Chapter 6. DERIVATION OF RELATIONSHIPS FOR THE CLASSIFICATION OF SENSITIVE SOILS.

It was recognised early in the project's formulation, that it would be necessary to develop a series of relationships to allow the parameters required for the classification of sensitive soils to be determined from easily measured soil properties. As a consequence, apparatus was designed to enable the field capacity moisture profiles of laboratory soil columns to be determined.

Initially this work was undertaken by the author through a series of supervised final year undergraduate projects (Sargent, 1983; Jones, 1985; Parsonage, 1986). These projects enabled the soil columns to be designed, constructed, evaluated and modified before the main series of tests, undertaken by the author, began in 1987. Over the same period that the undergraduate projects were carried out the necessary equipment was constructed or acquired for the analysis of both field and laboratory soil samples. Sect 6.1 briefly introduces the procedures employed in the soil analysis and the remainder of Chaper 6 is devoted to the laboratory experiments and the derivation of the relationships required for determining the sensitivity of soils to groundwater drawdown.

6.1 ANALYSIS OF SOIL SAMPLES.

Analysis results for the field samples and the soils used in the laboratory experiments are given in Appendix 2 and Appendix 3 respectively. The analytical methods employed are briefly described below.

6.1.1 STANDARD PROCEDURES.

The analytical techniques used to determine the following parameters were those detailed in BS 1377 (1975): specific gravity; particle size analysis - dry sieving for sand and the pipette method for the fine fraction; organic content - chemical method. For bulk density, undisturbed field samples were obtained using a corer based on the design recommended by Hall et al (1977), but modified to be more robust and to accept 150mm long pvc plastic liners cut from sections of standard house drainpipe (Hussein, 1979). pH measurements were made using a commercial colorimetric testing kit.

6.1.2 DETERMINATION OF SATURATED CONDUCTIVITY.

It was envisaged that, either at some stage during this project or at some time in the future, the moisture changes observed in both the laboratory soil columns and in the field profiles would be mathematically simulated. Therefore, in order to ensure that the maximum possible information was acquired from the soil samples, it was decided to measure saturated conductivity in addition to the parameters mentioned above. Under laboratory conditions this was most easily achieved by obtaining undisturbed samples and utilising a constant head permeameter.

Two cells were therefore constructed for use with the permeameter. The first accepted the pvc liners containing field samples obtained using the corer, and the second was designed to accommodate segments from the laboratory soil columns (see Sect 6.2). The principal components of the cells are illustrated in Fig 6.1.

Fig 6.1 Constant Head Permeameter Cell

6.2 SOIL MOISTURE COLUMN DESIGN.

Several research workers have used soil columns to investigate soil-water physics problems in the laboratory. However, these column experiments have tended to fall into two categories. The first group are those where no attempt was made to study internal moisture changes within the soil column - in these cases moisture fluxes were determined either by weighing the whole column (e.g. Gardner, 1959), by collecting the drainage water (e.g. Youngs, 1960), or by establishing a steady state condition through supplying water at a known rate (e.g. Gardner and Fireman, 1958; Staley,1957). In the second category of experiments workers made use of an appropriate non-destructive testing method to monitor moisture changes. In these instances either the researchers employed sophisticated measuring techniques (e.g. Childs and Collis-George, 1950; Anat et al, 1965), or the columns were substantial structures, large enough to accept instrumentation without affecting the soil characteristics or modifying moisture movement patterns (e.g. Moore, 1939).

Given that the aim of the soil column experiments was to enable relationships to be derived for determining the sensitivity of soils to groundwater drawdown, the column design had to satisfy a number of criteria:

1. the column length had to be such that a wide range of critical heights could be determined;
2. as many soil types were to be investigated as possible;
3. provision had to be made for the saturation of a column of soil and subsequent drainage until the field capacity profile above a water table was achieved;
4. the drainage had to be monitored in order to establish when the field capacity moisture profile had been achieved;
5. the bulk density of the soil within the column had to be as close as possible to conditions found in the field;
6. the field capacity moisture profile had to be determined;
7. the columns were to be reusable and constructed at minimum cost.

When the review of appropriate literature, given above, is compared with the design criteria it can be seen that there was no known published work on which to base the column construction. Development of the apparatus continued under the author's supervision over a period of four years (Sargent, 1983; Jones, 1985; Parsonage, 1986) at the end of which a simple, practical and economic system had been produced. With the exception of the steel base plate, all components were manufactured from standard easily obtained items.

Fig 6.2 is a section through a column and illustrates its construction. The two plates, Figs 6.3 and 6.4, show the apparatus in use and its disassembled main components. The length of the soil column itself was limited to two metres by the height of the laboratory ceiling. However, 2m was deemed adequate given the critical height of approximately 1.5m observed for the Newport soil series at Heath House (see Sect 5.4.3).

The heart of the apparatus is a stack of perspex segments 100 mm long with a nominal internal diameter of 52mm. These house the soil itself and enable samples of known volume to be extracted for analysis. Holding the perspex segments in a continuous column is a pvc sleeve, 64 mm i.d., cut from lengths of standard house rainwater downpipe. Perspex tube was used for the inner column, not because it was transparent, but because the walls were relatively thick and robust, and because it fit snugly inside the pvc pipe. Furthermore, both types of tubing were readily available off the shelf. So that the column can be stripped easily, the pvc sleeve is split lengthwise and the two halves held together around the perspex segments by five equally spaced jubilee clips. Stability is supplied by an outer tube of standard pvc water pipe, 114 mm i.d. with a wall thickness of 10 mm. The inner assembled soil column is held at the top by a support unit which slips into a collar at the upper end of the outer tube. The bottom of the outer tube ends in a flange, which sits on a rubber gaskett, and is bolted to the base plate.

The mild steel base plate provides a bottom support for the soil column, a mounting for the outer tube, holes for anchoring the entire assembly to the floor, and a system for allowing water to enter or drain from the soil. The brass plate which supports the soil column has holes and grooves machined into it to facilitate the collection and removal of drainage water. Water enters the column via the same route that the drainage water leaves, flooding upwards in order to minimise the retention of air within soil pores during the saturation process. Sandwiched between the brass plate and bottom soil column segment is a filter disc cut from 150µm sieve mesh. Soil is retained in the lowest segment by means of a perspex disc, again drilled and machined to aid drainage, held in place by two grub screws.

Water enters or leaves the assembly under gravity through an inverted U shaped pipe that is fitted into the bottom of the outer sleeve as shown in Fig 6.2. This pipe contains a valve to regulate the flow, and a T junction from which a transparent observation tube runs up the outside of the outer sleeve to enable continuous monitoring of the water level. The

Fig 6.2 Section Through a Laboratory Soil Column.

