THE IMPACT ON AGRICULTURE OF THE DRAWDOWN OF SHALLOW WATERTABLES.

VOL I

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SUMMARY.

The promoters of the large groundwater developments implemented in the 1970's paid little attention to the effects of pumping on soil moisture. A field study, conducted in 1979 in the Tern Area of the Shropshire Groundwater Scheme, revealed that significant quantities of the available moisture could be removed from the root zone of vegetation when drawdown of shallow watertables occurred. Arguments to this effect, supported by the field study evidence, were successfully presented at the Shropshire Groundwater Scheme public inquiry.

The aim of this study has been to expand the work which was undertaken in connection with the Shropshire Groundwater Scheme, and to develop a method whereby the effects of groundwater pumping on vegetation can be assessed, and hence the impacts minimised. Two concepts, the critical height and the soil sensitivity depth, formulated during the initial work are at the core of the Environmental Impact Assessment (EIA) method whose development is described.

A programme of laboratory experiments on soil columns is described, as is the derivation of relationships for determining critical heights and field capacity moisture profiles. These relationships are subsequently employed in evaluating the effects of groundwater drawdown.

In employing the environmental assessment technique, digitised maps of relevant features of the Tern Area are combined to produce composite maps delineating the extent of the areas which are potentially sensitive to groundwater drawdown. A series of crop yield/moisture loss functions are then employed to estimate the impact of simulated pumping events on the agricultural community of the Tern Area.

Finally, guidelines, based on experience gained through evaluation of the Tern Area case study, are presented for use in the design of soil moisture monitoring systems and in the siting of boreholes. In addition recommendations are made for development of the EIA technique, and further research needs are identified.

KEY WORDS:

ENVIRONMENTAL IMPACT ASSESSMENT, SOIL MOISTURE, CROP YIELDS, GROUNDWATER ABSTRACTION.

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A special debt of gratitude is owed to my colleague and the Supervisor of the project, Bill Walley, for his unfailing encouragement and guidance. It was as a result of our collaborative work, undertaken prior to the Shropshire Groundwater Scheme public inquiry, that the project came into being. In particular, Bill was responsible for developing two key concepts employed in this work - 'the critical height' and 'the soil sensitivity depth' .

I have reserved the final thanks for my family, who at times must have wondered if I was just a figment of their imagination and questioned whether I really lived with them. Ten years is a long time: without their love, stamina, tolerance and encouragement this thesis would never have come into being - to them, and Diane especially, thank you.

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NOTATIONS.

A	total irrigation application in mm
a	an empirical parameter. In the field capacity moisture profile model it is a function of the soil properties S and BD
A_{vt}	available water
B	moisture benefit
b	an empirical parameter in the field capacity moisture profile model - a function of parameter a
BD, ρ_b	bulk density
C	% clay content of a soil
C	neutron probe count rate prior to air-soil interface correction
CF_0	neutron probe count rate correction factor for air-soil interface
C_{max}	neutron probe count rate at 200mm depth for air-soil interface correction
D	the soil sensitivity depth - maximum water table depth for a soil to be sensitive to groundwater drawdown: *or* volume of moisture remaining in the profile after time t
dD/dt	the drainage rate from a soil column in mm/day
d_r	crop rooting depth
DRT_m	the drawdown response time (days) for the profile to have lost m% of the drainable moisture.
E_w	the fraction of extractable moisture remaining in the crop root zone at a particular point in time
ΣE_a	cumulative actual evapotranspiration
ΣE_p	cumulative potential evapotranspiration
g	acceleration due to gravity
h	height above a water table, matric suction head
hc	saturated capillary fringe
h_o	critical height

k_s	stress factor applied in connection with crop growth
K	unsaturated conductivity
K_s	saturated hydraulic conductivity
m	an empirical parameter
MD	moisture debt in mm days
ML	moisture loss from the root zone in mm
m_s	mass of soil
m_w	mass of water
n	an empirical parameter
PDM	the proportion of drainable moisture remaining at time t
r	coefficient of correlation
R	neutron probe count rate
R_w	neutron probe count rate in water standard
S	% silt content of a soil
S	suction or tension
Sd	% sand content of a soil
S_o	critical tension
t	time
TDR	time of drawdown response
u	an empirical parameter in the drainage rate equation - a function of parameter w
v	rate of discharge per unit area
VD	volume of moisture lost from a profile in draining from saturation to the field capacity profile
w	an empirical parameter in the drainage rate equation - a function of θr
Y	actual crop yield
Yp	potential (maximum possible) yield
z	height above a datum

ΔY	crop yield increase
ΔYD_b	reduction in number of beef cattle supported per ha
ΔYD_c	crop yield decline of cereals in kg/ha
ΔYD_d	loss of milk production in litres per ha
ΔYD_p	crop yield decline of potatoes in tonne/ha
ΔYD_s	crop yield decline of sugar beet in tonne/ha
α	an empirical parameter
ε	total pore space or porosity
Φ	total potential
ϕ	hydraulic potential
ϕ_g	gravitational potential
ϕ_m	matric potential
ϕ_o	osmotic potential
θ_m	moisture content - by mass
θr	residual moisture content
θs	saturated moisture content
θ_v, θ	moisture content - volumetric fraction
ρ_b	bulk density
ρ_s	soil particle density
ρ_w	density of water
Ψ	the reduced water content

Chapter 1. INTRODUCTION.

> "In the middle of the 20th century, we saw our planet from space for the first time. Historians may eventually find that this vision had a greater impact on thought than did the Copernican revolution of the 16th century, which upset the human self-image by revealing that the Earth is not the centre of the universe. From space, we see a small and fragile ball dominated not by human activity and edifice but by a pattern of clouds, oceans, greenery, and soils. Humanity's inability to fit its doings into that pattern is changing planetary systems, fundamentally. Many such changes are accompanied by life-threatening hazards. This new reality, from which there is no escape, must be recognised - and managed."

So begins "Our Common Future", the report of The World Commission on Environment and Development (1987). This document is now frequently referred to as the Brundtland Report, after Gro Harlem Brundtland the Chairman of the Commission and Prime Minister of Norway, and is directed to long-term environmental strategies for achieving sustainable development for the benefit of humankind on a global scale - "a global agenda for change". In the preface to the report Brundtland states:

> "... the 'environment' is where we all live; and 'development' is what we all do in attempting to improve our lot within that abode. The two are inseparable."
>
> (The World Commission on Environment and Development,1987)

This thesis is concerned with one aspect of human exploitation of the environment in the name of development. This is not one of the

> "complex problems bearing on our survival: a warming globe, threats to the Earth's ozone layer, deserts consuming agricultural land";

but none-the-less one which affects peoples all around the globe - the abstraction of groundwater. Poor management of groundwater has caused land to subside, streams to dry up and the degradation of soils through overgrazing and hence to the onset of desertification (Falkenmark and Lindh,1976).

The aspect of groundwater development addressed is the effect of abstraction on vegetation. It is shown that providing soils are in hydraulic continuity with the aquifer, then the drawdown of shallow water tables can affect vegetation growth through the removal of moisture which would otherwise be available. A methodology is developed which enables the impact of a pumping scheme to be evaluated. Strategies are also suggested which, if adhered to in the scheme design, will enable developments to take place for the benefit of people without causing any significant degradation to the environment. The outcomes of the thesis are, therefore, an environmental impact assessment technique and a strategy for certain aspects of groundwater development. By accepting the results of this research any threat to the flora within the environment can be

"recognised - and managed"

- as demanded in the opening paragraph of Our Common Future.

1.1 THE ORIGINS OF THE PROJECT.

The need for research into the effects of groundwater drawdown upon available soil moisture first became apparent through involvement in the Shropshire Groundwater Scheme public local inquiry. Interest in this scheme was aroused as the result of a paper presented in 1978 at a meeting of the Midlands section of the Institution of Civil Engineers (Sharp, 1978b). This meeting was attended by the author and Mr. W.J. Walley - both of the Department of Civil Engineering at Aston University.

In the course of the presentation Sharp stated that there would be no adverse effects on agriculture through loss of soil moisture when drawdown of the water table occurred during pumping operations. Walley disagreed. He believed that the effects could be significant, particularly where shallow water tables existed. He later approached Severn Trent Water Authority with a view to carrying out a joint research project into the problem, but his invitation was declined.

An interested party subsequently put Walley in touch with farmers in the Shropshire area who were concerned about the proposed development. An agreement was reached whereby the farmers would jointly fund an investigation with the Department of Civil Engineering. The Water Authority agreed to the use of three of their borehole sites, subject to their being reimbursed for the pumping costs, and in 1979 a field study was undertaken to investigate the relationship between groundwater drawdown and soil moisture.

The local public inquiry into the Shropshire Groundwater Scheme was conducted during September 1979 in Shrewsbury. Walley's evidence (Walley, 1979), presented on behalf of a group of 39 farmers objecting to the scheme, was founded on the inadequacy of the work relating to soil moisture carried out by the Water Authority, and on the results of the field study. The arguments tendered were strong enough to force the Authority to reorganise their plans for the phased development of the scheme during the course of the inquiry. The inspector presented his report to the Secretary of State for the Environment in March 1980, and approval for the full development of the scheme was given in May 1981.

The evidence presented at the inquiry showed that knowledge about the effects of groundwater drawdown upon soil moisture in the unsaturated zone above the water table was very limited. The inspector was sufficiently concerned that he recommended that a monitoring programme should be conducted in the most sensitive area, not only to investigate the effects of pumping on soil moisture, but also to assess the effect on crop yields (Gray, 1980).

The author continued to monitor soil moisture at one of the three field sites in Shropshire, after pumping had stopped, in order to study the changes that occurred as the water table recovered to its original level. This work ceased in August 1980 when the farmer concerned no longer showed interest in the project.

The theoretical background, upon which the initial rejection of Sharp's statements and the field study were based, is presented in Chapter 4 of the thesis. Following this, the 1979 field study, the debate at the public inquiry, and the continued monitoring of soil moisture into 1980 are all described and discussed in Chapter 5.

In the intervening period between 1980 and the present, work on the project continued. During the field study, undertaken jointly by Walley and the author (Walley and Hedges, 1979b), it was realised that the subject had the potential for developing into a Doctoral thesis. The subject itself was considered to be important, especially in view of the future potential for schemes which involve the conjunctive use of groundwater and surface water (see Chapter 2). More recently, with the implementation of the 1985 EEC Directive on environmental impact assessment (EIA), it has proved highly topical. EIA, and particulary the state of the art with respect to groundwater development prior to the 1979 public inquiry, is discussed in Chapter 3.

1.2 AIMS AND OBJECTIVES.

The overall aim of the research has remained constant since the conception of the project in 1979:

> To develop a methodology whereby the potential effects of groundwater pumping on crops and vegetation can be assessed, and the impacts minimised.

As stated in the first year report following registration for a higher degree (Hedges, 1984), the objectives defined in order to enable the project's aim to be achieved were:

i) the identification of those soil types which, when drawdown of the water table occurs, experience a loss of soil moisture which could affect the growth of vegetation and crops;

ii) assessment of the costs which could be incurred as a result of the effects of groundwater abstraction on trees and crops, by using the Shropshire Groundwater Scheme as a case study;

iii) the development of a set of guidelines for use in the design of a soil moisture monitoring scheme for evaluating the effects of groundwater drawdown, as a result of pumping, on soil moisture;

iv) the development of design criteria to enable planners to avoid areas sensitive to groundwater drawdown when selecting sites for boreholes.

It was proposed in the first year report, that if the standard required for a higher degree by research had not been met in realising the above objectives, then the work should be expanded to include a fifth objective. This was:

v) the development of a computer model to enable planners to assess the effects of any particular groundwater project on trees and crop yields.

1.3 THE THESIS STRUCTURE.

Chapters 2, 3, 4 and 5 have already been alluded to in Section 1.1. The first two chapters provide an historical background for the project regarding groundwater development and environmental impact assessment. The second two are an introduction to the relevant underlying soil moisture theory (Chapter 4), and a description and discussion of the field study prior to and following the local public inquiry, and of the Shropshire Groundwater Scheme public inquiry itself (Chapter 5).

In order to achieve the first objective listed in Sect 1.2, it was necessary to undertake a series of laboratory experiments to investigate the moisture profiles developed in soil columns. The design of the apparatus, the experimental procedures and the analysis of the results are described in Chapter 6.

Chapters 7 and 8 are concerned with the development of a methodology for assessing the impact of groundwater drawdown on vegetation. Chapter 7 is primarily involved with aspects relating to the vegetation of the Tern Area of the Shropshire Groundwater Scheme - the area most at risk from the effects of groundwater drawdown: 'the study area'. Chapter 8 shows how, by combining the appropriate crop rooting depths with the results obtained from the laboratory studies of soil columns, a technique for identifying areas sensitive to groundwater drawdown was developed. In addition, following the application of this technique to the Tern Area, a method of evaluating the impact on crop yields is described. This employs a series of crop yield/moisture relationships, whose derivation is traced out in Chapter 7 - where appropriate relevant data are presented in a series of Appendices. A list of notations is provided at the begining of the thesis and a glossary of terms, particularly those unique to this work, is provided in Appendix 9.

A brief evaluation of the EIA methodology is given in Chapter 9, which also speculates on its potential for incorporation into a Geographical Information System (GIS).

Chapter 10 is devoted to meeting objectives (iii) and (iv). The experience gained through participation in the Shropshire Groundwater Scheme public inquiry and the Tern Area field study, together with the development of the EIA methodology, are drawn upon to produce a series of guidelines for the design of soil moisture monitoring systems and for the siting of boreholes. The procedures required for environmental assessment of groundwater pumping schemes are also discussed, and an EIA decision network is presented which indicates, through a series of questions and answers, whether action is necessary and if so what action should be taken.

The research itself is evaluated in Chapter 11, and areas requiring further study are identified. Finally, the threads the thesis are drawn together in the concluding chapter, Chapter 12, in which the success of the project in meeting the aims and objectives is assessed.

Chapter 2. HISTORICAL BACKGROUND.

2.1 HISTORY OF GROUNDWATER DEVELOPMENT.

The second most basic requirement for human survival is, after air, water. Without a daily supply of at least 0.85 of a litre, life expectancy is only a matter of days. This need for a regular, reliable supply of drinking water has influenced human activities throughout the ages. It has even been argued that the need to control water resources for irrigation in arid areas led to the emergence of civilised society (Wittfogel, 1957).

The origins of the development of groundwater as a source of supply are lost in antiquity. Tolman (1937) suggested that primitive man possibly learned to dig for water by observing the actions of wild horses and wolves. Smith (1976) surmised that the skills required for locating underground water may have been acquired from the driving of shafts and drifts, in the pursuit of metallic ores. He concludes that:

> "in the final analysis one is bound to suppose that well-sinking was wholly speculative".

Authors (Smith, 1976; Tolman, 1937; DeWeist, 1965; ASCE, 1972) agree that in humid areas early mankind's needs were met from surface water sources, and that it was in the more arid areas that the first man-made wells were constructed. Without undertaking a literature search outside the terms of reference of this project, it is difficult to find specific examples of wells further back in time than the age of the patriachs in the bible, circa 1900 B.C. (Keller, 1956). The twenty-sixth chapter of Genesis shows that Abraham and his son Isaac were prolific well builders, and Tolman (1937) notes that the earliest romances in the Bible, those of Rebekah and Rachel, were enacted at wells!

Although the origins of groundwater development are unknown, the evolution of the technologies involved is better understood and the reader is directed to the discussions of Bowman (1911), Tolman (1937) and Smith (1976) for detailed accounts. For the purposes of this work, however, it is worth making a few brief observations.

Although the ancient Egyptians had perfected core drilling techniques for stone quarry operations as early as 3000 B.C. (Davis and DeWiest, 1966), water wells throughout the near east and Europe were dug by hand up to the twelth century A.D. Also about 3000 B.C., the Chinese developed a churn drill for water wells, but since contact with China was extremely limited, the development of percussion methods of well drilling in Western Europe had to wait for the discovery of artesian water in Flanders, about 1100 A.D. The desire to develop these "flowing wells" stimulated a rapid development of drilling techniques. Percussion drilling remained the prime method of deep well construction, until in the 1890's rotary drilling methods, using thick muds to retain the sides of the hole, were developed by the petroleum industry (ASCE, 1972). The successful drilling of the Spindle Top oil field in 1901 confirmed the potential of rotary drilling methods, and the technique has grown in popularity ever since. Although the water industry has persistently borrowed technology from the oil industry ever since, it has produced many refinements of its own, notably reverse rotary drilling and gravel-envelope wells.

The step that finally opened the doorway to large scale groundwater exploitation, was the development of deep well turbine pumps during the period 1910 to 1930 (Davis and DeWiest, 1966). Prior to this, pumping had been either by small capacity piston pumps of poor efficiency, or by the use of compressed air.

At the same time that well technology was making rapid strides, so too was the art of hydrogeology. Up to the end of the Renaissance, about 1600 A.D., hydrological thinking was dominated by the teachings of the ancient Greek philosophers. Biswas (1970) gives a comprehensive account of the development of the science of hydrology up to the end of the nineteenth century, and in the process discusses these ancient teachings in full. Despite the numerous publications on groundwater which appeared from the middle of the sixteenth century onwards, the old Greek hypotheses held sway until the close of the seventeenth century. Although Palissy (1509-1589) correctly explained the origin of springs and rivers, the hydrological cycle, and changes in water levels in wells, it was Perrault, Mariotte and Halley who, through their experimental work, laid the foundations for the science of groundwater hydrology. Perrault (1608-1680) demonstrated that rainfall is more than adequate to account for the discharge of rivers and springs. Mariotte (1620-1684) showed that the flow of springs varied according to rainfall, and that the origin of springs and well water was infiltrating rain. In 1693 Halley demonstrated that evaporation from the sea was ample to supply the quantity of water returned to a sea by the rivers flowing into it.

Walton (1970) described how, from this point onwards, the science of groundwater hydrology developed rapidly. Of particular note as milestones of understanding are the works of Darcy, Dupuit, Thiem and Theis. Darcy (1803-1858) undertook experimental work on the flow of fluids in porous media, and derived a formula which expresses the relationship between velocity of percolation, permeability of water-yielding materials, and the hydraulic gradient. Darcy's law serves as the basis for numerous quantitative methods in groundwater evaluation. Dupuit utilized it in 1863 to produce the first steady-state formula for the flow of water into a well. Thiem, in 1870, modified Dupuit's formula in order to compute the hydraulic characteristics of an aquifer from field observations of a pumped well. Finally, a great advance in hydrogeology was made in 1935, when Theis introduced an equation for the non-steady-state flow to a well.

At the begining of the twentieth century, well technology and the science of hydrogeology were sufficiently advanced to enable the rapid and economical development of undeveloped resources on a regional scale. Selected examples of such schemes in the United States are given in ASCE, 1972.

Until the Water Resources Act 1963, the exploitation of groundwater in the United Kingdom had been poorly planned. Many schemes had been implemented without consideration of wider issues, and consequently led to persistent over-pumping in a number of areas (Smith, 1972). With the formation of the River Authorities and the Water Resources Board, under the Act of 1963, the concept of regional management for water resources was born, and the control of groundwater abstractions placed on a more formal footing.

2.2. CONTROL OF GROUNDWATER ABSTRACTIONS IN ENGLAND AND WALES.

Prior to 1945, landowners' common law rights to water underneath their property was absolute. They could abstract as much water as they required for their own use, or for sale to others, regardless of the effects on other users . As a result of this inadequacy of the common law, there were no curbs on groundwater development. Consequently, when the needs of the Industrial Revolution stimulated the rapid and indiscriminate sinking of wells, there were no controls, and so in certain areas of the country the aquifers were over exploited and the groundwater "mined". The classic example was London where, as a result of continually falling water tables between the begining of the eighteenth century and 1950, saline water was drawn into the Tertiary sands, the London Clay settled causing subsidence, and the flow of rivers fed by the aquifer was reduced (Porter, 1978).

Concern at the over-development of aquifers led to the first attempts to conserve groundwater, in the Water Act 1945. The Act required that in defined areas, where the Minister of Health was satisfied special measures were needed, proposals for further development had to be submitted to the Minister for approval and licensing. This legislation limited the overdevelopment of the more critical aquifers, but made no provision for any nationwide safeguards for groundwater. In addition, the information which was available was inadequate to check that the measures taken were sufficient to secure future supplies in critical areas.

The Water Resources Act 1963 provided for the establishment of twenty seven River Authorities and the Water Resources Board. The powers vested in these bodies resulted in a much greater control and understanding of groundwater resources. Under Section 23 of this Act the licensing of groundwater abstractions was extended to all situations except the purely domestic. This has not corrected all cases of overdevelopment, but "mining" is no longer an acute problem.

The general duty of River Authorities in relation to water resources was specified in the 1963 Act as:

> ".. to take all such action as they may from time to time consider necessary or expedient, or as they may be directed to take by virtue of this Act, for the purpose of conserving, re-distributing or otherwise augmenting water resources in their area, or of transferring any such resource to the area of another river authority." (Water Resources Act 1963, Section 4).

Although the Water Resources Board could only play an advisory role in relation to the River Authorities, it was charged under Section 12 of the Act to:

> ".. consider in what way action needs to be taken for the purposes of conserving, re-distributing or otherwise augmenting water resources, or of securing the proper use of water resources, either in England and Wales generally or in relation to any particular river authority area ..".

These requirements, when applied to groundwater, highlighted the need for a series of intensive monitoring and research programmes and, once implemented, these led to a much better understanding of groundwater behaviour (Water Resources Board, 1974). The Water Resources Board's own fundamental work in this field underlies several of the schemes either recently completed or under development.

In 1973, the Water Resources Board was disbanded, and the "revolutionary" (Okun, 1977) concept of regional management instigated, with the replacement of the River Authorities and other water undertakings by ten Water Authorities. Under the Water Act 1973, the old powers of the River Authorities were vested in the new Water Authorities who were given effective responsibility for the entire water cycle in their area. Licensing of groundwater abstractions has continued, but a much more integrated view of water resources management has emerged, and current thinking is towards the conjunctive use of groundwater and surface sources rather than abstraction for direct supply.

2.3 CONJUNCTIVE USE OF GROUNDWATER AND SURFACE SOURCES.

Historically, as demand for water has grown, mankind has utilised the most convenient sources of supply first. When the most readily accessible have been developed, new ones have had to be sought further afield. With the expansion of populations, and new supplies becoming scarcer, scientific management becomes a necessity in order to exploit existing resources to the full. It has even been claimed that without effective water resources management, the development of nations, and even continents, will be severely limited in the future (Falkenmark and Lindh, 1976).

Effective water resources management and planning requires that the scientific tools and organisational structures must be capable of meeting the demands placed on them. The move towards regional management in the water industry of England and Wales, and the eventual emergence of the Water Authorities, has already been described. Rapid advances in understanding the various components of the hydrological cycle have been made since the early 1960's, and the production of digital computers heralded the advent of numerical models designed to simulate water resource systems. With the availability of these tools, the planner has been able to integrate and co-ordinate the use of resources with much greater effectiveness. This facility has also caused traditional ways of thinking to be modified and, in many instances, changed completely.

The responsibility for regional and national planning, placed on the Water Resources Board under the 1963 Water Act, meant that all resources within a chosen area had to be considered together, and not as a set of isolated components. Where groundwater was concerned, the thinking of the Board moved away from the conventional approach of exploiting individual boreholes to their fullest, towards considering the storage available in an aquifer as a whole (Water Resources Board, 1974). It was only a matter of time therefore, before the study of the combined use of surface water and groundwater led to the concept of conjunctive use.

The National Water Council, in its publication Water Industry Review 1978, adopted the view that the term "conjunctive use" refers to any scheme where sources are used conjunctively. However, most authors (for instance Porter, 1978 and Shaw, 1983) reserve the use of the term for the integration of surface water and groundwater sources. The natural characteristics of each system are exploited in order to provide greater flexibility in the management of supplies and greater yields than for the same sources operated separately.

Groundwater and surface water are inter-linked in the hydrological system. For detailed discussion the reader is referred to standard hydrology textbooks such as those by Shaw (1983), Ward (1979) and Chow (1964). However, put simply, during periods of high rainfall the flow in rivers is correspondingly high, and at the same time the groundwater store is recharged by infiltration. In dry months, river flow is maintained by the base flow component contributed from groundwater, which in turn results in the depletion of the water stored in aquifers. Formerly, development of groundwater and surface water sources tended to proceed independently (Fig 2.1a), but water planners now think in terms of the complete hydrological system, and consider them as inter-related.

Groundwater

Fig 2.2 Lancashire Conjunctive Use Scheme (after Law, 1965).

There are various ways in which the integration of groundwater and surface water resources can be achieved. The most straightforward involves the supply system drawing on surface sources when they are abundant, and then switching to pump groundwater when river levels fall, as illustrated in Fig 2.1b. At any one time the supply may come from either groundwater or surface water, or be a mixture of the two. This provides a high degree of flexibility in the operation of the system, and overall the combined yield of the integrated resources is substantially greater than when the two are managed separately. One of the first such conjunctive use schemes was that in the Fylde area of Lancashire, where supplies are taken from the Bunter Sandstone, the River Lune and from storage in the Stocks reservoir (see Fig 2.2). The scheme itself was described by Law (1965), and has been the subject of considerable study in devising control rules for the management of the two sources (Walsh, 1971). Computer modelling of supply and demand (Burrow, 1971) and of the aquifer behaviour (Oakes and Skinner, 1975) has added greatly to the prospective success of optimising management methods.

Groundwater augmentation of river flows is a more complex technique than the method of conjunctive use described above. The aim of river regulation is to maintain flows above the natural dry weather conditions, so that abstractions and in-stream use can continue downstream at a level greater than could be achieved normally. The addition of groundwater, as illustrated in Fig 2.1c, is one method of achieving this. The benefits of groundwater augmentation are that many uses and reuses of the additional water are possible, and the water is provided more cheaply and more conveniently from the aquifer than from new surface storage (Porter, 1978).

The final stage of integrated development is the artificial recharge of the aquifer, in combination with either straightforward conjunctive use or groundwater augmentation (Fig 2.1d). In theory, when there is surplus surface water and the groundwater store is depleted, spare storage below ground can be artificially filled by passing treated surface water down wells or recharging the aquifer through shallow basins. The art of groundwater recharge is well developed in the USA, and was first employed in California as early as 1895 (O'Hare et al.,1986). However, despite the efforts of a number of major research programmes, such as those associated with the Lee Valley (Hawnt et al., 1981) and the River Trent (Water Resources Board, 1972), in the UK the technique remains primarily at the development stage. The exception is the Lee Valley scheme itself, which employs twelve wells and is incorporated into Thames Water Authority's regional resource system (Brandon,1986). On an operational basis, artificial recharge is attractive as the replenishment of groundwater in this way converts the aquifer into a reliable long term store that can be operated in a similar manner to a surface reservoir. Furthermore, this approach may provide the solution to the problem of finding new sites for the storage of surface water which are acceptable to the environmental lobby.

Currently, major groundwater development in England and Wales is following the pattern encouraged by the Water Resources Board (1973) and as recommended in their report Water Resources in England and Wales:

> "Over wider areas, however, groundwater resources can be more effectively deployed by using them intermittently for river regulation, or in combination with surface sources, and we believe that most new groundwater sources should be developed on these lines. Some existing groundwater sources now used for direct supply could also be used to better advantage in this way".

At the time this report was written (1973), demand for water was expected to grow so that by the end of the century there would be an estimated deficiency in England and Wales of some 12.1 million cu.m/d. Included in the Water Resources Board's strategic plans to meet this expected deficiency, was the development of a number of schemes for groundwater augmentation of river flows. The first stage of the Thames Groundwater Scheme had received approval from the Secretary of State in 1972, and was to be implemented by 1974. The first stages of three other schemes were to be completed by 1976 (Great Ouse), 1978 (Shropshire) and 1984 (Vale of York).

2.4 GROUNDWATER AUGMENTATION OF RIVER FLOWS IN ENGLAND AND WALES.

The first recorded suggestion that groundwater should be used for stream flow augmentation was made as long ago as 1949. After observing public opposition to the proposed Enborne Reservoir, Messrs. Guthrie and Collin Allesbrook made the recommendation that the River Thames could be regulated by pumping groundwater from the Chalk into the river to provide additional supplies for London (Hardcastle, 1978). This novel concept was kept alive, and in 1956 the Metropolitan Water Board and the Conservators of the River Thames commissioned consultant engineers to investigate the feasibility of its application to the River Kennet catchment. The consultant's report in 1957 was favourable; and in 1961 the Conservators initiated a more detailed study of the Kennet and Lambourne valleys.

1965 saw the Thames Conservancy publish proposals to develop groundwater in the Chalk of the Berkshire Downs for augmentation of the River Thames. In the same year, the Ministry of Housing and Local Government published proposals for the development of water resources in the Great Ouse basin, and these included the regulation of the main river's tributaries with groundwater (Downing et al., 1981). Since these proposals were rather unusual, and aquifer modelling was in its infancy, when the Water Resources Board were consulted they advised that major pilot schemes should be initiated in the Lambourne Valley of the Upper Thames basin, and in the Thet valley of the Great Ouse basin. The principles of river augmentation, and the conclusions from these and other contemporary investigations, were discussed in a paper by Downing et al. (1981).

Downing's paper covered the most important schemes of the time (see Fig 2.3). When the position was reviewed by Owen in January 1983 (Headworth et al., 1983a) fourteen schemes were either already in existence, being implemented, or had been adopted in development programmes. The review was kept to a manageable size only by restricting it to those schemes that augmented river flow for subsequent abstraction which were already being implemented. However, this meant that several proposals were not considered - notably Stage 2 of the Thames Groundwater scheme. The gross yields, of those schemes which were reviewed, varied from 10 to 380 Ml/d. The numbers of boreholes ranged between 2 and 70, and the works covered areas from 100 to 800 sq km.

A survey conducted by the author in 1988 revealed that, with the exception of Anglian Water, no new schemes had been planned or implemented since the publication of the paper by Headworth et al (1983b). In certain instances operating rules had been changed and further phases of existing schemes constructed, but the only new developments were the

Stour Augmentation Groundwater Scheme and the Bure and Waveney Groundwater Scheme, both Anglian Water projects.

Fig 2.3 Location of Major Groundwater Schemes for River Augmentation in 1981. (Downing et al, 1981)

1. Great Ouse; 2. Vale of York; 3. Shropshire; 4. Lambourne (Thames); 5. Fylde; 6. Lincolnshire Limestone.

Of the four schemes included in the Water Resources Board's strategic plan (Water Resources Board, 1973) that involved groundwater augmentation of rivers, three are operational. The Thames Groundwater Scheme was the subject of a conference held in 1978 (Hardcastle, 1987), at which all aspects of its implementation were discussed. The locations of the 33 operational Stage 1 boreholes, for which authorisation was given following a public inquiry in spring 1972, are shown on Fig 2.4. The total yield is 80 Ml/d, but ultimately if the scheme is ever fully developed a yield of 300 Ml/d is expected.

Existing wells are mainly in Chalk outcrops, but some penetrate the confined aquifer. The scheme will probably be brought into use once every seven years, and it will be fully used about once every twenty to twenty five years. In the latter event, the pumping period is likely to exceed 200 days.

Whereas the Thames scheme pumps groundwater into rivers when flows fall below prescribed minima, and thus only operates intermittently, the Great Ouse scheme will result in almost continuous abstraction. The object of this scheme is to effect a four metre drawdown of the water table over a large area (see Fig 2.5) so that aquifer storage can be more completely controlled (Porter, 1978). Eventually water will be pumped out of the ground for support of river flows, for direct abstraction, and for transfer south across the watershed into Essex. Development of this scheme is proposed in three stages over a period of about twenty years. The net yield is estimated at 250 Ml/d if the current situation remains unaltered, but, if less water is required to dilute effluent in the King's Lynn area, it may be possible to achieve a net yield of 330 Ml/d. Like the Thames scheme, the aquifer under development in the Great Ouse scheme is the Chalk. The Shropshire Groundwater Scheme is different in that the Triassic sandstones of the Severn basin are exploited.

The sixty four boreholes of the Shropshire scheme are designed to augment the flow of the River Severn in times of drought. When completed it is anticipated that pumping will occur, on average, once every three years, and the output will then be 225 Ml/d. Since it was direct involvement with the Shropshire Groundwater Scheme public inquiry which initiated this research, it is necessary, in order to provide a background for later discussions, to consider the stages of its development in detail.

2.5 THE SHROPSHIRE GROUNDWATER SCHEME.

The River Severn is the largest river in Great Britain and plays a key role in water resources management for the West Midlands. There are seven major abstraction points along its course which provide public water supplies for about six million people (see Fig 2.6). The industrial and agricultural sectors place additional demands on the river, and amongst the former, the C.E.G.B.'s Ironbridge B power station, which employs evaporative cooling, is particularly important. Though individually small, the numerous licensed abstractions for spray irrigation can put a particular strain on the system, since these demands occur specifically during dry periods and thus at times of low flow.

Increased demands for water during the 1960's were met by the construction of Llyn Clywedog, a large regulation reservoir in the headwaters of the River Severn (Fig 2.6).

Fig 2.4 The Great Ouse Groundwater Scheme (from Porter, 1978)

Fig 2.6 The Severn Resource System in 1979 (Sharp,1979).

The original operating rules for this reservoir, as set out in the Clywedog Reservoir Joint Authority Act 1963, were designed to ensure that the flow of the River Severn at Bewdley never fell below 727 Ml/d (Sharp, 1978a). Releases made from the reservoir during natural periods of low flow have enabled an additional 492 Ml/d to be abstracted.

In 1971 the Water Resources Board published their assessment of future demands for water in Wales and the Midlands (Water Resources Board, 1971). It was estimated that by 1981 the Severn River Authority area would have a total deficiency of 155 Ml/d, rising to

940 Ml/d by the year 2001. Prior to this publication hydrological studies had indicated that should a severe drought occur in 1978, then releases from Llyn Clywedog would only just be sufficient to guarantee abstractions from the River Severn (Severn River Authority, 1972). The River Authority had, as a consequence, decided to promote a new regulating reservoir in the Dulas Valley near Llanidloes. Following a public inquiry in March 1970, the Secretary of State ruled that site investigations relating to this proposal could not be undertaken. Despite this setback, the Water Resources Board and the River Authority still considered that additional reservoirs regulating the River Severn would be necessary. The best option was considered to be the enlargement of the existing Craig Goch reservoir owned by Birmingham Corporation (Water Resources Board, 1971). Although this was sited in the neighbouring Wye Catchment, it was envisaged that releases would be made to the Severn by way of a tunnel and the River Dulas. However, experience had shown that it took between eight and ten years between the conception of a major reservoir project and its final completion. It was therefore important to find an alternative source to meet demands during the intervening period up to 1978.

Under their programme of short-term developments designed to meet growth in demand before 1978, the Water Resources Board included the Development of Groundwater in the Severn Basin and specifically

> ".. in Shropshire where water from the Triassic sandstone could be used conjunctively with abstraction from the Severn, or possibly for regulating the Severn".

Subsequently, the progressive development of groundwater in the Severn basin for river regulation was included in all nine Development Programmes considered for the region. However, the Water Resources Board (1971) specified that:

> ".. development can take place only as field investigations and test pumping are progressively carried out".

In June 1971 the Severn River Authority submitted a pilot scheme for grant approval to the Water Resources Board, under Section 18 of the Water Resources Act 1963. The original proposal was for the construction of a total of 14 boreholes, to the north-east of Shrewsbury in a sub-catchment of the River Tern, and to the north-west in a sub-catchment of the River Perry (Fig 2.7). It was estimated that the planning, design, construction and operation of the pilot scheme would take five years at a cost of £550,000. After due consideration, the Board decided that the scheme should be divided into two stages. This would enable the results from the first stage to be used to judge whether "any modification is necessary in respect of proposals for the remainder of the scheme" (Severn River Authority, 1972). Following further discussions it was agreed

Fig 2.7 Shropshire Groundwater Scheme - Location of Pilot Areas and Extent of Aquifer. (Sharp, 1979)

that investigations should start in the Tern pilot area, and the River Authority received a grant of £151,575 from the Board.

By the begining of 1975 two reports had been produced by the Severn River Authority (1972 and 1974) describing the investigations in the Tern pilot area. Proposals for the Perry pilot area were revised in the light of a preliminary geophysical survey, and work commenced on this stage in 1974. The third report was published by the Severn Trent Water Authority (1975), which had assumed responsibility for the work of the Severn River Authority on 1st April 1974 as a result of the Water Act 1973. The Fourth Report, produced in June 1976, concluded that:

> ".. a conjunctive yield of 225 Ml/d might be expected from a full development of the Shropshire Development Scheme".

By 1977 the Water Authority was sufficiently satisfied that the groundwater from the Triassic sandstones could be used for regulation of the River Severn, to produce a report summarising the investigations and setting out proposals for full development (Severn Trent Water Authority, 1977). The plan was to undertake a comprehensive design, publish the details in the form of a draft parliamentry order by late 1978, commence construction in 1981, and have the scheme fully committed by the early- to mid-1990's.

The programme of investigation continued with the final report, the fifth, being published in 1978 (Severn Trent Water Authority, 1978). This report, besides expanding on the work in the Perry and Tern pilot areas, detailed hydrogeological studies undertaken in an area, designated the North Shrewsbury - Roden Area, which lies between the two pilot projects (see Fig 2.8). The data obtained were used to show how information from the two pilot schemes could be applied to areas with similar hydrogeological conditions.

In 1978, Sharp (1978a) published a paper on Planning and Management of River Basin Resource Systems, and in this he detailed plans for the River Severn basin. The prescribed flow requirements for releases from Llyn Clywedog were to be changed from an unconditional maintained residual flow at Bewdley of 727 Ml/d, to a conditional maintained flow of 850 Ml/d. The condition being that releases from the reservoir would be limited to 500 Ml/d, whilst the gauged flow at Bewdley used for determining regulation would be a five day rolling average. This would enable better use to be made of Clywedog storage to meet more frequent, but less extreme, drought events. It was calculated that under this arrangement Clywedog reservoir could support a total net abstraction of 500 Ml/d (Sharp, 1979).

The next step in the management of the basin was to change the pattern of compensation releases from Lake Vyrnwy (see Fig 2.9). This would have the result that, for only a small cost, a net increase in yield from the River Severn of 25 Ml/d could be obtained.

The combined resources provided by Clywedog and the Lake Vyrnwy variation of compensation releases were expected to be fully deployed by 1982, as shown in Fig 2.9. The next major stage of river regulation for the Severn was to be the Shropshire Groundwater Scheme. At the time that Sharp's paper was presented, this scheme was favoured over the proposed enlargement of Craig Goch on economic grounds - it would cost only 40 per cent of the reservoir scheme. It was envisaged that the Groundwater Scheme would be developed over a period of some ten years and, when fully implemented, would produce an additional net yield of 225 Ml/d (see Fig 2.9).

Aston University

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The final stage in the management plan for the Severn basin was to be the enlargement of Craig Goch, which in the time of the Water Resources Board had been seen as so essential. By 1978, demand estimates had fallen so much that this scheme was regarded as a long term development project, and would not be required until 1993 at the earliest. Plans were still in hand to promote, "but not yet construct", the proposed reservoir enlargement in association with the Welsh Water Authority.

The public local inquiry on the Shropshire Groundwater Scheme was held during September 1979 in Shrewsbury. The Severn Trent Water Authority were seeking an Order under Section 67 of the Water Resources Act 1971, and Section 36 of the Compulsory Purchase Act 1965, to enable the full development of the scheme to proceed (Gray, 1980). Applications were also made by the Authority for a licence authorising the abstraction of water from the proposed boreholes, and for planning permission for the various works. The main components of the proposed scheme were:

i. the construction of 58 new abstraction boreholes and works at 10 existing sites;
ii. construction of 38 new observation boreholes, and maintenance powers for 53 existing ones;
iii. construction of 39 new pipelines and ancilliary works, and maintenance and duplication of 5 existing pipelines. Pipelines, totalling 72 km in length would then link the boreholes with their associated outfalls.
iv. 8 area control buildings and a telemetry network.

The development plan, as put to the Inspector at the public inquiry, was for construction to take place in stages keeping just ahead of requirements for water from the River Severn (Sharp, 1979). Eight areas, shown on Fig 2.8, were chosen for development. Each area contained a group of abstraction boreholes, observation boreholes to monitor the effects of abstraction, pipelines, sand removal and aeration structures, and outfalls to convey and discharge the water to the nearest suitable river or stream. Each group of installations would also have an area control building with the provision for radio telemetry links to the main monitoring centre near Shrewsbury. The proposed sequence of development was:

1. North Tern
2. Ollerton
3. South Tern
4. Roden
5. Astley
6. Leaton
7a. South Perry
7b. Montford
8. North Perry

Details of each development area are given in Table 2.1 taken from Skinner (1979), the locations of the principal elements are shown on Fig 2.8, and the effects of the staged introduction of the scheme on the Severn resource system are illustrated in Fig 2.10 (Sharp, 1979).

(1) Borehole Group	(2) Number of borehole sites	(3) Number of boreholes not exceeding	(4) Aggregate of the individual annual abstraction limits for all b'holes in group (Ml)	(5) Rate of abstraction not exceeding per annum period (Ml)	(6) Rate of abstraction not exceeding per 5 yr (Ml)
1 North Tern	9	13	(8700)[1]	6600	14300
2 Ollerton	4	6	(4000)[1]	2700	5900
3 South Tern	14	25	(16400)[1]	10200	22100
4 Roden	5	8	(5300)[1]	2700	5700
5 Astley	8	16	(10400)[1]	6500	14100
6 Leaton	11	20	(13100)[1]	5600	12200
7A South Perry	3	4	(2700)[1]	1900	4100
7B Montford	8	16	(10400)[1]	4600	10100
8 North Perry	6	12	(7800)[1]	4200	9300
	68	(120)[2]		(45000)[3]	(97800)[4]

Figures shown in brackets are not part of the licence but are shown in the table to demonstrate the restrictions on quantity imposed by the grouping of the boreholes. The various limitations are as follows, identified by superscripts in the table.

1 - the maximum annual abstraction for each group is limited to the quantity shown in the corresponding row of column 5.
2 - the maximum number of boreholes is restricted overall to 81.
3 - the maximum annual rate of abstraction is restricted overall to 39000 Ml.
4 - the maximum five year rate of abstraction is restricted overall to 84000 Ml.

