot.* **25**, 461-475.

Weste, G.M. and Taylor, P. (1971). The invasion of native forest by *Phytophthora cinnamomi*: I. Brisbane Ranges, Victoria. *Aust. J. Bot.* **19**, 281-294.

Weyman, D.R. (1973). Measurement of the downslope flow of water in a soil. *J. Hydrol.* **20**, 267-289.

Whipkey, R.Z. (1965). Subsurface stormflow from forested slopes. *Bull. Int. Assoc. Sci. Hydrol.*, **10**, 74-85.

Zentmyer, G.A. (1986). *Phytophthora cinnamomi* and the disease it causes. Monogr. 10. Am. Phytopathol. Soc. St Paul. Minnesota.