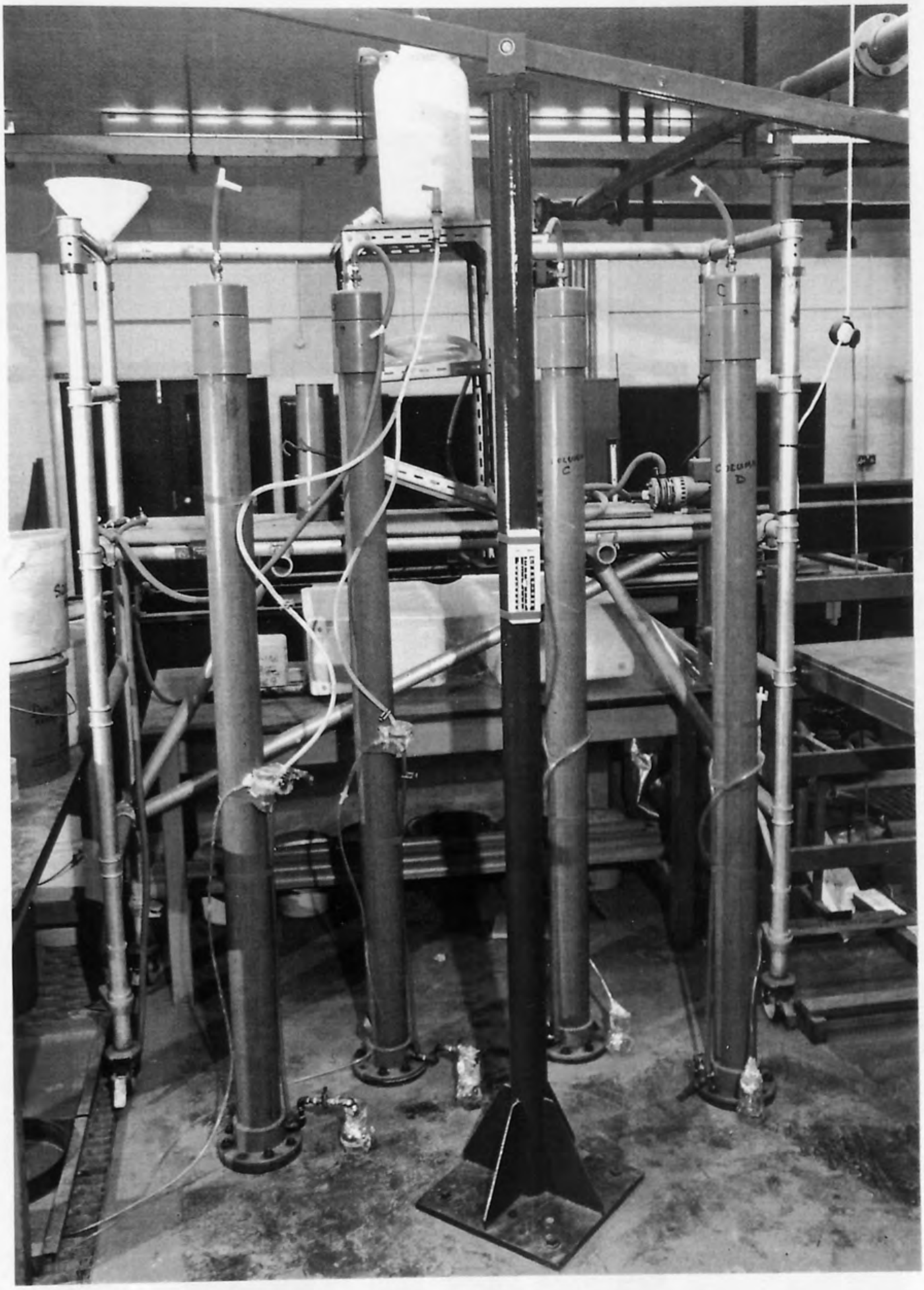


Fig 6.3 Soil Columns in Operation.

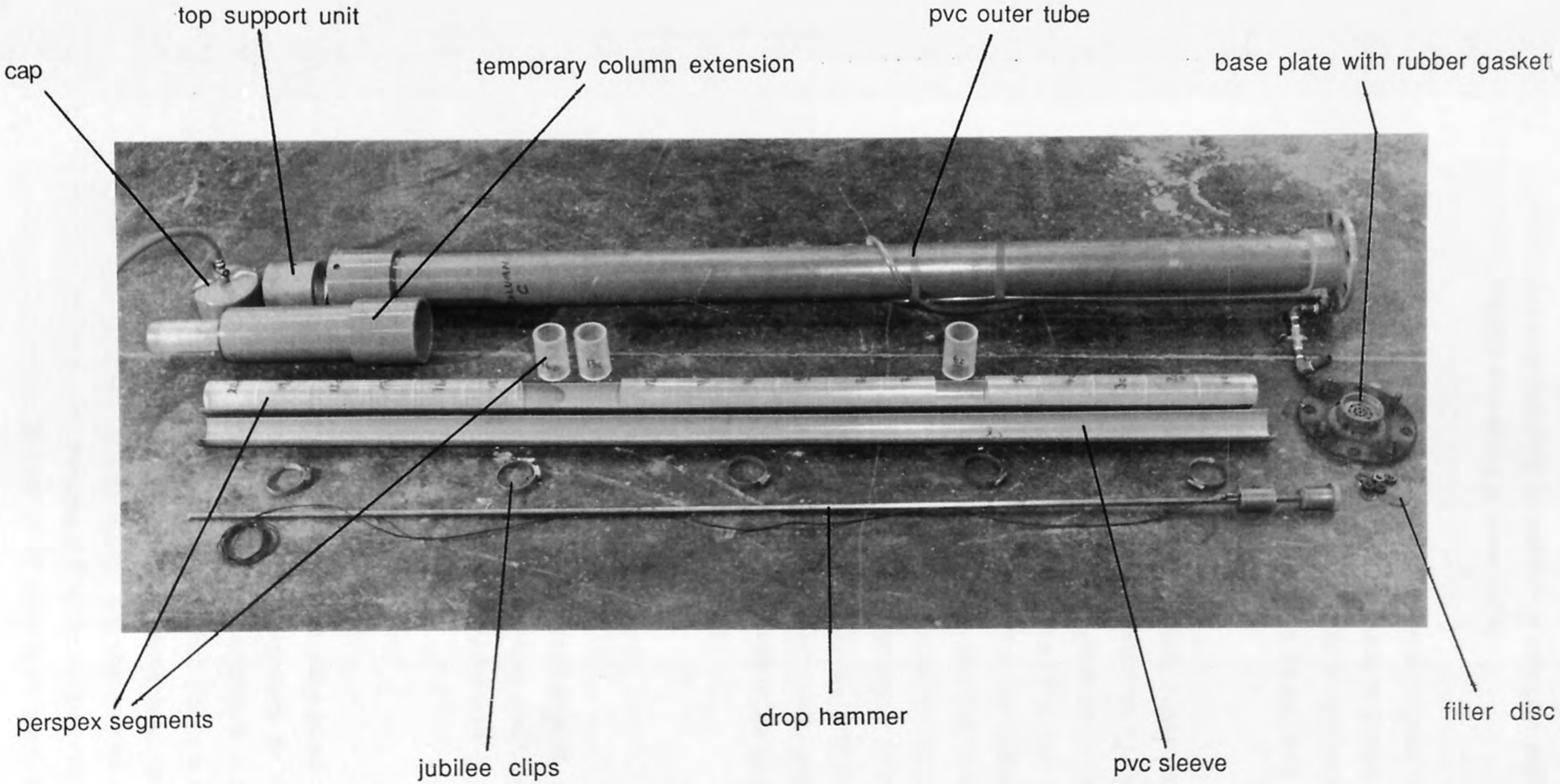


Fig 6.4 Soil Column Components and Drop Hammer.

inverted U in the inflow/outflow pipe was designed to maintain a constant water level within the bottom soil segment, thereby simulating a water table.

Finally, the whole apparatus is topped by a cap. This serves the dual purpose of minimising evaporation during experiments, and of providing a seal to enable partial evacuation of the column during saturation. This latter is intended to facilitate air removal from soil pores. The cap is made air-tight by covering joints with electrician's tape, and a vacuum pump is attached via a valve located in the top of the cap.

Four complete column assemblies were constructed and, in general, experiments run in pairs. The initial intention was that moisture changes would be monitored by means of a simple balance - this can be seen on Fig 6.3. The balance consisted of an arm which pivoted, on ball bearings, in both vertical and horizontal directions. The four columns were therefore located on an arc of a circle with the balance pivot at the centre. Weighing was achieved by attaching a rod, suspended from the balance arm, to a bar which passed through the top of the outer tube above the soil column itself. The counter weight was a bucket of sand from which small quantities were removed until the weight of the column was balanced. The sand removed was subsequently weighed and by applying the principle of moments the drainage from the column could be determined. Unfortunately at low drainage rates the sensitivity of the balance proved inadequate and resort was made to direct collection of the drainage water - which proved quite satisfactory.

6.3 THE EXPERIMENTAL PROGRAMME.

In order to provide the necessary background to the main programme of tests, as described in Sect 6.3.4, reference will be made to the soil compaction technique employed, the experimental procedure adopted and the selection of suitable soils for testing.

6.3.1 SOIL COMPACTION.

Given the small internal diameter of the columns, two techniques were available for compacting soils in order to achieve bulk densities of a similar magnitude to those found in the field - vibration and imposed pressure . In each instance it is difficult to predict with any certainty the outcome of a given application (Gray, 1968). For vibratory methods compaction is a function of the characteristics of the particles themselves, the vibration parameters (frequency, amplitude, direction, energy input), and the overall system (in this instance the soil column). Van Brakel and Heerjes (1974) found that only when particles were vibrated during the deposition process could packing densities be reproduced with any degree of regularity. When pressure is applied to granular material the degree of compaction achieved is again dependent on several factors: the method of deposition, particle characteristics, the effect of container walls, bridging between particles and capillary forces.