Table 2.1 Summary of Quantities to be Abstracted Under the Shropshire Groundwater Scheme Licence (Skinner, 1979)

In May the Secretary of State for the Environment gave his approval for the scheme (Musgrave, 1981). During the public inquiry the Water Authority had agreed to change the order of implementation of the various phases of the scheme as a result of objections from agricultural interests. Concern was expressed over the possible loss of soil moisture, which was normally available to crops and trees during dry periods, as a result of groundwater drawdown. The fieldwork undertaken by Messrs. Hedges and Walley (of Aston University) in the Tern area, which was considered to be particularly sensitive, together with the evidence presented by Mr Walley on behalf of the concerned farmers, are discussed in Chapter 5. As a consequence of the objections raised during the inquiry, the approved scheme differed from the original proposal in that:

a) the effects of abstraction from the boreholes on groundwater levels AND soil moisture conditions should be monitored;
b) development of the Tern area should "proceed cautiously", with further development after the North Tern stage "proceeding only if justified by the monitoring results" (Musgrave, 1981);
c) the proposed staging of construction should be:

1. North Tern
2a. South Perry
2b. Montford
3. Leaton
4. Ollerton
5. Astley
6. Roden
7. North Perry
8. South Tern.

Since the Severn Trent Water Authority received approval for the Shropshire Groundwater Scheme demand projections have continued to fall. Pearce (1982) argues that the groundwater scheme was only chosen as a result of "bitter feuding" between the Severn Trent and Welsh Water Authorities over the price to be paid for the water from Craig Goch. Sharp's arguments relating to timing, the advantages of staged development and relative capital costs presented at the public inquiry (Sharp, 1979) are, however, more convincing. Whatever the truth behind the demise of the Craig Goch project, with hindsight the selection of the Shropshire Groundwater Scheme for development has proved to be the correct one. The economic recession of the mid-1980's has caused demand projections to be further reduced, emphasising the wisdom of selecting a scheme which can be developed incrementally.

A drought in the summer of 1984 led the Water Authority to bring forward the inauguration of the first stage of the scheme. Tern Stage 1, as it is now known, consists of ten abstraction borehole sites providing a net yield of 31 Ml/d. In August 1984 Sharp was quoted in Water Bulletin as stating that no decision had been "taken yet on further stages" of the scheme. The article continued:

> "Present plans say that the scheme should be completed 'post 1995', but Mr Sharp considers that it could be a lot longer after that. 'The phasing and timing will be geared to demand and further resource development'".

Correspondence in June 1988 with Dr A.C. Skinner of Severn-Trent Water verified the observations made by Sharp in 1984 regarding the future of the Shropshire Groundwater Scheme. Responding to questions about the scheme concerning: (a) the current state of its development; (b) plans for further development; and (c) in relation to Government plans for privatisation of the water industry, who in the future would be responsible for development and management, Skinner (1988) replied:

"Referring to your questions by your own reference:-

(a) Phase 2 of the scheme is under construction; observation boreholes have been completed and abstraction boreholes will be started soon; completion date for this phase is 1992 but there will be some intermediate commissioning trials to help us understand certain water quality issues.

(b) Current plans envisage the scheme being completed as put to the inquiry in 1979 although demand projections are flatter than at that time with the result that it is not likely that the scheme will be fully implemented before about 2015. You may recall that flexibility of deployment to reflect changing demand projections was one of the key features which attracted the Authority to the scheme.

(c) I do not expect forthcoming privatisation to affect the construction or use of the scheme although its management will be somewhat complicated in that the works will be owned by the Utility but operated at the instigation of and at the cost of the NRA *(National Rivers Authority)*. The NRA will fund and continue all relevant monitoring."

Chapter 3. THE ENVIRONMENTAL IMPACT OF GROUNDWATER SCHEMES.

3.1 ENVIRONMENTAL IMPACT ASSESSMENT AND THE CONSULTATION PROCESS.

Objections to development schemes are not a recent phenomena. In 1602 Queen Elizabeth I initiated one of the first environmental impact assessments of a water supply scheme, when she directed the Sheriffs of Hertfordshire and Middlesex to inquire whether the proposed construction of the New River aquaduct "would injure the inhabitants of the two counties and whether it would diminish the flow of any navigable river" (Berry, 1956). This scheme, privately sponsored by Sir Hugh Myddleton, was designed to convey water from Ware in Hertfordshire to north London. Landowners along the proposed route were afraid their property would be both subject to flooding and divided by the aquaduct. Her Majesty was assured that the inhabitants would not suffer, provided that compensation was paid to those whose lands were crossed and that sufficient bridges were constructed and maintained.

Objections there may have been, but in the main these centred on the impact on individuals, and their personal and business interests. Manchester Corporation's proposal, in the 1870's, to develop Lake Thirlmere in the Lake District as a source of water supply was unusual, in that it met with determined opposition, not only from a long list of objectors concerned for personal or business reasons, but for the first time on aesthetic and amenity grounds (Smith, 1976). With the publication of reports and books highlighting man's effect on the environment, starting perhaps with Rachel Carson's Silent Spring (1965), and the resultant emergence of articulate pressure groups, over the past twenty years or so a widespread awareness has grown of the finite nature of natural resources, including, as Smith (1975) puts it in his introduction to The Politics of Physical Resources:

> "the less material aspects which have come to be known collectively as the 'quality of life'."

Gregory in The Price of Amenity (1971), comments regarding developments of all types, from industrial and mining to housing estates and New Towns:

> ".. all invade the countryside and change the face of cities and towns. Necessary and desirable they may be; but, often as not, these developments interfere with the amenities of the locality chosen for the project. Indeed, their impact is frequently felt far beyond the particular patch or strip of land on which they are situated. They may spoil the natural beauty of the countryside and coastline, ruin the appearance of part of a town, destroy buildings of historic and architectural value, or wipe out precious reserves of wild life. In their

> wider effects, they may create noise disturbance, or pollute the atmosphere, rivers and lakes".

Public unease concerning the 'quality of life' has in turn led to an increasing demand for public consultation, particularly in relation to environmental impact. The physical elements of a development project can, generally, be assessed in financial terms and cost-benefit analysis employed to evaluate the scheme's worth to the community. The evaluation of tangible benefits provides a framework for arguing the value of a scheme in concrete terms. However, where benefits are intangible (i.e. they cannot be evaluated in monetary terms) any conflict of interests is much harder to resolve as arguments become more emotive. Any decision-making body has, therefore, to attempt to separate 'fact from fiction' when weighing up the evidence in order to come to as fair a judgement as possible. The need to evaluate these intangible benefits has resulted in a variety of methods being adopted, some relying on a highly structured approach, others involving a straightforward debate where arguments and counter-arguments are presented before an independent arbitrator.

Environmental Impact Assessment (E.I.A.) is the term which has come to be used to describe these methods. Thirlwall (1978) defines E.I.A. as:

> ".. a system or process for determining, evaluating and reporting environmental effects which could be expected to result from carrying out a proposal".

He continues:

> "The word proposal is used because E.I.A. has been applied not only to specific developments involving civil engineering and building works, and plant installations and processes but also for policies, plans and programmes which, if adopted, could have significant environmental effects whether or not they lead in due course to specific developments".

3.1.1 ENVIRONMENTAL IMPACT ASSESSMENT IN THE U.S.A.

The structured form of E.I.A. originated in the United States of America as a result of the National Environmental Policy Act passed by Congress in 1969. This Act made it mandatory for federal agencies to evaluate the environmental impacts of their projects and programmes during the earliest stages of planning. The requirment for E.I.A., when it was first introduced, only applied to federal agencies, but since that time it has been extended to other public sector developments and to the private sector through legislation by individual states (Thirlwell, 1978). The process is carried out openly with opportunities for other bodies and the general public to give their views. A draft impact statement must be made available for 90 days for public comment, and the final statement for 30 days, before any action can be taken. The final statement is a public document submitted to the President and to the Council on Environmental Quality.

Initially there was a gap between the need to perform E.I.A. and the ability to do so (Whitman et al, 1971). With time and experience considerable advances were made, and a number of techniques developed. These were reviewed in general by Jain et al (1977), and for water resources applications specifically by Canter (1985), and ranged from an Ad Hoc approach, employing a group of experts to converge on a concensus view by a process of iteration and feedback, to more structured methods using checklists, networks and matrices to rank impacts, and/or to attempt to give them a numerical value.

3.1.2 THE POSITION IN ENGLAND AND WALES.

Almost any development in the United Kingdom now needs legal authorisation unless it is specifically exempted in law. In the middle of the nineteenth century developers sought powers by means of a private Act of Parliament. The private Act is still a feature of the British system, but the procedures, costs and uncertainties are such that this route is rarely used today (Grove-White,1975). Over the last 130 years Parliament has delegated, to Ministers and lesser public authorities, more and more of its powers to regulate developments affecting the environment.

A succession of Town and Country Planning Acts, particularly between 1932 and 1971, have progressively expanded the scope of the powers exercised by the appropriate Minister (now the Secretary of State for the Environment) and by local planning authorities. Planning law and procedure is extremely complex, and the reader is referred to standard texts such as that by Telling (1977) for detailed study. In essence, however, local planning authorities, under the Secretary of State's guidance and control, are responsible for defining and describing the context within which particular developments may take place. They also decide whether to allow particular proposals to be accommodated within this planning context, embodied in a Development Plan, by awarding planning permission.

The procedure for obtaining planning permission involves the developer lodging a planning application, in outline or detail, with the responsible authority. People or bodies with objections to the application then send comments to the planning authority or the Secretary of State, as appropriate. With the majority of cases, the process ends when the planning authority considers the application and either gives permission or rejects it. If the applicant appeals direct to the Secretary of State following a rejection, or objections sent direct to him suggest a controversial proposal, it is likely that he will order a public local inquiry to be held. If this is the case, the inquiry is held locally, and is conducted by an Inspector appointed by the Secretary of State to supervise, record and evaluate the proceedings. Where evidence of a specialist or technical nature is presented, the Inspector may have one or more Assessors to help in the evaluation of these facts and expert opinions. After the inquiry has been closed the Inspector submits a report of his findings and recommendations to the Secretary of State. This report forms the basis for the Minister's decision, though he/she is in no sense bound to follow the Inspector's advice, and in fact the final decision may reflect government policies which were not raised at the inquiry (Grove-White, 1975). The only appeal against the Minister's decision is to the High Court on a point of law.

Within the legal framework described above, there is no formal requirement for Environmental Impact Assessment. In 1974 the Secretaries of State for the Environment, for Scotland, and for Wales commissioned a study of E.I.A. The resulting report was published in 1977 (Catlow and Thirlwall), and concluded that there was a need for E.I.A. in the United Kingdom, but its use should be confined to a limited number of developments where there was a likelihood of large scale and complex environmental effects. No specific technique was recommended for adoption. The overall concensus of a symposium, held in 1978 by the Institution of Water Engineers and Scientists (I.W.E.S.,1978), was that there was no case for introducing a statutory requirement for E.I.A., on the grounds that the water industry had accepted the need for such studies, which were already undertaken in essence, if not in name, as part of the normal planning and development process.

Over the years developers learned that to omit such aspects from their plans was to court disaster - when challenged by objectors, applications were rejected on the grounds of inadequate preparation. Consequently the consideration of environmental factors has become an accepted procedure during the appraisal stage of all capital projects, but structured techniques, such as those employed in the USA, are rarely adopted. Instead, it has become the custom, especially when public utilities are the appellants, to conduct informal discussions with interested parties in order to obtain at least some measure of agreement before any public inquiry. Experts are often employed to evaluate the impact of particular aspects of the proposal. Their reports are subsequently presented, together with verbal evidence, to the Inspector at the public inquiry, where both appellant and objectors have the opportunity to cross examine and counter the other side's evidence.

As far as the water industry is concerned, proposed developments have, in addition to seeking normal planning permission, to comply with relevent sections of the various Water and Water Resources Acts. Of particular interest to this discussion, is a statutory obligation under the Water Act 1973 for Water Authorities to have regard to the environment, specifically any impact upon the natural beauty of the countryside and upon flora, fauna, geological or physiographic features, historic buildings and archaeological features. The same section of the Act, Section 22, requires the Authorities to have regard to the desirability of preserving public rights of access to areas of natural beauty, whilst Sections 20 and 21 encourage the use of water, and land associated with water, for recreational purposes. Consequently, any promotion by a Water Authority must also take these requirements into consideration at the consultation and planning stage.

3.1.3 THE E.E.C. DIRECTIVE ON ENVIRONMENTAL IMPACT ASSESSMENT.

Whilst the procedures for obtaining authorisation for development at the time the Thames, Great Ouse and Shropshire groundwater schemes were promoted, was as outlined in Section 3.1.2, on July 3rd 1988 Environmental Impact Assessment (or Environmental Assessment as it is known at present) became a legal requirement for many schemes. After a lengthy period of gestation, brought about largely by the stalling of certain European Governments (amongst whom the British were prominent (New Civil Engineer, 1984)), in June 1985 the Council of the European Communities approved a Directive on Environmental Assessment (EEC,1985). The Directive (EEC/85/337), which is legally binding on the Member States, provides a framework and guiding principles for the implementation of Environmental Assessment (EA) anywhere in the EEC. However, the detailed mechanics are for each Member State to determine.

The main features of the Directive are that, for a project which is likely to have a significant effect on the environment, the developers are required to submit information on the project and its effects (i.e. an EA report), to a "competent authority". This "authority" must in turn make the information received available to other public bodies with responsibilities to the environment, and to the public who may be affected, so that these parties can express their opinions. When making its decision concerning authorisation of the proposed project, the "competent authority" is required to take into account the EA report submitted by the developer, together with any responses that it receives.The Directive applies to two lists of projects, Annex 1 and Annex 2, which are likely to have significant effects on the environment as a result of their nature, size or location. Project types listed in Annex 1 are always expected to have significant effects, and these must be assessed. Those listed in Annex 2 may or may not have significant effects depending on each individual situation, and have to be assessed "where Member States consider that their characteristics so require".

A separate authorisation procedure is not required by the Directive. The EA "may be integrated into the existing procedures for consent to projects in the Member States or, failing this, into other procedures or into procedures to be estasblished to comply with the aims of this Directive". In the UK, therefore, the requirements of the Directive will be incorporated into the existing planning process where, as already noted, ad hoc environmental impact assessment already occurs, particularly during a public inquiry.

In April 1986 the Department of the Environment issued a consultation paper (D.o.E., 1986) setting out the Government's proposals for implementation of the Environmental Assessment Directive. Having taken into acount the comments received, the D.o.E. issued a Draft Circular in January 1988 titled Environmental Assessment: Implementation of EEC Directive (D.o.E., 1988). The letter accompanying the Circular invited "comment by 28th March, prior to legislation, insofar as that is needed, in time to implement the Directive by July". The ensuing response was so critical that, at the time of writing (mid-July 1989), no instructions relating to the implementation of the Directive have been published. Milne (1988), in an April edition of Planning, reviewed some of the comments submitted. He predicted that, as a result of the response to their attempt at minimising the number of projects requiring EA and the possibility of a legal dispute with the EEC over interpretation of the intentions of the Directive, the Goverment would need to make significant amendments to the text of the final circular.

Regardless of the final instructions issued by central government, local planning authorities are likely to require developers to submit EA reports whenever there is a possibility of questions relating to environmental impacts arising. In the event that a project is refused planning permission on environmental grounds, the local authority will not wish to risk the developer appealing against the decision on the grounds that an EA was not requested. Standard formalised procedures, as favoured in the USA (see Sect. 3.1.1), are unlikely to become common practice, as, for most cases, they would be too costly and time consuming. Instead, environmental consultants will probably adopt procedures already developed, whereby for the project in question a hierarchy of impacts is identified and evaluation starts with the most significant of these. The logic behind this approach is that, should a scheme "fail" in relation to an impact high up in the hierarchy, then there is no point in considering less important ones.

3.2 THE PROMOTION OF GROUNDWATER SCHEMES.

Historically the promotion of groundwater schemes has been piecemeal, licences being obtained for individual boreholes as and when demand called for a new development. The large scale exploitation of groundwater resources for river augmentation has much wider implications, both from the planning aspect, and from the scale of their impact on the environment. Immediately the Water Resources Board became involved with the Thames and Great Ouse Groundwater schemes, they recognised this fact and called for major pilot schemes to be undertaken so that the effects of the proposals could be investigated (see Section 2.4).

There are three approaches to the promotion of large scale groundwater schemes (Headworth et al, 1983a; New Civil Engineer, 1983). The first method is that employed by the original and largest developments, the Thames, Great Ouse and the Shropshire schemes. Intensively monitored pilot schemes are carried out over a number of years, the normal planning application and licencing procedures are followed, and the appropriate orders obtained after a public local inquiry. To date every scheme that has followed this route has been successful, with only minor modifications to proposals being required by the Secretary of State for the Environment.

The Clwyd Scheme in North Wales, the Candover Scheme in Hampshire, and the Malmesbury Scheme near Bristol all followed the second course of action and obtained authorisation, after extensive liaison with the public and amenity interests, without a public inquiry being held. For the Malmsbury Groundwater Scheme, Wessex Water Authority conducted a three year investigation, during which public relations played an important part: in particular, close contact was maintained with interested individuals and groups (Swinnerton and Hillyer, 1983). At the end of the investigation a brochure was circulated, and when the abstraction licence application was advertised only 20 objections were received. A great deal of time was then spent in discussion with, and presentation of the test results to, these objectors. Consequently only four objections remained when the application was referred to the Secretary of State - three of which were from people outside the proposed development area. The Authority was granted the licence with no significant amendment without a public inquiry being held.

The final method is stage by stage development, with authorisation sought after each phase. Although at the time Headworth et al (1983a) published their paper no scheme had been promoted in this way, they suggested that it was likely that this method would be adopted in the future. However, it possesses the inherent danger that the appellants might be accused of trying to obtain permission for a large scale development in small increments, and thereby deliberately misleading the public regarding their intentions.

3.3 THE EFFECTS OF GROUNDWATER DEVELOPMENT ON THE ENVIRONMENT.

The gradual piecemeal exploitation of groundwater resources meant that, historically, there was no concerted attempt to conduct research into the environmental effects of large scale developments. Consequently, where abstractions ultimately reached such a level that they exceeded recharge, a variety of undesirable effects often occurred. These ranged from the regional fall in rest water levels and subsidence of the ground surface, as occurred in the Thames basin around London (Porter, 1978), to the intrusion of saline water into the aquifer, as into the Permo-Triassic sandstones of south Lancashire (Bow et al, 1969). Burgess and Smith (1979) described the consequences of the over-development of the Southern Lincolnshire Limestone aquifer. The effects included the reduction of river baseflows, the cessation or reduction of natural flow from artesian wells, the intrusion of fossil saline groundwater into the abstraction zone, and the periodic drying up of springs and private groundwater supplies. A secondary effect, due to the reduction in river baseflows, was the change in the pattern of recharge, which in turn resulted in a deterioration in the quality of the groundwater.

It is possible that there may be a gradual occurrence of undetected environmental effects (such as modifications to the ecology of affected streams), which are less direct and obvious than those described above, during the progressive incremental development of any groundwater resource. The planned large scale exploitation of groundwater for river augmentation led to the recognition that intensively monitored pilot schemes were needed, not simply to investigate the effects of abstraction on the aquifers concerned, but also to study environmental impacts (see Section 2.4). These latter have been found to vary widely since the areas concerned are so diverse - some aspects are common to all proposals, whereas others are specific to a particular project.

Since a major objective of river augmentation schemes is the use of natural water courses as aqueducts, the addition of abstracted groundwater could affect the biology and water quality of the receiving streams. Where intermittent streams are involved, such as those of the Chalk Downs of the Thames Groundwater Scheme, the dry period could be prolonged as a result of groundwater drawdown and the aquatic ecology temporarily lost (Hardcastle, 1978). Biological and water quality investigations have, therefore, become essential components of pilot studies. Work undertaken on the aquatic ecology of the Rivers Lambourne and Winterbourne for the Thames Conservancy led to a national chalk stream research programme.

Headworth has summarised the environmental effects which were encountered, prior to January 1983, as a result of the implementation of both pilot and fully commissioned schemes (Headworth et al, 1983a and 1983b). He observed that:

> "The potential detriment to fisheries has been an important issue in several schemes, notably the Clwyd Scheme in North Wales, the Calder Schemes in Cumbria, the Thames and Itchen Schemes in Southern England. In the last two of these schemes extensive fisheries and biological studies were carried out, which showed that the effects of low flow augmentation were likely to be more beneficial than harmful. The same two schemes made provision for maintaining flows along lengths of ephemeral stream above the perennial head."

The only comments made by Headworth regarding water quality problems relate to the Shropshire, Isle of Wight, and Wallers Haven Schemes, where:

> ".. the discharge of iron-rich groundwaters may require some form of pre-treatment. The discharge of anaerobic water from confined aquifers requires aeration to introduce oxygen to preserve fauna and flora".

In certain cases precautions have had to be taken in response to specific problems (Headworth et al, 1983a). Special borehole discharges have been provided as part of Stage 1 of the Great Ouse Scheme to protect springs and wet lands of scientific interest. Similar protection may be needed on the Isle of Wight for copses (called Withy Beds) in spring-fed boggy ground. Flowing artesian boreholes supplying commercial watercress beds were affected by the Candover Scheme in Hampshire, and pumps had to be provided.

Archaeological sites have required consideration during the design of a number of schemes. In particular the Shropshire, Thames and Great Ouse schemes have been affected, and in some instances boreholes or pipelines have had to be relocated. The experiences of the Thames Groundwater Scheme, where the number of archaeological sites involved increased from eight to sixty during the public inquiry, were related by Hall (1978) and highlighted the importance of including an archaeologist early in the planning process.

The limited visual impact and the minimal land required by groundwater schemes is one of their principle advantages when compared with surface reservoirs of equivalent yield. Skinner (Headworth et al, 1983a) does not mention any problems which have arisen in connection with these aspects and states:

> "In many schemes the object of abstraction borehole site design has been to reduce above ground works to a minimum. A popular format is to keep all borehole headworks below ground with the exception of electrical control and metering equipment which is housed in a glass reinforced cabinet of standard design. Site landscaping is aimed at integrating the site into the, normally rural, landscape using agricultural fencing rather than walls or railings."

Although groundwater developments on the scale of the current river augmentation schemes have little impact at the ground surface, lowering of the water table can occur over a wide area. The first major pilot schemes, those of the Thames and Great Ouse Groundwater Schemes, were:

> ".. something of a novelty and led to anxiety in the farming community over the widespread groundwater lowering on agriculture" (Headworth et al, 1983a).

In response to this "anxiety", which has consistently arisen in connection with such schemes, studies have been undertaken which, in Headworth's words:

> ".. showed that in these (Thames and Great Ouse pilot schemes) and similar chalk catchments no harmful effects would result, and in fact positive benefits could occur in low-lying and water-logged ground. This was not the case in the Shropshire Scheme where the subdued landscape and shallow groundwater levels was considered more vulnerable to groundwater lowering and several boreholes were relocated to lessen the effects of drawdown."

As far as is known all studies relating to agriculture have been undertaken, on behalf of the Water Authorities concerned, by Dr Drennan an Agricultural Botanist from Reading University. In view of the subject of this research thesis, and that it is at variance with some of Drennan's opinions, where his early studies relate to soil moisture they are given more detailed consideration in Section 3.4.

Drennan (1979) has grouped the "agricultural consequences" of groundwater schemes into two categories. One, the possible drainage effects on farmland and the crops grown, has already been mentioned above; the other relates to the effects on existing farm water sources. These sources, stock watering or irrigation points on small streams and farm wells, are protected by law. Water Authorities are therefore required to make good any detriment or to provide alternative sources where supplies are affected adversely. Prior to the commissioning and operation of Stage 1 of the Thames Groundwater Scheme, a survey of existing supply sources and subsequent simulation of water table lowering caused by pumping, revealed that some 130 private groundwater sources could have been at risk (Goddard and Peters, 1978). A variety of alternative measures were adopted for the protection of these sources:

i) installation of mains service connection;
ii) lowering of existing pumps;
iii) replacement of existing pumps by ones of higher duty installed at a lower depth;
iv) deepening of existing well to permit (ii) or (iii) to be implemented;
v) drilling new borehole to permit (ii) or (iii) to be implemented.

3.4 AGRICULTURAL CONSEQUENCES OF GROUNDWATER DRAWDOWN - EXPERIENCES PRIOR TO THE SHROPSHIRE GROUNDWATER SCHEME.

It has already been noted in Section 3.3 that Dr Drennan of Reading University has acted as agricultural consultant for the majority, if not all, of the schemes involving the augmentation of river flows by groundwater. His advice and the results of his field work have allayed the fears of the farming communities during the promotion of both the Thames and the Great Ouse Groundwater Schemes. The arguments and thinking used have been summarised in a paper presented at a seminar on Man's Impact on the Hydrological Cycle in the United Kingdom (Drennan, 1979). The consequences of groundwater pumping for farm water supplies were covered in Section 3.3, and the more detailed review presented here is confined to the effects on vegetation.

3.4.1 ARGUMENTS RELATING TO THE EFFECTS OF GROUNDWATER DRAWDOWN ON AGRICULTURE.

Areas which could be affected by the lowering of groundwater levels through pumping, are restricted to those in which the root zone of the soil is in direct hydraulic continuity with the aquifer being pumped. Where these conditions exist Drennan (1979) observes that:

> "There is usually no discernible change in the quantity of water held in soils by capillary forces in drained soil layers with water tables already at a moderate depth, say 1 to 1.5m, if such water tables are lowered by a further 0.5 to 1m".

This statement is qualified when he notes that laboratory studies, using suction plate apparatus, suggest that some soil types should experience small losses. However, in the field these effects are masked by the natural wetting and drying patterns caused by the prevailing weather conditions.

Drennan counters the "misconception" that plants benefit from water supplied through capillary rise, by arguing that the rate at which water is supplied is small, and only significant within a limited distance above the water table. The actual height of the capillary zone and the rate of moisture movement are dependent upon the soil type (see Fig 3.2). Thus, Drennan argues that for capillary rise to be at all effective the water table must be located 0.25m to 1m beneath the bottom of the root zone. Since there are few crops with roots below 1.5m, even in deep rooting species, then where water tables are more than 2m below the surface any drawdown can be assumed to have no influence on the available moisture. Trees in the United Kingdom root to depths of 2.5 to 3m, and consequently water tables more than 4 or 5m below ground level are of little benefit to them either.

Fig 3.1 Relationship between Capillary Rise into a Moderately Dry Root Zone and Water Table Depth below the Root Zone in 3 Soil Types (after Rijtema, 1968).

Regarding the suggestion that benefits may accrue to farmers as a result of drainage through pumping, Drennan comments that:

> "Since few plants will root into waterlogged soil, drainage may in some circumstances give plants access to more soil water by deeper rooting than in undrained soils. In addition, drainage may give better soil conditions for cultivation, mineral uptake, weed control and harvesting crops. Drainage can increase yields of crops but the depth of water table which is critical varies with soil type and rainfall amounts".

River augmentation schemes are usually only intended for use during periods of water shortage to supplement river flows, and so pumping will not occur during wet years when land drainage would be most beneficial. It is, therefore, most unlikely that farmers would cultivate the very land, with shallow water tables, that might benefit from the lowering of groundwater levels. Drennan unwittingly made this point when discussing capillary rise:

> "Soils which might have water tables high enough to be beneficial by supporting capillary rise at a sufficient rate in mid-summer are likely to be too wet to cultivate in early spring and at risk for harvesting in wet autumns. Farmers recognize this and either do not crop such land or spend large sums draining it".

Furthermore, Drennan comments that much of the "wet" land, which would benefit from drainage or be affected by moisture loss through the removal of the capillary zone, is riparian and might thus be buffered from the effects of groundwater drawdown by the maintenance of water table levels through leakage from the adjacent river. If, however, drainage as a result of pumping is experienced, because of the nature of augmentation schemes this is likely to occur during drought conditions when water tables fall naturally. The frequency of these occurrences would therefore not be increased, but:

> ".. the drainage effect would be more severe than in the absence of nearby pumping and the recovery to "wet" conditions might take a little longer to achieve".

In concluding his paper, Drennan (1979) states that:

> "Given care in choice of well sites and suitable monitoring of potentially sensitive areas there need be no serious or long lasting harmful agricultural or ecological changes resulting from sensible programmes of groundwater development".

3.4.2 THE THAMES GROUNDWATER SCHEME.

During the promotion of Stage 1 of the Thames Groundwater Scheme, very little work was carried out on the effects of groundwater drawdown on soil moisture as Drennan's advice and evidence was generally accepted with very little debate (Robinson, 1984).

In evidence presented at the public inquiry in March 1972, Drennan considered separately the effects of pumping on agriculture in the chalk downland areas and in the riparian valleys (Drennan, 1972).

The arable areas of the chalk downlands were located on the undulating areas between valleys, and on valley sides where the gradient was not too steep. Cereals were the dominant crop on this arable land which covered about 60% of the downland, with the majority of the remaining 40% being grassland. Drennan stated that significant capillary rise in fragmented chalk and weathered chalk sub-soils was restricted to a zone extending 0.9 to 1.2m above the water table. Any beneficial effects from capillary rise which might be experienced by crops, except trees and a few deep rooting varieties such as lucerne, would therefore be limited to locations where the water table was within 1.5 to 1.8m of the ground surface. He pointed out that deep rooting crops and trees would find root penetration to such depths difficult in the parent material. Since there were few areas of the downland with high water tables, there were no reasons why drawdown as a result of pumping should affect crop "water supplies". Where shallow water tables existed they were generally found close to the spring line on the northscarp slope, which was normally so steep that cropping was not possible.

With respect to the natural vegetation, Drennan said that an analysis of the factors influencing the distribution of plant communities on the downlands did not suggest that water table levels played a significant part in their choice of habitat.

In the riparian valleys the majority of the land cover was permanent pasture and trees. The proportion of arable land was very small and comprised only about 1% of the total, again mainly planted with cereals. Water tables alongside the streams were very close to river levels, but fell to about 1m or more below ground towards the edge of the valley deposits. Much of the grassland was found to be so wet that, for at least some part of the year, it could be classed as marsh or bog. In these areas, Drennan stated, the effect of pumping was known to be slight and would only occur well into summer, usually in a drier than average year, when even these areas would be drying out. Bank leakage, from perennial streams carrying pump discharges, would help to mitigate any tendency for water levels to drop. The main effect, if abstraction created any drawdown, would be that these areas would "dry out a little more and for a little longer" than without pumping.

When he dealt with the more economically viable areas of the valley lands, Drennan said that most forms of trees, grasses and other crop species would respond to a small fall in water table by rooting deeper, and would thus not suffer any loss of moisture. He continued that:

> "A rapid drop in water table early in spring when crop growth is starting and root development is small is the only situation where a water table effect could be important. The water table would then at this time of year only be important if within 2ft (0.6m) of ground surface".

This statement was qualified with the observation that it was unlikely that land with such a shallow water table would be cropped, but would be permanent grass or natural vegetation with a well established root system.

Drennan concluded his evidence at the public inquiry with the statement that, for the reasons given above:

> ".. strongly suggest that fears of crop damage or substantial harm to natural vegetation will not be realised. Despite this the Conservators have agreed assurances with the National Farmers' Union to meet any crop damage claims that are shown to be due to pumping".

3.4.3 THE GREAT OUSE GROUNDWATER PILOT SCHEME.

Arguments, essentially the same as those used in Drennan's evidence to the Thames groundwater scheme public inquiry, were employed in relation to the high ground within this pilot scheme area. However, in the final report on the project (Great Ouse River Authority, 1972) it is concluded that extensive groundwater pumping may affect crop yields:

> ".. by reducing soil moisture in the riparian zone where the natural water table is close to the root zone and so possibly affecting some crop yields. The reduction in soil moisture can, however, be beneficial to crop yields in some areas where it improves drainage".

Throughout the Great Ouse Pilot Scheme, soil moisture levels were monitored at twenty sites within the area by the "neutron scatter technique" (Great Ouse River Authority, 1969, 1970, 1971, and 1972). The analysis of these data showed that pumping from the chalk affected soil moisture content only where groundwater levels were relatively close to the surface. However, even where moisture losses were anticipated, it was found that the nature of the deposits overlying the chalk was the factor which dictated whether there was any effect or not. The superficial deposits flanking the rivers were generally relatively impermeable peats, peaty silts and clays, with very low hydraulic conductivities, which prevented direct hydraulic continuity with the aquifer being pumped, and possessed groundwater levels closely related to river levels (Great Ouse River Authority, 1970). Thus, when drawdown occured as a result of pumping, no loss of soil moisture was observed (Figs 3.2 and 3.3 were presented in the report as evidence of this). However, about 80m from the rivers the peaty and clayey deposits tended to thin out and were replaced by sands. Where these sands sat directly on the chalk it was found that water level changes within the aquifer affected soil moisture in the overlying sands, as illustrated by Fig 3.4.

Fig 3.2 Great Ouse Pilot Scheme - Seasonal Changes in Soil Moisture Content in the Riparian Zone (Great Ouse River Authority, 1970).

During the pilot scheme a number of complaints were received alleging that pumping had caused a reduction in crop yield. One complaint was received in 1969 and seven in 1970, but none in 1971. In 1970 two complaints of trees dying were also received. These were investigated in detail, those relating to crops by Drennan, a copy of whose report is included in the Steering Committee's Final Report (Great Ouse River Authority, 1972).

Of the seven complaints concerning crop losses only one, involving a 3 ha field of sugar beet, was considered to be related to pumping. The River Authority agreed to compensate the farmer for a small part of the field (about 0.2 ha) immediately around a spring area. Drennan concluded that the water table before pumping was at such a depth that a shallow rooting crop would not have been affected, and that the benefit to the sugar beet was very marginal. Crop damage at the remaining sites was attributed mainly to the drought conditions which prevailed at the time.

When the Final Report was published investigations into the tree damage, being conducted by the Woodland Management Association Limited, were incomplete. However, it seemed likely that one, involving a young stand of poplar trees growing along a spring line, was valid.

Drennan's overall conclusion was that only 1 to 1.5% of the cropped area was:

> ".. the subject of any major unexpected concern in a year (1970) in which the highest possible pumping rates were superimposed on a period of substantial drought".

He ends his report with the following paragraph.

> "With such a severe test as 1970 successfully passed and a year of more normal pumping duty in 1971, without any crop damage complaints at all, it may safely be concluded that crops grown in the pilot scheme area have not been influenced harmfully by the changes in water levels caused by the pumping programmes of the past three years. It may equally safely be concluded that future groundwater operations of the same scale in similar areas should be substantially free from crop damage situations".

3.4.4 SUMMARY OF THE EARLY PHILOSOPHY RELATING TO THE AGRICULTURAL CONSEQUENCES OF GROUNDWATER DRAWDOWN.

1. Crops, trees and vegetation only benefit from the presence of a water table through additional moisture supplied by capillary rise, and that only when their roots extend into a zone of height 0.25 to 1m above the water table.

2. Arable crops (with the exception of deep rooting varieties), grassland and natural vegetation will not benefit from water tables which are deeper than 2m below the surface. However, since tree roots extend 2.5 to 3m below ground they will be able to take advantage of water tables down to a depth of 4 to 5m.

3. For water tables and soil moisture to have any response to groundwater drawdown as a result of pumping, there must be hydraulic continuity between the soil horizons concerned and the aquifer being pumped. Soils of low conductivity can, for practical purposes, be considered to isolate upper horizons from the effects of a falling water table.

4. Despite claims to the contrary, the discussion and case studies presented above, in Section 3.4, suggest that it is doubtful whether drainage as a result of pumping is of any practical benefit to the farming community. The operation of river augmentation schemes, in particular, is so unpredictable that farmers are unlikely to risk intensive use of the wet, generally riparian, lands that might be beneficially affected by falling water tables. When drawdown as a result of pumping does occur, it is in dry years when the water table is already falling naturally. Finally, the very act of lowering the water table may well induce leakage through the bed and banks of an adjacent stream, thereby maintaining moisture levels which would otherwise be reduced.

Chapter 4. THE THEORETICAL CONSIDERATIONS AND BACKGROUND EXPERIENCE.

If a saturated or near saturated natural soil is allowed to drain, under the ideal conditions of zero rainfall and zero evaporation and transpiration, moisture will be removed from the profile until, for all practical purposes, a state of equilibrium is achieved. This state, at which the forces retaining moisture within the soil matrix balance the downward pull of gravity, is commonly referred to as field capacity.

The moisture content at field capacity is not constant with depth, but is influenced by the texture and structure of the various soil horizons, and their height above the water table. In general the position of the water table is only a significant factor when it is relatively close to the horizon in question. Should a water table, near enough to the ground surface for roots to benefit from its effect on the moisture profile, be drawn down during a dry period, the amount of available water will be reduced and the vegetation may be affected adversely. Groundwater augmentation schemes, as described in Chapter 2, operate in precisely this manner.

4.1 BASIC CONCEPTS IN SOIL PHYSICS.

An unsaturated soil is a complex system comprising mineral and organic matter, air and water. The latter may be present in any combination of its solid, liquid or gaseous phases, and may contain a wide range of solutes in varying concentrations. Natural soil profiles are spatially variable, non isothermal, and incorporate microorganisms and the roots of higher plants in their upper horizons. Significant advances in understanding the complex nature of soil moisture physics in unsaturated soils have been made since the work of Buckingham (1907) at the turn of the century. Empirical measurements and quantitative interpretations have gradually been replaced by mathematical descriptions of soil water phenomena based on fundamental mechanics. The main driving force behind these developments has been a desire to understand the relationship between soil water and plant growth.

Within the context of this research the provision of a wide ranging review of current unsaturated flow theory is not necesary, and the reader is referred to Klute (1969), Hagen et al. (1967), Groenevelt and Kijne (1972), and Marshall and Holmes (1979) for general studies of the subject. As there are no universally recognised standards, the terminology and notations employed throughout the work will be defined prior to embarking on a discussion of the soil physics concepts which are specifically relevant.

4.1.1 NOTATION AND DEFINITIONS.

Wherever feasible the parameter definitions comply with those adopted by the Soil Survey of England and Wales (Hall et al., 1977; Avery and Bascomb, 1982). A list of the notations used is provided immediately before the Introduction chapter, and definitions of the basic parameters are given below.

a) *Density or Particle Density* (ρ_s): the density of the soil material alone - where not measured it is assumed to be 2.65 g.cm^{-3} for soils containing no or insignificant quantities of organic matter.

b) *Bulk Density* (ρ_b or BD): the apparent density of soil calculated from the oven-dry (105°C) mass divided by the in situ volume.

c) *Total Pore Space or Porosity* (ε): the % volume of bulk soil not occupied by solid material.

$$\varepsilon = \frac{\text{Vol of sample - Vol of solid soil material}}{\text{Vol of sample}} \times 100$$

$$\varepsilon = \left[1 - \rho_b/\rho_s \right] \times 100$$

d) *Moisture Content*: the amount of water in soil expressed ;

as a volumetric fraction $\theta_v = \dfrac{\text{Vol of water}}{\text{Total sample vol}}$

on a mass basis $\theta_m = \dfrac{\text{Mass of water}}{\text{Total sample mass}}$

The water content is most commonly obtained by finding the loss of mass (m_w) when the soil is dried in an oven at 105°C to a constant mass (m_s) thus:

$$\theta_m = m_w/m_s \qquad \text{hence} \qquad \theta_v = \theta_m(\rho_b/\rho_w)$$

Whenever reference is made to water content (θ) without further qualification, it will be the volumetric fraction (θ_v) which is referred to.

e) *Available Water* (A_{vt}): the quantity of water in the soil available for use by plants. For practical purposes this is defined as the moisture retained in the soil between the field capacity and the permanent wilting point (see Sect. 4.1.2).

4.1.2 SOIL MOISTURE SUCTION OR TENSION.

The water in unsaturated soils is retained in the soil matrix against the action of gravity by several different types of force. For the range of conditions under which moisture is available to plants, the most significant of these forces is that due to surface tension. The terms suction and tension are both used to denote this force, and the terminology employed in the literature depends on the individual author's preference.

In a freely draining saturated soil, water first drains from the largest soil pores - a process that continues until capillary forces balance the action of gravity. At this point, field capacity, a plant has to apply a suction of approximately 0.1 bar in order to absorb water. As the moisture content continues to fall, moisture film thicknesses reduce, small pores empty, and as a consequence plants have to exert greater and greater suctions in order to meet their water requirements. Finally at a suction/tension of approximately 15 bars (the permanent wilting point) roots are incapable of abstracting further moisture and plants will die unless irrigated immediately. At suctions greater than 31 bars the remaining water is termed hygroscopic; it is essentially non-liquid and bound to the soil particles.

The name given to the relation between water content (θ) and suction (S) is the *soil moisture characteristic*. Characteristics vary according to soil type, texture and pore size distribution, and Fig 4.1 shows some examples for typical British soils (after Hall et al., 1977). The curves are derived under controlled laboratory conditions by equilibrating samples under a range of suctions or pressures, as described by Avery and Bascombe (1982). Fig 4.2 illustrates the relationship between the different terms used to describe water in soils, and shows the moisture characteristic for a loam soil (Brady, 1974).

4.1.3 MOISTURE MOVEMENT IN UNSATURATED SOILS.

Moisture moves in an unsaturated soil in response to a potential energy gradient. It is common practice to distinguish the following component potentials for water in an isothermal soil (Day et al.,1967; Marshall and Holmes, 1979).

a) *Gravitational Potential* (ϕ_g): the potential energy by virtue of the height of the water (z) relative to some pre-determined datum.

$$\phi_g = \rho_w g z$$

Fig 4.2 Different Terms Used to describe Water in Soils Illustrated in Relation to Loam Soils (Brady, 1974).

b) *Matric Potential* (ϕ_m): the pressure potential that arises from the interaction of water with the matrix of solid particles within which it is embeded. Above the groundwater table a continuous film of soil water is "under suction", i.e. the matric forces have the effect of a negative hydrostatic pressure (Groenevelt and Kijne, 1972).

$$\phi_m = \text{fn}\ (\theta,\ \text{soil type})$$
$$\phi_m = \rho_w g h$$

where h = the matric suction head.

c) *Osmotic Potential* (ϕ_o): the potential resulting from the osmotic pressure caused by dissolved solutes in the water.

The *total potential* (Φ) is obtained by combining the component potentials, thus giving:

$$\Phi = \phi_g + \phi_m + \phi_o$$

The osmotic potential is only significant for saline groundwaters and the influence of dissolved solutes will not be considered during the course of this project. It is therefore only necessary to consider the *hydraulic potential* (ϕ):

$$\phi = \phi_g + \phi_m$$

Substituting for ϕ_g and ϕ_m gives:

$$\phi = \rho_w g z + \rho_w g h$$

which expressed in terms of metres head, i.e. per unit weight, is:

$$\phi = z + h \qquad \text{- Eqn 4.1}$$

Richards (1931) proposed the extension of the application of the Darcy equation, for flow in saturated media, to the unsaturated state. Although it has been claimed that Darcy's law does not hold when flow velocities are very small, this has not been demonstrated to the satisfaction of most workers in the field (see Marshall and Holmes, 1979), and it is still in common useage. The generalised form of Darcy's law for one dimensional vertical flow in saturated soils is:

$$v = -K_s . \frac{d\Phi}{dz}$$

where, v is the rate of discharge per unit area (in cm/sec), and K_s is a constant, the saturated hydraulic conductivity. The minus sign indicates that the flow is in the direction of decreasing potential.

Richard's modification of Darcy's law is written as:

$$v = -K.\frac{d\Phi}{dz}.$$

where K is the unsaturated conductivity, which is no longer constant and varies as a function of the moisture content. The minus sign now relates to the direction of flow when the positive direction is taken as vertically upward from the selected datum. Considering the hydraulic potential alone, and substituting from Eqn 4.1 gives:

$$v = -K.[1 + \frac{dh}{dz}] \qquad \text{- Eqn 4.2}$$

The unsaturated conductivity (hereafter referred to simply as the conductivity) is the parameter which defines the ease with which water can move through an unsaturated soil. At high moisture contents conductivity is high and moisture movement takes place readily, but at low moisture contents conductivity is greatly reduced and moisture movement is highly restricted. However, the change from high to low conductivity is not gradual, but takes place rapidly over a small range at a relatively high moisture content (i.e. a relatively low soil moisture tension) as illustrated in Fig 4.3. Klute (1969) has suggested that this is due, not only to the reduction in both the cross sectional area available for moisture movement and the size of the flow channels, but also because the detailed microscopic flow paths become more tortuous. The increase in viscosity of the water due to its close proximity to solid surfaces could also be a contributory factor.

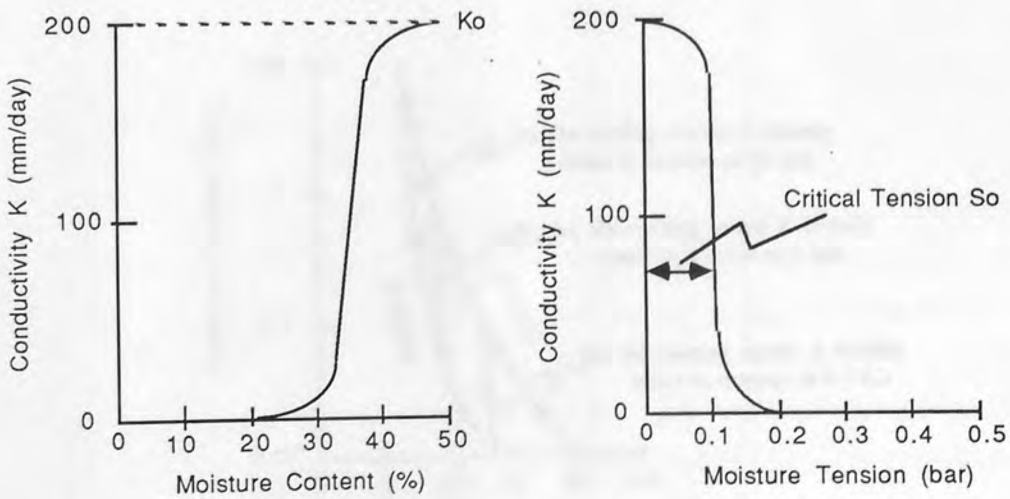


Fig 4.3 Typical Moisture Content/Conductivity and Moisture Tension/Conductivity Relationships.

Before proceeding, in Sect. 4.2, with a discussion on the importance of the conductivity/suction relationship to the soil moisture profile above a water table it is necessary to deal with the phenomena of hysteresis which introduces complications into the treatment of unsaturated flow.

4.1.4 HYSTERESIS.

The soil moisture characteristics discussed in Sect. 4.1.2 were derived by increasing the soil suction and monitoring the corresponding decrease in water content - a drying soil. Upon rewetting a different path is traced by the moisture content/suction curve, as illustrated in Fig 4.4. Furthermore, if the process is reversed at any intermediate stage of wetting or drying, the curve will follow a different course within the limits set by these two boundary curves. Two mechanisms are commonly advanced to explain hysteresis: the "ink bottle" effect, which occurs because many pores are larger than the openings into them; and, the contact angle theory. In the latter the argument is that the contact angle between the fluid and a solid boundary tends to be larger when the fluid is advancing (wetting) than when it is retreating (draining). This means that the energy needed to fill a pore is greater than that required for drainage. The ink bottle effect is illustrated in Fig 4.5.

As a consequence of hysteresis the soil mosture/suction relationship for a given soil is not unique, but depends on its wetting/drying history. The relevance of this phenomena to the problem under consideration will be explained in Sect. 4.2.2.

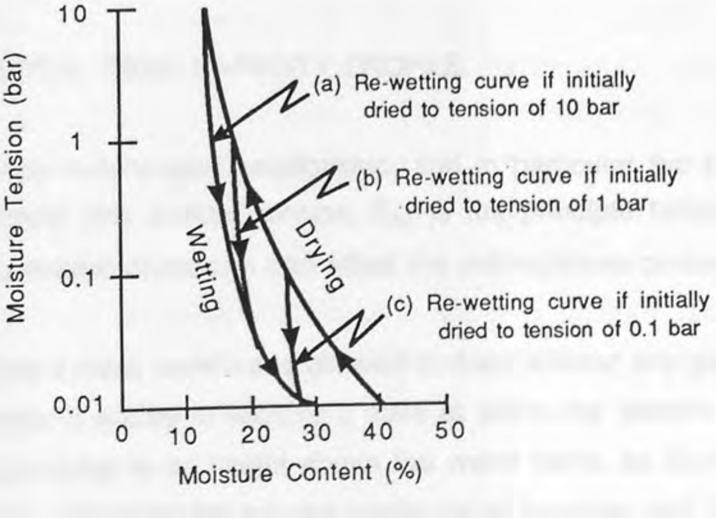
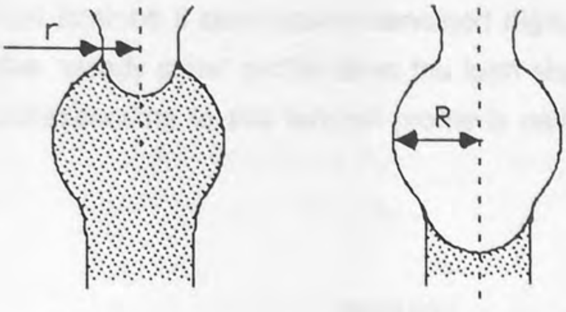


Fig 4.4 Moisture Content/Tension Relationship Showing Typical Hysteresis Effect.



(a) Drying (b) Wetting

Fig 4.5 Hysteresis in the Amount of Water Contained in a Pore at a Given Suction Due to the 'Ink Bottle' Effect.

If suction = $\frac{2\sigma}{\rho g} . r^{-1}$ where σ = surface tension and

R is the maximum and r the minimum radius of the pore, then:

(a) when draining the pore remains full of water until suction exceeds $\frac{2\sigma}{\rho g} . r^{-1}$

(b) when rewetting water can only refill the pore when the suction falls to the lower value $\frac{2\sigma}{\rho g} . R^{-1}$

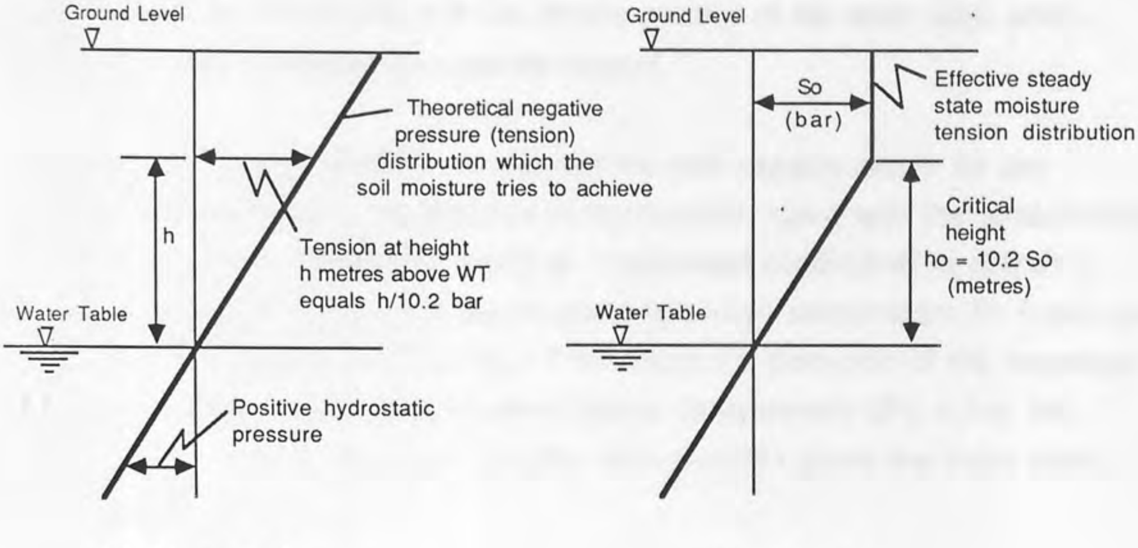
Thus at any given suction the water content of the drying pore exceeds that of the pore on re-wetting.

4.2 THE THEORETICAL EFFECT OF WATER TABLE DRAWDOWN ON AVAILABLE SOIL MOISTURE.

4.2.1 THE THEORETICAL FIELD CAPACITY PROFILE.

The form of the conductivity/tension relationship, and in particular the tension at which conductivity falls rapidly (the *critical tension*, S_o) is the principle factor governing the extent to which groundwater drawdown can affect the soil moisture content.

When a soil containing excess moisture is allowed to drain without any gain or loss of moisture at the surface, it will try to achieve a state at which the tension at any given point is directly proportional to its height above the water table, as illustrated in Fig 4.6a. However, as the soil drains the tension continues to increase until it reaches the critical tension (S_o). At this point the conductivity drops very rapidly and further drainage is reduced to negligible proportions. Thus, the theoretical state of tension equilibrium, which would be attained if conductivity remained high, is never achieved. As a consequence the effective "steady state" profile takes the form shown in Fig 4.6b. The moisture content curve corresponding to this tension profile is called the field capacity profile.



(a) Theoretical (b) Effective

Fig 4.6 Theoretical and Effective Steady State Moisture Tension Distributions.

Attempts have been made to relate field capacity to the moisture content that pertains for one particular value of tension. Peters (1965) defined it as the moisture content corresponding to a tension of 0.33 bar, while Penman (1965) proposed 0.5 bar. Thomasson (1967) and Webster and Beckett (1972) concluded, after investigations into field soil moisture regimes, that the range of 0.03 to 0.07 bar was more representative of British conditions. The Soil Survey have standardised on 0.05 bar for field capacity in their laboratory determinations of available water and moisture characteristics (Avery and Bascomb, 1982). Such definitions are useful in that they define a standard for laboratory investigations, but they are of little value in field studies because they do not relate to the conductivity/tension relationship and, in particular, the critical tension at which conductivity drops rapidly. It therefore follows that 'field capacity' can not be considered as a single value of moisture content, but must be viewed as the full moisture profile which develops under the critical tension.

It is now necessary to introduce the concept of critical height. The definition adopted is that:

> the *critical height* (h_o) is the height above the water table at which the tension becomes equal to the critical value, S_o.

Below this level, h_o in Fig 4.6b, it is the relative position of the water table which controls the tension and hence the moisture content.

Theoretically it should be possible to construct the field capacity profile for any particular soil by combining the moisture content/tension curve with the tension/height above the water table relationship. However, unsaturated conductivity is difficult to measure, and so little is known of the conductivity/tension relationships for British soils that this is not possible in practice. Fig 4.7 illustrates the derivation of the theoretical field capacity profile (Fig 4.7d) from the moisture characteristic (Fig 4.7a), the conductivity/tension curve (Fig 4.7b), and the tension height above the water table relationship (Fig 4.7c).

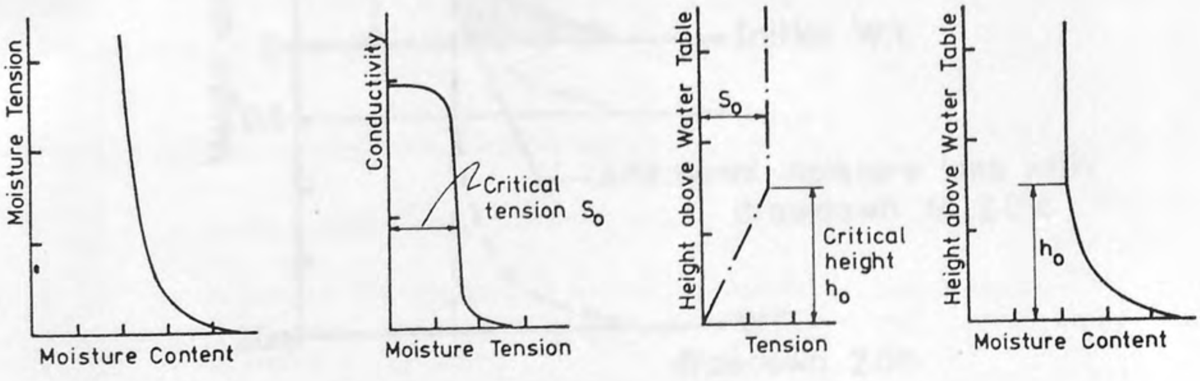


Fig 4.7a Fig 4.7b Fig 4.7c Fig 4.7d

Fig 4.7 Construction of Theoretical Field Capacity Profile.

4.2.2 THE EFFECT OF GROUNDWATER DRAWDOWN.

Although in practice it is not possible to derive the actual field capacity profile for a soil, the theoretical profile enables the effects of groundwater drawdown upon available moisture to be anticipated.

Pumping will cause the water table to fall, and as it does so the field capacity profile will effectively follow the phreatic surface down, as illustrated in Fig 4.8. The moisture content of the soil within the original critical height will decrease and, if the water table is close enough to the surface for roots to extend into this zone, the crops and other vegetation will experience a reduction in the moisture available to them. In addition, those roots which have penetrated into the capillary fringe will also lose the moisture they would otherwise gain from capillary rise.

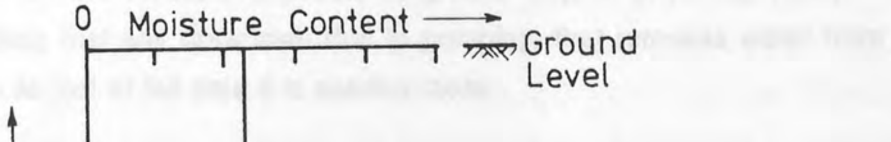


Fig 4.8 Effect of Groundwater Drawdown on the Field Capacity Profile.

A further consideration, which is relevant to this problem, is whether or not the moisture lost as a result of drawdown is replenished when the water table recovers to its original position. Theoretical considerations indicate that, as a result of hysteresis, there will only be partial replenishment of the moisture within the zone of the original critical height. In a discussion of capillarity, Lambe and Whitman (1969) confirm this view, and present evidence from test data obtained by Lane and Washburn (1946) to verify their argument. As a consequence of this hysteresis effect, a drawdown which lasts for only a few days may result in moisture being lost for the remainder of the growing season, or at least until rainfall returns the soil to field capacity.

So far all discussion of the effect of drawdown has assumed that the soil is initially at field capacity, but in practice this is unlikely to be so. In particular, for groundwater augmentation schemes pumping will only commence when river flows, and hence moisture levels, are low. Thus drawdown of the water table will occur when a fairly substantial soil moisture deficit exists. Under these conditions the roots may already have abstracted some of the water which would otherwise be lost due to drawdown. However, roots tend to obtain most of their water from topsoil layers, and only as this source becomes depleted do they increasingly draw on the moisture available at greater depths (Rijtema, 1965). Therefore, it is likely that any drawdown due to pumping, that removes water from the root zone, will do so just at the time it is needed most.

4.3 THE STUDY OF SOIL MOISTURE AT ASTON PRIOR TO 1979.

Although prior to 1979 a number of research projects undertaken by Aston University's Water Resources Group had embraced soil moisture as a minor component within hydrological studies, only the work of Hussein (1979), supervised by W.J. Walley, was specifically directed to the subject.

The initial objectives of Hussein's research were:

i) to review existing direct and indirect methods of soil moisture monitoring;

ii) to investigate the spatial and temporal variability of soil moisture using the neutron scattering method and to explain where possible the causes of this variability;

iii) to assess the feasibility of developing soil moisture networks based upon neutron probe practice, and to make recommendations concerning the design of monitoring sites.

At a later stage a fourth objective was added:

iv) to develop a computer based soil moisture model with a view to improving existing indirect monitoring systems.

The knowledge gained through Hussein's project provided an invaluable foundation for this work, particularly in relation to the field study associated with the Shropshire Groundwater Scheme (see Sect. 5.3). The site work undertaken by Hussein resulted in:

a) the rectification of initial problems with the Neutron Probe;
b) the development of equipment for the installation and extraction of access tubes; and
c) the acquisition of experience in the calibration and operation of the probe.

The study of spatial and temporal variations in soil moisture had emphasised the importance of on-site rainfall monitoring for localised water balance studies. For such studies it was also shown that, providing soil moisture deficits did not exceed 100mm, weekly estimates of evaporation obtained from the Meteorological Office's MORECS system (Institute of Hydrology, 1981) were adequate, and that the monitoring of additional meteorological parameters was unnecessary.

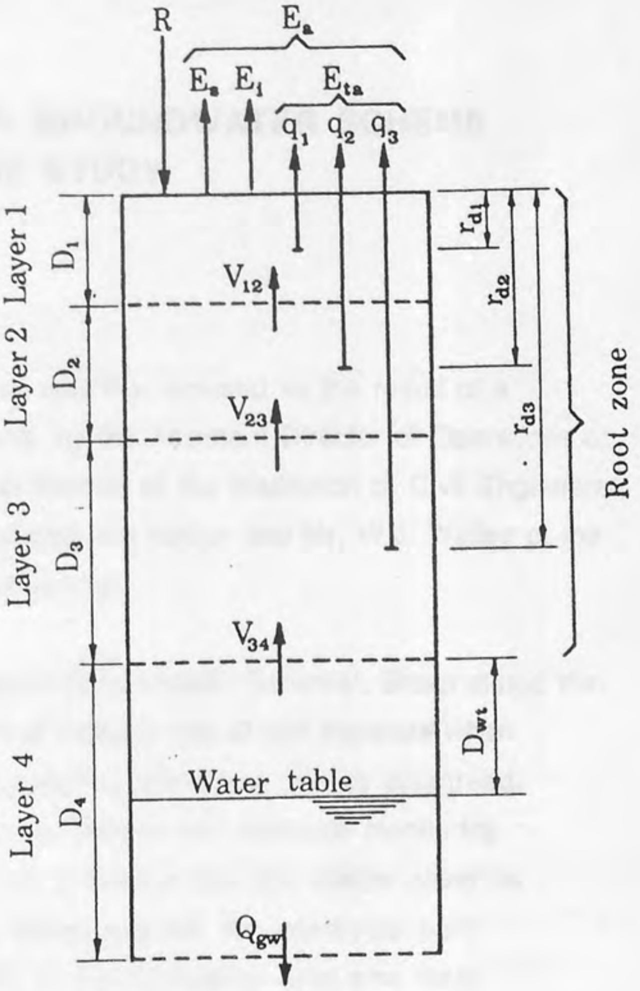
The soil-moisture-plant model, developed to meet the fourth objective, was designed to simulate moisture variations in each of three soil layers and was comprised of two main components. The first was responsible for the movement and distribution of moisture within the unsaturated soil. The second component dealt with the plant, and embraced:
(i) the rate and distribution of moisture abstraction by the rooting system of the plant;
(ii) the response of leaf suction, and hence transpiration rate, to the water supply; and
(iii) the effect of the degree of crop cover.
The root abstraction algorithm provided the point of interaction between the two components. Fig 4.9 is a schematic diagram illustrating the soil-moisture-plant model, which is described in detail in Hussein (1979) and in Walley and Hussein (1982).

Hussein's model in its entirety is not of immediate interest to this study. However, the soil moisture movement component could form the basis of a program to provide planners with a tool for determining the field capacity profile of non-uniform soils above a water table, and hence the critical height. Development of this component of the model would also enable the time taken by a soil to respond to groundwater drawdown to be determined - see Sect 6.6.

4.4 SUMMARY.

As pointed out in Sect. 4.2.2, due to the practical difficulty of determining the critical tension, considerations of the theoretical effect of groundwater drawdown upon the field capacity profile could only provide an indication of what might happen in the field. Therefore, in order to advise farmers concerned over the potential effects of the Shropshire Groundwater Scheme, it was necessary to conduct a field study to establish whether or not the soils in Shropshire would be sensitive to groundwater drawdown.

R	Rainfall
E_a	Actual evapotranspiration
E_s	Evaporation from soil surface
E_i	Evaporation of intercepted rainfall
E_{ta}	Actual transpiration
q_1	Root abstraction from Layer 1
D_1	Thickness of Layer 1
V_{12}	Moisture transfer to Layer 1 from Layer 2
r_{d1}	Mean root depth in Layer 1
D_{wt}	Depth to water table below root zone
Q_{gw}	Groundwater discharge



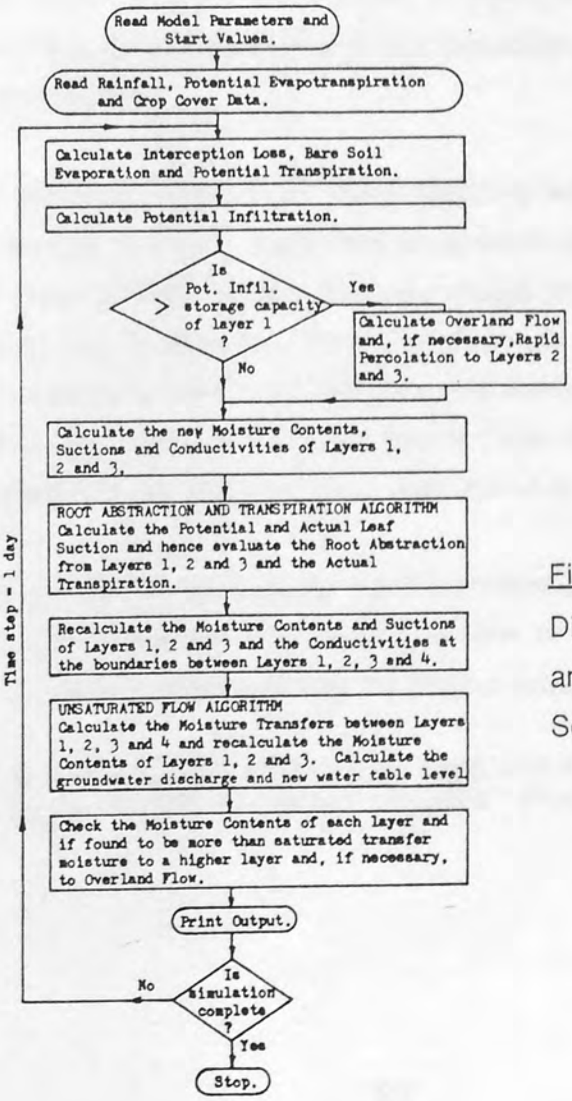


Fig 4.9

Diagramatic Representation of Walley and Hussein's General Purpose Soil Moisture-Plant Model.

Chapter 5. THE SHROPSHIRE GROUNDWATER SCHEME - A CASE STUDY.

5.1 BACKGROUND TO INVOLVEMENT.

Interest in the Shropshire Groundwater Scheme was first aroused as the result of a discussion paper presented in Novemeber 1978, by the Assistant Director of Operations of Severn Trent Water Authority, to the Midlands Branch of the Institution of Civil Engineers (Sharp, 1978b). This meeting was attended by both the author and Mr. W.J. Walley of the Department of Civil Engineeering at Aston University.

In the course of his presentation, 'The Shropshire Groundwater Scheme', Sharp stated that there would be no adverse effects on agriculture through loss of soil moisture when drawdown of the water table occurred during pumping operations. Walley disagreed. Experience gained, as a result of the research project on soil moisture monitoring referred to in Sect. 4.3 (Hussein 1979), led him to believe that the effects could be significant, particularly where shallow water tables existed. An interested party subsequently put Walley in touch with farmers in the Shropshire area who were concerned about the proposed development, and discussions began on the possibility of conducting an investigation.

During January 1979 the Severn Trent Water Authority was contacted, but declined an invitation to co-operate in a joint programme of research. Consequently an agreement was reached with a group of local farmers that they should jointly fund an investigation with the Department of Civil Engineering. The initial proposals (Walley and Hedges, 1979a) proved to be too expensive, and in addition time was limited, so a compromise solution was adopted. The Water Authority agreed to the use of three of their borehole sites providing pumping costs were met, and the field study went ahead on this understanding.

One condition of the agreement, between the Department of Civil Engineering and the 'Agricultural Sponsors', is worth emphasising in view of the later participation in the public inquiry. The agreement stated that the project should be:

> "undertaken on a completely impartial basis and that all reports to the outside sponsors shall be 'without prejudice'" (Walley and Hedges, 1979a).

5.2 EXPERIMENT DESIGN.

5.2.1 THEORETICAL CONSIDERATIONS.

Under normal field conditions there are four hydrological processes affecting the amount of water in the soil moisture store: rainfall, evapotranspiration, interflow to drainage channels, and percolation to the groundwater. Providing the effects of rainfall, evapotranspiration and interflow can be eliminated, then the desired cause - effect relationship, between groundwater drawdown and loss of soil moisture due to deep percolation, can be investigated in isolation.

If the effects of rainfall, evapotranspiration and interflow cannot be eliminated, then this cause - effect relationship can only be studied if it is possible to quantify these parameters. Unfortunately, the instrument that was available for measuring soil moisture change, a neutron probe, was not capable of determining the direction of moisture movement, and hence of differentiating between interflow and percolation. However, by selecting a flat field site, interflow, which could neither be measured nor calculated, could be assumed to be negligible. In addition, provided the rainfall intensity was not excessive and the soil remained in a state of slight moisture deficit, the infiltration would equal the rainfall. Due to its high spatial variability it was essential that rainfall measurements were made on site. The loss of moisture due to evapotranspiration could be estimated, to an acceptable degree of accuracy, from local weather records.

5.2.2 THE ORIGINAL PROPOSAL.

The method recommended in the initial proposals (Walley and Hedges, 1979a) required a flat, horizontal working area of approximately 20 metres square, with a shallow water table. In order to isolate percolation to the water table from the other parameters which influence soil moisture, the ground was to be covered with an impermeable membrane such as polythene sheeting. This would prevent transpiration, but past experience had shown that it would not adequately exclude rainfall since leaks tended to occur. As a consequence a system of interlocking units with sloping roofs was designed. These units, as shown in Fig 5.1, were to be provided with gutters to collect the rainfall so it could be led away. To ensure that infiltrating rainfall from outside the experimental area did not reach the soil under observation, an area of 10 metres square was to be covered.

Two possibilities were considered for lowering the water table. Firstly, this could be achieved through pumping an existing borehole, either privately owned or belonging to

TIMBER FRAME

Fig 5.1 Diagramatic Layout for Site Roof: from Original Research Proposal (Walley and Hedges, 1979a).

Severn Trent Water Authority. Fig 5.2 demonstrates the principle of employing the cone of depression around a pumped well for drawing down the water table. The second method involved the use of well point dewatering equipment. In order to monitor changes in the groundwater level some form of observation was also required.

Equipment for measuring soil moisture content was to consist of:

i) a neutron probe, together with the aluminium soil moisture tubes which would have to be sunk into the ground;
ii) tensiometers located at different levels in the soil;
iii) any meteorological instruments (e.g. raingauges) deemed necessary.

Fig 5.2 Schematic Diagram of Requirements Using a Borehole: from Initial Research Proposal (Walley and Hedges, 1979a).

Fig 5.3 Layout of Experimental Area Using Well Points: from Initial Research Proposal (Walley and Hedges, 1979a).

The proposed layout for the experimental area with the well point technique employed is illustrated in Fig 5.3.

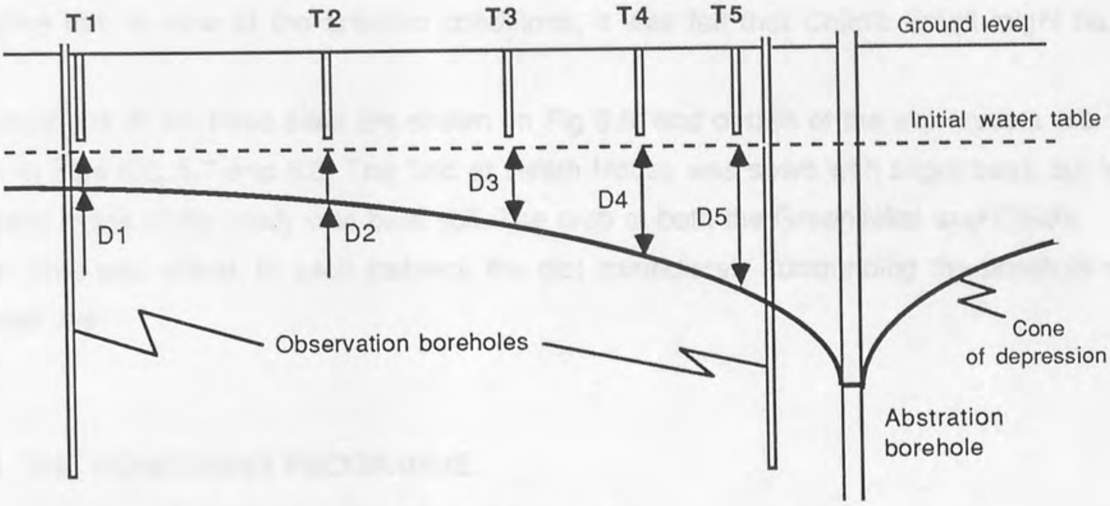
In spite of the advantages to be gained from using the method recommended in the original proposals, circumstances required that a modified procedure be adopted. Firstly, the cost of constructing the 10m by 10m roof and installing well points would have restricted the investigation to one site. Secondly, regarding the use of a pumped well, there were technical problems relating to the control of the drawdown which could have proved difficult to overcome. Finally, time was short. The draft proposals were put forward in February 1979, and the report evaluating the findings and making recommendations had to be submitted before the public inquiry, which was scheduled for September of the same year.

5.2.3 THE METHOD ADOPTED.

In order to gain the maximum amount of relevant data in the time available it was decided to adopt a method which utilised an existing borehole and did not require the ground surface to be covered. It was realised that this approach involved the risk that a prolonged wet or dry period could result in failure to adequately investigate the problem, however there was no alternative but to proceed. A meeting was therefore arranged with representatives of the Severn Trent Water Authority with a view to obtaining the Authority's co-operation. After due consideration the Authority agreed to pump water from three of their boreholes in the Tern area, on the condition that the pumping costs were paid for by the Agricultural Sponsors.

The basic principle of the adopted method was to install a set of soil moisture monitoring tubes (commonly called access tubes) at different radial distances from each borehole. The soil moisture profile would then be monitored before, during and after pumping, which was to be at a constant rate over a period of about four weeks. In this way it was planned to use the cone of depression, produced by the pumping, to investigate the effects of different drawdown depths upon soil moisture content. Fig 5.4 illustrates the principle as envisaged.

For monitoring the development of the cone of depression it was necessary to observe the water table depth at a number of points radiating out from each well. This was achieved by monitoring water levels in the three observation wells the Authority had drilled at different distances from each borehole. Since, at each of the three chosen sites, one observation well was set at 90° to the selected line of access tubes, it was considered desirable to install one 10m long tubewell near to access tube No. 3 (see Fig 5.4). Initially the Authority indicated that it would be able to assist with the drilling for this, but later decided that it could not co-operate and the idea had to be abandoned.



D1, D2, D3, D4 and D5 are the drawdowns
at access tubes T1 to T5 respectively.

Fig 5.4 Variation of Drawdown with Distance from an Abstraction Well

5.3 THE FIELD INVESTIGATION.

5.3.1 THE SITES.

Theoretical considerations indicated that the sensitivity of a site to loss of soil moisture due to groundwater drawdown was primarily dependent upon soil type and the initial water table depth. Clearly, the soils associated with boulder clay (e.g. the Salop Series) were in general unlikely to be sensitive because of the relative impermeability of their underlying parent material. On the other hand, it was felt that the lighter soils associated with the Triassic Sandstones and Glacial Sands (e.g. Newport and Bridgenorth Series) would be sensitive if the natural water table was relatively close to the surface.

Initially it was intended that only one site would be investigated, and it was decided that the location most likely to be sensitive to drawdown should be chosen. The field adjacent to the Heath House borehole was selected as the soil was of the Newport Series, and the natural rest level of the water table was between 2m and 3m below the ground surface. After further discussions with the sponsoring farmers it was decided that two additional sites would be studied; Greenfields and Child's Ercall. The soil type at both of these was Salop Series, and the water table lay at a depth of about 2.5m at Greenfields but was artesian by about 1.5m at Child's Ercall. It seemed unlikely that the Greenfields site would be sensitive but, in view of the artesian conditions, it was felt that Child's Ercall might be.

The locations of the three sites are shown on Fig 5.5, and details of the site layouts are given in Figs 5.6, 5.7 and 5.8. The field at Heath House was sown with sugar beet, but in the early stage of the study was bare soil. The crop at both the Greenfields and Child's Ercall sites was wheat. In each instance the plot immediately surrounding the borehole was grassed over.

5.3.2 THE MONITORING PROGRAMME.

The instrument used to monitor the soil moisture profiles was a Wallingford Neutron Probe of the same type used by the Severn Trent Water Authority in its own studies. The access tubes were installed at the locations shown on Figs 5.6, 5.7 and 5.8, to depths of between 2.0m and 2.5m below ground level. This was the maximum depth that could be achieved using a hand auger and guide tubes. The procedures for access tube installation and neutron probe operation were in accordance with the recommendations of the Institute of Hydrology (Eeles, 1969; Bell, 1976), and utilised the equipment developed by Hussein (1979).

Fig 5.9
The Neutron Probe: Illustration of Components and Operation (from Bell,1976).

Fig 5.5

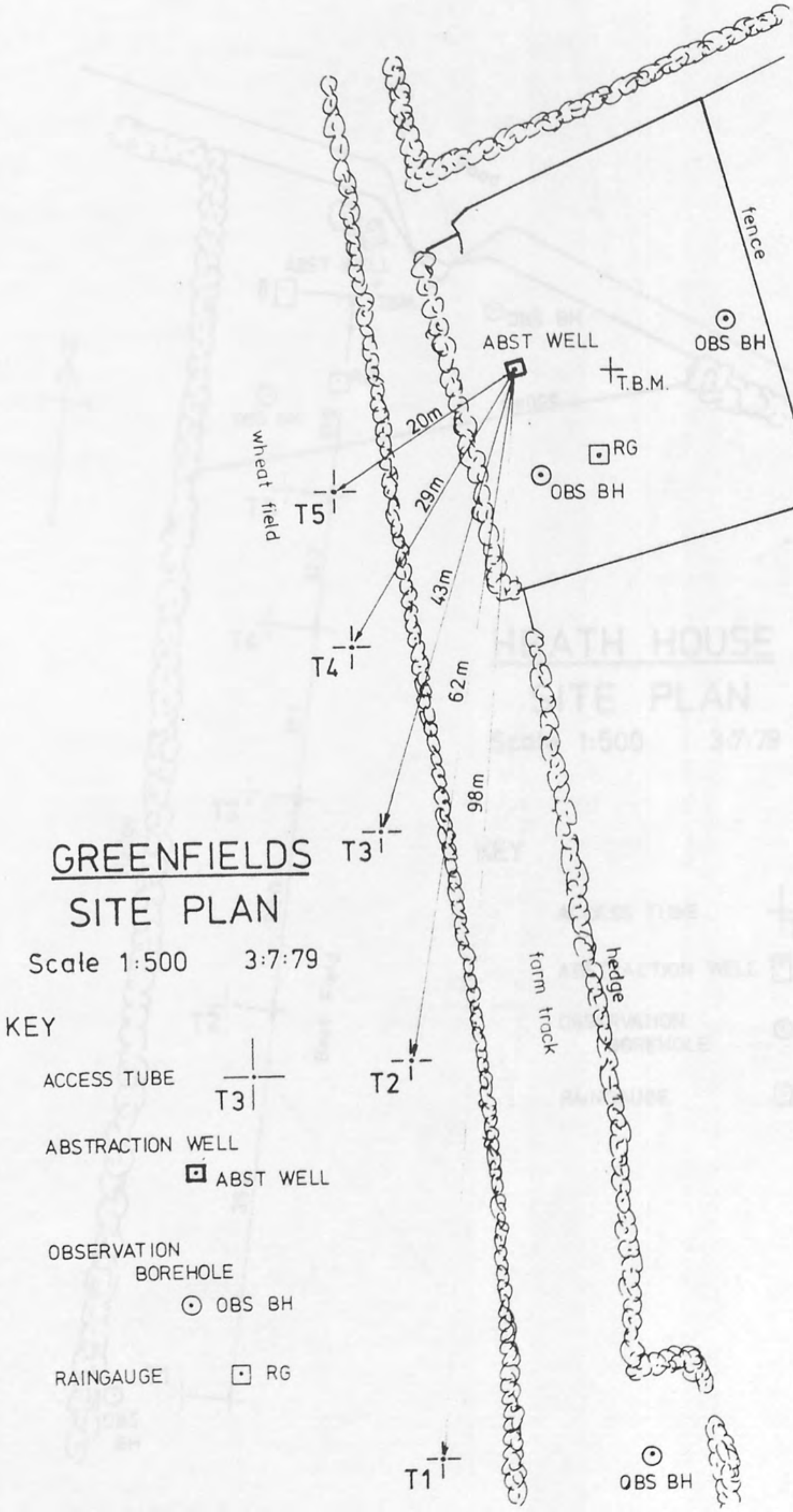


Fig 5.6 Greenfields: Site Plan.

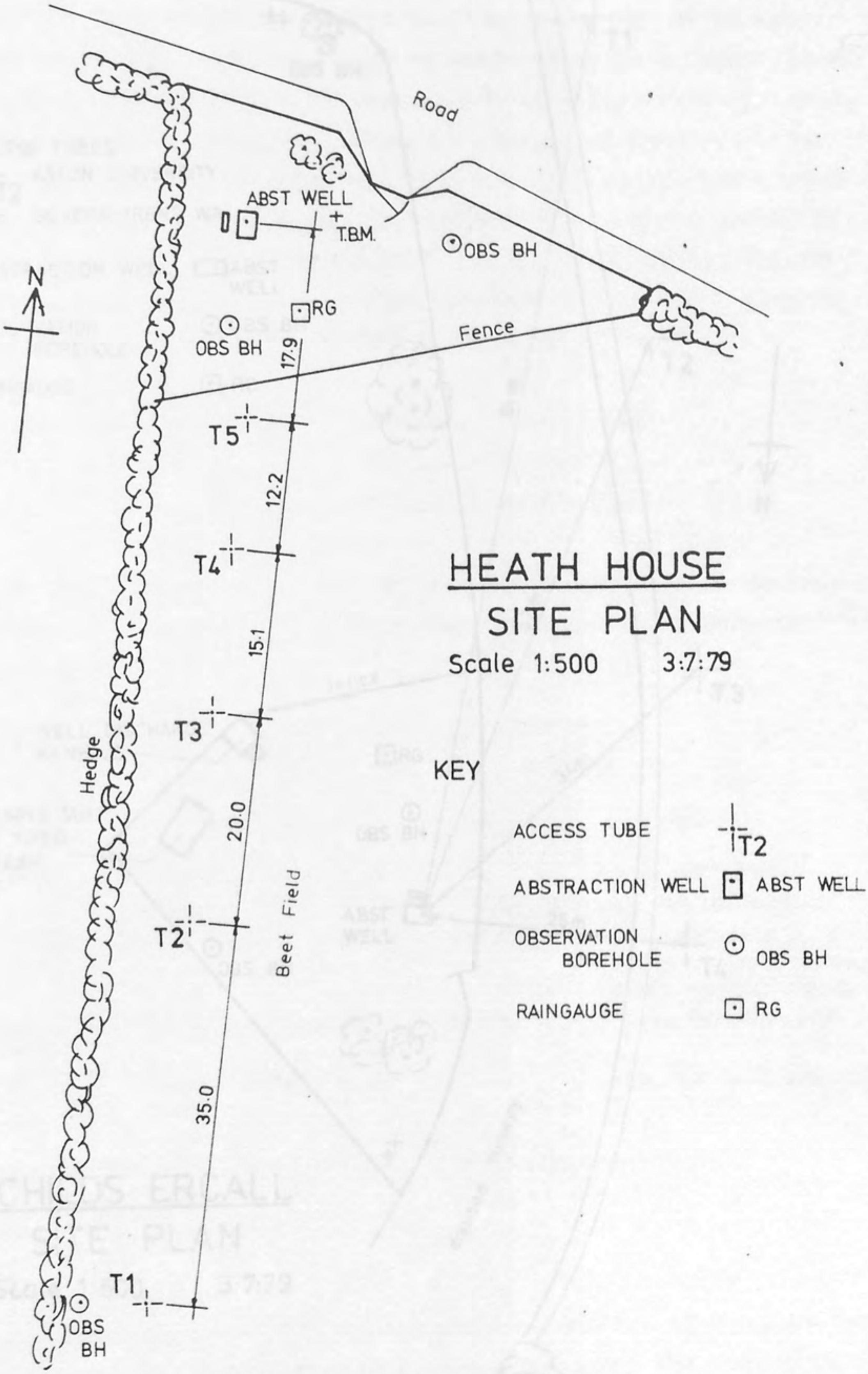


Fig 5.7 Heath House: Site Plan.