Although vibration was considered, two factors militated against its adoption. Firstly, it was feared that the perspex segments might work apart during the vibration process. Secondly, no suitable vibrator could be found within the budget immediately available. It was therefore decided to design and construct a manually operated drop hammer.

After some experimentation a hammer was developed which, for the soil textures used in the experimental programme, produced relatively consistent bulk densities throughout the length of any given soil column. The hammer, shown in Fig 6.4, consists of:

i. a steel anvil - 1.5 mm smaller in diameter than the perspex segments to allow displacement of air during compaction and to minimise binding problems when the hammer assembly is withdrawn;

ii. a cylindrical 44 mm dia steel hammer weighing 702 gm - this is provided with a central vertical hole to allow it to ride on the steel shaft, and it is small enough to avoid impact with the column walls when being dropped;

iii. a steel shaft fitted with a grub screw stop to give a constant lift height for the hammer - the shaft provides both a guide for the hammer and a handle for withdrawl from, and admission to, the column;

iv. a cable for raising the hammer.

Initially an attempt was made to determine the optimum conditions for compaction, but from experience it was found that practical considerations tended to impose constraints on what was possible. Kolbuszewski (1948; and, Kolbuszewski and Jones, 1961), in a series of studies on porosity and packing, found that for dry sands a continuous rain of material produced the most uniform bed of deposited material and also avoided the problem of segregation. Under the conditions prevailing for the columns this was not a practical proposition since the column diameter was small and the use of a drop hammer meant that the soils had to be compacted in a series of layers. It was felt that moistening the sand prior to deposition would prevent segregation by causing the finer fractions to adhere, through surface tension, to heavier particles and all would therefore fall together at the same velocity. No detailed study was undertaken to verify this theory. However, it was found that if the soils were too wet a film of water formed at the surface during compaction. This caused a suction to be exerted on the anvil, making removal of the hammer very difficult. A moisture content of approximately 4 to 6% was found to be practicable - under these conditions sandy soils loosely retained their shape when squeezed tightly in the hand.

A series of experiments revealed that after approximately 20 blows with the hammer, the rate of increase in bulk density was too slow to justify the additional energy expended (see Fig 6.5). The hammer weight and height of drop were dictated by what was physically practical for the operator. The criteria finally adopted for compaction of all columns were: hammer weight = 702 gms; drop height = 500 mm; number of blows = 20.

A standard measure was used to ensure that the quantity of soil entering into the column, prior to each compaction, was constant. This measure resulted in a layer approximately 90 mm thick being deposited. The soil was poured into the column through a wide necked funnel which was manually vibrated to prevent clogging. So that the top segments received the same compaction as those at lower levels, a temporary column extension of 500mm was provided. This enabled compaction to continue for approximately 200mm above the end of the permanent fixture.

In practice the method of compaction adopted proved satisfactory. The bulk densities achieved within the soil columns were compatible with values obtained from field samples taken down to a depth of approximately 1m below ground level (see Appendices 2 and 3).

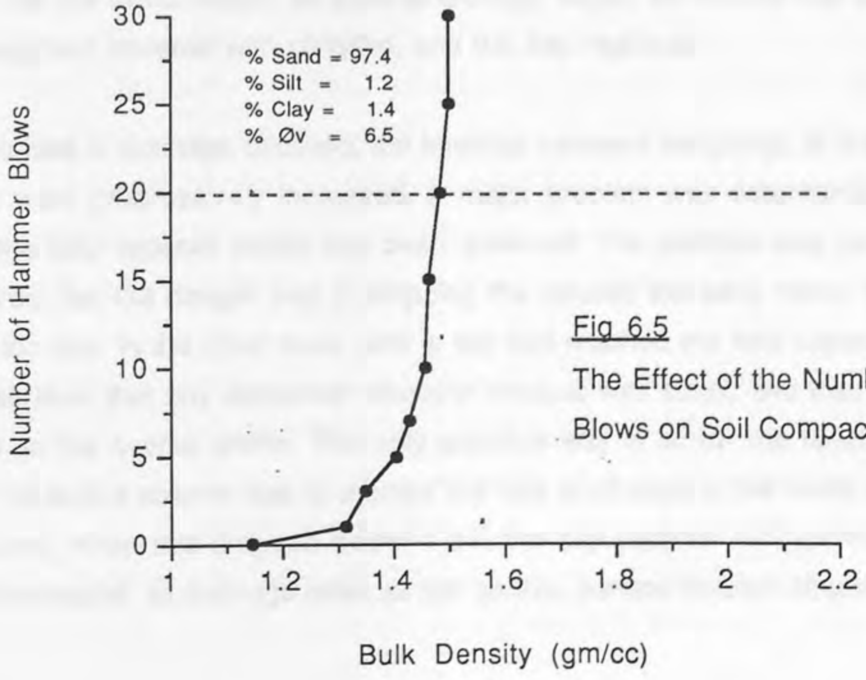


Fig 6.5

The Effect of the Number of Hammer Blows on Soil Compaction

6.3.2 EXPERIMENTAL PROCEDURE.

Whilst soil was being packed into a column the water supply reservoir was connected to a vacuum pump and the water partially de-aired. On completion of the packing process, the column cap was sealed in position and the vacuum pump attached. Saturation of the soil column took place, over a period of two to four hours, from the base upward to enable air in pores to be driven out as the water level rose. Once bolted firmly to the base, the outer tube provided a watertight shell. At intervals during the saturation process the vacuum pump was briefly switched on to ensure that the pressure in the column was maintained below atmospheric pressure.

After the vacuum pump and water supply had been disconnected and any sealing tape removed, the saturated column was drained by partially opening the tap in the base. Often columns were left overnight after saturation both to allow the system to settle, and to allow a full days monitoring during the early stages of drainage. The initial drainage rate was controlled in order to minimise translocation of fine particles down through the soil profile. Measurement of the first discharge was impractical as not only was the soil column draining, but the void between the outer shell and the column was also being emptied of water. As soon as the water table in the observation tube was seen to reach its final level, after about five minutes, collection of the drainage water began.

Drainage from the column was monitored by weighing the water collected in glass flasks placed under the discharge pipe. In order to minimise evaporation loss the flask contained a thin film of oil, as shown in Fig 6.6, and clingfilm was wrapped around the pipe and flask neck. For the same reason, as soon as drainage began the column cap was removed, the top soil segment covered with clingfilm, and the cap replaced.

As the rate of drainage declined, the intervals between weighings of the collected drainage water were progressively increased. A major problem was determining at what point in time the field capacity profile had been achieved. The problem was never completely resolved, but the danger was in stripping the column too early rather than in being a few days too late. In the latter case, after a soil had reached the field capacity state drainage was so slow that any additional moisture removal was small, and thus had an insignificant effect on the overall profile. The only practical way in which the researcher could decide when to strip a column was to monitor the rate of change in the water collected. As a rule of thumb, when this dropped below 1 gm per day (approx 10^{-3} gm/min) the experiment was terminated. At drainage rates as low as this, surface tension effects tended to cause

Fig 6.6 Collection of Drainage Water from Soil Columns.

water to discharge from the outflow pipe in short bursts, rather than in a slow gentle stream of drips which would have been ideal.

It was also noticed that the temperature within the laboratory, which could exhibit a diurnal variation in the order of 8 ^{o}C during warm summer months, could also affect the final discharge of drainage water. A maximum and minimum thermometer was therefore installed during the first series of experiments in 1987, and temperature variations recorded whenever drainage rates were monitored. Although no temperature measurements were made within the column itself, the air pocket between the soil column and the outer tube had an insulating effect. Furthermore, the high thermal capacity of the soil water would have moderated temperature changes. The soil moisture, therefore, could not have experienced the temperature fluctuations observed in the laboratory itself. Should the drainage process in the columns be mathematically modelled in the future, it is recommended that the average of the recorded maximum and minimum values is taken when considering the fluid's surface tension and viscosity.