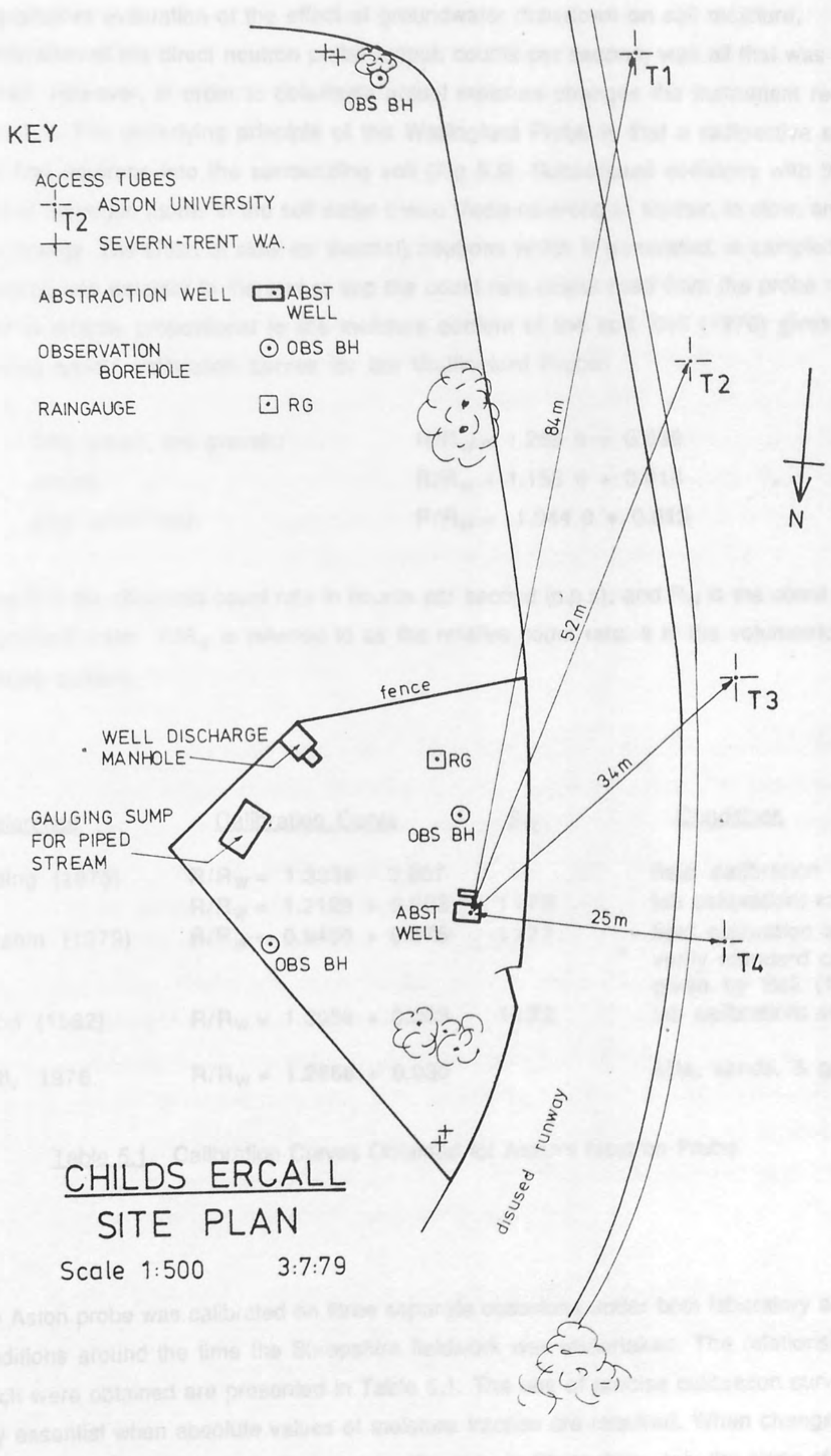


Fig 5.8 Childs Ercall: Site Plan.

For qualitative evaluation of the effect of groundwater drawdown on soil moisture, consideration of the direct neutron probe output, counts per second, was all that was required. However, in order to determine actual moisture changes the instrument required calibration. The underlying principle of the Wallingford Probe is that a radioactive source emits fast neutrons into the surrounding soil (Fig 5.9). Subsequent collisions with the nuclei of hydrogen atoms in the soil water cause these neutrons to scatter, to slow, and to loose energy. The cloud of slow (or thermal) neutrons which is generated, is sampled by an appropriate detector in the probe, and the count rate output read from the probe rate scaler is directly proportional to the moisture content of the soil. Bell (1976) gives the following typical calibration curves for the Wallingford Probe:

Silts, sands, and gravels: $R/R_W = 1.266\ \theta + 0.030$
Loams: $R/R_W = 1.153\ \theta + 0.018$
Clay (and Peat): $R/R_W = 1.044\ \theta + 0.013$

where R is the observed count rate in counts per second (c.p.s), and R_W is the count rate in standard water. R/R_W is referred to as the relative count rate. θ is the volumetric moisture content.

Reference	Calibration Curve	R_W	Conditions
Binding (1975)	$R/R_W = 1.333\theta - 0.007$		field calibration
	$R/R_W = 1.212\theta + 0.003$	1178	lab calibration: sand
Hussein (1979)	$R/R_W = 0.940\theta + 0.075$	1177	field calibration to verify standard curves given by Bell (1973)
Wood (1982)	$R/R_W = 1.395\theta + 0.003$	1172	lab calibration: sand
(Bell, 1976	$R/R_W = 1.266\theta + 0.030$		silts, sands, & gravels)

Table 5.1 Calibration Curves Obtained for Aston's Neutron Probe

The Aston probe was calibrated on three separate occasions under both laboratory and field conditions around the time the Shropshire fieldwork was undertaken. The relationships which were obtained are presented in Table 5.1. The use of precise calibration curves is only essential when absolute values of moisture fraction are required. When changes in moisture content are being studied, as was the case in Shropshire, only the slope of the

Shropshire, only the slope of the calibration curve is of importance. Since Hussein's work had been undertaken only shortly before the groundwater study, his relationship (i.e. a slope of 0.94) was employed in 1979 whenever actual moisture content values were determined.

In the soil horizons immediately below the air-soil interface both fast and thermal neutrons are lost from the cloud generated within the soil by the neutron probe. This means that within the top 200mm of the soil count rate readings are not simply related to moisture content, but are also a function of the depth below the ground surface. A variety of techniques have been suggested in order to overcome this problem. Eeles (1969) proposed the use of neutron reflectors, and Bell (1973) experimented with 'surface extension trays' which were filled with the local topsoil and planted with the appropriate crop. The former method proved to be unreliable. Although the latter enables sensible readings to be obtained for surface soil layers, it has several drawbacks: it is only appropriate for flat sites where the crop can not be damaged by the tray; it is cumbersome; the extension trays have to be prepared well in advance of the study period; and, errors are introduced due to the differences between the soil-plant characteristics of the tray and the in-situ soil.

Because of the problems associated with the above techniques, and the non-availability of specially designed surface probes, whenever it was necessary to determine moisture readings for this zone, the correction factors employed by Hussein (1979) were adopted . The observed count rate (C), taken at any depth between 0 and 200mm below the soil surface, can be corrected by dividing the reading by an appropriate correction factor, $CF_0 = C/C_{max}$. This method was developed by Cole and Green (1969), and relies on two broad assumptions. Firstly, it is assumed that the moisture content over the top 200mm soil layer is constant and equal to that pertaining at 200mm (C_{max}). Secondly, for the first assumption to have any validity, all infiltration and moisture redistribution following a period of rainfall must have been completed. Hussein tested the sensitivity of the technique by comparing a series of readings taken in the field with those obtained by Cole and Green. He was satisfied that, providing only changes in moisture content were being considered, the precision of the method was acceptable.

Since neutron probe readings were taken at 20cm intervals during the Shropshire field study, it was only necessary to correct the count rate obtained at the ground surface. The correction factor derived by Hussein (1979) for the soil-air interface ($CF_0 = 0.34$) was therefore adopted.

A raingauge was installed at each of the three sites. Standard Meteorological Office gauges were employed at Heath House and Childs Ercall, and an autographic raingauge was used at Greenfields. The reason for installing the autographic raingauge was to enable daily rainfall estimates to be made for all three sites. Greenfields was selected for this because the site was secluded, and the gauge was therefore less susceptible to vandalism than it would have been at the other sites.

Water levels in the observation wells were measured using a depth probe manufactured in the Department of Civil Engineering. This probe consisted of two electrodes connected by cable, wound on a drum, to a battery and light bulb. When the electrodes dipped into the water, the circuit was completed and the light bulb lit up. The depth could then be read using a scale marked on the cable.

An intensive monitoring programme was undertaken, which involved about three visits to each site per week, to maintain a close check upon the changes taking place. The observations made during each visit to a site were:

a) the soil moisture profile for each access tube;
b) the water table depth in each of the three observation wells; and,
c) the rainfall since the previous visit.

Weekly estimates of evapotranspiration were obtained from the Meteorological Office.

Although the studies at Heath House and Child's Ercall continued into 1980 (see Sect. 5.7), the report prepared for the Agricultural Sponsors (Walley and Hedges, 1979b) only covered the following periods of the monitoring programme :

Greenfields:	26th April to 6th July 1979
Heath House:	26th April to 31st July 1979
Child's Ercall:	7th May to 31st July 1979.

The abstraction rate at each site was maintained at about 24 l/s throughout the duration of the pumping periods, which were:

Greenfields:	30th May to 26th June 1979
Heath House:	10th May to 3rd July 1979
Child's Ercall:	21st May to 26th June 1979.

5.3.3 USE OF EXPERIMENTAL CONTROLS.

In view of the Severn Trent Water Authority's use of 'control sites' in its own investigations (Severn Trent Water Authority, 1977), a small number of control sites (see Fig 5.5) were selected and instrumented for inclusion in the study. However, when further consideration was given to the use of controls in scientific investigations, it was decided that their use was inappropriate unless far greater standardisation of sites could be achieved than had been accomplished by the Authority . The reason for this decision was that the use of controls in 'cause and effect' (or 'with and without') studies relies upon all factors relating to the control and the experiment being identical, other than those being investigated (in this case drawdown and soil moisture content). In this type of study it is extremely difficult to satisfy this condition because it requires that:

a) the slope, aspect and exposure of the sites be the same;
b) the soil profiles be very similar in terms of horizons present, texture, structure and bulk density;
c) the crops be identical, not only in type but also at similar stages of growth;
d) the initial depths to water table be identical;
e) the natural variations in water table level at the control site be eliminated; and
f) the rainfall and evapotranspiration at the sites be identical, or at least their differences be allowed for in the analysis.

Many of these conditions could have been satisfied by very careful site selection, but this would have been both expensive and exceedingly time consuming.

Having abandoned the use of control sites, the 'with and without pumping' comparison was achieved by using the traditional water balance method of estimating soil moisture deficits. The soil moisture change from date to date, which would have occurred without pumping, was therefore evaluated using the rainfall measured on site and estimates of evaporation obtained from the Meteorological Office. It was hoped that the weather conditions would maintain a small soil moisture deficit (e.g. less than 100mm) throughout the study period so that the method could be relied upon (see Sect. 4.3).

5.4 ANALYSIS OF THE FIELD STUDY RESULTS OBTAINED PRIOR TO 18th JULY 1979.

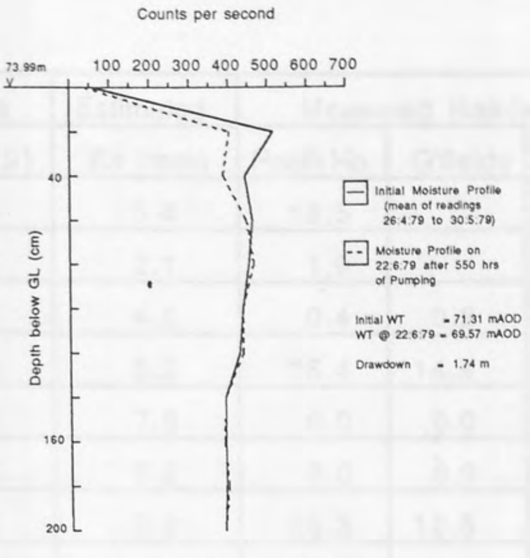
5.4.1 ESTIMATION OF SOIL MOISTURE DEFICITS 'WITHOUT PUMPING'.

Although the crops covering the sites were not fully developed at the start of the pumping tests, evapotranspiration was assumed to be at the potential rates estimated by the Meteorological Office's MORECS system. This assumption was justified because up to the 8th of June the soil moisture deficit did not exceed 13mm, and at Heath House the deficit remained under 15mm until the 3rd of July, by which time the crop, sugar beet, was well established. Under low deficit conditions, such as these, bare soil evaporation occurs at such a rate that the overall evapotranspiration is at, or near, the potential rate.

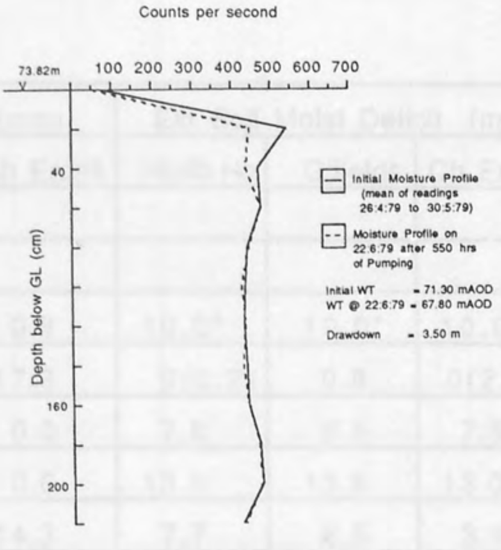
Table 5.2 gives details of the estimation of soil moisture deficit for the Heath House, Greenfields and Child's Ercall sites. If the rainfall and soil moisture deficit figures for the three sites are compared (e.g. the period 22nd to 26th June) the importance of providing each with its own raingauge is clearly illustrated.

5.4.2 THE GREENFIELDS SITE.

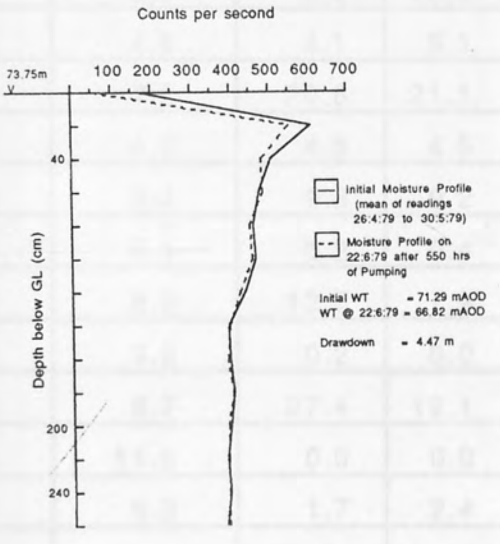
Fig 5.10 shows the changes in the soil moisture profiles for the five access tubes at Greenfields after 550 hours of pumping. The profiles for Tubes 1, 2 and 5 were the most representative, as Tubes 3 and 4 were affected by localised surface ponding which resulted from excessive rainfall during part of the time. It was clear from the results of this test that the observed moisture losses occurred only at the tops of the profiles and were entirely due to evaporation and transpiration. There was no evidence of loss due to the groundwater drawdown, which varied from 1.7m to 5.7m. As had been anticipated, the boulder clay layer above the aquifer was effective in isolating the soil profile from the effects of pumping. A summary of the site conditions at Greenfields and the changes which took place over the duration of the pumping period is given in Table 5.3.



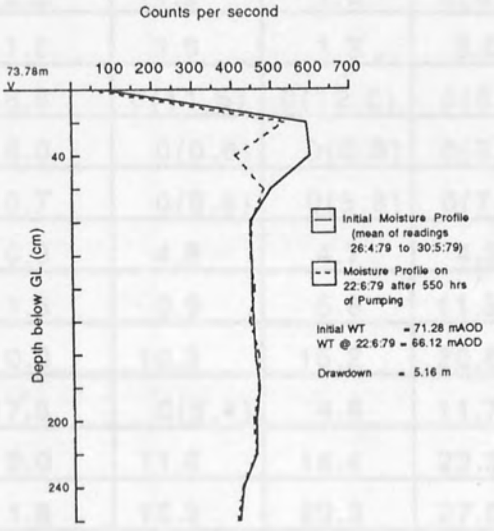
GREENFIELDS TUBE 1



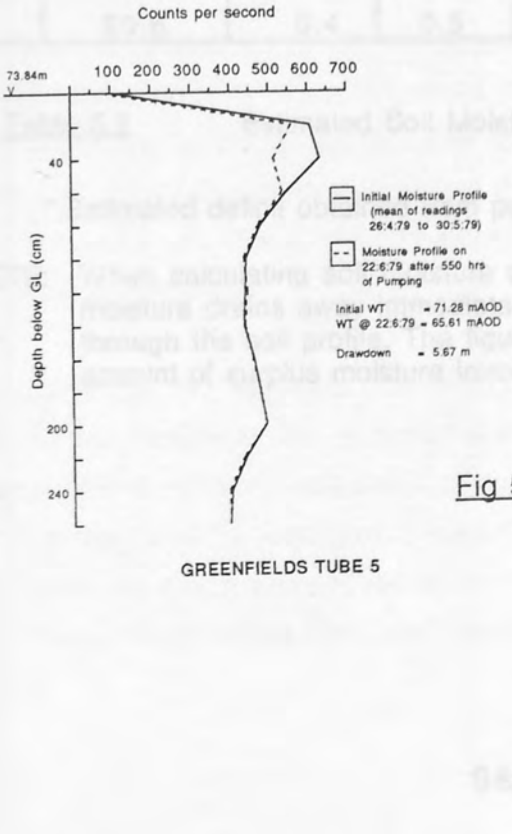
GREENFIELDS TUBE 2



GREENFIELDS TUBE 3



GREENFIELDS TUBE 4



GREENFIELDS TUBE 5

<u>Fig 5.10</u> Effect on Soil Moisture Profiles at Greenfields of Groundwater Drawdown.

Date	Estimated	Measured Rainfall (mm)			Est Soil Moist Deficit (mm)		
(1979)	Ea (mm)	Heath Ho	G'fields	Ch Ercall	Heath Ho	G'fields	Ch Ercall
26/4	15.4	19.5					
7/5	2.1	1.9					
9/5	4.6	0.4	0.8	0.8	10.0*	10.0*	10.0*
11/5	5.2	15.4	14.4	17.2	0(0.2)	0.8	0(2.0)
14/5	7.8	0.0	0.0	0.0	7.8	8.6	7.8
16/5	5.2	0.0	0.0	0.0	13.0	13.8	13.0
18/5	5.2	10.3	10.5	14.3	7.7	8.5	3.9
21/5	7.8	10.1	9.5	8.3	5.4	6.8	3.4
23/5	5.0	9.2	10.2	12.3	1.2	1.6	0(9.6)
25/5	4.8	4.1	5.1	1.8	1.9	1.3	3.0
28/5	7.2	20.6	21.1	18.8	0(11.5)	0(12.6)	0(8.6)
30/5	4.2	4.8	4.5	8.0	0(0.6)	0(0.3)	0(3.8)
1/6	3.4	9.3	9.2	10.7	0(5.9)	0(5.8)	0(7.3)
4/6	5.1	0.3	0.4	0.9	4.8	4.7	4.2
8/6	8.8	12.7	7.9	1.5	0.9	5.6	11.5
12/6	9.6	0.2	0.0	0.3	10.3	15.2	20.8
15/6	8.7	27.4	19.1	17.8	0(8.4)	4.8	11.7
19/6	11.6	0.0	0.0	0.0	11.6	16.4	23.3
22/6	6.3	1.7	2.4	1.8	15.2	20.3	27.8
26/6	8.4	46.2	30.9	12.8	0(22.6)	0(2.2)	23.4
29/6	8.7	0.0	0.0	0.0	8.7	8.7	32.1
16/7	50.6	0.4	0.5	0.3	58.9	59.1	82.4

Table 5.2 Estimated Soil Moisture Deficits During the Pumping Period

* Estimated deficit obtained from published Meteorological Office data

NOTE: When calculating soil moisture deficits it is normally assumed that surplus moisture drains away immediately, but in fact it takes several days to drain through the soil profile. The figures enclosed in brackets represent the amount of surplus moisture introduced since the previous date.

Start of Study	26th April 1979	End of Study		6th July 1979	
Start of Pumping	30th May 1979	End of Pumping		26th June 1979	
Soil Type	Salop Series	Crop Cover		Wheat	
Tube Reference	T1	T2	T3	T4	T5
Distance from abst well (m)	98	62	43	29	20
Pre-pumping GW Depth(m)	2.68	2.52	2.46	2.50	2.56
Groundwater drawdown (m)	1.74	3.5	4.47	5.16	5.67
At End of pumping (29/6/79)					
Observed moisture loss (mm)	24.1	19.54	*	*	27.2
Estimated Deficit (mm)	20.3	20.3	20.3	20.3	20.3
At End of Study (31/7/79)					
Observed moisture loss (mm)	88.9	85.0	*	*	78.1
Estimated deficit (mm)	91.9	91.9	91.9	91.9	91.9

Table 5.3 Site Conditions at Greenfields and Changes Observed During Field Study

NOTE: * Tubes 3 and 4 affected by localised ponding

5.4.3 THE HEATH HOUSE SITE.

The results of the tests at the Heath House site are summarised in Figs 5.11 to 5.15. These figures show the change in moisture content over time (in terms of Neutron Probe count rate) for soil layers within the profile. The rainfall pattern and variation in groundwater levels are also shown to enable their effects on the moisture content to be illustrated. It is clear from these figures that substantial quantities of water were removed from the soil as a direct result of pumping.

Moisture losses due to evaporation only affected the top 50 cm soil layer as demonstrated by Fig 5.16. This compares the estimated soil moisture deficits (Table 5.2) with the mean of the measured variations in soil moisture content of the top 50 cm layer for the five tubes. The similarity of the two curves shows that up to the cessation of pumping on the 3rd July, when the deficit approached 20mm, the entire evapotranspiration could be accounted for by the moisture loss from the top 50 cms. Thus all additional moisture lost

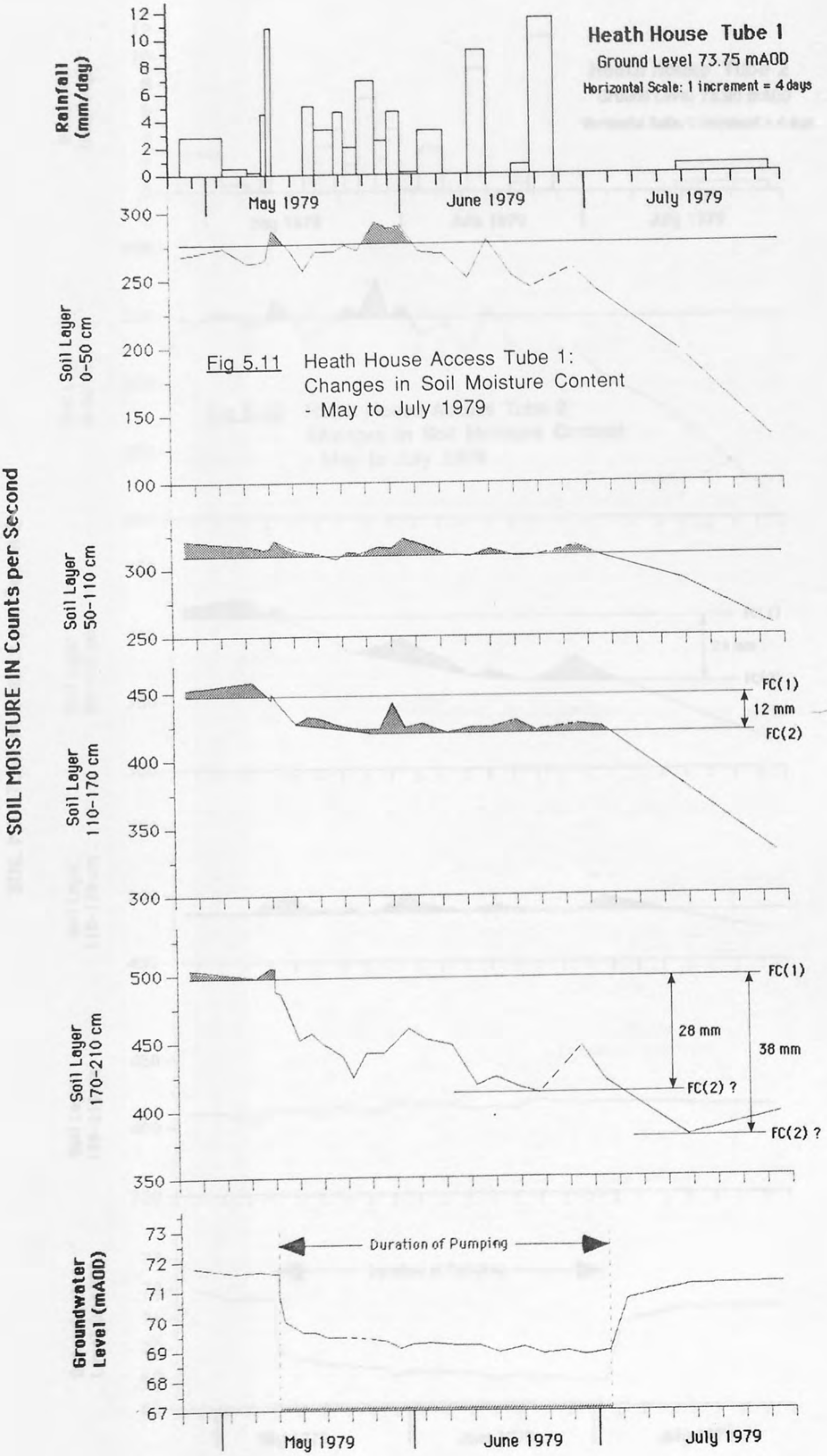


Fig 5.11 Heath House Access Tube 1: Changes in Soil Moisture Content - May to July 1979

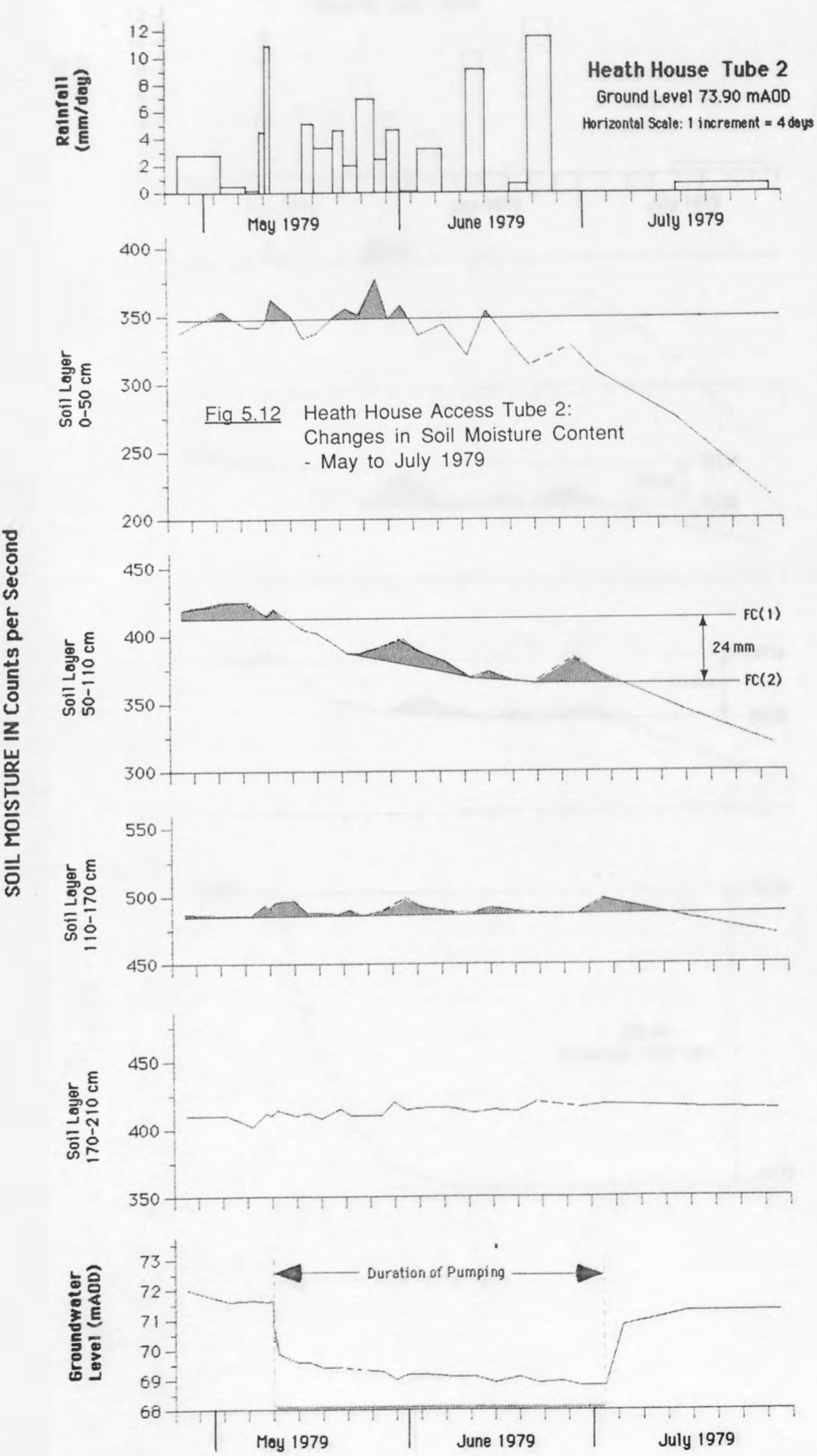


Fig 5.12 Heath House Access Tube 2: Changes in Soil Moisture Content - May to July 1979

Fig 5.13 Heath House Access Tube 3: Changes in Soil Moisture Content - May to July 1979

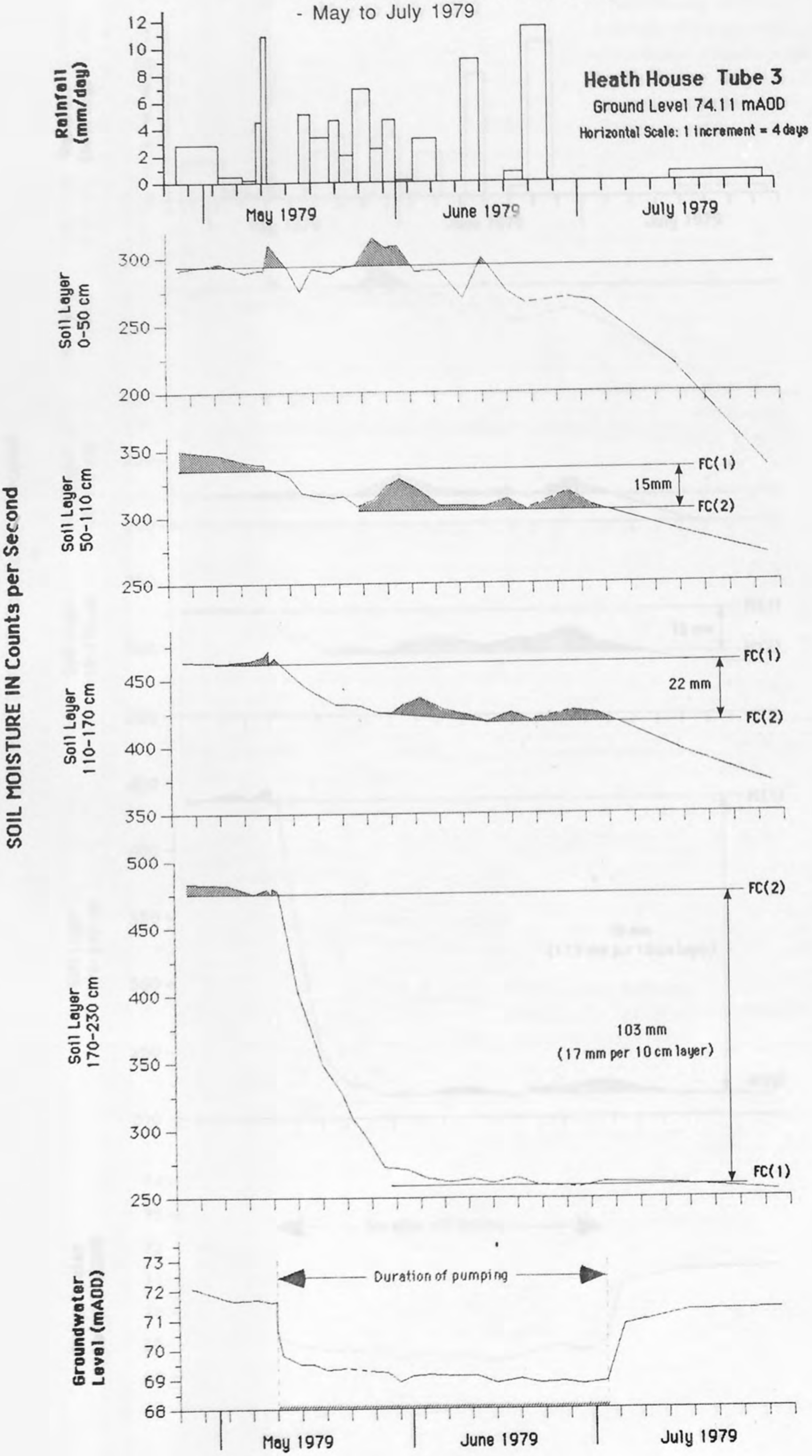
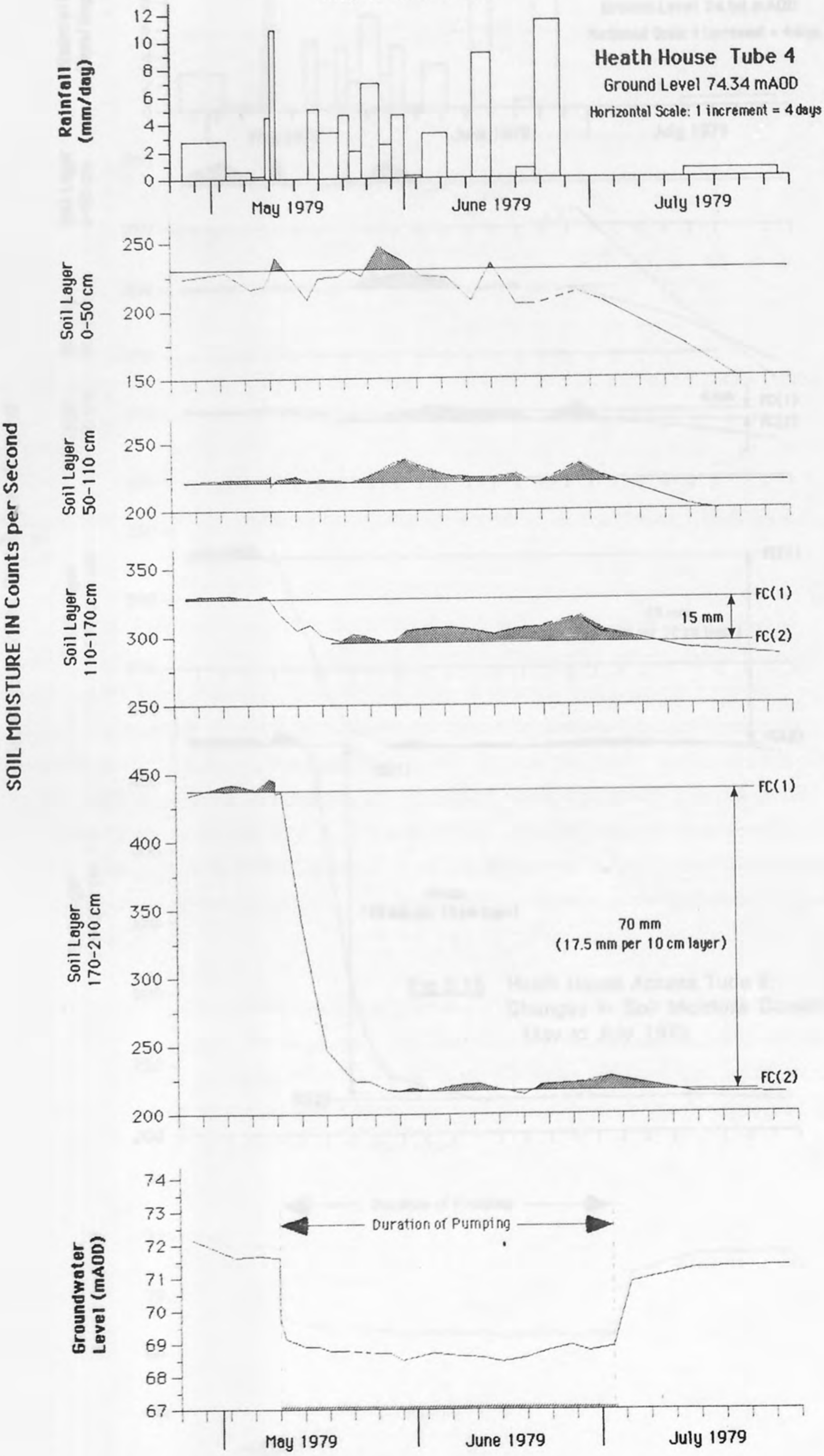


Fig 5.14 Heath House Access Tube 4: Changes in Soil Moisture Content - May to July 1979



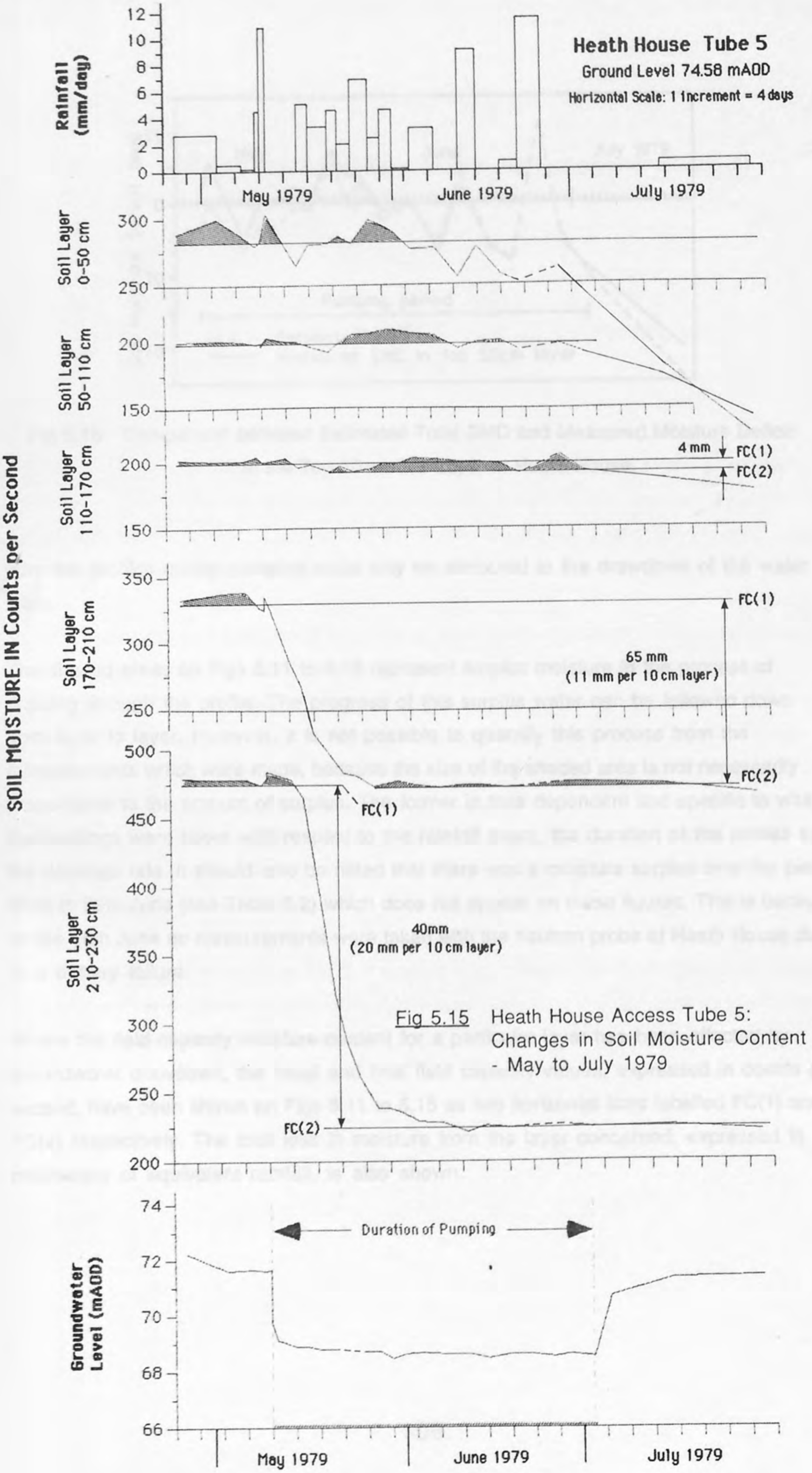


Fig 5.15 Heath House Access Tube 5: Changes in Soil Moisture Content - May to July 1979

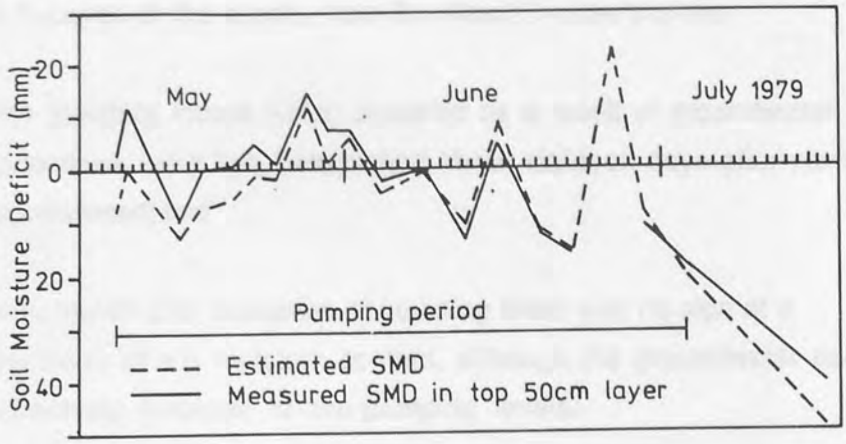


Fig 5.16 Comparison between Estimated Total SMD and Measured Moisture Deficit in the Top 50cm Soil Layer at Heath House.

from the profiles during pumping could only be attributed to the drawdown of the water table.

The shaded areas on Figs 5.11 to 5.15 represent surplus moisture in the process of draining through the profile. The progress of this surplus water can be followed down from layer to layer. However, it is not possible to quantify this process from the measurements which were made, because the size of the shaded area is not necessarily proportional to the amount of surplus. The former is time dependent and specific to when the readings were taken with respect to the rainfall event, the duration of the rainfall and the drainage rate. It should also be noted that there was a moisture surplus over the period 22nd to 29th June (see Table 5.2) which does not appear on these figures. This is because on the 26th June no measurements were taken with the neutron probe at Heath House due to a battery failure.

Where the field capacity moisture content for a particular layer has been affected by groundwater drawdown, the initial and final field capacity values, expressed in counts per second, have been shown on Figs 5.11 to 5.15 as two horizontal lines labelled FC(1) and FC(2) respectively. The total loss in moisture from the layer concerned, expressed in millimeters of equivalent rainfall, is also shown.

Two important features of the results from the Heath House site are:

a) the moisture losses which occurred as a result of groundwater drawdown were fully established about eighteen days after pumping commenced; and

b) one month after cessation of pumping there was no sign of a recovery of soil moisture content, although the groundwater had effectvely returned to pre-pumping levels.

This has the important implication that for this type of site, during a period of drought, eighteen days of pumping is sufficient to remove a very significant quantity of moisture from the soil profile for the remainder of the growing season. This moisture depletion will persist until replenishment occurs during the winter months as a result of the drainage of surplus surface moisture down through the profile

Fig 5.17 shows the moisture losses observed at each of the five access tubes after 29 days of pumping. Also shown is the height of the profile above the initial water table (the critical height) which was affected by the drawdown, and it is clear that even over the relatively short distance between tubes the response is quite varied. The effect at Tubes 3, 4 and 5 was similar, in that they all lost considerable quantities of water from the bottom of the profile and had critical heights of between 1.3m and 1.9m. The losses measured at Tubes 1 and 2 were far less than those for Tubes 3, 4 and 5, but their distribution indicates that either the water tables were perched or that deep percolation was impeded by a relatively impermeable layer.

The moisture losses recorded at the five tubes are summarised in Table 5.4. In estimating the moisture loss over the critical height, it has been assumed that the zone between the bottom of the tube and the initial water table lost 17mm per 10 cm layer (see Figs 5.11 to 5.15).

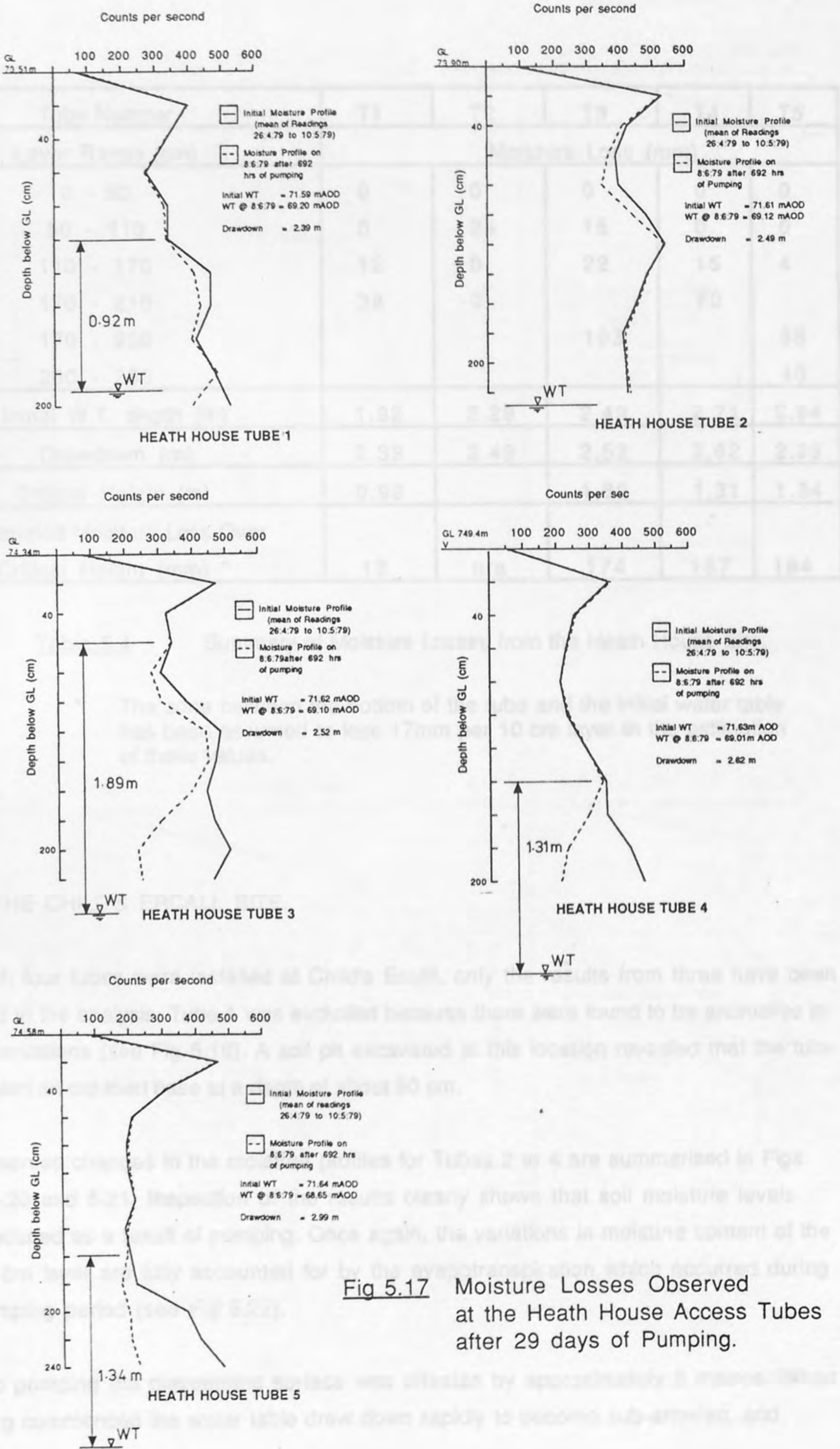


Fig 5.17 Moisture Losses Observed at the Heath House Access Tubes after 29 days of Pumping.

Tube Number	T1	T2	T3	T4	T5
Layer Range (cm)	Moisture Loss (mm)				
0 - 50	0	0	0	0	0
50 - 110	0	24	15	0	0
110 - 170	12	0	22	15	4
170 - 210	38	0		70	
170 - 230			103		65
230 - 250					40
Initial W.T. depth (m)	1.92	2.29	2.49	2.71	2.94
Drawdown (m)	2.39	2.49	2.52	2.62	2.99
Critical Height (m)	0.92		1.89	1.31	1.34
Estimated Moisture Loss Over Critical Height (mm) *	12	n/a	174	187	184

Table 5.4 Summary of Moisture Losses from the Heath House Site.

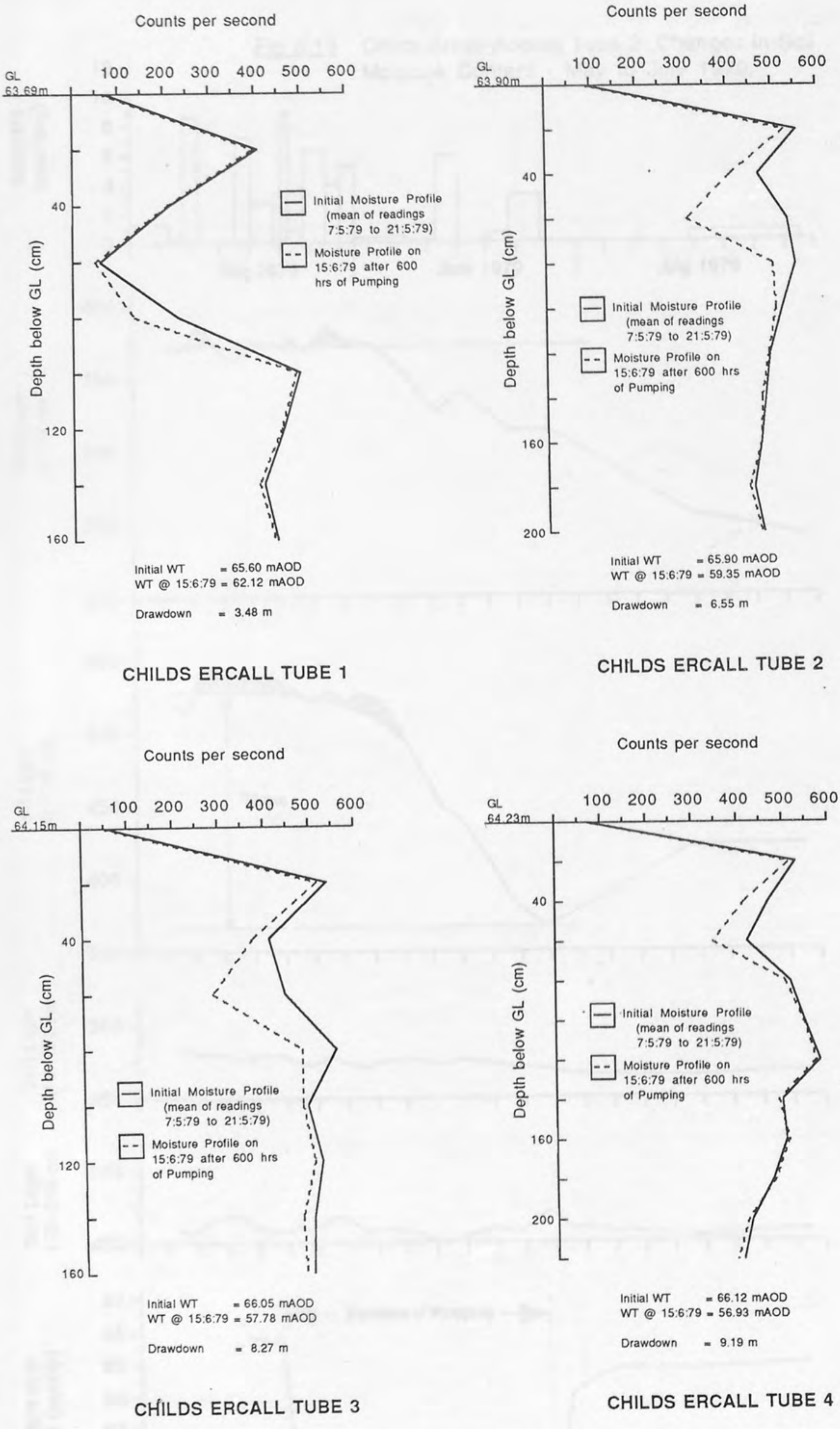
* The zone between the bottom of the tube and the initial water table has been assumed to lose 17mm per 10 cm layer in the estimation of these values.

5.4.4 THE CHILD'S ERCALL SITE.

Although four tubes were installed at Child's Ercall, only the results from three have been included in the analysis. Tube 1 was excluded because there were found to be anomolies in the observations (see Fig 5.18). A soil pit excavated at this location revealed that the tube penetrated an old road base at a depth of about 50 cm.

The observed changes in the moisture profiles for Tubes 2 to 4 are summarised in Figs 5.19, 5.20 and 5.21. Inspection of the results clearly shows that soil moisture levels were reduced as a result of pumping. Once again, the variations in moisture content of the top 50 cm layer are fully accounted for by the evapotranspiration which occurred during the pumping period (see Fig 5.22).

Prior to pumping the piezometric surface was artesian by approximately 2 metres. When pumping commenced the water table drew down rapidly to become sub-artesian, and



Initial WT = 65.60 mAOD
WT @ 15:6:79 = 62.12 mAOD

Drawdown = 3.48 m

CHILDS ERCALL TUBE 1

Initial WT = 65.90 mAOD
WT @ 15:6:79 = 59.35 mAOD

Drawdown = 6.55 m

CHILDS ERCALL TUBE 2

Initial WT = 66.05 mAOD
WT @ 15:6:79 = 57.78 mAOD

Drawdown = 8.27 m

CHILDS ERCALL TUBE 3

Initial WT = 66.12 mAOD
WT @ 15:6:79 = 56.93 mAOD

Drawdown = 9.19 m

CHILDS ERCALL TUBE 4

Fig 5.18 Moisture Losses Observed at the Childs Ercall Access Tubes after 25 days of Pumping.

Fig 5.19 Childs Ercall Access Tube 2: Changes in Soil Moisture Content - May to July 1979.

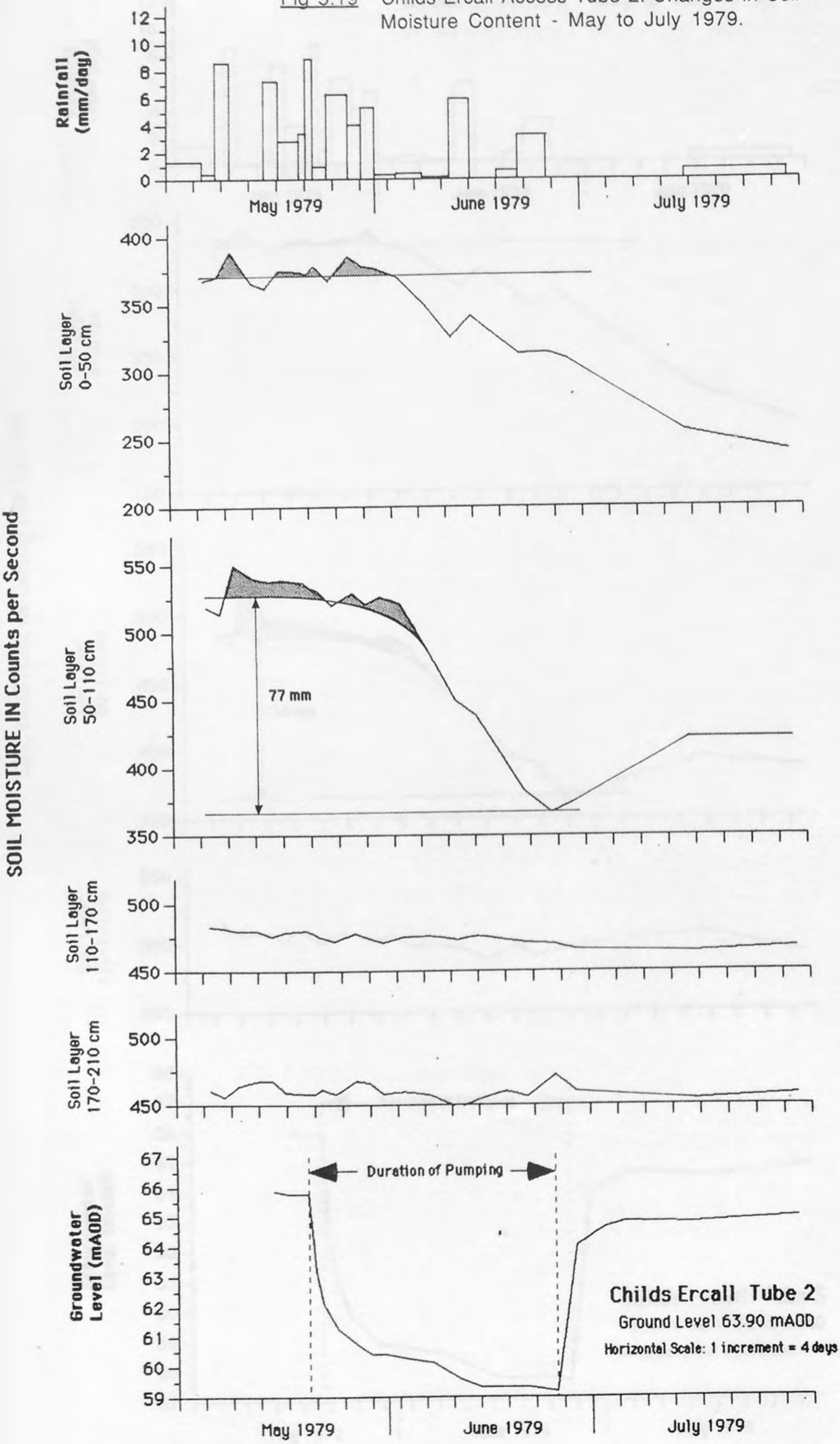


Fig 5.20 Childs Ercall Access Tube 3: Changes in Soil Moisture Content - May to July 1979.

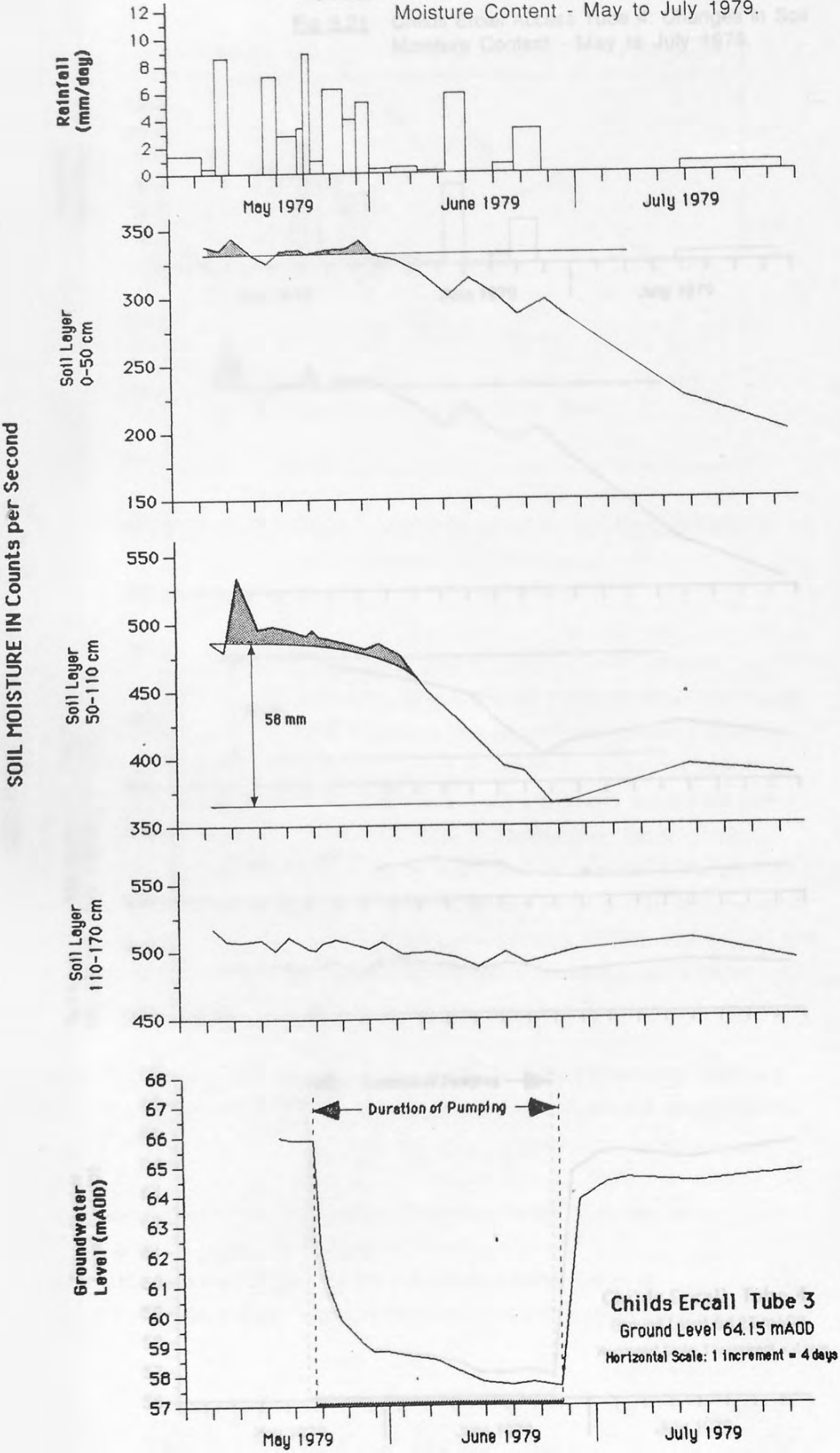
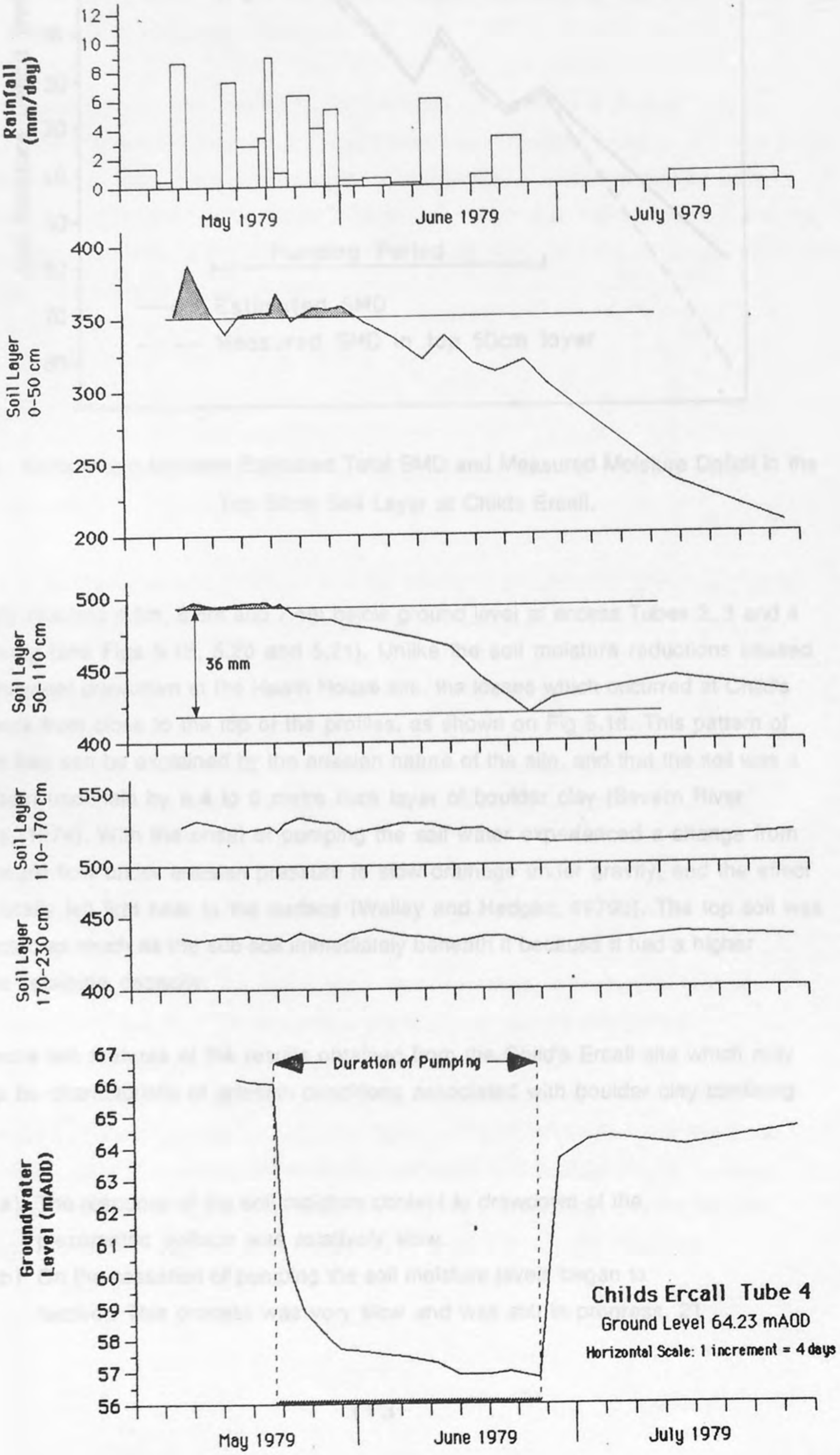


Fig 5.21 Childs Ercall Access Tube 4: Changes in Soil Moisture Content - May to July 1979.



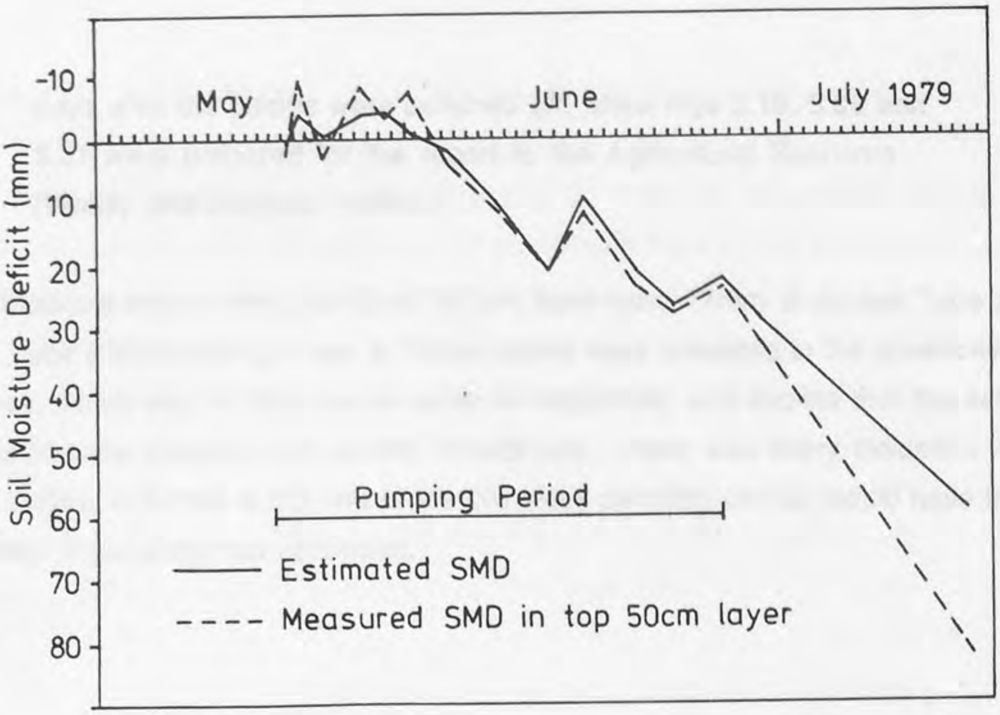


Fig 5.22 Comparison between Estimated Total SMD and Measured Moisture Deficit in the Top 50cm Soil Layer at Childs Ercall.

eventually reached 4.6m, 6.5m and 7.4m below ground level at access Tubes 2, 3 and 4 respectively (see Figs 5.19, 5.20 and 5.21). Unlike the soil moisture reductions caused by groundwater drawdown at the Heath House site, the losses which occurred at Child's Ercall were from close to the top of the profiles, as shown on Fig 5.18. This pattern of moisture loss can be explained by the artesian nature of the site, and that the soil was a sandy loam underlain by a 4 to 5 metre thick layer of boulder clay (Severn River Authority, 1974). With the onset of pumping the soil water experienced a change from slow upward flow under artesian pressure to slow drainage under gravity, and the effect was naturally felt first near to the surface (Walley and Hedges, 1979b). The top soil was not affected as much as the sub-soil immediately beneath it because it had a higher moisture retaining capacity.

There were two features of the results obtained from the Child's Ercall site which may prove to be characteristic of artesian conditions associated with boulder clay confining layers.

a) The response of the soil moisture content to drawdown of the piezometric surface was relatively slow.
b) On the cessation of pumping the soil moisture levels began to recover. This process was very slow and was still in progress, 21

days after the pumps were switched off, when Figs 5.19, 5.20 and 5.21 were prepared for the report to the Agricultural Sponsors (Walley and Hedges, 1979b).

The soil moisture losses from the 50 to 110 cm layer were 77mm at access Tube 2, 58mm at Tube 3 and 36mm at Tube 4. These losses were unrelated to the drawdowns at the three tubes, which were in the reverse order of magnitude, and implies that the same losses would have occurred with smaller drawdowns. There was every indication that the moisture losses, recorded at the end of the five week pumping period, would have increased substantially if pumping had continued.

5.5 CONCLUSIONS OF THE FIELD INVESTIGATION PRIOR TO THE PUBLIC INQUIRY.

The field investigation results indicated that the effects of groundwater drawdown upon available soil moisture could be divided into four categories.

1) *Water table 2m or more below the bottom of the root zone.*
The maximum critical height observed for the Heath House sandy loam was 1.9m. It is therefore unlikely that the drawdown of a water table, which is initially 2m or more below the bottom of the root zone, will have any effect upon available soil moisture levels.

2) *Water table within 2m of the root zone but isolated from the effects of drawdown by an impermeable layer.*
Under these conditions the water table after drawdown, if not before, will be perched and soil moisture conditions will therefore remain unaffected. However, this assumes that the impermeable layer is extensive and continuous. This is often not the case with boulder clay, a material which is well known for its variability in thickness and texture. Caution therefore needs to be exercised when drawing conclusions about the effectiveness of a boulder clay in isolating the soil from the effects of drawdown. At the Aston Greenfields site the boulder clay layer was clearly an effective barrier and no losses were observed.

3) *Water table within 2m of the root zone and in effective hydraulic continuity with it.*

The results obtained for three of the access tubes at Heath House confirmed the theoretical conclusions, that a relatively small drawdown in the water table can remove substantial quantities of the soil moisture normally available to vegetation whose roots penetrate into the zone of critical height. In addition, as was predicted by consideration of the hysteresis effect, after cessation of pumping soil moisture levels did not recover as the groundwater table rose. It was not possible to confirm the theoretical argument that small drawdowns (of about 0.5m) can also cause significant moisture losses, because the groundwater drawdown at all tubes was more that 2.5m.

The two Heath House tubes furthest from the well, Tubes 1 and 2, showed relatively small losses. The cause could not be attributed to reduced drawdown levels as these were of the same magnitude as experienced at Tubes 3 to 5. It seemed likely that these small losses were due to a relatively impermeable layer between the aquifer and the upper soil horizons, which impeded deep percolation.

4) *Artesian zones.*

In artesian zones where the water table is confined by an impermeable layer, soil moisture conditions will be isolated from the effects of groundwater abstraction. However, when the confining layer is relatively thin and leaky, upward seepage from the aquifer will feed the soil moisture reservoir - a form of natural irrigation. If the aquifer is then made sub-artesian, as a result of pumping, the seepage will change from an upward to a downward direction, thereby reducing soil moisture levels and removing the source of the natural irrigation.

The results of the Child's Ercall study clearly illustrated the changes in moisture regime for a thin leaky confining layer. The soil moisture was relatively slow to respond to the drawdown, but once losses began the moisture content continued to decrease steadily until pumping ceased. Immediately pumping stopped and artesian conditions were restored a slow recovery of moisture levels began.

The field study results show that considerable quantities of available soil moisture can be lost as a result of groundwater drawdown, and that these losses once established may persist until the following winter, irrespective of whether pumping continues or not. For some soils (e.g. sandy loams) continuous pumping for as little as two weeks can remove over 150mm of soil moisture for the remainder of the growing season.

It was not possible from the results of the tests at Heath House to draw conclusions concerning the magnitude of the drawdown necessary to cause significant losses. However, theoretical arguments suggest that drawdowns of between 0.5m and 1.0m would be sufficient to cause ninety-five percent of the total possible loss to occur (Walley and Hedges, 1979b).

The implications of the results obtained from the field study are that a soil will not be sensitive to loss of available moisture if its initial water table is greater than a depth (D) below the ground surface, where:

$$D = \text{critical height } (h_o) + \text{crop rooting depth } (d_r) \qquad \text{- Eqn 5.1}$$

This assumes that deep drainage is not impeded by a highly impermeable layer overlying the aquifer. Table 5.5 summarizes the conclusions drawn for the soils found in the Tern area of the Shropshire Groundwater Scheme.

5.6 THE PUBLIC LOCAL INQUIRY.

A report (Walley and Hedges, 1979b) was produced and submitted to the Agricultural Sponsors in August 1979. This report provided a discussion of: the theoretical effects of groundwater drawdown on soil moisture; a description of the sites used and the techniques employed in the field investigation; an analysis and discussion of the field investigation results obtained up to the 17th July 1979; and the conclusions drawn as a result of the study.

After the submission of the Aston report to the Agricultural Sponsors, Mr. W.J. Walley was retained by a group of 39 concerned farmers to appear, as an expert witness in soil water physics, on their behalf at the Shropshire Groundwater Scheme public inquiry.

The public inquiry was held at the Lord Hill Hotel in Shrewsbury. It was opened by the Inspector, Mr F.E.G. Gray, on 11th September 1979 and formal proceedings were completed on the 10th October, after which the inspection of sites continued until 19th of October 1979. The Inspector submitted his report (Gray, 1980) in March 1980 to the

Soil Type	Assumed value of critical height h_o (m)	Value of D from Eqn 5.1 (m)		Comments
		Rooting depth d_r = 1.5m (ie farm crops)	Rooting depth d_r = 3.5m (ie trees)	
Newport Series (loamy sand, sandy loam,sand)	1.5	3.0	5.0	Sensitive to drawdowns of less than1.0m if initial water table is less than D (m) below ground surface. If initial water table depth is (D - 1.5)m, losses of available moisture could easily exceed 100mm if pumping continues for more than two weeks, and these losses could remain throughout the growing season.
Bridgnorth Series (sand, loamy sand)	1.0	2.5	4.5	
Crannymoor Series (sand)	0.5	2.0	4.0	Sensitive to drawdowns of less than 0.5m if initial water table is less than D (m) below ground surface. Losses could exceed 50 mm.
Wem Series (sandy clay, loam, sandy loam)	1.5	3.0	5.0	As per Newport and Bridgenorth Series if deep drainange is not impeded. Insensitive if underlain by an impermeable layer. May be sensitive under artesian conditions depending upon the degree of impermeability of the confining layer.
Salop Series (sandy clay loam, loam)	-	-	-	Unlikely to be sensitive, except perhaps under artesian conditions

Table 5.5 Summary of Conclusions Drawn from the Results of the Tern Area Field Study.

Secretary of State for the Environment, whose decisions were published on 29th May 1981 (Musgrave, 1981).

Severn Trent Water Authority, the appellants, were seeking powers to implement their proposals to develop the Shropshire Groundwater Scheme under:

the Water Resources Acts 1963 and 1971;
the Water Resources (Licences) Regulations 1965;
the Compulsory Purchases Act 1965;
the Town and Country Planning Act 1971.

The main details of the scheme have already been described in Section 2.4, and Fig 2.8 shows the location of the eight proposed borehole groups.

During the inquiry the Inspector was assisted by three Assessors: Mr S.S.D. Foster, Hydrogeologist Assessor; Mr T.R. Graham, Hydrobiological Assessor; and, Mr S.G. McRae, Soil Science Assessor. Each of the Assessors produced a report which was appended to the Inspector's submission to the Secretary of State. In his conclusions the Inspector dealt with the issues raised by the Water Authority's proposals under the headings of: available water resources and future demand for water; alternative schemes; the planning applications; the objections to the proposals.

5.6.1 AVAILABLE WATER RESOURCES, FUTURE DEMAND AND ALTERNATIVE SCHEMES.

Few doubts were cast upon the Authority's use of existing resources and their demand forecasts during the course of the inquiry. The Secretary of State saw no reason to disagree with the Inspector's view that:

> "on the evidence (presented) it is reasonable to expect the River Severn resource system to be fully committed after 1982 but before 1986; and that the Authority will require a new resource sometime between those years." (Musgrave, 1981).

Furthermore, it was accepted that there were uncertainties in future demand projections and the proposed phased development of the groundwater scheme was commended because of the flexibility this approach offered.

The only alternative to the Shropshire scheme discussed at the inquiry was the enlargement of Craig Goch Reservoir in the Elan Valley. The viability of this as an alternative was discounted by the Inspector on cost grounds, and his view was supported by the Secretary of State.

5.6.2 PLANNING APPLICATIONS.

Regarding the planning applications submitted by Severn Trent Water Authority, the Secretary of State accepted the Inspector's conclusion that the proposed developments would not cause any serious detriment to the visual amenities of the localities concerned. At one site additional screening with trees and shrubs was recommended, and for a second it was suggested that further consideration needed to be given to parking facilities.

5.6.3 OBJECTIONS TO THE PROPOSALS.

Objectors to the Authority's groundwater scheme were mainly concerned with the effects of lowered groundwater levels on private water supplies, crops and trees, water quality, ecology and fisheries. The effects of groundwater drawdown on crops and trees proved to be the most contentious of these issues and, as this aspect is of direct concern to this research, it is given detailed consideration in Sect. 5.6.4.

The evidence presented at the inquiry convinced the Inspector and Assessors that the hydrogeological aspects of the scheme were sound. There were some uncertainties over the spatial variation of the Triassic sandstone aquifer's hydraulic properties, the estimates of natural recharge and the hydraulic behaviour of the aquifer's boundaries. These in turn affected the estimates of net scheme yield, the detailed distribution of groundwater drawdown levels, and the rate of recovery of groundwater levels following pumping. However, these aspects were all considered to have been investigated adequately by the Water Authority over the eight year study period. From a hydrogeological standpoint the Assessor considered the only really undesirable features to be:

> "the derogation of a large, but uncertain, number of private water supplies and amenities, and the probable intermittent effect on the soil moisture regime in certain areas and the associated risk of a reduction in the yield of agricultural crops and of damage to trees" (Foster, 1979).

Regarding the first, the effect on private water supplies, for those affected the Authority in consultation with the Country Landowners Association and the National Farmers Union had drawn up model terms and conditions for the provision of an alternative water supply or compensation water. By offering to enter into an agreement on these terms, with any landowner or occupier, it was considered that the Authority had "shown proper regard to the interests of those persons with rights to private water supplies" (Musgrove, 1981).

As far as ecology and fisheries were concerned, the Hydrobiological Assessor concluded that aquatic flora and invertibrate fauna would not be significantly threatened by any physical and chemical changes to their habitat which would result from discharges of groundwater to surface watercourses (Graham, 1980). Graham also concluded that, with the addition of pumped groundwater from the fully developed scheme, as a raw water source for potable supply the quality of the River Severn would be acceptable, meet EEC limits, and be of National Water Council River Class 1B. Both the Inspector and the Secretary of State accepted the Assessor's conclusions, together with his advice that a water quality monitoring station be established "on the River Severn just below the most downriver input of groundwater" (Musgrave, 1981).

The Hydrobiological Assessor, having considered the evidence presented, considered that

> "matters of chemical quality, of ecology and of fisheries of the watercourses are largely subservient to other issues of the inquiry ... " (Graham, 1980).

Both the Hydrogeological and Soil Science Assessors concluded that the scheme should be allowed to proceed. They welcomed the proposal for implementation in stages, but both expressed deep reservations regarding the uncertainties of the effect of groundwater drawdown on crops and trees (Foster, 1979; McRae, 1979). As has already been stated, this issue proved to be the most contentious at the public inquiry and the ensuing debate is examined in detail in the following section.

5.6.4 THE EFFECT OF GROUNDWATER DRAWDOWN ON CROPS AND TREES - THE INQUIRY DEBATE.

The physical characteristics of the area covered by the Shropshire Groundwater Scheme, and in particular the Tern Area, will be described in Chapter 8, but for the present discussion the landscape comprises undulating, open countryside predominantly in agricultural use, within which there are woodlands and trees, and a number of small settlements. The solid geology associated with the scheme, Triassic sandstones, is often overlain by boulder clay. This is at its thickest to the west of the project area, where depths in excess of 50m occur in the vicinity of the North Perry, South Perry and Montford borehole groups. To the east, in the Tern area, aquifer outcrops are common and drift thicknesses seldom exceed 5m. As a result of glacial over-deepening the main river valleys in North Shropshire now show several levels of terracing and there are few truely riparian areas.

The majority of the agricultural soils within the groundwater scheme area are brown earths, gley soils and podzols with a loamy texture. The lighter soils developed on the Triassic sandstone outcrops and on sandy drift material are generally classified as grade 2 agricultural land. Heavier soils associated with the less permeable clayey drift tend to fall into the grade 3 classification. Grade 4 land is found along river courses, where flooding restricts the use of the land and there are heavy textured soils with poor drainage properties. The Shropshire County Council, in the course of their evidence highlighted the much higher proportion of land devoted to arable farming in the Tern/Roden/North Shrewsbury area (48.2%) and the South Perry area (42%) than in the country as a whole (35%). The attention of the Inspector was also drawn to the importance of agriculture to the economy of Shropshire, and the county's adopted policy that:

> "Every effort will be made to safeguard high quality agricultural land and to take full account of the size and productivity of farming units" (Gray, 1980).

The County Council also voiced concern that the effects of the groundwater scheme would exacerbate an already serious problem of hedge and tree loss, which was due to intensive farming methods. It was stated that an enhanced rate of decline in trees and hedges would have a dileterious effect on this section of the county where they formed a valuable part of the landscape.

Given the importance of agriculture to the local economy it is not surprising that the effect of groundwater drawdown on crops and trees received considerable attention at the inquiry. The main protagonists in this debate were: Drs Skinner and Drennan, expert witnesses for the appellants; Drs Prentice and Ede retained by Shropshire County Council; and, Mr Walley presenting evidence on behalf of a group of 39 local farmers. Each produced a Proof of Evidence, and their main arguments have been summarised by the Inspector (Gray, 1981) and the relevant Assessors (Foster, 1979; McRae, 1979). The main areas of contention were: the significance of the problem; the extent of areas sensitive to drawdown; the validity of fieldwork undertaken in the area; and, the location of abstraction boreholes. Each of these aspects will now be considered in turn.

5.6.4.1. The Significance of Groundwater Drawdown on Soil Moisture and the Consequential Effects on Crops and Trees.

Drennan (1979b) in his Proof of Evidence presented rainfall and evaporation data for the area. He explained how these related to that portion of the soil moisture store which was available to meet the needs of plants during dry summer months when rainfall was insufficient to meet the demands of evapotranspiration. He stressed the importance of the development of a root system for adequate uptake of this moisture, and explained the root constant concept - the soil moisture deficit that can develop before the growth of a crop starts to be affected by a shortage of water. By combining the root constant with the available water for a particular soil, an estimate of the rooting depth was obtained for a variety of field crops in the loamy soils typical of North Shropshire. Further an estimate of the maximum rooting depth was obtained by considering the available water and the deficit at the wilting point . Using this approach Drennan argued that rooting depths would typically range from 0.6 to 1.5 metres for field crops and from 1.3 to 2 metres for trees.

To support these estimates, four methods of directly verifying rooting depths were described, of which one, the monitoring of soil moisture content in the field, had been employed in the pilot scheme investigations. Drennen stated that results of field measurements, made using a neutron probe, showed reasonable agreement with predicted values of root depth. Over the duration of his studies in Shropshire almost all the soil moisture deficit had occurred within the 0 to 0.9 metre soil zone, and only during the 1976 season was there any significant drying in a zone from 0.9 to 1.35 metres deep. Results from these observations and many other studies all supported his conclusion that the main root zone of most field crops lay in the uppermost 1 metre of a soil. Even in deep rooted crops few roots were found below 1.5 metres, and in the case of trees, below 2.0 to 2.5 metres.

Drennan was "very strongly of the opinion that crops and plants did not derive any substantial amounts of moisture by capillary rise during drought periods" (McRae, 1979). He presented results from Dutch work (Rijtema, 1968) that he believed supported this view and which showed that, for water tables deeper than 100 cm below the root zone, capillary rise made an almost insignificant contribution to plant water uptake. His conclusion from Rijtema's data was that a medium loam could only meet the requirements of an average summer evaporation rate of 3mm per day if the water table was within 0.5m of the root zone - providing the root zone did not become so dry that conductivity became negligible. Further Dutch evidence (Fig 5.23, after Wessling, Fig 5.23 The Effect of Mean Water Table Depth During the Growing Season on Crop Yield in 4 Soil Types (after Wessling 1968).