When the decision had been taken to strip a column, careful preparations were made to enable the process of determining the moisture content and bulk density of each segment to proceed as quickly as possible. The aluminium foil food containers, which were to accept the soil samples for drying, were weighed, tools laid out and lengths of clingfilm cut and place conveniently to hand. Immediately the outer tube had been lifted clear of the soil column, the latter was laid on the ground and one half of the sleeve removed to expose the soil filled segments. Two segments were separated manually by working a gap at their junction just wide enough to accept a palette knife. The soil was then sliced through to produce samples flush with the segment ends - hence of known volume. Whilst individual segments were being processed, the exposed column ends were wrapped with clingfilm to minimise evaporation loss. Although there was some danger of moisture redistribution taking place within the bottom portion of the horizontal column, the disadvantages associated with this were felt to be outweighed by maintaining the integrity of the remaining soil column whilst individual segments were processed.

The final procedure adopted, in the light of experience, was to separate the bottom four or five segements, where the soil was near saturation, and place them into individual containers which were covered with clingfilm. The next segments were processed completely until it was ascertained that the moisture content of consecutive samples had ceased to fall significantly. At this point the bottom segments which had been set aside, were attended to before completing soil removal from the final top length of the column.

Processing individual segments involved digging the soil out of each perspex segment with a palette knife and emptying it into a foil container. The segments were then scraped as clean as possible with the aid of the palette knife and a plastic kitchen spatula. The weight of the full container was then recorded before placing it aside to await drying in an oven at 105 °C.

An attempt was made to evaluate the losses of moisture and soil engendered by the method of column stripping which had been adopted. After emptying the segments some moist soil remained adhering to the perspex. By obtaining the weights of segments immediately after emptying, the segments with retained soil after drying in air, and the clean dry segments themselves, it was found that for the worst situation (i.e. a saturated soil) an average of 0.8 gm of moisture and 0.2 gms of soil were lost from each sample. For a column of saturated soil this would mean an error of 16 gm in total moisture content and 4 gms in total soil weight. Extracting and emptying each segment, and weighing the moist sample, took approximately 1.5 minutes. By placing nearly saturated samples on the balance and monitoring the change in weight, it was ascertained that the moisture loss during this process was approximately 0.005 gm/min - a total of only 0.15 gms of moisture for the twenty segments of the column. Finally, after three of the columns had been stripped, the initially clean floor was swept and the soil retained on the pvc sleeves collected. Together these measurements indicated that the combined soil loss experienced by each column due to the removal of segments from the sleeves was approximately 3 gms.

Thus, at the very worst, during the segment extraction and soil removal process approximately 7 gms of soil and just over 16 gms of moisture were lost. Taking average values of 6780 gms of dry soil and 660 gms of moisture as being the norm for the measured contents of a column at the time of stripping, then the maximum measurement error could not exceed 0.1% for soil and 2.4% for moisture. Clearly this is quite acceptable with regard to the soil. Given that these moisture losses have been determined for a saturated soil, and the comparison is with the moisture content of an average column, then 2.4% is an upper bound. However, the moisture lost during the initial stripping of the column, before the segments were extracted, could not be determined - this still remains an unknown.

Consideration was given to speeding up the stripping process and minimising moisture loss by simply weighing the perspex segments full and putting them directly into the oven for partial drying. The simple test of putting an empty segment in a hot oven revealed that significant distortion occurred after only two hours. Continuation with this approach would have necessitated a complete new set of segments for each experiment. Under the circumstances therefore, the disadvantage that there was a small loss of moisture was considered acceptable given the benefits accruing from the simplicity of the method adopted.

To enable the experimental programme to be dovetailed into the author's teaching and administrative commitments, columns were operated on a 'batch' bais. The first two columns were packed and whilst these were being saturated, the second two soil columns were prepared. During initial drainage of the first pair the second two were saturated and the following day these too were drained down. Similarly, stripping of the columns took place in pairs - often on consecutive days.

6.3.3 SELECTION OF SOILS FOR TESTING.

During the early stages of the experimental programme several tests were run using readily available sandy soils. These were either at hand in the laboratories of the Department or obtained from a nearby quarry. In order to extend the range of soil textures two silica flours, whose grading was predominantly in the silt range, were purchased (HPF1 and HPF5 from British Industrial Silica Ltd.). In addition both commercially available kaoline and a clay used for undergraduate experiments were obtained. A waste sand, sieved to remove particles greater than 1.18 mm, was adopted as the 'base sand' to which silt and clay were added to produce 'designed' soils. A computer programme was written in BASIC for the BBC micro to assist in this design process.

A pattern of desirable soils for testing was marked on a triangular particle size distribution diagram, as shown on Fig 6.7. By taking 7.5 kg of the base sand as a starting point and inserting appropriate particle size distributions into the design computer program, the quantities of silica flour and clay required to achieve a soil of a particular texture were determined. Sadly, after mixing the constituents as calculated, the desired result was seldom achieved. This was in large part due to one of the two silica flours deviating from the manufacturer's published particle size distribution - eventually confirmed through back calculation from particle size analysis results. Other reasons for the inaccuracy in the design process were: the clay used for undergraduate experiments had a higher proportion of silt and fine sand than initially believed; the waste sand adopted as the base material varied from batch to batch; particle size distribution results for the base sand were subject to error. In the latter case, analysis of particle size distributions were undertaken in accordance with the procedure specified in BS1377 for fine soils. This method was strictly only valid where more than 10% of the sample passed the 63μm sieve, but in the absence of a viable alternative it had to be accepted for very sandy samples in order that the proportions of silt and clay could be assessed.

The final outcome of the experimental programme was, as illustrated by Fig 6.7, that field capacity moisture profiles were determined for a reasonable variety of soil textures. However, as explained above, the range of soil textures studied was not as controlled as had initially been planned, and time constraints did not permit the programme to be extended to cover sandy loam soils.

6.3.4 THE PROGRAMME OF EXPERIMENTS.

During their undergraduate final year projects, the three students who were involved in the development of the soil column apparatus, between them ran fourteen experiments (Sargent, 1983; Jones, 1985; Parsonage, 1986). In evaluating their work the author was not satisfied that adequate detail had been provided to allow any of the results to be included in the final analysis. A full programme of experimental work was therefore instigated in 1987.

The first series of experiments were run between May and October 1987. These involved using soils which were either readily available (tests 87/0, 87/1, 87/7 and 87/8) or the base sand mixed with increasing proportions of either one or other of the two silica flours purchased (HPF1 in tests 87/2, 87/3 and HPF5 in tests 87/4, 87/5 and 87/6).

It was intended that the soils used in the second series of twelve experiments would be more carefully selected. In practice, as discussed in Sect 6.3.3, the outcome of the 'design' process was not particularly successful. However, by mixing the base sand with differing proportions of silica flour and clay, a range of soils in the sand and loamy sand texture classes were produced (tests 88/1 to 88/11). The final experimental soil (88/12) fell on the boundary between loamy sand and sandy loam. These experiments took place between May and August 1988.

Finally, the four columns were packed with the same soil and operated together in November and December 1988 in an attempt to simulate the effects on soil moisture of the recovery of groundwater levels. The experiment itself is discussed in Sect 6.5, but the results from one column, 88/H3, were included in the analysis of the results from the main programme.

6.4 ANALYSIS OF RESULTS.

In determining the extent of areas sensitive to groundwater drawdown the critical height (h_o), together with the crop rooting depth, is the key to the method forwarded by Walley and Hedges (1979b) and adopted for this thesis. The prime objective of the column experiments was therefore to produce relationships for predicting this parameter. For evaluating the effects of drawdown the shape of the field capacity profile is required in order to determine the quantity of moisture removed from the soil. The data obtained from the experimental work were therefore analysed with these objectives in mind. Furthermore, should the rate of soil moisture removal be very slow, then during the main growing season there would be little or no effect on vegetation even were the area deemed sensitive on other grounds. A general relationship expressing the rate of drainage of a soil was required, and the drainage data obtained from the columns were analysed with this in mind.

Before detailed discussion of the analysis begins, in order to simplify the discussion of the analysis of results, a brief review is provided of the data handling and manipulation techniques that were used.