1968) was presented to reinforce his view that, for a water table to have any effect on available soil moisture it had to be between 0.4 and 1.2 metres below the soil surface.

Considerable effort was expended by Drennan in trying to allay fears that the effects of groundwater development on trees would be an ecological disaster. His arguments were not supported by factual evidence, but hinged on the belief that trees derived more than adequate moisture from the available water within their 2 to 2.5 metre rooting zone. With regard to depth to groundwater, he recognised the following situations.

>4 to 5 m - Tree roots entirely independent of groundwater.

2 to 3m - Trees may derive some benefit from capillary rise, but groundwater lowering would compensate by permitting better root penetration into formerly saturated layers. Young and moribund trees could be at risk.

1 to 2 m - Trees already adapted to adjusting their root system to the water table rise and fall, which is likely to be small in these riparian areas.

Perched water tables - Many of the larger groups of trees are in these situations, where effects will be slight or absent due to the groundwater being isolated from the aquifer by impermeable bands of clay.

Wet habitats - Drawdown effects are slight and may even be beneficial.

The depths to water table regarded by Drennan as of relevance to the selection of borehole sites were:

less than 2 m -	no development sites in such areas and neighbouring sites to be checked;
2 to 5 m -	no affect on crops, but there may be localised effects on trees;
more than 5 m -	no affect on trees and crops.

In his proof of evidence Drennan stated that:

> "The depths of groundwater used in making these criteria are known to be conservative for the use made of them and give a considerable margin of safety in the choice of sites".

Under cross-examination Drennan was challenged on the definition of field capacity that he used, and about the actual moisture status of the soil horizons influenced by the "so-called capillary fringe" (McRae, 1979). He maintained that his definition was that accepted by the Ministry of Agriculture and that contributions from the capillary fringe were minimal. Questioned about the concept of root constant he accepted that it was crude, but believed that it was of some value in assessing the response of crops to reductions in soil moisture. Challenged that his quoted root constant figures were on the low side Drennan maintained that they were merely an indication of the commonly accepted range. He discounted the criticism that the hysteresis effect in the re-wetting of a dried soil was of significance.

A considerable amount of cross-examination was concerned with the relevance of data presented in various Dutch publications. Drennan explained that the Dutch work had some unique elements within it, particularly controlled water table levels, that did not apply to Shropshire. He was therefore very reluctant to accept that many of the conclusions could be related to the situation in North Shropshire. His opinion was that generalised diagrams, such as those he himself had presented (i.e. Fig 5.23), could not be used to predict normal crop yields within the groundwater scheme area. He felt that for a particular crop or field there was no optimum position for the water table, although he conceeded that this was one possible interpretation of Fig 5.23 . Drennen admitted that the full diagram, on which his own figure (Fig 5.23) was based, continued to show further slight reductions in crop yield as the water table fell from 2 to 4m. However, he maintained that the conditions under which these data were produced did not parallel the situation in Shropshire. He stated that he knew of no British information similar to the Dutch work, even from the Fens which themselves had controlled water tables.

Ede in his evidence on behalf of the Shropshire County Council, like Drennan, began by discussing soil moisture deficit data for the area. He concluded that though the average summer deficit was moderate compared with other parts of the country, additional moisture from irrigation or groundwater, if accessible, would improve crop production in drier years - exactly those years when operation of the groundwater scheme would be most likely.

In dealing with the principles affecting water uptake by plants, Ede stressed that the groundwater table was not a sharp demarcation line but the level at which the pressure of the water in the soil was equal to atmospheric pressure. Although it was held at a slight tension there was almost as much water stored in the few centimeters above this level as in the saturated zone below it. He described soil moisture as normally held in a continuously linked system above the water table. As moisture is withdrawn by plant roots from upper horizons the suction gradient produced enables water to move upwards through the profile. Ede (1979) considered "the soils of the low lying lands of the appeal area broadly correspond with the required optimum conditions" for this process. Where conditions were favourable, in addition to the upward movement of water into the unsaturated zone, root systems were able to pursue a retreating water table downwards. However, they might not be able to grow fast enough if the water table dropped rapidly to be able to benefit from this source. It was pointed out that a subsequent rise in the water table would kill off much of the root system and weaken the plant. In circumstances of a falling water table, soil changing from saturated to unsaturated conditions could supply enough moisture to meet the needs of a crop for several weeks. Finally, a water table too near the ground surface would cause crop yield reductions due to inadequate access to aerated soil.

Having discussed the possible responses of plants to different groundwater conditions, Ede then reviewed published data, mainly Dutch, relating to the optimum water level for crops. From this information he arrived at the conclusion that, for crops growing with water tables at increasing distances from ground level, productivity first increased, then when the groundwater was about 1 to 2 metres below the surface it reached an optimum level, and subsequently with increasing groundwater depth the effect on yield diminished (as illustrated in Fig 5.23). Ede admitted that "the (Dutch) situations are certainly not exactly comparable with those in Shropshire", but he felt that it was most unlikely that crops in Shropshire obeyed quite different rules to the same crops grown under broadly similar climatic conditions in the Netherlands. Ede did not discount the few isolated experiments which had been carried out in the UK, such as those referred to and undertaken by Drennan, but preferred to base his conclusions on the analysis of data from many thousands of observations made by experienced multi-disciplinary teams, such as those of the Dutch Institutes. All the evidence quoted and reviewed supported his conclusion that yield reductions occurred when there was a fall in shallow groundwater levels.

Regarding trees, although he was in agreement with some of the views expressed by Drennan, Ede cited publications and correspondance with a tree specialist which cast doubts on a 5 metre depth to the water table as being the limiting depth for any contribution of moisture from groundwater.

Ede's overall conclusion was that the limiting depths to groundwater of 2m and 5m for crops and trees respectively, adopted by the Severn Trent Water Authority, were an understatement. They were at best a rough guide and could be as much as 20% in error.

The research report written by Hedges and Walley (1979b) was submitted by Walley as evidence on behalf of the Group of 29 Farmers. He chose not to describe the theoretical aspects discussed in the report (see Sect 4.2) but drew the Inquiry's attention to the fact that 'field capacity' was in reality a moisture content profile which, for a specific location, was a function of the moisture content/tension and tension/conductivity relationships of that particular soil. Elaborating on this aspect, Walley introduced the concept of critical height (as per Sect 4.2.1) and concluded from his consideration of the physical characteristics of the field capacity profile that, providing the soil was not isolated from the effects of drawdown by an impermeable stratum, the practical consequences were:

i) that where a water table was sufficiently close to the surface for its critical height to extend within the root zone of the crop, a drawdown of the water table would remove some of the soil moisture from that zone;
ii) that, due to the effects of hysteresis, once soil moisture had been removed the subsequent return of the water table to its original level would only replenish part, if any, of the lost moisture;
iii) that the maximum amount of moisture which might be lost from a soil depended upon the physical properties of that soil; and,
iv) that relatively small drawdowns of the water table, of the order of one metre or less, could cause the removal of the majority of the water which the soil was capable of losing (Walley,1979).

Walley next described the field study, as detailed in Sections 5.3 to 5.5 of this thesis. He concluded this aspect of his evidence by referring to Table 5.5 (Table 8.1 on page 47 of the research report), which summarised the findings and gave details of the depths to initial water table which he recommended should be used to define the extent of areas sensitive to drawdown.

In reviewing the evidence presented by all parties at the Inquiry, both McRae (1979) and Foster (1979) commended the concept of the critical height. Foster, as Hydrogeologist

Assessor, was not willing to pursue this aspect further and left McRae to evaluate the evidence. McRae's conclusions were that:

> "capillary effects do occur and that their effect on soil moisture contents in a zone above the water table is more substantial than Dr Drennan considered, but not of the importance attributed to them by Dr Ede" (McRae, 1979).

Regarding the effects of drawdown on crops and trees he was of the opinion that the situations in the Netherlands and North Shropshire were sufficiently different that it would be "extremely unwise to extrapolate results" from the one area to the other. He concurred with Drennan that there was no significant evidence from Britain to show that crops benefited from water tables deeper than about 1.2m below the soil surface. He accepted that the critical depth to the water table for trees was 5 metres.

5.6.4.2 The Extent of Areas Sensitive to Drawdown.

The term "potentially sensitive area" was used by all parties at the Inquiry to indicate those areas in which drawdown of the main regional groundwater level in the Triassic Sandstone aquifer might result in a reduction in the availability of soil moisture to crops or trees. Severn Trent Water Authority's estimate of the sensitive area was based on water table depths below ground level of 2m for crops and 5m for trees. As described in Sec 5.6.4.1 above, these figures were contested by both Ede and Walley.

Initially Skinner, Principal Hydrogeologist for Severn Trent W.A., presented little evidence on the definition of potentially sensitive areas. Two maps showing the predicted effects of the operation of the pumping scheme on groundwater levels were tabled (Skinner, 1979). However, in response to cross-examination and Assessors' requests these were complemented by two more maps showing the thickness and lithology of the superficial drift (ACS 13), and the depths to sandstone water level and piezometric surface (ACS 17). From the latter, which was the subject of repeated detailed debate during the course of the Inquiry, the potentially sensitive areas could be derived.

Using Skinner's map ACS17, Drennan computed the water table zones shown in Table 5.6. From this analysis he concluded that the potentially sensitive area for crops totalled 27.7 km^2 and for trees 86.7 km^2. On detailed consideration of the soil profiles and vegetation types involved, he contended that only 2 to 3 km^2 in the Tern Area had significant risk of proving at all sensitive to drawdown in practice. Under cross examination Drennan defended his assessment of the likely sensitive area, and emphasised that "it was a composite judgement by a team" (McRae, 1979).

Table 5.6 Breakdown by Drennan of Areas into Water Table Zones - areas in km^2.
(after McRae, 1979)

The existence of fairly extensive, shallow perched water tables in the drift was recognised by both Drennan and Skinner. However, Drennan was of the view that, due to the isolating effect of the clayey drift, for the most part these would be insensitive, or very slow to respond, to drawdown of the piezometric surface of the sandstone aquifer.

On behalf of Shropshire County Council, Prentice, giving evidence on Hydrogeological aspects, disputed Skinner's and Drennan's evaluation of the extent and sensitivity to drawdown of perched water tables. On the direction of the Inspector, Skinner and Prentice produced a joint paper setting out areas of agreement and disagreement. Of the differences, only that of the possible sensitivity of perched water tables in the North and South Perry areas had direct agricultural implications.

Ede disputed Drennan's calculations of the potentially sensitive areas on the grounds that he did not accept the 2m and 5m depth to groundwater criteria adopted by the Water Authority. He presented five transects, taken across representative parts of the area, which showed ground surface, rest water level, geological information and the likely drawdown of the water table. The conclusion he came to, from consideration of the transects, was that Severn Trent W.A. had drastically underestimated the actual area where the water table was within 2m of the surface, and slightly underestimated where it was within 5m.

Walley too suggested that the Authority had neither correctly indentified the potentially sensitive areas nor discovered all the artesian areas. Although repeatedly asked to supply a contour map showing the likely extent and magnitude of the drawdowns resulting from full operation of the scheme, the Authority had failed to do so. This he contended had been well within the Authority's capability since it had developed its computer simulation model of groundwater flow in 1973. He had therefore (together with the author of this thesis) produced his own map for the Tern area (Fig 5.24), compiled from the ground level contours on the 1:25000 Ordnance Survey maps of the area (Sheets SJ 52 and SJ 62/72) and the water table contours for February 1972 given on Drawing No 8.8 of the First Report (Severn River Authority, 1972). He justified the use of winter contours on the grounds that water table levels during the 1970's were low and that those conditions would therefore be more representative of normal summer ones. Walley's map showed four quite extensive artesian zones within the Tern area, as compared with the single one identified by the Authority. In addition the boundaries of the 2m and 5m depth zones differed substantially in shape and extent from those of the Authority's map.

In a supplementary proof of evidence Walley noted that the revised water table level map presented by Skinner had made his own map out of date. However, he still felt that the Authority had not adequately identified the potentially sensitive areas, and was firmly of the opinion that the actual extent of the sensitive areas in the Tern region could be determined from a properly designed field study.

The evidence furnished by Severn Trent W.A. did not convince the Hydrogeological Assessor that, as had been claimed, only a very few of the large number of shallow perched watertables would be affected by groundwater pumping. He commented in his report (Foster, 1979) that:

> "I suspect that potentially sensitive shallow water tables could, perhaps be even more extensive than indicated by either Skinner or Prentice".

In Foster's opinion, Skinner by eventually producing map ACS17 effectively rebutted many of Walley's points. However, he could not rule out the possible occurrence of localised artesian areas in parts of the Tern catchment in addition to the one already identified around the Child's Ercall borehole.

McRae in his report, while commending Walley's method of defining sensitive areas, accepted that the Severn Trent W.A. were obliged to adopt the more rigid "blanket" approach of 2m and 5m depths to groundwater. He did not accept that these were conservative, as claimed by Drennan, but did accept that they served adequately to define potentially sensitive ares. Like Ede and Walley, he was concerned

> "at the lack of detailed information whereby potentially sensitive areas were subsequently classed as not likely to be sensitive or actually sensitive" (McRae, 1979).

Fig 2.4 Water Table Depths in the Tern Development Area as Derived by Walley and Hedges

5.6.4.3 The Fieldwork.

Initially little reference was made by Drennan to the fieldwork undertaken by the Water Authority, other than to draw the Inquiry's attention to reports already published (Severn River Authority, 1972 and 1974; Severn Trent Water Authority, 1975 and 1976). He pointed out that:

> "measurements of shallow water tables and soil moisture changes had been carried out for varying periods at a substantial number of locations typical of the different parts of the aquifer system."

The field study was only referred to on two other occassions in his initial proof of evidence (Drennan, 1979b). Firstly, in ascertaining crop rooting depths (see Sect 5.6.4.1) and secondly with regard to the large number of augerholes drilled when determining the extent of the potentially sensitive areas.

Considerable criticism of the standard and adequacy of the field investigations was levelled at Drennan during cross-examination. The Solicitor, Mr Kelly, representing the Group of 39 Farmers, contended that the field study was inadequate for several reasons. His accusations were countered by Drennan who explained the extent to which he, the Water Resources Board, the Severn Trent Water Authority, and their predecessor the Severn River Authority, had been involved with the studies since 1971. He was of the view that sufficient work had been undertaken, but admitted that the Tern was one particular area where additional information would have been useful. Kelly voiced the further criticism that unsuitable criteria had been adopted for the selection of those boreholes where a detailed study of the effects of groundwater pumping on soil moisture had been undertaken. Drennan's opinion was that the options were limited in 1972, and that the choice was made on the grounds of the best evidence available. Kelly pointed out that three of the five sites had water tables at depths greater than 4m, and that the two remaining ones, Greenfields and Childs Ercall, should have been recognised as unlikely to be sensitive due to the presence of clayey drift. Drennan's response was that part of the reason for choosing the first three was to allay local fears that abstraction from any depth would affect soil moisture. Greenfields was chosen for its proximity to the wetlands of Hodnet Heath, and Childs Ercall because it was artesian and therefore atypical. Kelly stated that, even in 1972 Heath House should have been recognised as a valuable site because of the relatively shallow water table and sandy soils. He also criticised the studies because of the lack of on-site raingauges and the inadequate calibration of the Authority's neutron probe.

Ede, on behalf of the County Council, also criticised the investigatory work. His accusations were strongly refuted by both Drennan and Sharp, the Authority's Assistant Director of Operations.

Walley, who had been working closely with Kelly during the latter's cross examination of Drennan, reiterated the points made by Kelly concerning the Severn Trent Water Authority's field work. He believed the Authority had not adequately investigated the soil moisture problem and that its studies were ill conceived, lacked detailed analysis and drew conclusions which could not be substantiated by the field observations. His own investigations indicated that there were considerable grounds for concern regarding the effect of groundwater abstraction on soil moisture levels. The field study undertaken by Walley and Hedges was described and the conclusions presented (see Sections 5.2 to 5.5 inclusive).

The criticisms made by Kelly, of the sites chosen by the Authority for their soil moisture studies, were elaborated upon by Walley in his evidence. In his examination of the reports published by the Authority he had found a number of discrepancies, amongst which was an inconsistancy in the analysis of the results obtained from the Greenfields site. In the Third Report (Severn Trent Water Authority, 1975) field soil moisture observations for 1973 appeared to have been related to theoretical soil moisture deficit values determined using meteorological data from 1974! In order to check the validity of these data Walley had been able, using information from the Authority's publications, to produce a comparison of the measured and calculated soil moisture deficits for the period August to December 1973 (Fig 5.25). His conclusion was that the effect of pumping had been to maintain a 38mm moisture deficit during a period when there was ample rainfall to return the soil to field capacity. He explained the difference between his own findings at Greenfields and his analysis of the Authority's data as being due to the latter's site being 130m away from the Aston one, and hence could have been subject to quite different soil conditions.

Under cross-examination Walley agreed that, in general terms, he had come to the same conclusions about the Greenfields and Childs Ercall sites as had the Authority. He rejected a possible explanation of the Heath House results put forward by the Authority. Drennan's rebuttal was mainly concerned with attempting to discredit the Heath House results, which he thought could be explained by the passage of wetting fronts through the profile. On the matter of a comprehensive field study, which Walley proposed should be undertaken before implementation of the Tern area proposals, Drennen felt that the only possible way of adequately assessing the scheme's impact was by linking the assessment with a programme of gradual development.

In their reports few of the Assessors' comments were directed towards the field studies themselves, but the results obtained clearly influenced their perceptions of the other problem areas. McRae (1979), however, in his 'Appraisal of Contentious Agricultural Issues' said:

> "While I do not accept the view that an investigation on the scale of some of the Dutch work referred to is either feasible or necessary, I consider the criticisms of the STWA field investigations to be reasonably justified. This, in itself, is not sufficient to require the postponement or rejection of the scheme, but makes the monitoring of the scheme as it is developed vital."

Aston University

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Fig 5.25 Comparison between Calculated and Measured Soil Moisture Deficits at Greenfields from August to December 1973 (Walley, 1979).

5.6.4.4 Borehole Location.

Sharp (1979), when discussing the locations of the abstraction boreholes, stated that their siting had been carefully designed to avoid lowering the groundwater table where it would be critical to soil moisture conditions within the rooting depths of crops and trees. Skinner (1979) listed the hydrogeological criteria used in the selection of the 68 abstraction sites as:

a) where adequate thickness of sandstone existed;
b) where adequate yields were expected;
c) boreholes were generally to be one kilometer apart;
d) avoidance of the deeper drift areas in the Perry catchment;

e) avoidance of locations which might affect surface pools;
f) avoidance of boreholes close to rivers;
g) avoidance of poor quality groundwater.

From consideration of the effects on soil moisture, Drennan regarded the depths to water table criteria of relevance to borehole site selection as:

less than 2m - no development sites in such areas and neighbouring sites to be checked;
2 to 5 m - no effect on crops, but may be localised effects on trees;
5m or deeper - no effect on trees or crops.

On this basis he grouped the 68 abstraction boreholes into:

41 - water tables deeper than 5 metres;
14 - water tables at 3 - 5 metres depth;
5 - water tables at 2 - 3 metres depth;
7 - in the North Perry area where the sandstone water table is confined and no change in soil moisture content is expected in response to groundwater abstraction;
1 - a double site at Child's Ercall where artesian conditions prevail. No harm to crop yields was expected in most summers.

Drennan stated that he had been consulted on the siting of each of the proposed boreholes that was within a potentially sensitive area, and that as a result many possible sites were either eliminated or their locations changed. However, he claimed that if there was any evidence of a decline in crop yields the individual boreholes responsible could be taken out of production.

The Inquiry's attention was drawn by Ede to the fact that 19 borehole sites were within the 2-5 metre zone and hence trees were likely to be affected. Further evidence relating to soil moisture effects and borehole location revolved around the definition of the depths to groundwater which were used to define the potentially sensitive areas.

The Assessors considered that all reasonable steps, "using the existing knowledge", had been taken to select borehole sites where they would cause least crop and vegetation damage, "with the possible exception of the Tern area" (McRae, 1979).

5.6.5 THE OUTCOME OF THE INQUIRY.

The Chief Executive of Severn Trent Water Authority was notified by the Department of the Environment in May 1981 that approval had been given for construction of the Shropshire Groundwater Scheme (Musgrave, 1981). No significant conditions were attached to the granting of the order.

Although the Group of 39 Farmers, who had co-sponsored the field study and retained the services of Mr Walley, had not achieved the rejection or postponement of the scheme that they had desired, their concern had been recognised. During the course of the inquiry the objectors had forced the Severn Trent W.A. to reorganise their initial proposals for staged implementation, and had secured the formation of a liaison committee to represent their interests. In addition, the Authority had agreed to undertake a comprehensive monitoring programme to study the effects of abstraction from the Tern I (North Tern) borehole group upon groundwater levels and soil moisture. Further development of the Tern Area was conditional, and could only proceed "if justified by the monitoring results" (Musgrave, 1981). The Secretary of State did not, however, agree with the Assessor's and Inspector's recommendations that crop yields and tree growth should be monitored - he was "not convinced that it would be reasonable or practicable".

Since 1981 Phase 1 of the scheme, Tern 1, has been constructed and was commissioned in 1984. Phase 2 is currently under development with completion expected in 1992 . The liaison committee is composed of representatives from Severn Trent Water, Shropshire County Council, the Nature Conservancy Council, the National Farmers' Union and the Country Land-Owners' Association. Skinner (1988) describes the role of the liaison committee as:

> "to overview the operation of the scheme and to ensure that interested parties have access to all relevant data. It meets no more frequently than once a year and all parties regard it as a useful forum for interchange. Perhaps its role has not been fully tested yet because hydrological conditions have been such over the last few years that the scheme has not been needed for intensive operation".

Hockin et al (1988) have recently reported that the monitoring programme includes observation boreholes, river flow measurement stations, gauge boards on lakes and pools, soil moisture measurement sites, and shallow water table tubewells. They also stated that:

> "the monitoring scheme provides an objective basis for settling any claims or loss of rights by other water users and to implement guarantees given by the Authority to local land holding interests".

5.7 COMPLETION OF THE FIELD WORK.

During the field study, but prior to the public inquiry, it was recognised that the work being undertaken could form the core for a PhD thesis. As a consequence it was decided, with the cooperation of the relevant landowners, that monitoring should continue at those sites where moisture losses had been observed - Heath House and Childs Ercall. The primary object of this exercise was to study the response of soil moisture to the recovery of the water table. In addition it was seen as an opportunity to gather additional data which could be used in the further development of the soil-moisture-plant computer model constructed by Walley and Hussein (1982).

Monitoring continued at Childs Ercall until April 1980, and the Heath House site was finally closed in September 1980. At all locations (including Greenfields) soil trial pits were dug when the access tubes were extracted. Both loose and core soil samples were obtained and, over the years, these have been analysed to determine particle size distribution, bulk density, saturated conductivity, and, where the samples were large enough or not too old, specific gravity and organic content. All the data collected has been stored and analysed using the Jazz package of programmes produced by Lotus Development Corporation for the Apple Macintosh Computer. The soil moisture data are presented in Appendix I, and the soil analyses results in Appendix 2.

Post public inquiry analysis of the soil moisture data has employed the correction for readings at the soil-air interface already discussed in Sect. 5.3.2. However, since Hussein (1979) undertook his work the Institute of Hydrology has revised its report on Neutron Probe Practice (Bell, 1976). Hussein had adopted the appropriate calibration curve given in the original guide (Bell, 1973). Earlier work undertaken at Aston by Binding (1975), and the later work of Wood (1982), agree best with the calibration curves published in Bell's 1976 report (see Table 5.1). As Wood's calibration curve was derived after the probe had been serviced in preparation for the Shropshire study, her relationship has been adopted where appropriate in the 'post inquiry analysis'.

The collection of soil samples and their analysis was undertaken in accordance with normal Soil Survey (Hodgson, 1974; Avery and Bascombe, 1982) and British Standards (BS 1377, 1975) practice. The core sampler was a modification of the Soil Survey's coring device, and contained a short plastic liner of known dimensions into which the sample was forced. In the laboratory a constant head permeameter was used to find the saturated conductivity of each core, still housed in the plastic liner, before the bulk density was determined. A fuller discussion of the laboratory soil analysis is included in Chapter 6.

5.7.1 GREENFIELDS.

As has already been established, no reduction in soil moisture was observed as a result of pumping the Greenfields borehole (see Sect. 5.4.2). The intention was to cease activity at this site after the 6th July 1979. However, due to a technician's mistake, a set of readings was taken on the 31st July - these results are considered below. Belatedly, well after the access tubes were removed, one trial pit was dug in October 1981 in the vicinity of Tube 1.

5.7.1.1 The Soil Profile.

The soil profile revealed by the trial pit proved to vary considerably over the small area exposed (see description in Appendix 2). Excavation of the pit ceased when groundwater seepage was encountered at a depth of 1.5m. Below 35 cm the mottled colouring of the soil was indicative of a gley soil, and no roots were observed below 85 cm.

In Fig 5.26 the main features of the soil analysis are set alongside the moisture profiles obtained at Tube 1 before pumping commenced and at the end of July 1979. The soil is relatively sandy in the middle of the profile, but below 90 cm the texture is dominated by the silt and clay fractions - evidence of the underlying boulder clay.

5.7.1.2 The Rooting Depth of Wheat.

For access Tubes 1, 2 and 5, Fig 5.27 compares the moisture profiles recorded on the 25th May with those obtained for 31st July 1979 . The 25th May was selected for the comparison as pumping had not started and there had been a relatively dry preceding period. It is therefore reasonable to consider the profile as representative of the field capacity condition. At this time the Meteorological Office's MORECS system indicated a soil moisture deficit of 3mm for cereals. By the 31st July the wheat crop had effectively reached full maturity and MORECS gave an SMD for cereals of 101mm. When the observed moisture profiles were compared it was found that 89mm had been removed at Tube 1, 85mm at Tube 2, and 78mm at Tube 5 (see Appendix 1) between these two dates.

The moisture distributions presented in Fig 5.27 indicate that the roots of the wheat had extracted water from the top 1m of the profile. This falls within the range of 0.6 to 1.5m for field crops given by Drennan (1979b) at the public inquiry. However, it is worth noting that 1979 was not a particularly dry year, and that the water available to crops in the sandy clay loam/loam soils of the Salop Series present at Greenfields is significantly greater than that of other sandy soils within the Tern Area. This suggests that in a dry year greater rooting depths would be achieved at Greenfields as roots penetrate further into the profile in search of moisture. For sandy soils, without the benefit of irrigation, it is reasonable to expect that for wheat rooting depths in excees of 1m are the norm.

5.7.1.3 Further Consideration of Walley's Interpretation of Severn Trent W.A's Soil Moisture Results.

At the inquiry Walley cast doubts upon the Authority's interpretation of the soil moisture measurements that they had made during pumping of the Greenfields borehole in 1973 (see Sect. 5.6.4.3). He presented Fig 5.25, a comparison of calculated and measured soil moisture deficits, and concluded that a 38mm moisture deficit had been maintained as a result of pumping whilst there was ample rainfall to return the soil to field capacity. He further explained that the absence of any observed effect due to pumping at the Aston site did not automatically mean agreement with the Authority's interpretation of their own results - that there was no effect. The two sites were 130m apart.

Whilst studying the Shropshire Groundwater Scheme Reports the Detailed Geological Section, Drawing No A 3.5 of the Second Report (Severn River Authority, 1974), was compared with the Plan of the Greenfields Test Site, Fig 6 in the Third Report (Severn Trent Water Authority, 1975). The Geological Section (Fig 5.28a) shows the boulder clay layer tapering to zero thickness between the abstraction borehole and the observation well (borehole B) 20m away. The site plan (Fig 5.28b) locates the soil moisture tubes on a direct line from the abstraction well through the 20m observation well, and some 80m beyond the latter. It is entirely feasible therefore that Walley's interpretation is correct, in that the impermeable boulder clay layer was absent at the Authority's site, which was therefore sensitive to the effects of drawdown. The Aston site, located on the opposite side of the site access road (see Figs 5.6 and 5.28b), was subject to the effects of the 4 to 5m thick impermeable boulder clay layer shown on Fig 5.28a.

If Walley's interpretation is correct, and the author can find no fault with it, it supports the contention that potentially sensitive areas do occur where the drift is thin or leaky. Their extent is, therefore, more widespread than indicated by maps which simply show where the aquifer outcrops or where it is covered by sandy drift. At Greenfields the Authority's geological section is at variance with their own maps of boulder clay thickness - notably the drawing in the Second Report on the previous page to Fig 5.28a!

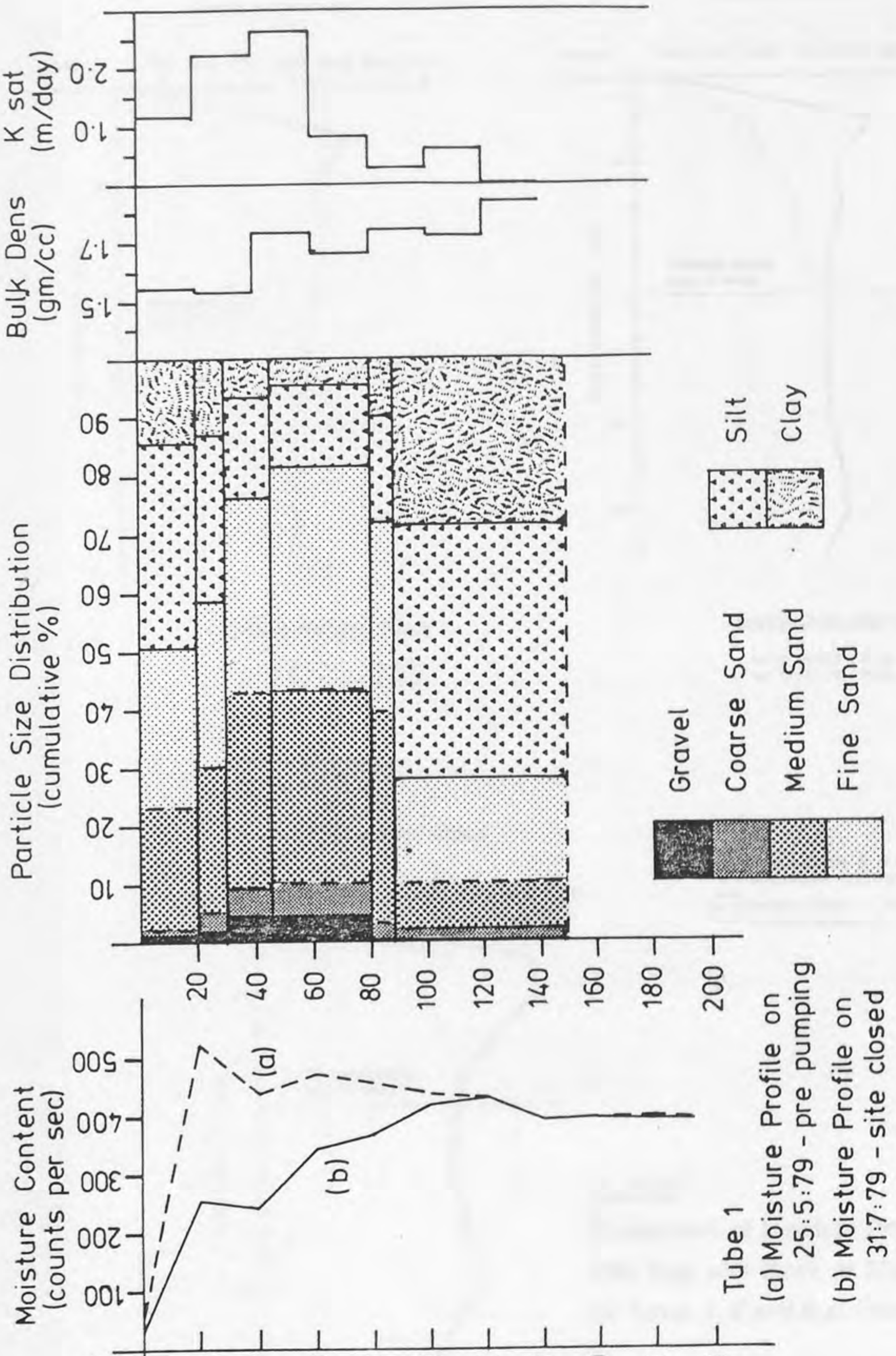
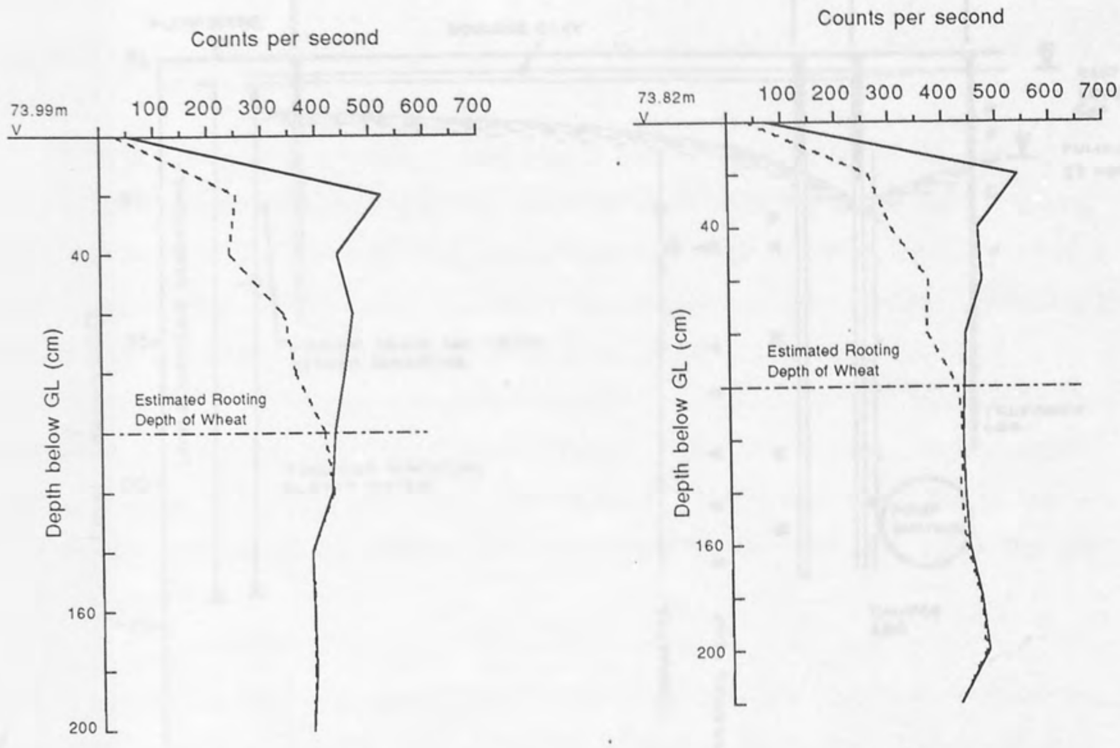


Fig 5.26 Soil Characteristics and their Relationship to Moisture Profiles at Greenfields Access Tube 1.

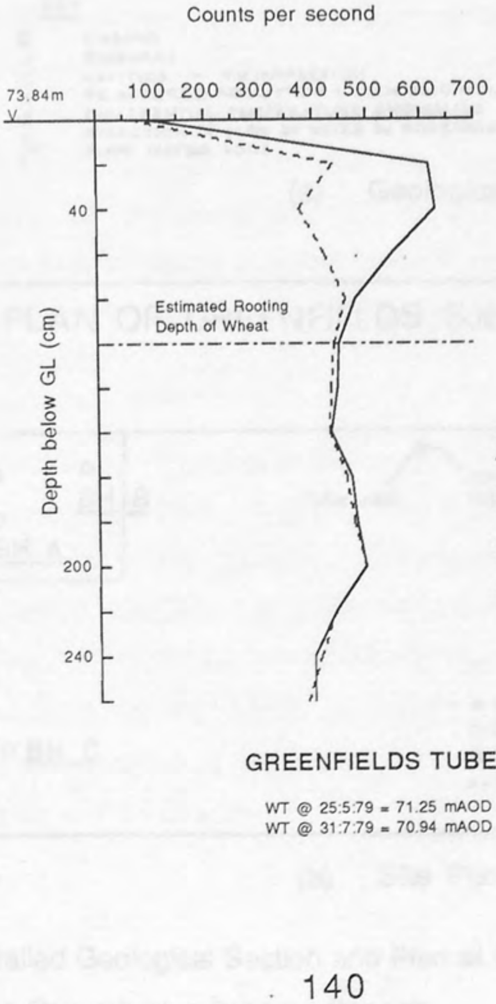


GREENFIELDS TUBE 1

WT @ 25:5:79 = 71.27 mAOD
WT @ 31:7:79 = 70.72 mAOD

GREENFIELDS TUBE 2

WT @ 25:5:79 = 71,25 mAOD
WT @ 31:7:79 = 70.85 mAOD



— Moisture Profile @ 25:5:79: Wheat approx 10cm High

-- Moisture Profile on 31:7:79: Full Crop Development

Fig 5.27
Comparison of Moisture Profiles at 25th May with those at 31st July 1979 for Tubes 1, 2 and 5 at Greenfields.

GREENFIELDS TUBE 5

WT @ 25:5:79 = 71.25 mAOD
WT @ 31:7:79 = 70.94 mAOD

(a) Geological Section (Severn River Authority, 1974).

(b) Site Plan (Severn Trent Water Authority, 1975).

Fig 5.28 Detailed Geological Section and Plan of Greenfields Test Site taken from 2nd and 3rd Groundwater Scheme Reports.

5.7.2 HEATH HOUSE.

The post-inquiry history of the Heath House site is somewhat checkered. Monitoring continued unhampered between July and December 1979, with the sugar beet reaching full leaf cover by the visit made in mid-September. However, on 10th January 1980 it was discovered that the access tubes had been severed by the farmer whilst harvesting the sugar beet. With the exception of Tube 1 all were replaced, but at the expense of disturbing the top 60 to 70 cm of soil and of a small loss in tube length. Monitoring then continued through February and March until Tubes 2, 3 and 4 were removed on April 15th, approximately 12 months after work commenced. Tube 5 was again cut by the farmer in August and, when its remains were extracted on October 29th 1980, the site was finally closed.

It should be noted that, from the outset, the access tubes at Heath House were deliberately located between the rows of sugar beet so that there was no danger of moisture readings being influenced by the water content of swelling tubers.

5.7.2.1 Soil Profiles.

Trial pits were dug and soil samples taken at each access tube location. Full profile descriptions and analyses results are provided in Appendix 2, whilst Fig 5.29 provides a summary of the soil properties for Tubes 2, 3 and 5. All profiles exhibited similar characteristics with the proportion of silt and clay decreasing from a total of 20-25% in the upper horizons, to 10-15% below 1m. With the exception of Tube 3, and to a lesser extent Tube 2, there was evidence of a thin layer of coarser material at roughly 1m down the profile, but this does not appear to have influenced the moisture retention charateristics of the soil.

No evidence was found of an increase in the proportion of silt and clay towards the bottom of Tubes 1 and 2, which would have supported the hypothesis that drainage in response to drawdown of the water table was impeded by an impermeable layer or that a perched water table existed (see Sect 5.4.3). However, both the one inch geological map of the Wem area (IGS, 1967) and the Drift Thickness and Lithology map (ACS 13) presented by the Water Authority at the inquiry show the aquifer to outcrop for approximately 150m south of the abstraction well, and overlain by boulder clay after this. This latter evidence indicates a grading from outcrop to overlying boulder clay in the vicinity of Tubes 1 and 2, and suggests that the hypothesis may be correct. However, without the expense of a further site investigation the explanation remains hypothetical.

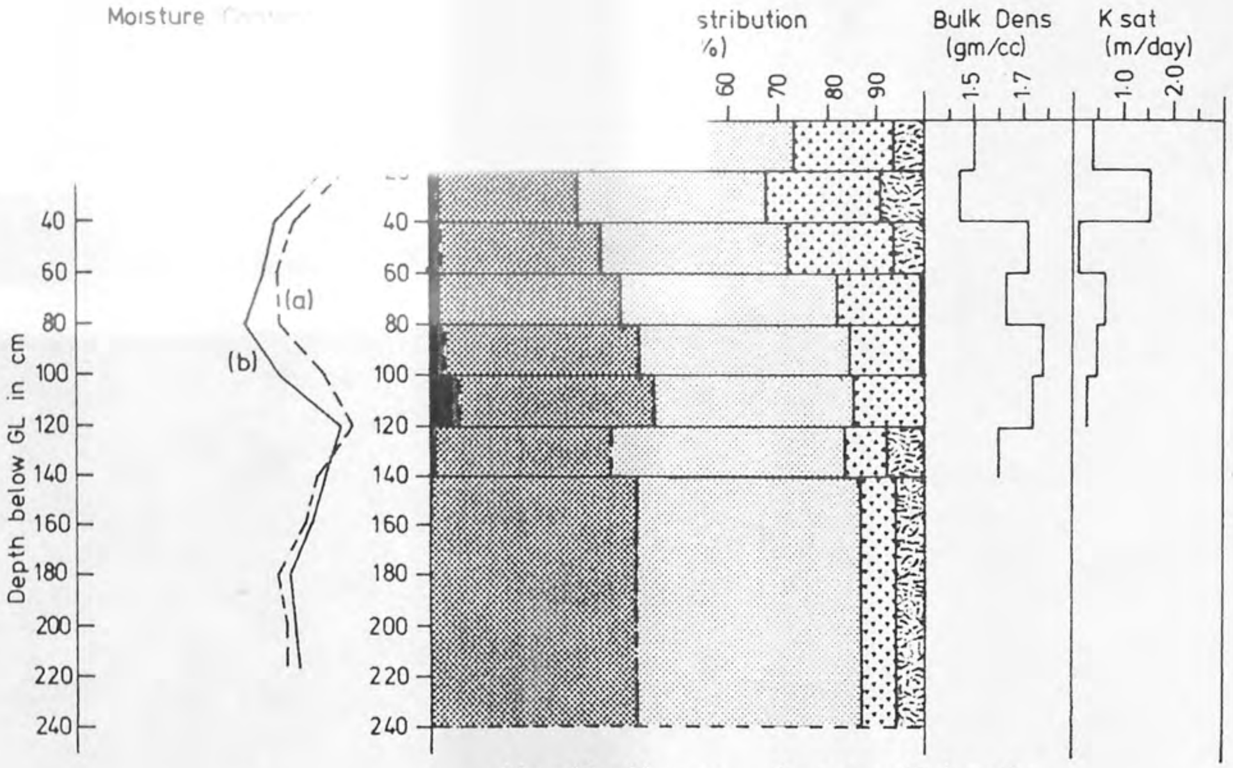
When the trial pits at Tubes 1 to 4 were dug in April 1979 seepage or saturated conditions were encountered between 1.1m and 1.5m below ground level. At the same time interpolation from groundwater level observations gave the water table to be between 1.6m and 2.1m below the surface. At all trial pits roots were found at or below 1.2m, with evidence of penetration to 1.46m at Tube 3 and 1.8m at Tube 5. At the latter roots had followed the side of the access tube to this depth.