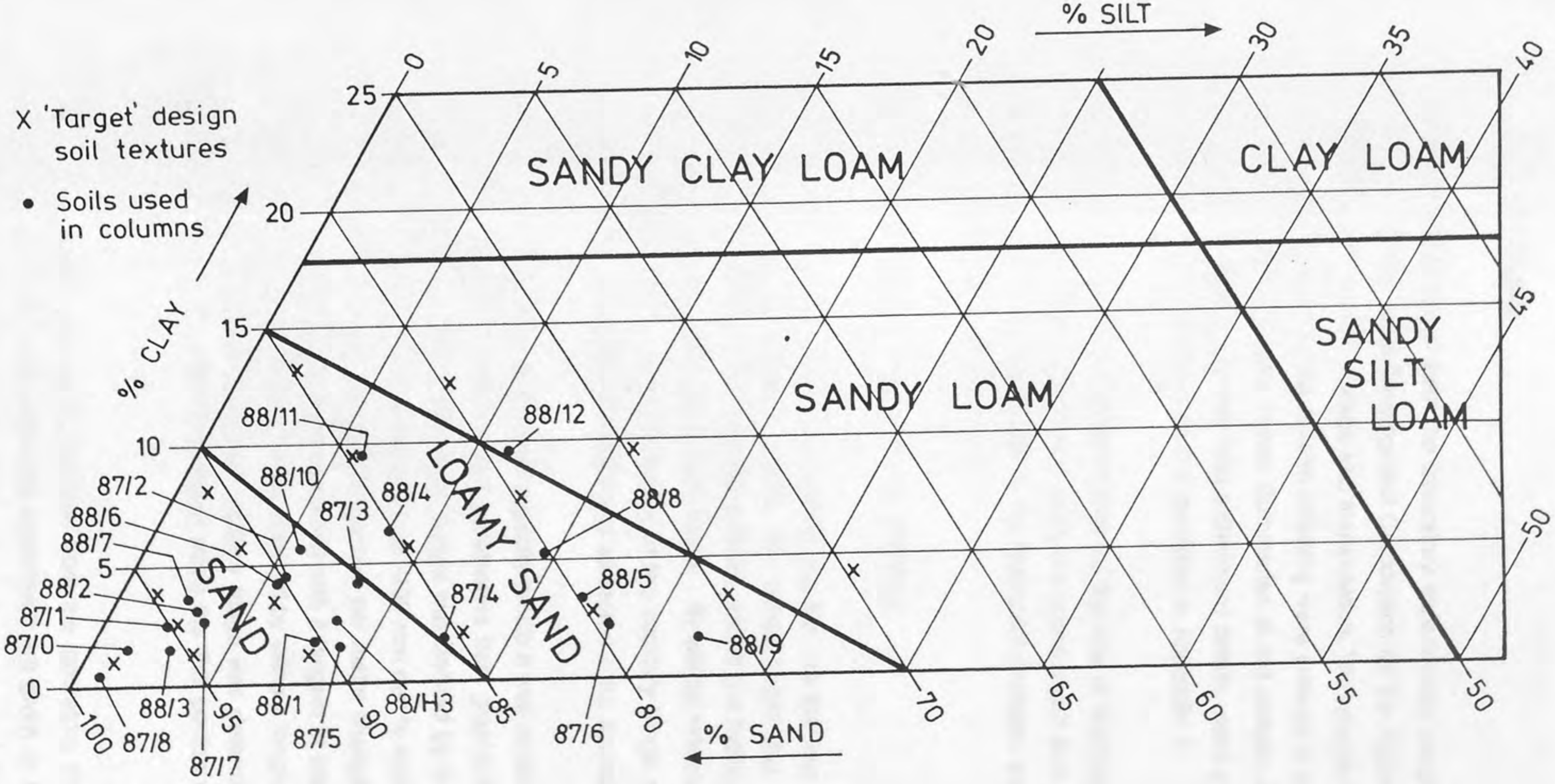


Fig 6.7 Selected Pattern of Soils for Testing and Soils Actually Tested.

6.4.1 DATA HANDLING.

For all the results obtained from the laboratory experimental programme the JAZZ package, produced by Lotus Development Corporation for the Apple Macintosh Plus computer, was used for data storage and manipulation. The records of column drainage and the measurements made during column stripping were entered to spreadsheets for analysis and, where appropriate, graphs drawn. Summaries of soil sample, drainage rate and moisture profile analyses, together with experiment details, were processed in the same way. Printouts for the relevant data are provided in Appendix 3.

Curve fitting, to obtain mathematical models for the rate of drainage and for field capacity moisture profiles, was also undertaken using the spreadsheet and graphics facilities of JAZZ. However, data were transferred to the Statworks package, also on the Macintosh, when statistical analysis was required.

6.4.2 THE FIELD CAPACITY MOISTURE PROFILE.

Shown on the idealised field capacity profile, Fig 6.8, are the four parameters which were determined from the experimental results. The critical height (h_o) has been defined in Sect 4.2.1. θs is the *saturated moisture content* and θr the moisture content of the field capacity profile at and above the critical height - θr will be referred to as the *residual moisture content*. Finally, h_c is the height of the capillary fringe within which the moisture content is effectively constant and saturated - the *saturated capillary fringe*.

Due to the S shaped nature of the field capacity profile it was necessary to define procedures for obtaining the above four parameters from graphical representations of the soil column moisture profiles. The critical height was defined by the point where the slope of the profile was tangential to a line of slope -400 mm per % moisture content, as shown on Fig 6.9 (i.e. 2.5% change in moisture content per metre change in depth). This gradient was chosen as, in general, the point of contact with a tangent of this slope was easily identified, and because the increase in h_o obtained by using a tangent of steeper slope was negligible. The height of the saturated capillary fringe was determined by the intersection of the line $\theta = \theta s$ and a straight line drawn along the 'flat' portion of the profile, as shown on Fig 6.9.

Table 6.1 summarises the results obtained from the laboratory column experiments. Details and profiles from each individual experiment are given in Appendix 3. For the majority of the columns the profiles obtained were as expected. However, for soils with a

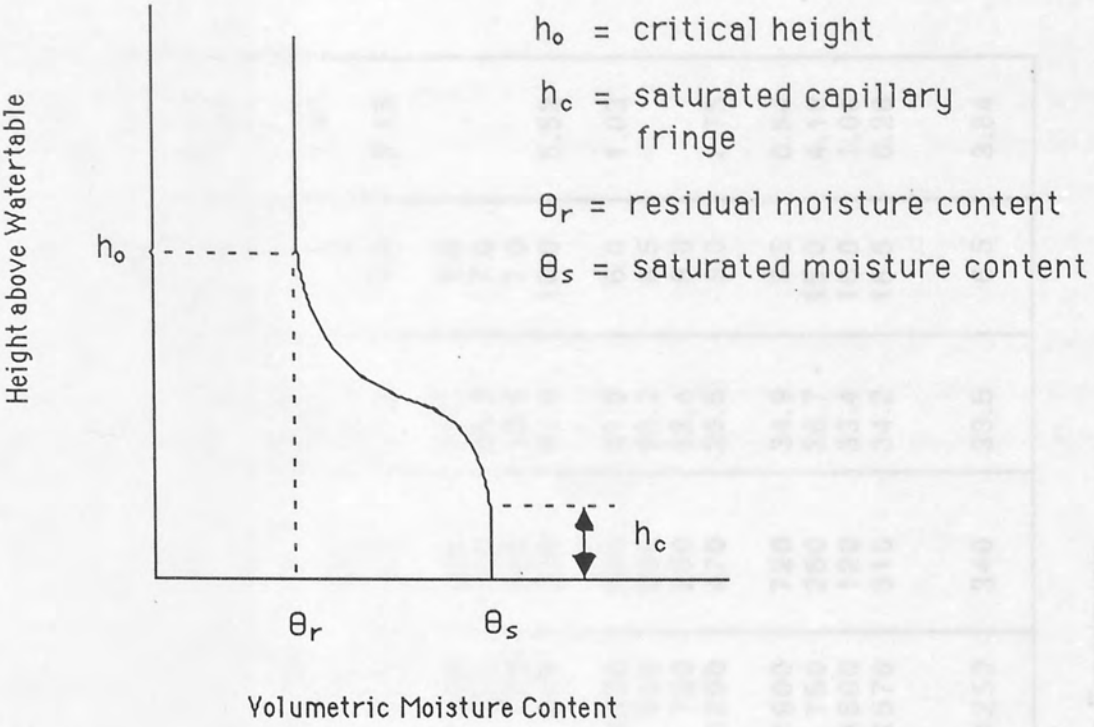


Fig 6.8 Idealised Field Capacity Profile

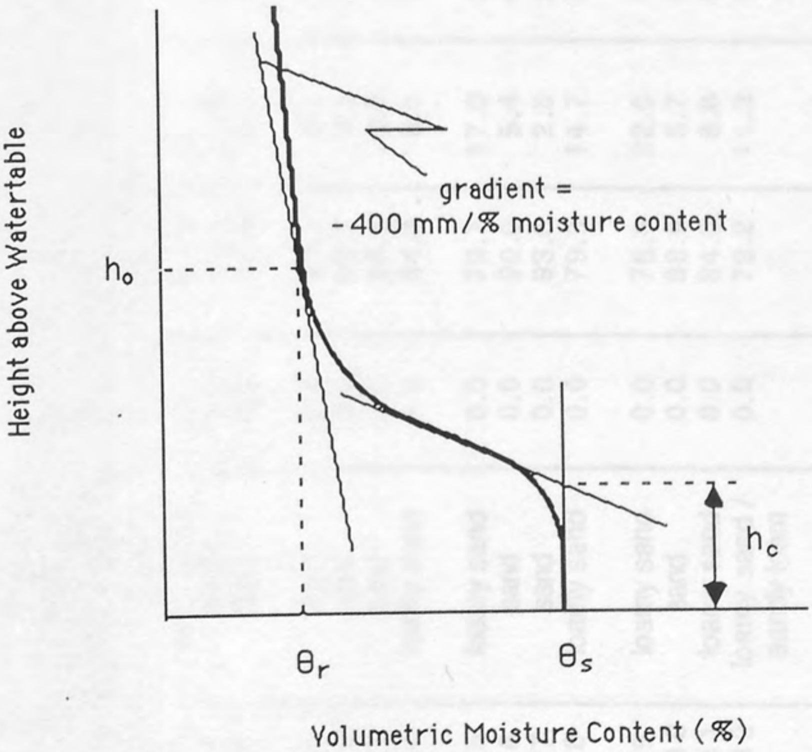


Fig 6.9 Determination of Parameters from Observed Field Capacity Profiles

Col Ref	Soil	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	BD (g/cc)	ho (mm)	hc (mm)	θs (%)	θr (%)	Ks (m/day)
87/0	sand	0.0	97.4	1.2	1.4	1.50	820	160	34.5	7.0	5.94
87/1	sand	0.3	95.1	2.1	2.5	1.53	760	140	33.1	9.0	7.21
87/2	sand	0.2	89.6	5.7	4.5	1.57	650	160	36.0	14.5	
87/3	sand/loamy sand	0.4	87.1	8.3	4.2	1.61	580	260	31.1	14.0	4.71
87/4	loamy sand	0.0	85.6	12.7	1.7	1.55	1500	350	31.9	7.5	1.55
87/5	sand	0.0	89.3	9.0	1.7	1.58	1400	150	34.0	7.0	
87/6	loamy sand	0.0	79.6	18.2	2.2	1.65	>2000	510	29.2	?	1.30
87/7	sand	0.0	93.7	3.5	2.8	1.51	860	250	35.4	8.5	
87/8	sand	0.2	98.9	0.2	0.7	1.63	800	320	32.6	5.0	5.13
88/1	sand	0.0	90.2	8.0	1.8	1.58	1260	320	37.7	6.5	
88/2	sand	0.0	93.7	3.3	3.0	1.55	800	300	36.3	7.0	
88/3	sand	0.0	95.5	3.0	1.5	1.53	770	250	33.6	7.0	
88/4	loamy sand	1.0	84.3	8.5	6.2	1.57	880	320	32.9	10.0	5.52
88/5	loamy sand	0.0	79.7	17.0	3.3	1.64	2300	540	31.9	6.0	1.03
88/6	sand	0.0	90.0	5.4	4.6	1.54	800	290	33.2	8.5	
88/7	sand	0.0	93.5	2.8	3.7	1.55	750	250	32.4	9.0	
88/8	loamy sand	0.0	79.9	14.7	5.4	1.6	1200	470	29.5	9.0	2.75
88/9	loamy sand	0.0	76.8	22.0	1.2	1.64	1900	720	34.9	8.5	0.54
88/10	sand	0.0	88.9	5.7	5.4	1.58	750	260	36.7	15.0	4.19
88/11	loamy sand	0.0	84.5	6.0	9.5	1.61	1500	120	33.4	16.0	1.00
88/12	loamy sand / sandy loam	0.0	79.2	11.3	9.5	1.53	1570	310	34.2	18.5	0.26
88/H3	sand	0.0	89.0	8.3	2.7	1.57	1250	340	33.5	6.5	3.84

Table 6.1 Summary of Results from Soil Column Experiments.

relatively high silt and clay content there was a tendency for zones of marginally lower bulk density to develop below zones where it was higher - this suggests bridging during the compaction process. For columns where the bulk density varied in this way, when it was high the moisture content was correspondingly lower than would have been expected. This can be seen for column 88/12 in Fig 6.10. The overall effect of this variation was to cause the moisture profile to waiver and to loose its definition, and this in turn caused some problems in parameter determination. Although there were no indications of impeded drainage in any of the columns, the packing procedure will have to be reviewed if future experimental work is extended to soils of a finer texture.

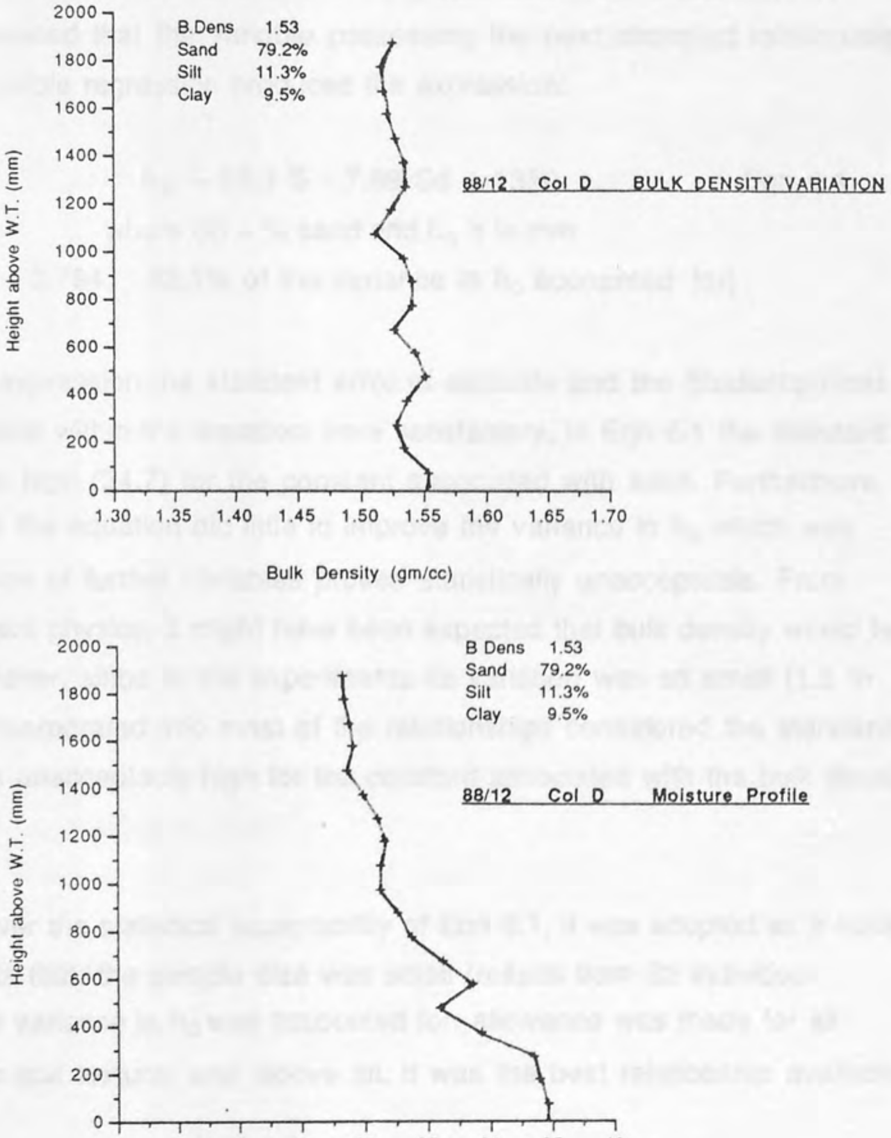


Fig 6.10 Variation in Bulk Density and Field Capacity Profile: Soil Column 88/12

6.4.2.1 The Critical Height.

Analysis of the data revealed that, statistically, the best relationship between the critical height and measured soil properties was:

$$h_o = 66.6\ S + 583$$

where S = % silt content.