5.7.2.2 Soil Moisture Recovery Following Pumping.

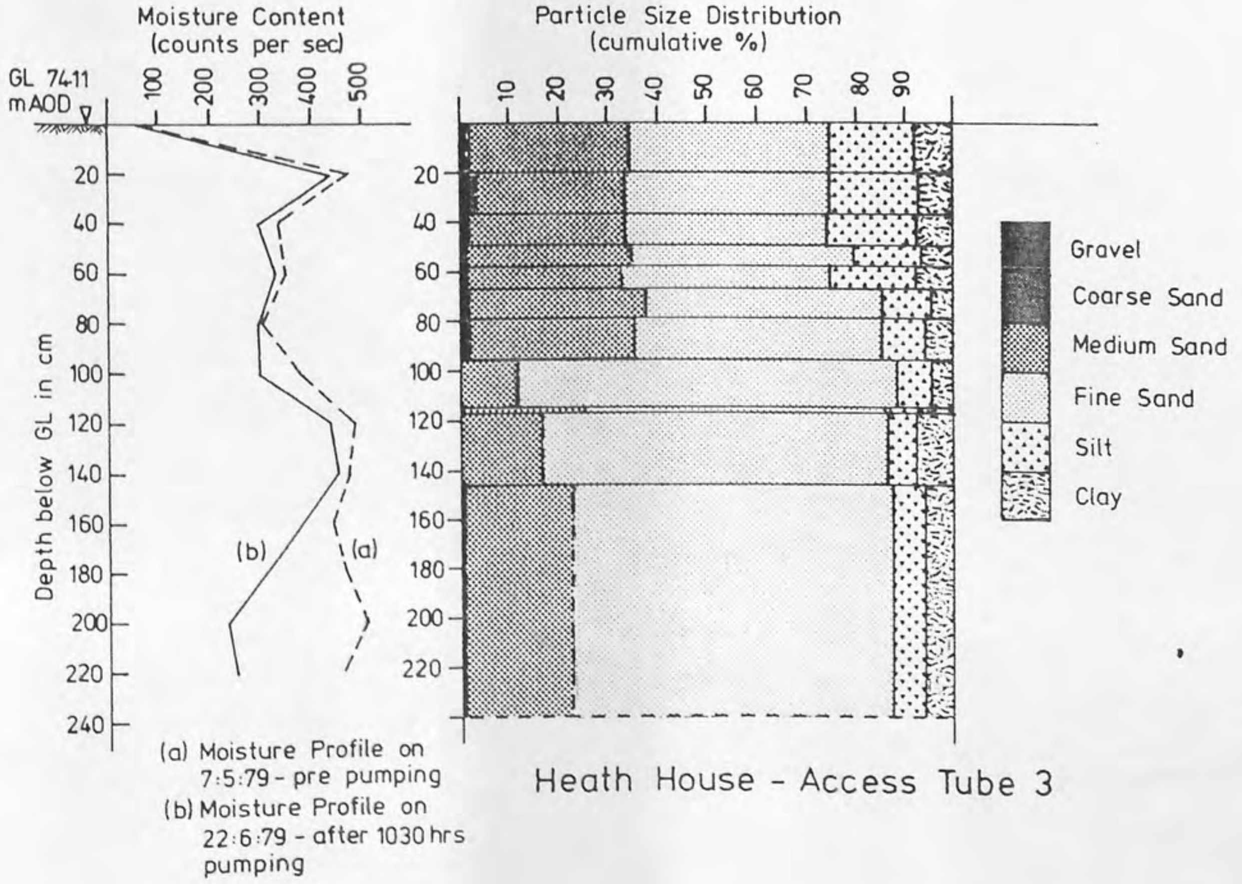
The results of soil moisture observations before the inquiry were summarised in Figs 5.11 to 5.15. These summaries have been extended in Figs 5.30 to 5.34 to cover the full study period for each tube. It should be noted, however, that different scales have been used and at the bottom of the profiles the layers considered have been adjusted so that pre- and post tube replacement conditions can be compared.

Following the reinstatement of the damaged access tubes in January 1980, water was found to be leaking past the bottom plugs into Tubes 3 and 4. Although a laboratory study supervised by the author (Wood, 1982) indicated that this had insignificant effects upon count rate readings, discussions with other research workers have cast doubts upon these findings. In view of this uncertainty, readings taken at these two tubes after January can not be considered reliable. Furthermore, there is a possibility that the replacement tubes did not fit the original holes tightly and thus drainage passages were formed alongside them. When this is considered in combination with the disturbed soil filling the depression excavated in order to extract the damaged tubes, the high moisture contents recorded through February to April 1980 could be explained by localised drainage and redistribution alongside the tubes. The 1980 results for Heath House must therefore be interpreted with extreme caution. On the other hand, given the rapid drainage characteristics of these sandy soils, the high rainfall experienced during this period and the high water tables, the observed moisture contents may well be truely representative of conditions at the site. However, the prime obective in continuing the study at Heath House was to observe moisture changes following the cessation of pumping, and the period up to the end of 1979 is sufficient for this purpose.

As Tube 2 experienced no loss as a result of pumping it can be used as an indicator of natural variations. It cannot be regarded as a true control since the presence of a perched

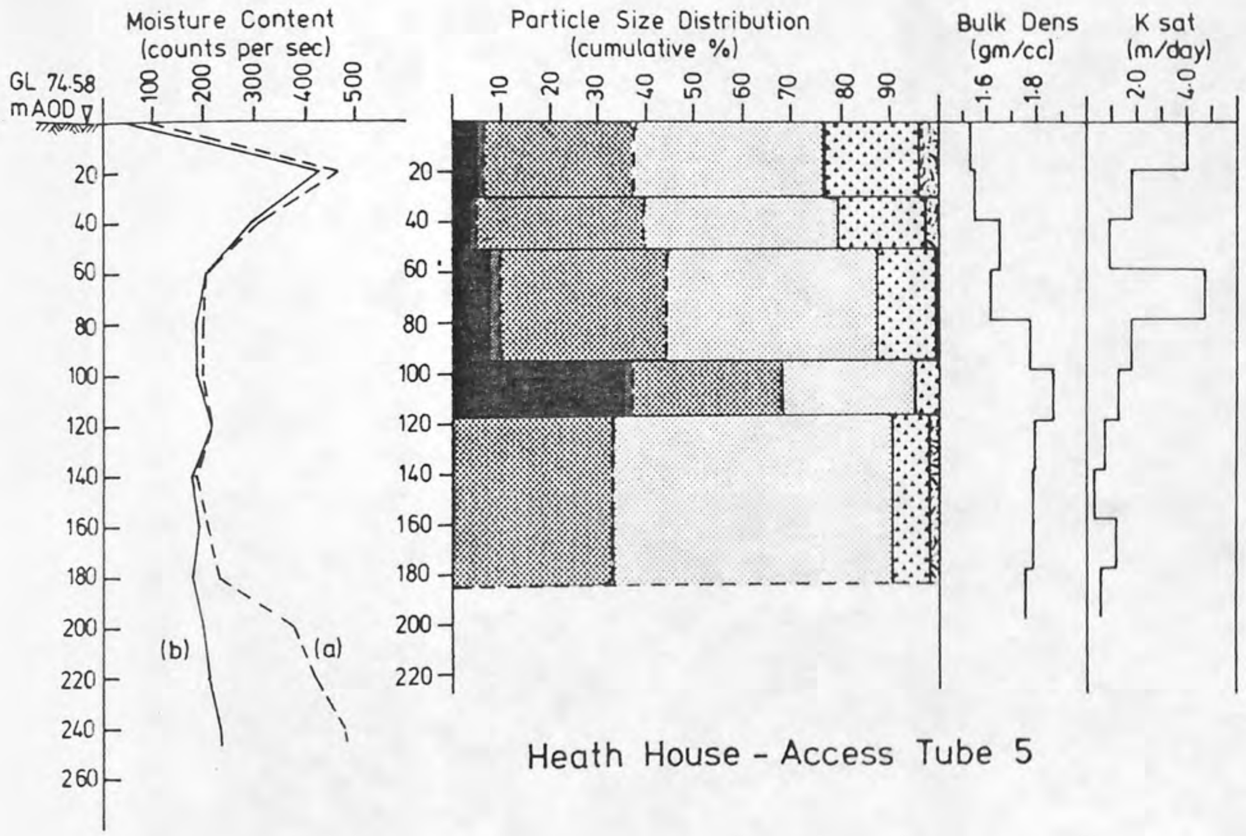


Heath House - Access Tube 2



(a) Moisture Profile on 7:5:79 - pre pumping
(b) Moisture Profile on 22:6:79 - after 1030 hrs pumping

Heath House - Access Tube 3



Heath House - Access Tube 5

Fig 5.29 Soil Characteristics and their Relation to Moisture Profiles at Heath House Access Tubes 1,3 and 5.

Fig 5.30 Heath House Access Tube 1: Changes in Soil Moisture Content Observed for Entire Study Period.

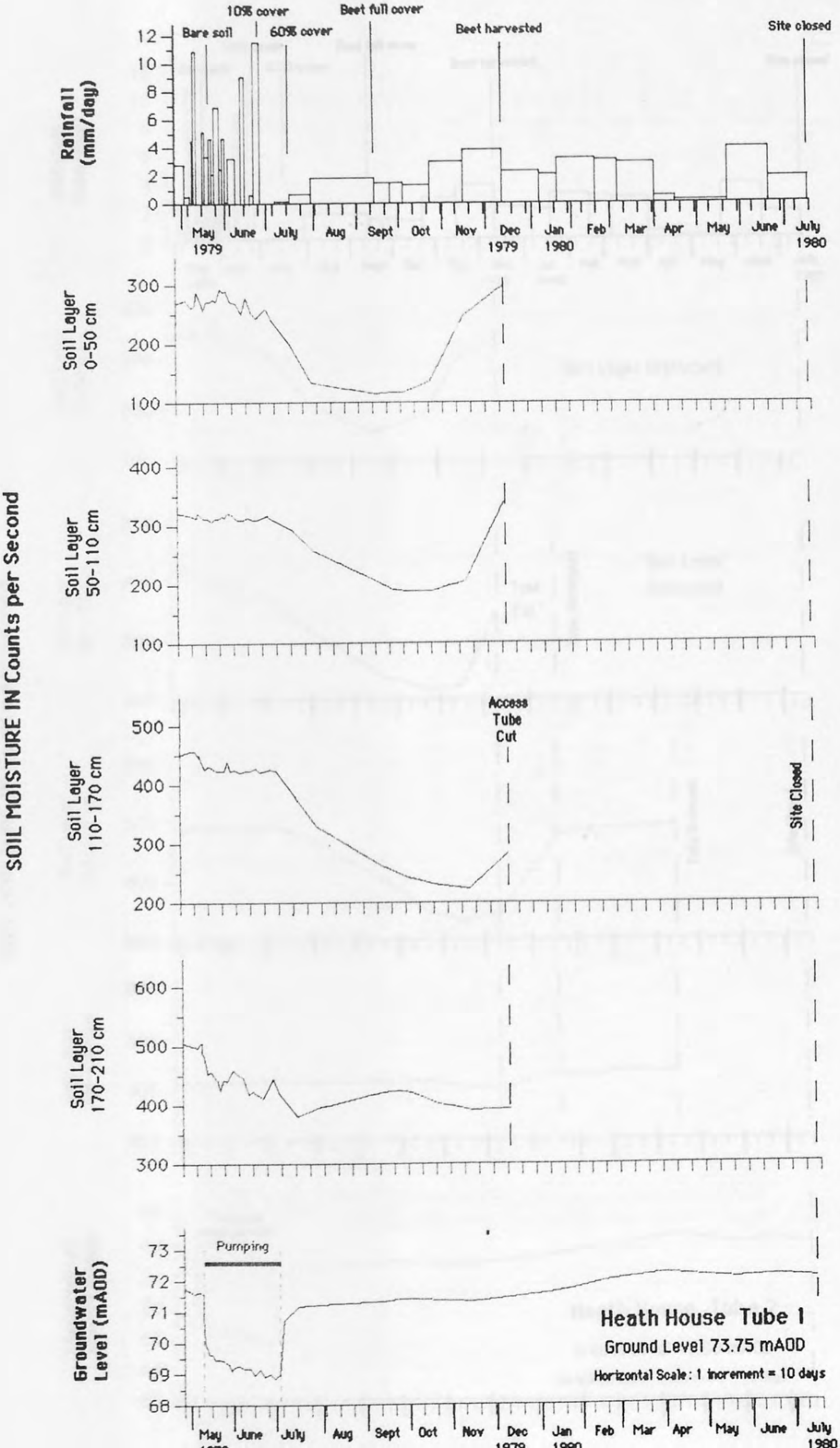
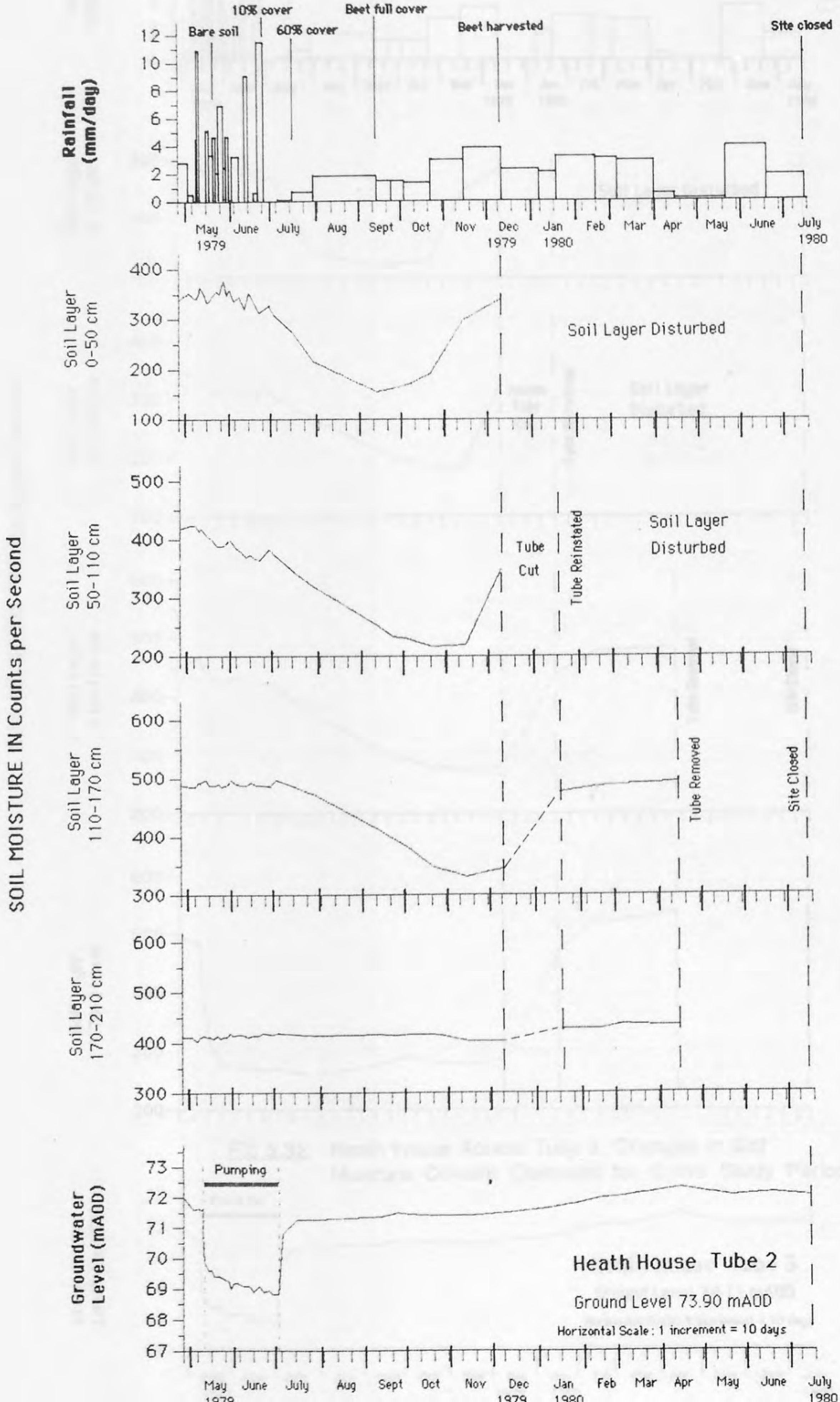


Fig 5.31 Heath House Access Tube 2: Changes in Soil Moisture Content Observed for Entire Study Period.



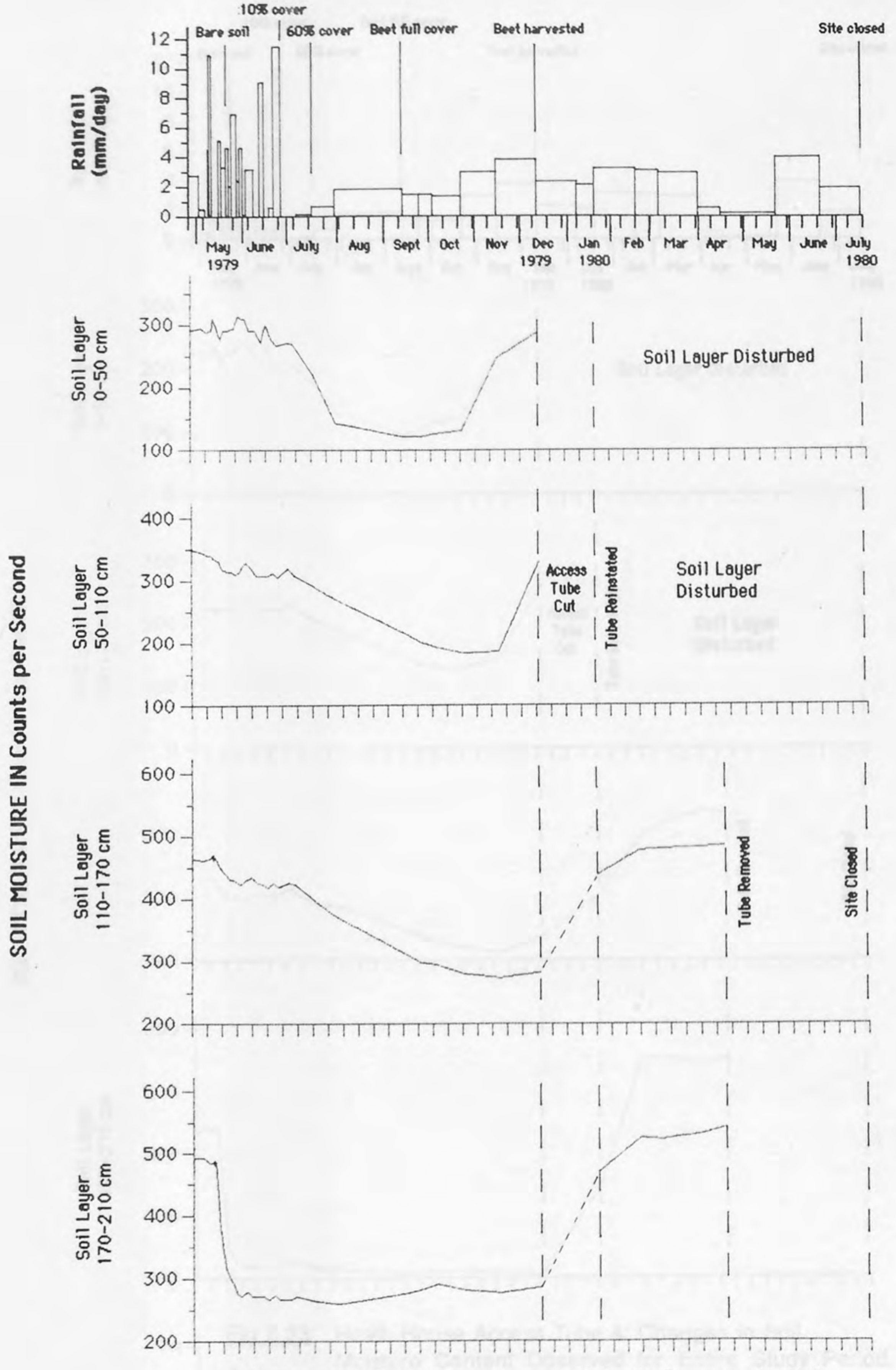
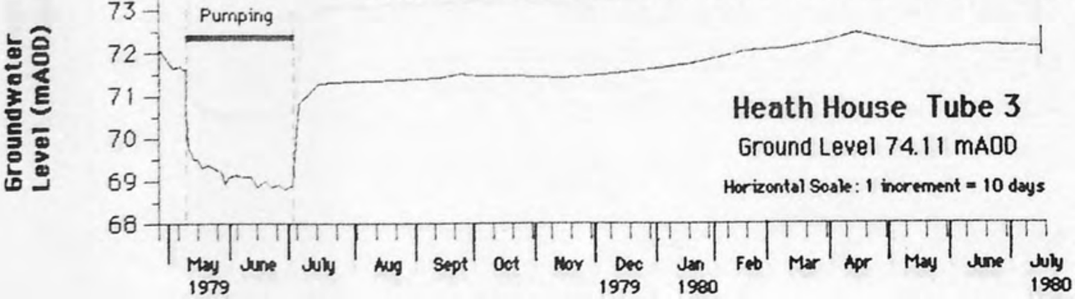


Fig 5.32 Heath House Access Tube 3: Changes in Soil Moisture Content Observed for Entire Study Period.



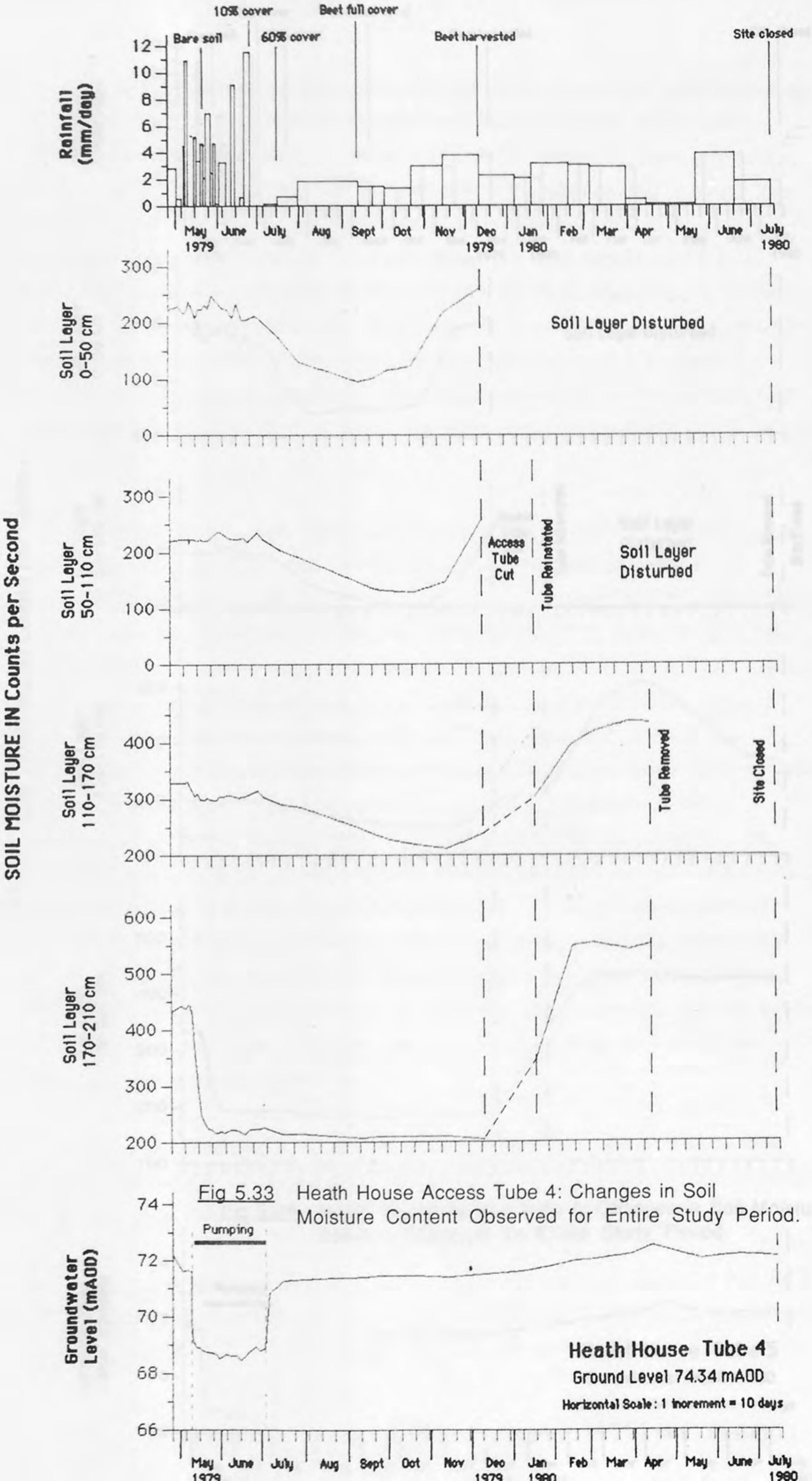


Fig 5.33 Heath House Access Tube 4: Changes in Soil Moisture Content Observed for Entire Study Period.

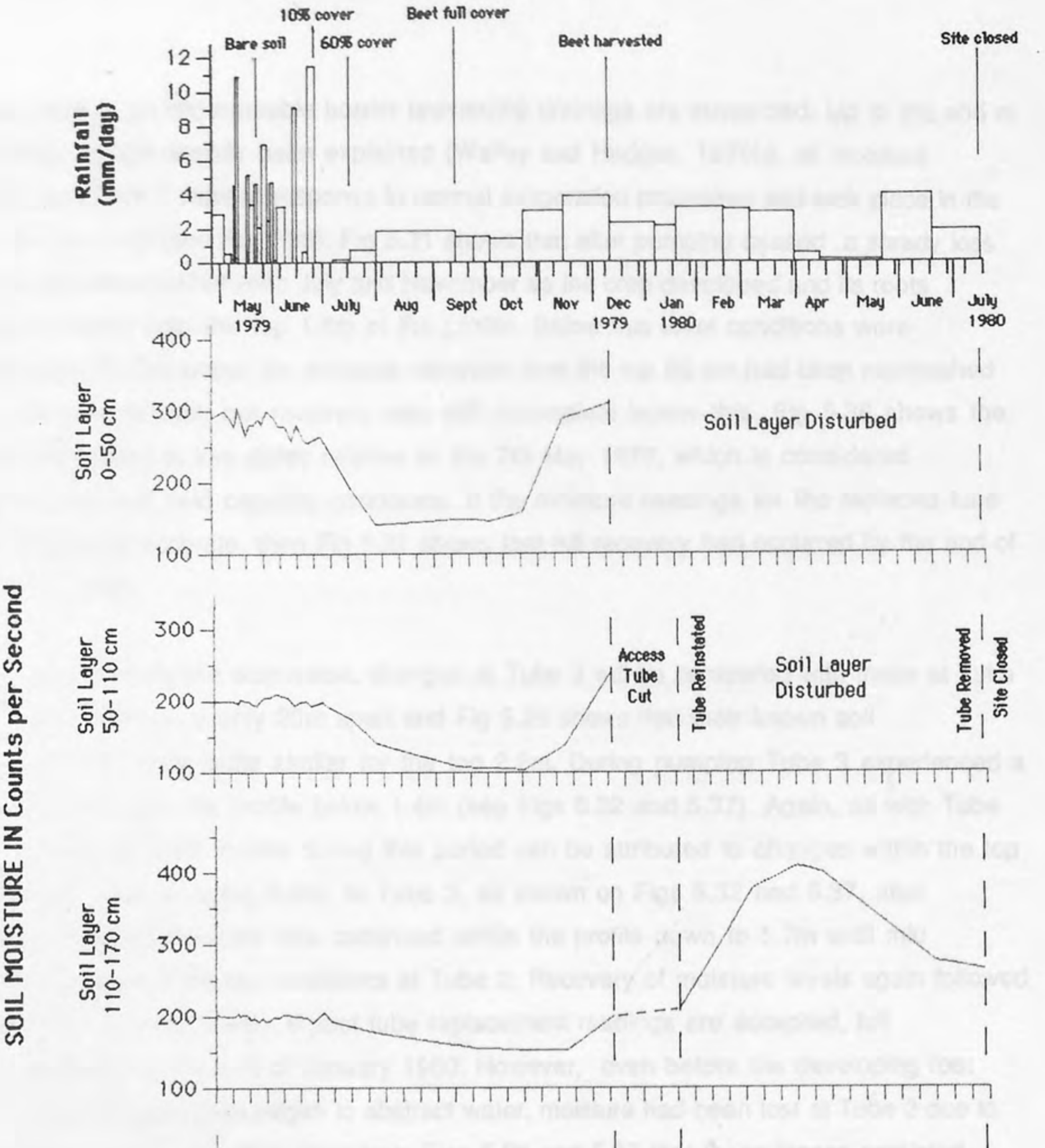
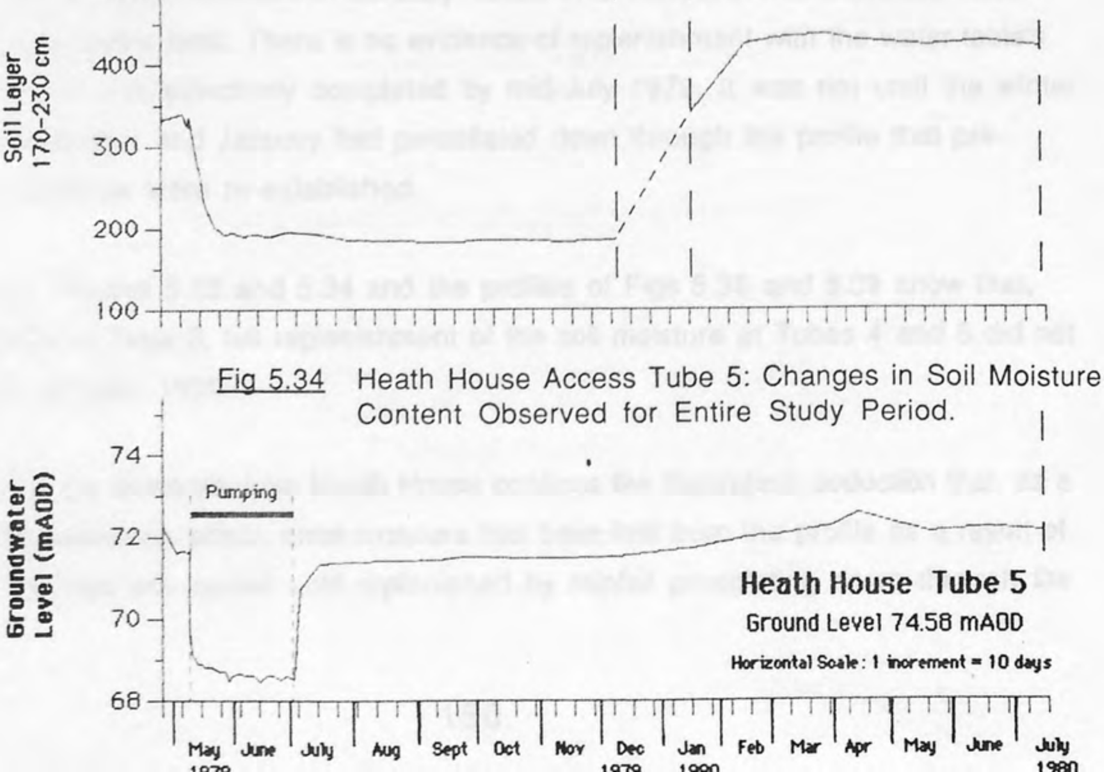


Fig 5.34 Heath House Access Tube 5: Changes in Soil Moisture Content Observed for Entire Study Period.



water table or an impermeable barrier preventing drainage are suspected. Up to the end of pumping, as has already been explained (Walley and Hedges, 1979b), all moisture changes at Tube 2 were in response to normal evaporation processes and took place in the top 50 cm of soil (see Fig 5.35). Fig 5.31 shows that after pumping ceased a steady loss of moisture occured between July and November as the crop developed and its roots removed water from the top 1.8m of the profile. Below this level conditions were unaffected. By December the moisture removed from the top 80 cm had been replenished by infiltrating rainfall, but recovery was still incomplete below this. Fig 5.36 shows the moisture profiles at key dates relative to the 7th May 1979, which is considered representative of field capacity conditions. If the moisture readings for the replaced tube are considered accurate, then Fig 5.31 shows that full recovery had occurred by the end of January 1980.

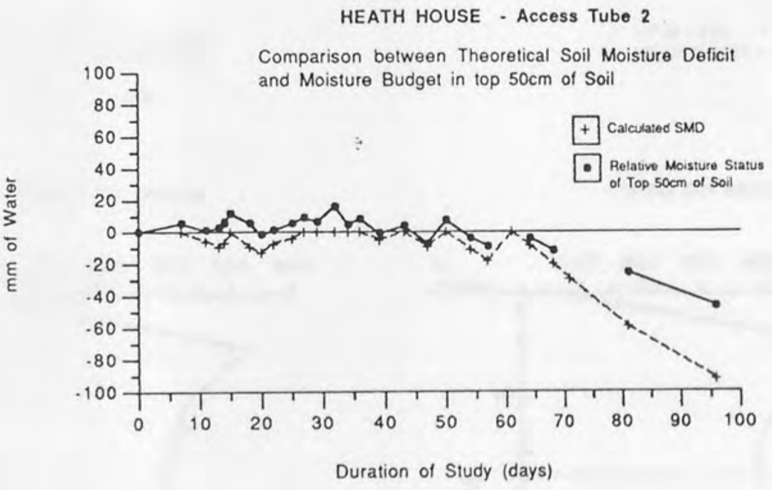
In order to simplify the discussion, changes at Tube 3 will be compared with those at Tube 2. These Tubes were only 20m apart and Fig 5.29 shows that their known soil characteristics were quite similar for the top 2.2m. During pumping Tube 3 experienced a loss of water from the profile below 1.4m (see Figs 5.32 and 5.37). Again, as with Tube 2, evapotranspiration losses during this period can be attributed to changes within the top 50 cm soil layer (see Fig 5.35). At Tube 3, as shown on Figs 5.32 and 5.37, after pumping ceased moisture loss continued within the profile down to 1.7m until mid November, paralleling the conditions at Tube 2. Recovery of moisture levels again followed the pattern at Tube 2 with, if post tube replacement readings are accepted, full replenishment by the end of January 1980. However, even before the developing root system of the sugar beet began to abstract water, moisture had been lost at Tube 3 due to the effects of pumping. It is clear from Figs 5.32 and 5.37 that these losses persisted through until full replenishment in January 1980. This moisture was therefore never available to the sugar beet. There is no evidence of replenishment with the water table's recovery, which was effectively completed by mid-July 1979. It was not until the winter rainfall of December and January had percollated down through the profile that pre-pumping conditions were re-established.

Furthermore, Figures 5.33 and 5.34 and the profiles of Figs 5.38 and 5.39 show that, like the profile at Tube 3, full replenishment of the soil moisture at Tubes 4 and 5 did not occur until January 1980.

In conclusion, the evidence from Heath House confirms the theoretical deduction that, as a result of the hysteresis effect, once moisture has been lost from the profile as a result of pumping, the loss will persist until replenished by rainfall percolating down through the profile. Moisture levels do not recover as groundwater rises back to its original level when pumping ceases.

5.7.2.3 The Rooting Depth of Sugar Beet.

Visual inspection of the soil profiles revealed roots present 1.45m below the ground surface, and extending down as far as 1.8m adjacent to Tube 5. The moisture profiles, illustrated in Fig 5.36, for Tube 2 exhibit moisture loss to a depth of 1.8m which can only be attributed to root abstraction. This can be confirmed for each of the five tubes, as Figs 5.30 to 5.34 all show a continued gradual removal of moisture in the 110 to 170 cm soil layer from July to October. For the soil conditions at the Heath House site, a rooting depth for sugar beet of 1.8m can safely be accepted.



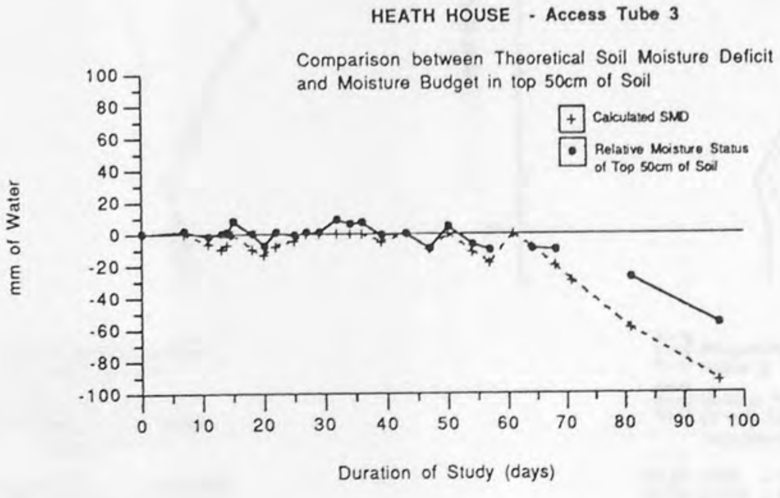
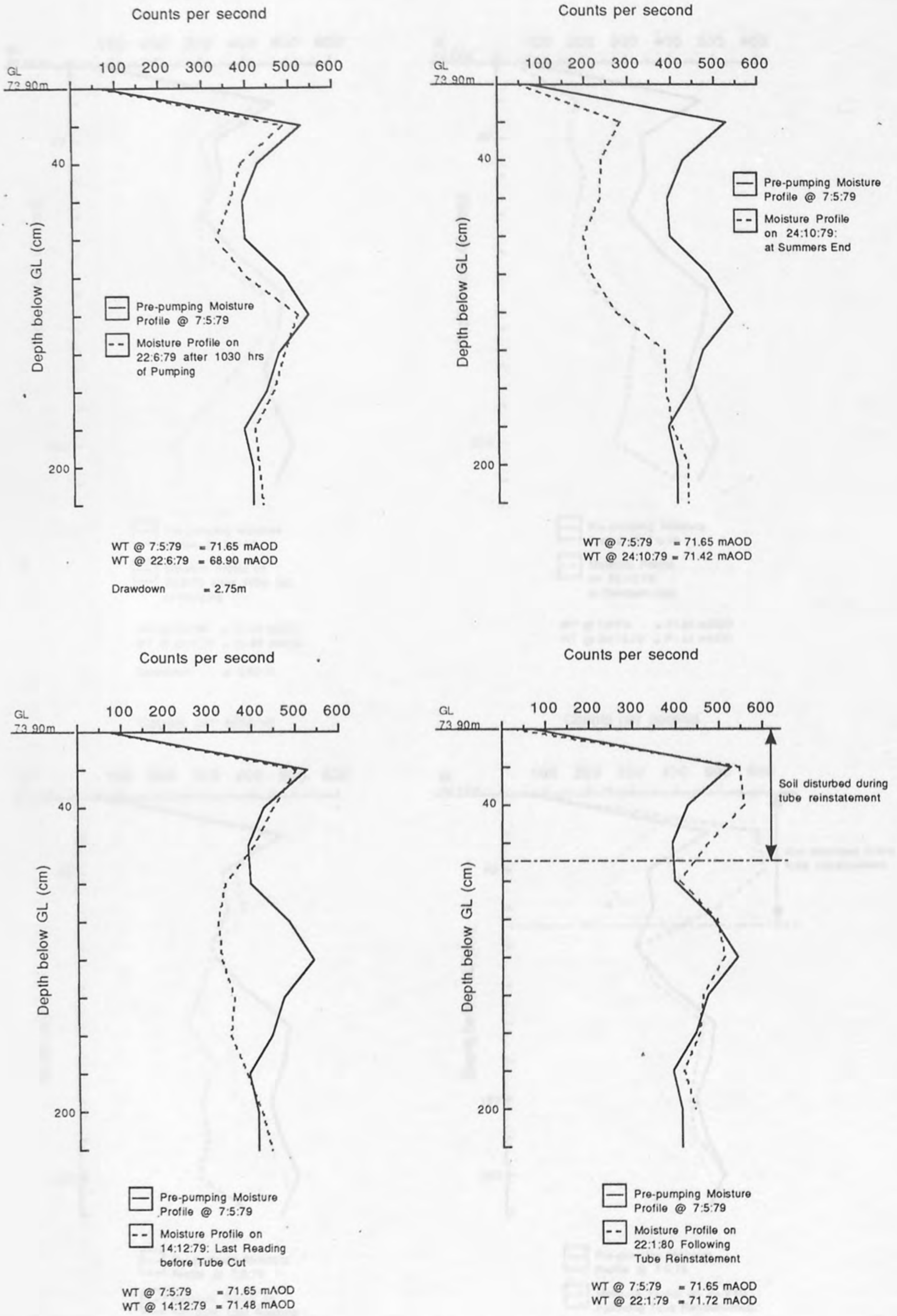


Fig 5.35 Comparison between Theoretical Soil Moisture Deficit and Moisture Budget in Top 50 cm of Soil for Access Tubes 2 and 3 at Heath House.



WT @ 7:5:79 = 71.65 mAOD
WT @ 22:6:79 = 68.90 mAOD

Drawdown = 2.75m

WT @ 7:5:79 = 71.65 mAOD
WT @ 24:10:79 = 71.42 mAOD

WT @ 7:5:79 = 71.65 mAOD
WT @ 14:12:79 = 71.48 mAOD

WT @ 7:5:79 = 71.65 mAOD
WT @ 22:1:79 = 71.72 mAOD

Fig 5.36 Changes in Moisture Profile on Key Dates in Relation to the Field Capacity Profile: Heath House Access Tube 2.