($r = 0.793$: 62.9% of the variance in h_o accounted for)

However, as a tool for predicting h_o this relationship only accounted for the silt content of the soil and made no allowance for variations in the proportions of sand and clay. A correlation matrix revealed that the variable possessing the next strongest relationship was sand content. Multiple regression produced the expression:

$$h_o = 58.3\ S - 7.89\ Sd + 1350 \qquad \text{- Eqn 6.1}$$

where Sd = % sand and h_o is in mm

($r = 0.794$: 63.1% of the variance in h_o accounted for)

Whereas in the first expression the standard error of estimate and the Student's t-test values for each variable within the equation were satisfactory, in Eqn 6.1 the standard error of estimate was high (24.7) for the constant associated with sand. Furthermore, the inclusion of sand into the equation did little to improve the variance in h_o which was accounted for. Addition of further variables proved statistically unacceptable. From consideration of the soil physics, it might have been expected that bulk density would have been important. However, since in the experiments its variation was so small (1.5 to 1.65 gm/cc), when incorporated into most of the relationships considered the standard error of estimate was unacceptably high for the constant associated with the bulk density term.

Despite the doubts over the statistical acceptability of Eqn 6.1, it was adopted as a suitable model on the grounds that: the sample size was small (results from 22 individual columns); 63% of the variance in h_o was accounted for; allowance was made for all possible variations in soil texture; and, above all, it was the best relationship available.

6.4.2.2 Residual Moisture Content.

Much of the discussion relating to the determination of a model for the critical height, also applies to the model for residual moisture content, and they will therefore not be repeated. It will suffice to state that the best relationship from the statistical viewpoint was:

$$\theta r = 1.22\ C + 4.45$$

where C = % clay and θr is expressed in %

(r = 0.873: 76.3% of the variance in θr accounted for).

However, to ensure that the expression could accommodate all variations in soil texture a second parameter was required. This was again the sand content, giving:

$$\theta r = 1.13\ C - 0.077\ Sd + 11.6 \qquad \text{- Eqn 6.2}$$

(r = 0.883: 78.1% of the variance in θr accounted for).

6.4.2.3 The Saturated Capillary Fringe.

As with critical height and residual moisture content, statistically the best model for saturated capillary fringe proved to be a linear regression with one soil parameter - in this instance % silt content.

$$h_c = 20.5\ S + 144$$

where h_c is in mm

(r = 0.827: 68.4% of the invariance in h_c accounted for).

Again to allow for variations in soil texture a second parameter was required, and the following was used for predictive purposes:

$$h_c = 34.7\ S + 13.9\ Sd - 1200 \qquad \text{- Eqn 6.3}$$

(r = 0.86: 74.0% of the variance in h_c accounted for).

6.4.2.4 Saturated Moisture Content.

After consideration of polynomial relationships and simple and multiple linear regression for both the basic data and logrithmic transformations, no sensible statistical relationship between soil properties and saturated moisture content could be determined. Scatter plots indicated a weak decreasing trend in the value of θs both with increasing bulk density and with increasing proportion of silt and clay. Particular attention was paid to the relationship with bulk density (BD) since it was anticipated that θs would be a function of the total pore space. Rogowski (1971) took the moisture content at saturation to be equal to the pore space, and Avery and Bascombe (1982) recommend the calculation of porosity (ε) from:

$\varepsilon = 1 - BD/\rho_S$ where, in general, the density of the soil, $\rho_S = 2.65$ gm/cc.

However, a search for a statistical relationship proved futile since the variation in bulk density for the soils tested in the columns was so small.

Finally, reversion to basic descriptive statistics revealed that the data could be regarded as normally distributed about a mean saturated moisture content of 33.5%. Since the standard deviation was only 2.15% it was decided, in the absence of a better relationship, to assume that for the soils studied in the columns there was no variation in θs, and that it was constant at 33.5%.

6.4.2.5 Equation of the Field Capacity Moisture Profile.

Field capacity moisture profiles exhibit the same S shape as soil suction / moisture content characteristics. van Genuchten and Nielsen (1985) reviewed the development of the four main mathematical functions that have been employed by researchers to simulate soil water retention data. Recently Evans (1989) has successfully fitted the following relationship to some of the field capacity profiles obtained from the author's laboratory experiments:

$$\Psi = [1 + (\alpha h)^n]^{-m} \qquad \text{- Eqn 6.4}$$

where h = height above the water table
and Ψ = the reduced water content (see Eqn 6.6 given below)
α, n and m are empirical parameters.

This function was originally suggested by van Genuchten (1980) and explored further in a later paper (van Genuchten and Nielsen, 1985).

Prior to Evan's work the author had chosen a modification of the Brooks and Corey equation (Brooks and Corey, 1964) as a model for the field capacity profile. This relationship had been used by Binley (1986) to describe observed soil moisture characteristics and took the form:

$$\Psi = a/(a + h^b) \qquad \text{- Eqn 6.5}$$

where a and b were empirical parameters.

For the field capacity profile, the *reduced water content* is defined as:

$$\Psi = \frac{\theta - \theta r}{\theta s - \theta r} \qquad \text{-Eqn 6.6}$$

By combining Eqn 6.5 and Eqn 6.6 the full relationship between % moisture content (θ) and height above the water table (h in metres) becomes:

$$\theta = (\theta s - \theta r)(\ a/(a + h^b)) + \theta r \qquad \text{- Eqn 6.7}$$

The Gauss-Newton method of least squares was used to fit Eqn 6.7 to each of the field capacity profiles obtained from the soil column experiments. The reader is referred to Dixon (1972) for the mathematical details of the method used.

For each of the 22 moisture profiles, therefore, the relevant values of the constants a and b were derived. Statistical analysis showed there to be a reasonably strong correlation between b and ln(a), and multiple regression revealed that a was related to the soil silt content and to bulk density. The expressions obtained were:

$$b = 2.32 - 0.651 \ln(a) \qquad \text{- Eqn 6.8}$$

(r = 0.787: 62.0% of the variance in b accounted for)

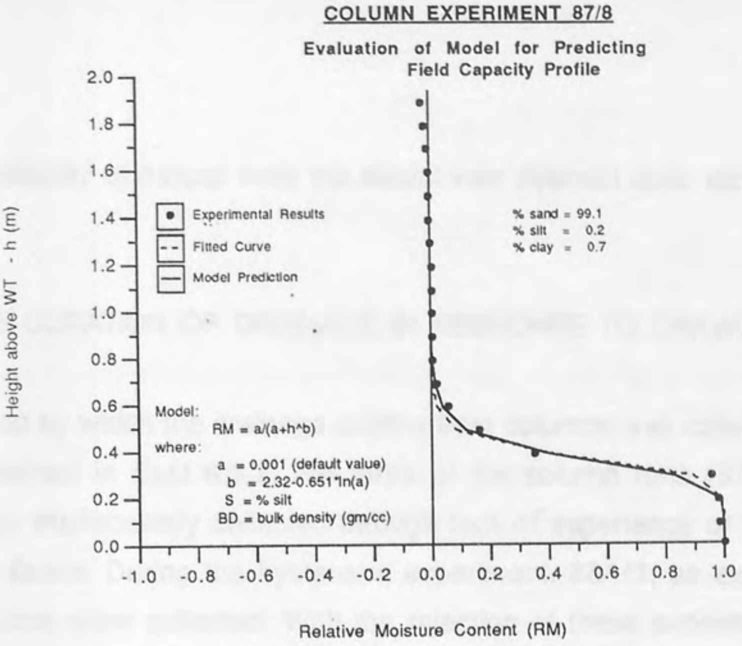
$$a = 0.0173\ S + 0.291\ BD - 0.494 \qquad \text{- Eqn 6.9}$$