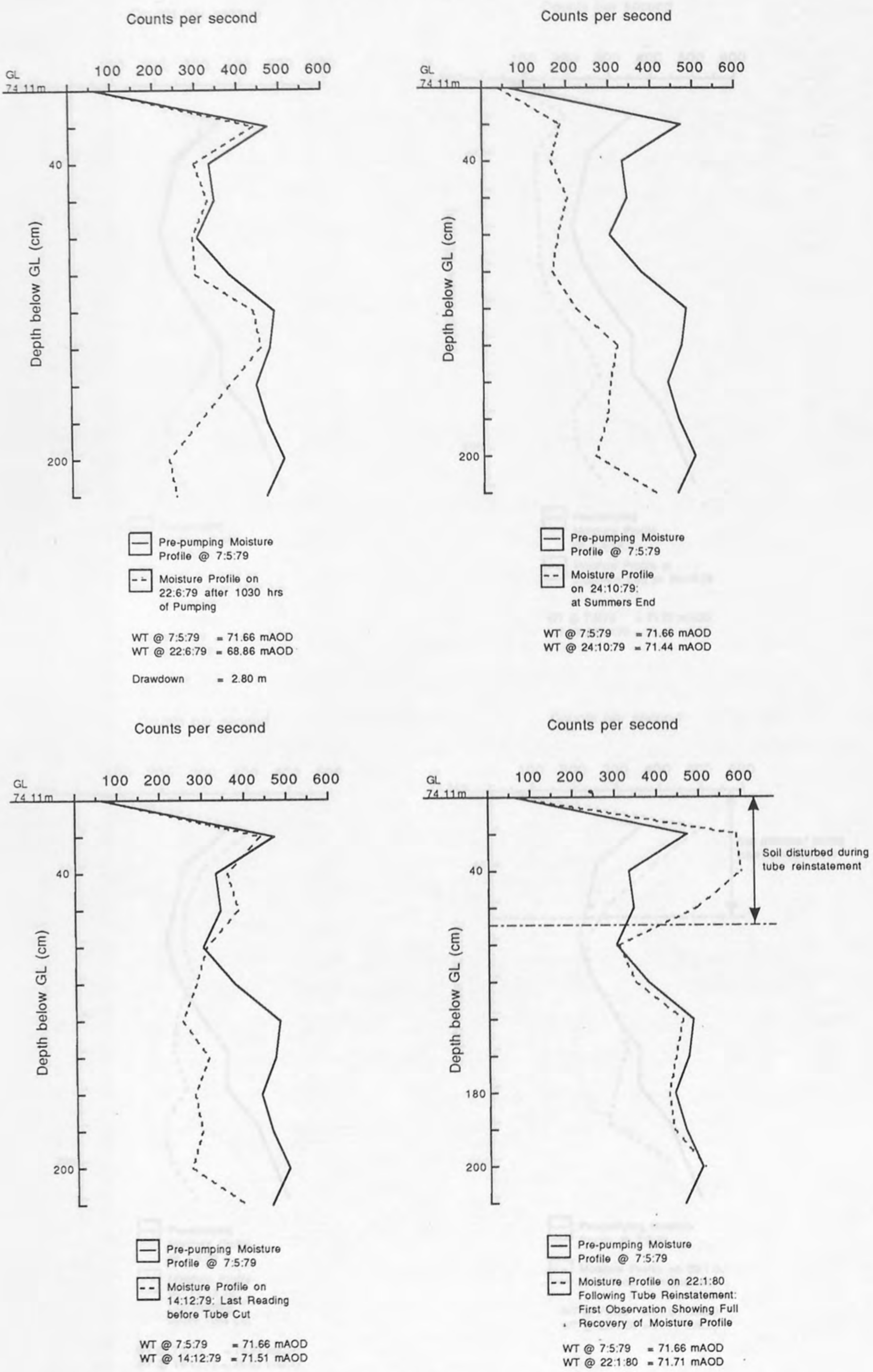


Fig 5.37 Changes in Moisture Profile on Key Dates in Relation to the Field Capacity Profile: Heath House Access Tube 3.

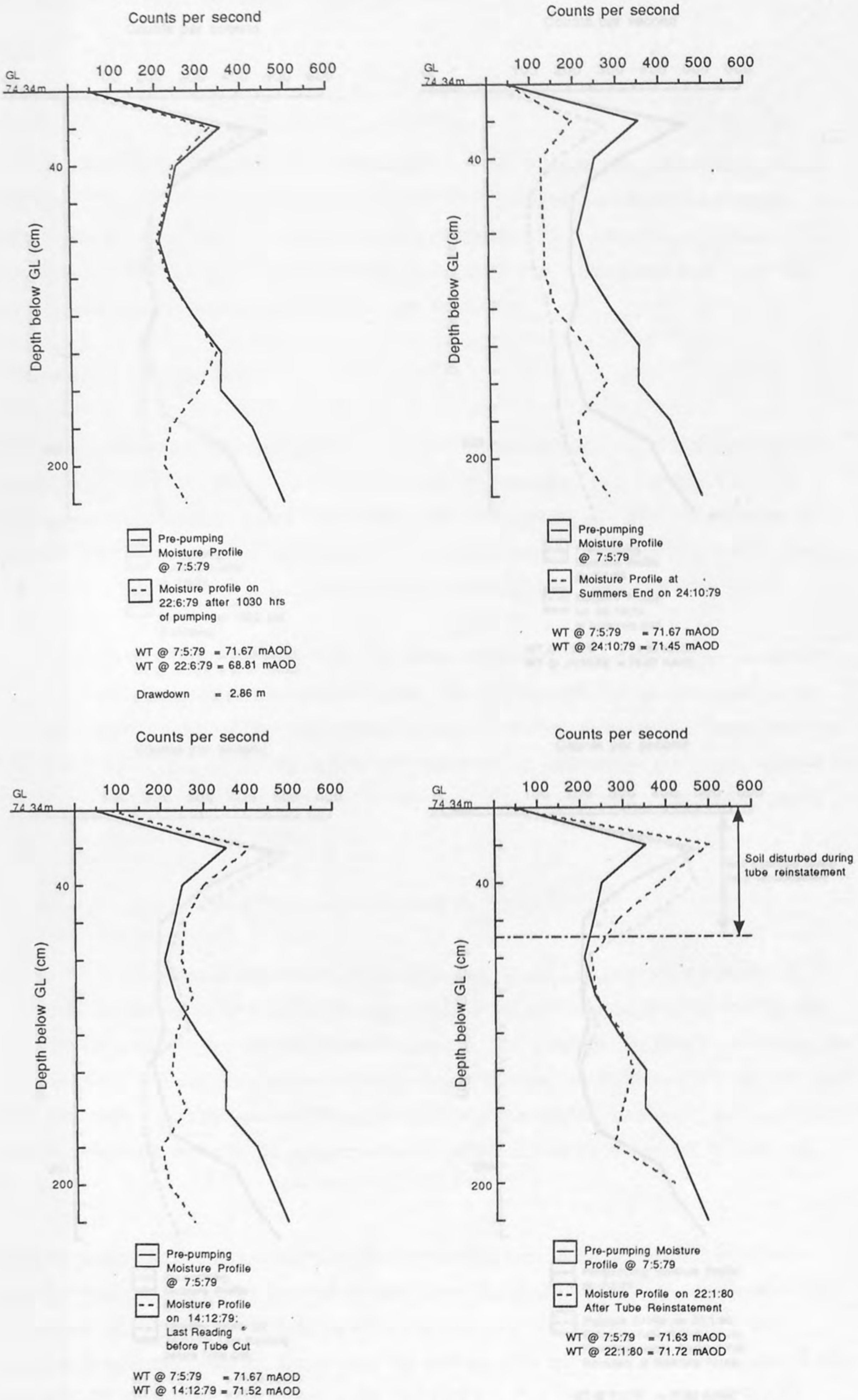


Fig 5.38 Changes in Moisture Profile on Key Dates in Relation to the Field Capacity Profile: Heath House Access Tube 4.

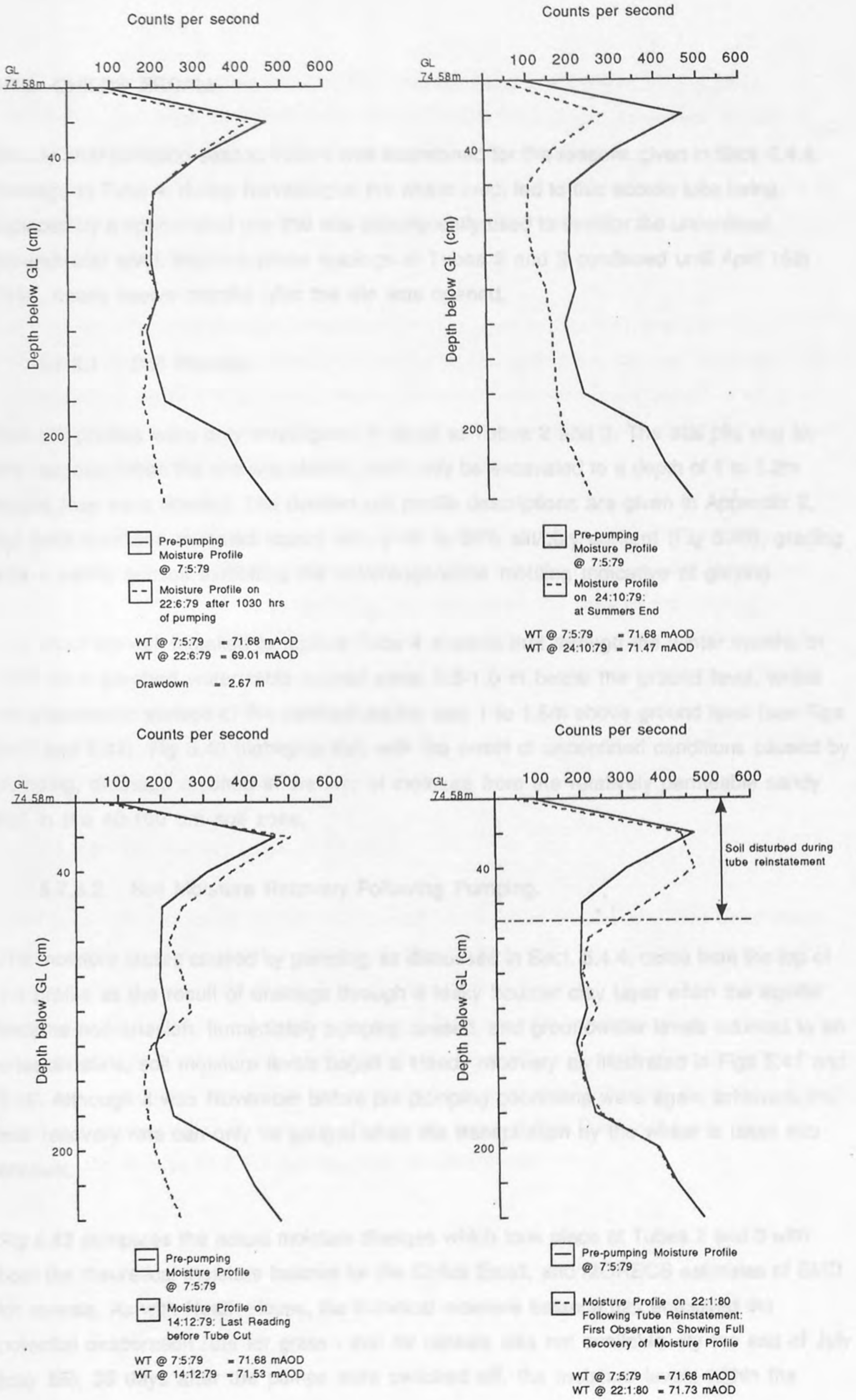


Fig 5.39 Changes in Moisture Profile on Key Dates in Relation to the Field Capacity Profile: Heath House Access Tube 5.

5.7.3 CHILDS ERCALL.

Shortly after pumping ceased Tube 1 was abandoned for the reasons given in Sect. 5.4.4. Damage to Tube 4, during harvesting of the wheat crop, led to this access tube being replaced by a open-ended one that was subsequently used to monitor the unconfined groundwater level. Neutron probe readings at Tubes 2 and 3 continued until April 16th 1980, nearly twelve months after the site was opened.

5.7.3.1 Soil Profiles.

The soil profiles were only investigated in detail at Tubes 2 and 3. The trial pits dug for this purpose, when the site was closed, could only be excavated to a depth of 1 to 1.2m before they were flooded. The detailed soil profile descriptions are given in Appendix 2, but both locations revealed topsoil with a 40 to 50% silt/clay content (Fig 5.40), grading into a sandy subsoil exhibiting the red/orange/white mottling indicative of gleying.

The short dip-well installed to replace Tube 4 showed that through the winter months of 1979-80 a perched water table existed some 0.5-1.0 m below the ground level, whilst the piezometric surface of the confined aquifer was 1 to 1.5m above ground level (see Figs 5.41 and 5.42). Fig 5.40 highlights that, with the onset of unconfined conditions caused by pumping, drainage resulted in the loss of moisture from the relatively permeable sandy soil in the 40-100 cm soil zone.

5.7.3.2 Soil Moisture Recovery Following Pumping.

The moisture losses caused by pumping, as discussed in Sect. 5.4.4, came from the top of the profile as the result of drainage through a leaky boulder clay layer when the aquifer became non-artesian. Immediately pumping ceased, and groundwater levels returned to an artesian state, soil moisture levels began a steady recovery as illustrated in Figs 5.41 and 5.42. Although it was November before pre-pumping conditions were again achieved, the true recovery rate can only be gauged when the transpiration by the wheat is taken into account.

Fig 5.43 compares the actual moisture changes which took place at Tubes 2 and 3 with both the theoretical moisture balance for the Childs Ercall, and MORECS estimates of SMD for cereals. As with Heath House, the theortical moisture balance has employed the potential evaporation rate for grass - that for cereals was not available. By the end of July (day 85), 35 days after the pumps were switched off, the moisture levels within the profiles compared favourably with both the moisture budget and the MORECS SMD predictions. Thereafter, observed levels and MORECS SMD values agree well, in spite of the latter being calculated for 40 km square areas. The divergence between the moisture measurements and the budget calculations is attributable to the continued transpiration of grass, whereas the wheat had reached senescence and had been harvested by the time of the visit on 15th September 1979.

Although the observed changes in moisture levels shown in Figs 5.41 and 5.42 suggest recovery to be a continued gradual process lasting throughout the summer, when the crop transpiration is taken into account a much greater recovery rate is suggested. A study of Fig 5.47 indicates that the conditions which would have existed, had pumping not occurred, were restablished 35 days after pumping ceased.

The complications introduced by the presence of the crop make determination of the real replenishment rate, due to the upward seepage caused by the reinstatement of artesian conditions, difficult. A more controlled experiment along the lines of the original experimental proposals (Sect. 5.2.2) would be necessary to achieve this. However, if the differences between the calculated moisture budget and the observed moisture profiles at Tubes 2 and 3 are plotted the graphs shown in Fig 5.44 are obtained. These indicate that, for the summer period after pumping ceased, there was a steady upward flow of moisture of approximately 0.9 mm/day.

5.7.3.3 The Rooting Depth of Wheat.

The complicating influence of the artesian conditions which existed at Childs Ercall mean that an estimate of the wheat rooting depth directly from the observed data is not possible. The fact that soil moisture levels remained constant in the 110-170 cm layer shown on Figs 5.41 and 5.42 does not necessarily mean that roots did not penetrate this deep - moisture abstracted could have been immediately replaced by upward seepage. However, the agreement between observed and estimated moisture conditions (see Fig 5.43) suggests that roots penetrated to at least the 50-110 cm layer of Figs 5.41 and 5.42, which supports the findings of a 1m rooting depth at Greenfields.

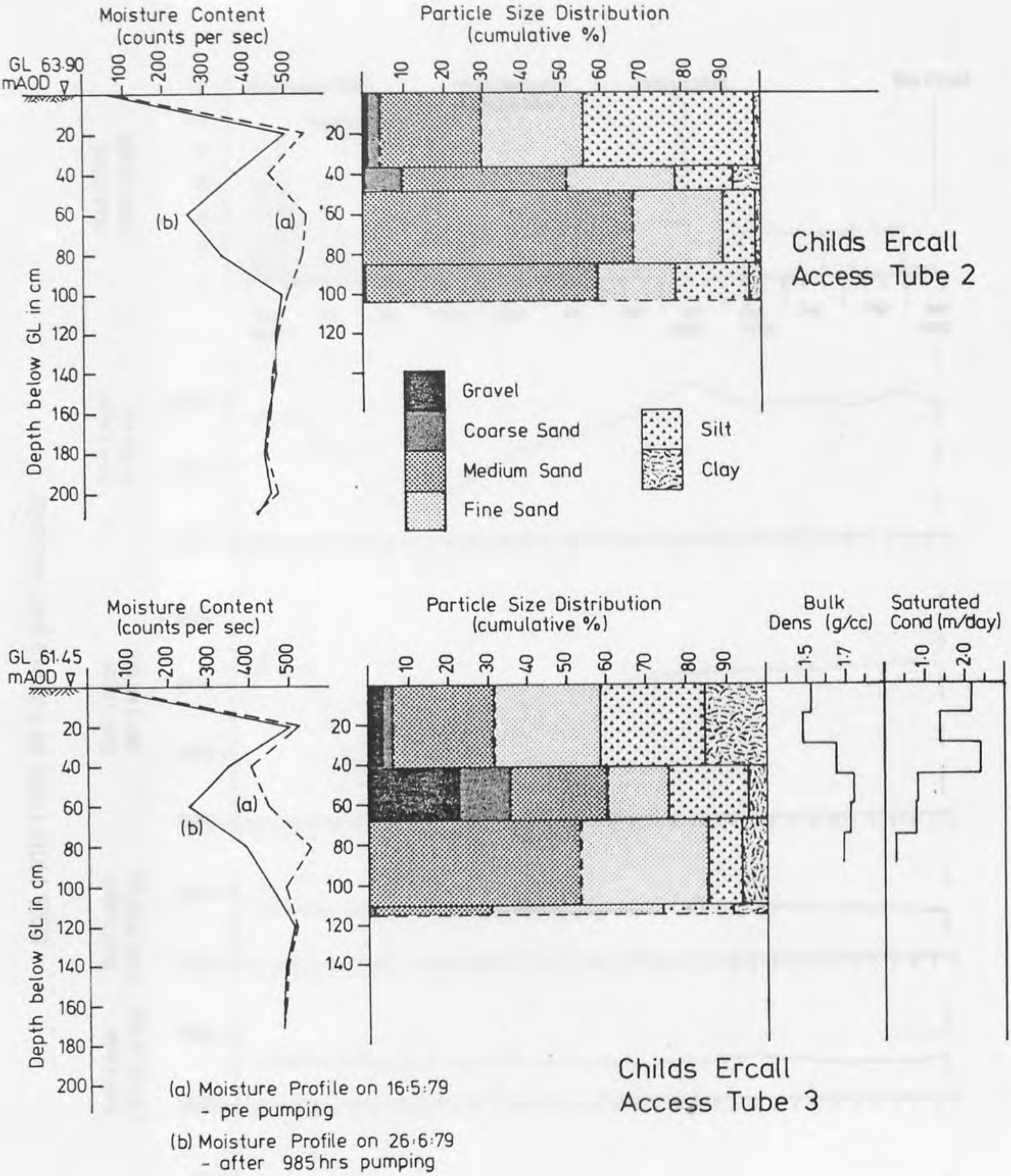


Fig 5.40 Soil Characteristics and their Relation to Moisture Profiles at Childs Ercall Access Tubes 2 and 3.

Fig 5.41 Childs Ercall Access Tube 2: Changes in Soil Moisture Content Observed for Entire Study Period.

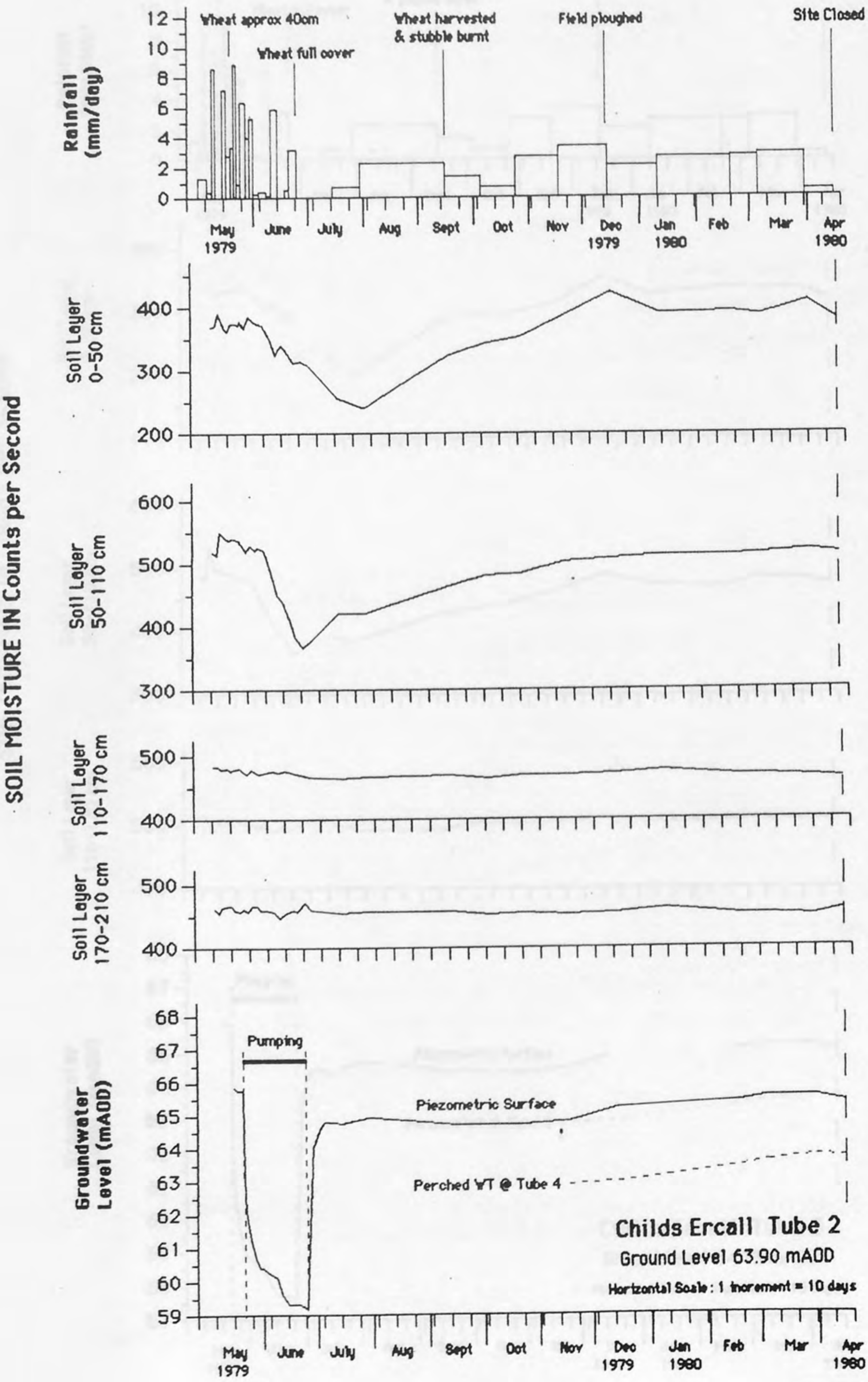
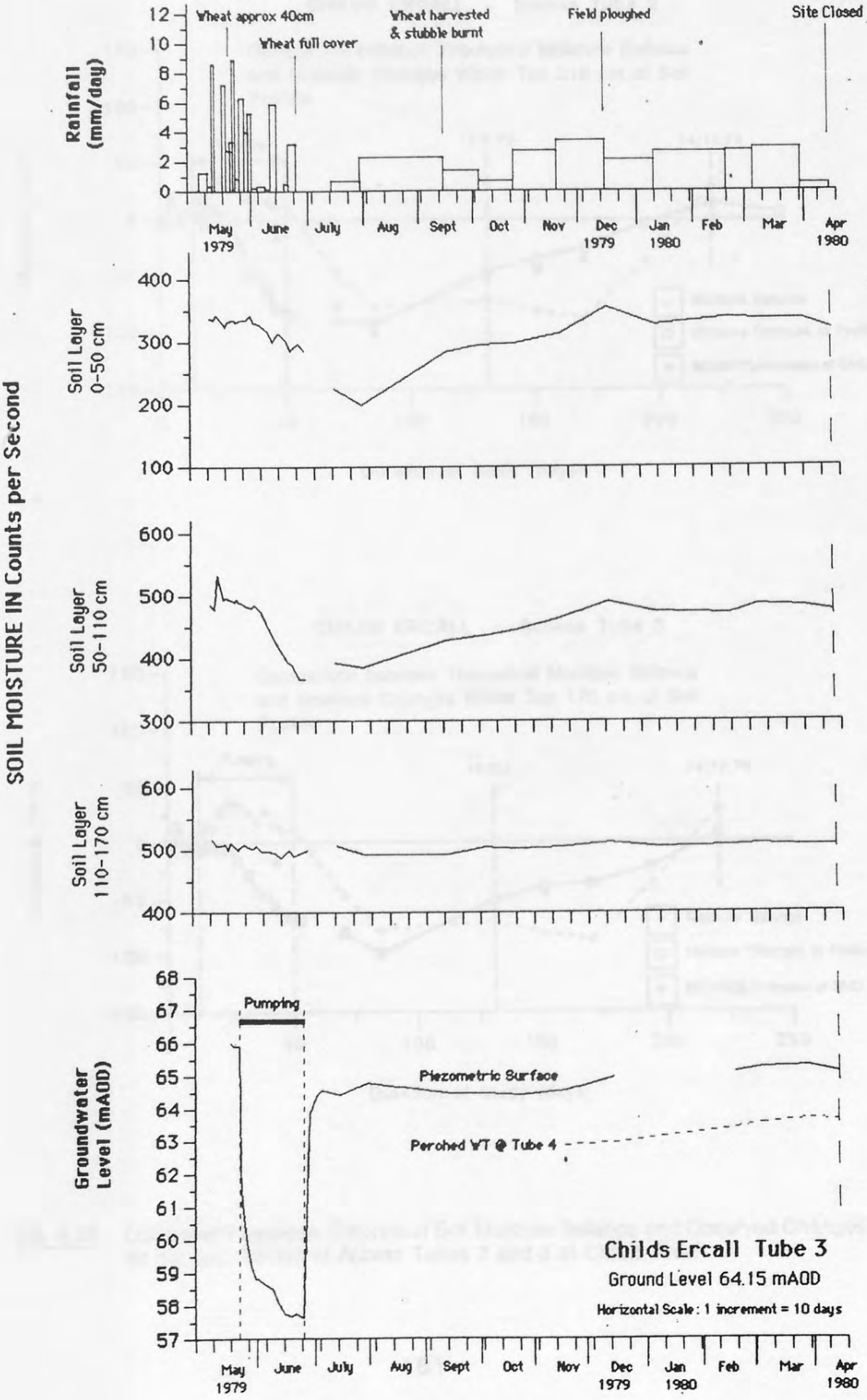
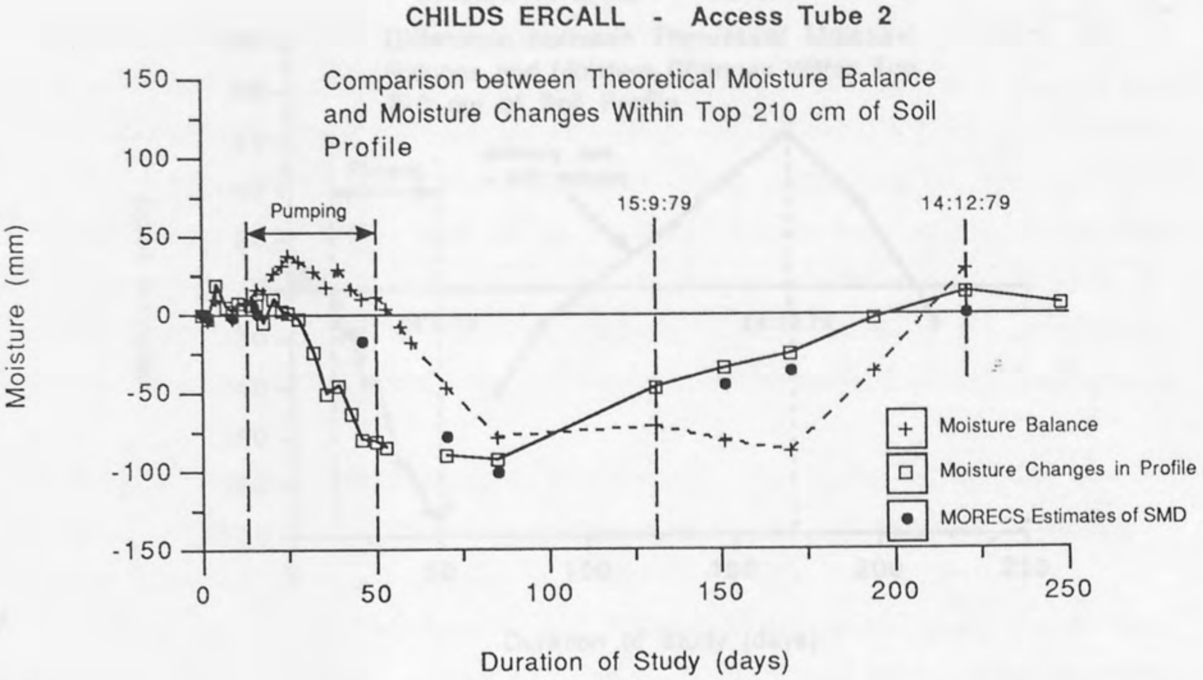


Fig 5.42 Childs Ercall Access Tube 3: Changes in Soil Moisture Content Observed for Entire Study Period.





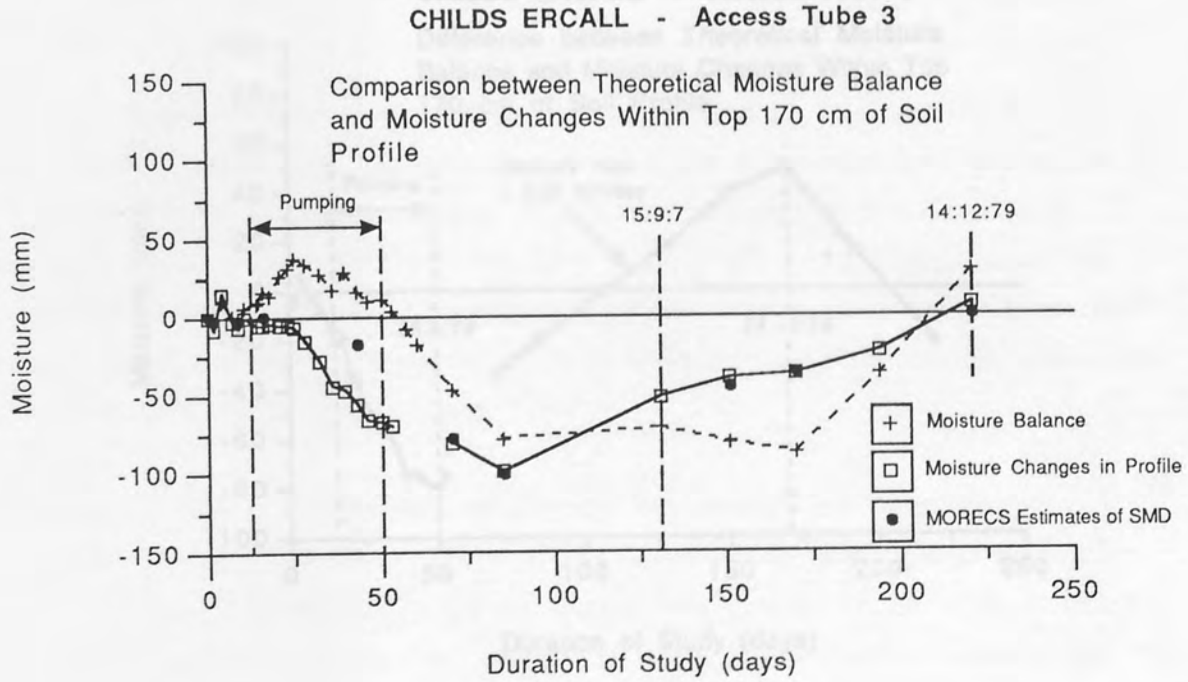


Fig 5.43 Comparison between Theoretical Soil Moisture Balance and Observed Changes for the Soil Profiles of Access Tubes 2 and 3 at Childs Ercall.

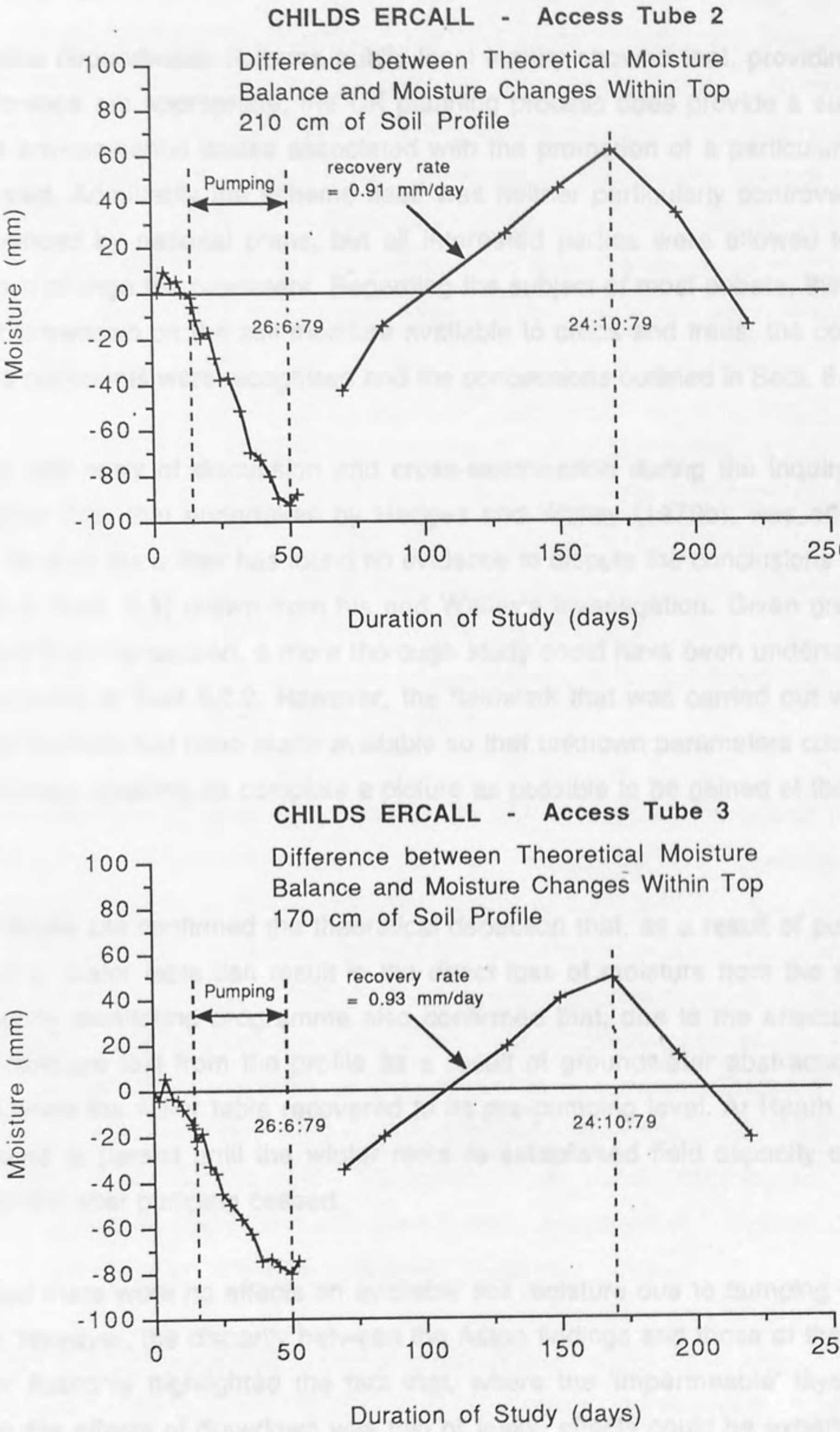


Fig 5.44 Difference between Theoretical Soil Moisture Balance and Observed Changes for the Soil Profiles of Access Tubes 2 and 3 at Childs Ercall.

5.8 REFLECTIONS ON THE PUBLIC INQUIRY AND SUBSEQUENT FIELD WORK.

The Shropshire Groundwater Scheme public local inquiry showed that, providing the terms of reference are appropriate, the UK planning process does provide a suitable forum at which the environmental issues associated wtih the promotion of a particular scheme can be debated. Admittedly the scheme itself was neither particularly controversial nor directly influenced by national plans, but all interested parties were allowed to air their views and to challenge the promoters. Regarding the subject of most debate, the effect of groundwater drawdown on the soil moisture available to crops and trees, the concerns of the scheme's opponents were recognised and the concessions outlined in Sect. 5.6.5 gained.

In the thrust and parry of discussion and cross-examination during the inquiry, all fieldwork, other than that undertaken by Hedges and Walley (1979b), was effectively discredited. To date the author has found no evidence to dispute the conclusions (as summarised in Sect. 5.5) drawn from his and Walley's investigation. Given greater time and increased financial support, a more thorough study could have been undertaken along the lines proposed in Sect 5.2.2. However, the fieldwork that was carried out was well planned, and facilities had been made available so that unknown parameters could be estimated, thereby enabling as complete a picture as possible to be gained of the processes at work.

The Heath House site confirmed the theoretical deduction that, as a result of pumping, the drawdown of a water table can result in the direct loss of moisture from the soil profile. The post-inquiry monitoring programme also confirmed that, due to the effects of hysteresis, moisture lost from the profile as a result of groundwater abstraction was not replenished when the water table recovered to its pre-pumping level. At Heath House the loss was found to persist until the winter rains re-established field capacity conditions, some six months after pumping ceased.

As anticipated there were no effects on available soil moisture due to pumping at Greenfields. However, the disparity between the Aston findings and those of the Severn Trent Water Authority highlighted the fact that, where the 'impermeable' layer isolating the soil from the effects of drawdown was thin or leaky, effects could be experienced. This indicates that the area where soils are potentially sensitive is not simply confined to those where, on maps, the aquifer outcrops or is overlain by sandy drift. Significant variations in conditions can be experienced over short distances: at Greenfields the Aston site was only 130m away from the Authority's; at Heath House conditions differed between Tubes 2 and 3 which were 20m apart.

The artesian conditions present at Childs Ercall resulted in moisture removal from the profile when the aquifer became unconfined, but the loss was made good when pumping ceased and upward seepage from the groundwater was re-established. It is difficult to ascertain the rate of this recovery, due to transpiration from the crop complicating the issue. However, it appears that the moisture levels which would have existed, had there been no drawdown, were achieved approximately 35 days after pumping ceased. A comparison between the theoretical moisture balance and the observed moisture profile indicates that the upward rate of seepage, after artesian conditions were re-established, was 0.9 mm/day.

Fig 5.24 produced by Walley and Hedges indicates that artesian conditions are more extensive in Shropshire than suggested by the Authority, and the Hydrogeological Assessor was in sympathy with this view. However, without access to alternative sites further investigation of the effects of pumping at such locations is not possible. Whether the conclusions drawn from the work at Childs Ercall are general or site specific remains to be seen, but it does seem reasonable to conclude that where the confining layer is thin and leaky similar phenomena to those observed will occur.

The fieldwork results could shed little light on the thorny issue of the effective crop rooting depth - or depth from which vegetation can abstract moisture. Obsevations at Heath House and Greenfields indicated rooting depths of 1.8m and 1m respectively for sugar beet and wheat - which tend to support the contentions of the Water Authority. This issue is fundamental to the identification of potentially sensitive areas and, together with the 'critical height' concept, forms the basis of the method proposed by Walley and Hedges. The criteria adopted by the Authority in their selection of borehole sites are, in principle, reasonably sound. However, they are based on the crude assumption that if the groundwater level is at least 2m below the surface crops will not be affected - 5m for trees. There was also no recognition that even a small drawdown in the water table can have a significant effect on available soil moisture levels.

For the author, the overwhelming impression left by the inquiry itself was of the high degree of uncertainty surrounding the effects of groundwater drawdown on vegetation. The Secretary of State was satisfied that the Authority had taken all reasonable steps at the time, but attached the condition that a programme of monitoring should take place in the Tern Area. The situation was summed up by the Hydrogeological assessor in his 'Additional Observations' (Foster, 1979):

> " A clear need was identified for research, at a national level under typical British hydrogeological conditions, on the affects, if any, of groundwater abstraction on soil moisture and, more especially on crop growth in areas of shallow water-table."

5.9 IDENTIFICATION OF FURTHER RESEARCH NEEDS.

As discussed in the preceding section, the inquiry highlighted the uncertainties surrounding the effects of groundwater drawdown on available soil moisture. Although a large body of knowledge relating to the problem existed, it was clear that a great deal of work was still required to provide a comprehensive set of guidelines for evaluating the extent and impact on vegetation of constructing a groundwater scheme. The main aim, therefore, of the continued research at Aston was focused on developing such a set of guidelines, and in producing the associated design criteria for the siting of boreholes.

In order to meet this overall aim, three goals had to be achieved. These were based on the concept, already established, that a soil will be sensitive to loss of available soil moisture if its water table is within a distance from the ground surface equal to the sum of the critical height and the crop rooting depth (Eqn 5.1 of Sect. 5.5). The first of the new research goals was to determine which soil types were sensitive to groundwater drawdown. The second was to identify typical crop rooting depths. Finally, having met the first two goals, a methodology had to be developed whereby the information acquired could be used to evaluate the impact any particular groundwater scheme would have.

It was quickly recognised that the sensitivity of soils could be studied under laboratory conditions, but that time constraints and lack of facilities would mean that the identification of typical rooting depths had to rely on published data. The accessibility and rapid advances in computer technology, in the years following the inquiry, quickly led to the adoption of this medium for assessing the impact of groundwater schemes. Since the value of any set of guidelines produced would need to be proven, the Shropshire Groundwater Scheme was to continue as the 'testing ground' for ideas. The methods employed and steps undertaken in achieving the overall aim of the continued reseach programme, are discussed in the following three chapters.

At the end of the field study a considerable body of data had been amassed, much of which was only marginally relevent to the subject of this research. One of the original intentions was to develop further, using the Shropshire data, the soil-moisture-plant model of Walley and Hussein (1982) and to incorporate this into the impact assessment procedure. However, it was decided that the scope of the undertaking was becoming too wide, and in 1987 a second research project, with the model development as its aim, was begun under Walley's supervision.