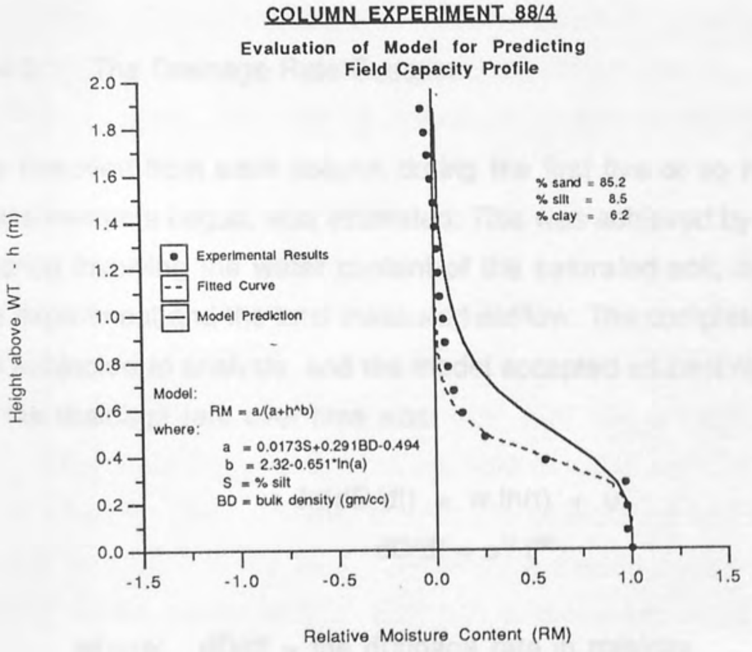
where BD = bulk density in gm/cc

(r = 0.78: 60.8% of the variance in a accounted for).

The full model for the field capacity profile, therefore, comprises Eqn 6.7 with: a defined by Eqn 6.9; b defined by Eqn 6.8; θr defined by Eqn 6.2; and $\theta s = 33.5$. Furthermore h is in metres.

As a simple evaluation of Eqn 6.7 the model was used to determine the field capacity moisture profiles for several of the column experiments. Fig 6.11 compares the experimental data with the fitted curves and the model predictions for three examples. As can be seen the results were satisfactory, rather than outstanding, but given the highly





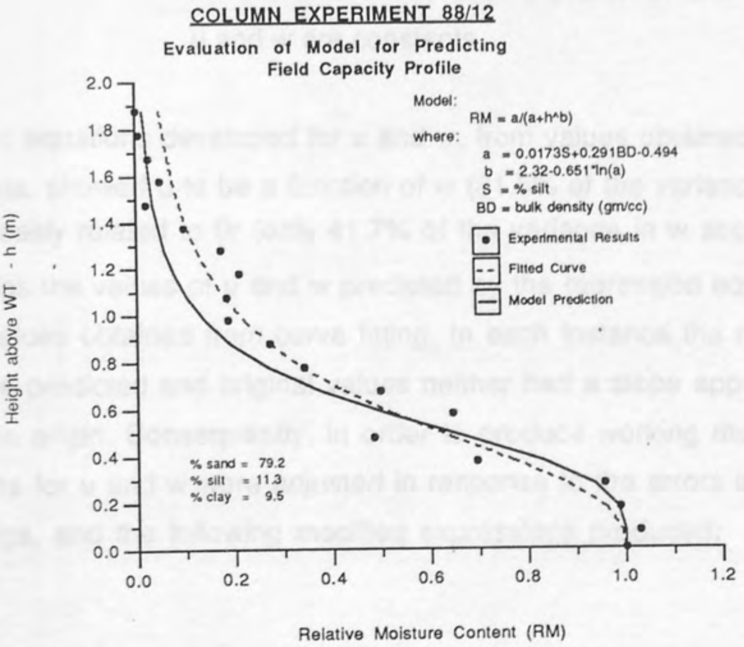


Fig 6.11 Comparison between Observed, Fitted and Predicted Field Capacity Profiles; Soil Columns 87/8, 88/4 and 88/12.

spatial variability of natural soils the model was deemed quite acceptable as a planning tool.

6.4.3 THE DURATION OF DRAINAGE IN RESPONSE TO DRAWDOWN.

The method by which the drainage outflow from columns was collected and processed has been explained in Sect 6.3.2. For three of the column runs (87/0, 87/1, and 87/3) data were either inadequately collected through lack of experience or lost through breakage of the glass flasks. During the hysteresis experiment, 88/H3, as explained in Sect 6.5 no drainage data were collected. With the rejection of these experiments the results from 18 columns remained for analysis.

6.4.3.1 The Drainage Rate Equation.

The water removed from each column during the first five or so minutes of drainage, before measurements began, was estimated. This was achieved by conducting a simple water balance involving the water content of the saturated soil, the water remaining at the end of the experiment and the total measured outflow. The completed drainage data sets were then subjected to analysis, and the model accepted as best representing the decaying nature of the drainage rate over time was:

$$\ln(dD/dt) = w.\ln(t) + u$$

hence:

$$dD/dt = e^{u}\, t^{w} \qquad \text{- Eqn 6.10}$$

where: dD/dt = the drainage rate in mm/day
t = the time in hrs after the start of drainage from saturation
u and w are constants.

Regression equations developed for u and w, from values obtained by fitting Eqn 6.10 to the column data, showed u to be a function of w (81.5% of the variance in u accounted for) and w to be weakly related to θr (only 41.7% of the variance in w accounted for). To test these relationships the values of u and w predicted by the regression equations were compared with the values obtained from curve fitting. In each instance the regression equation relating the predicted and original values neither had a slope approximating 1 nor passed through the origin. Consequently, in order to produce working models the original expressions for u and w were adjusted in response to the errors indicated by the test relationships, and the following modified expressions produced:

$$w = 0.032\,\theta r - 1.57 \qquad \text{- Eqn 6.11}$$

$$u = 3.12 - 3.33\,w \qquad \text{- Eqn 6.12}$$

Evaluation of the resultant drainage rate model (Eqns 6.10, 6.11 and 6.12) yielded the comparisons between observed and predicted drainage rates shown in Fig 6.12.

The rate at which a soil profile drains is of prime importance for determining whether the soil is sensitive to groundwater drawdown or not. If drainage is extremely slow the effects of moisture removal from the profile will not become apparent during the growing season, and therefore crops and trees will not be physically affected. A parameter was sought, therefore, which expressed how quickly the soil attained its field capacity profile following drawdown. It was decided that the time taken for a soil column to drain from saturation to the field capacity moisture profile would be used as an index of the soil's sensitivity to drawdown - the *Time of Drawdown Response* (TDR).

Although the drainage rate model, Eqn 6.10, was deemed acceptable on the basis of the comparison with observed results (see Fig 6.12) it was found that it could not be used satisfactorily for determining the time of drawdown response. Direct use of the model required that the drainage rate be known at the time the field capacity profile was established - an unknown factor which varies with soil properties. Furthermore, integration of the equation to determine the time taken to remove a given moisture volume also proved unacceptable. In theory the volume of moisture lost from a profile (VD) when draining from saturation to the field capacity state can be determined by comparing the field capacity profile (obtained from Eqn 6.7) with the saturated moisture content. Subsequent integration of the drainage rate equation, as shown below, between the limits t = 0 and t = TDR should yield the appropriate value of TDR.

$$\int_0^{VD} dD = e^u \int_0^{TDR} t^w \, dt$$

hence: $$VD\,(w+1) = e^u\,TDR^{w+1}$$

where VD = moisture volume lost from the soil in draining from saturation to the field capacity profile.

Using this approach the resulting calculated times of drawdown response were found to be low when compared to the values obtained from laboratory observations. The reasons for this were threefold.

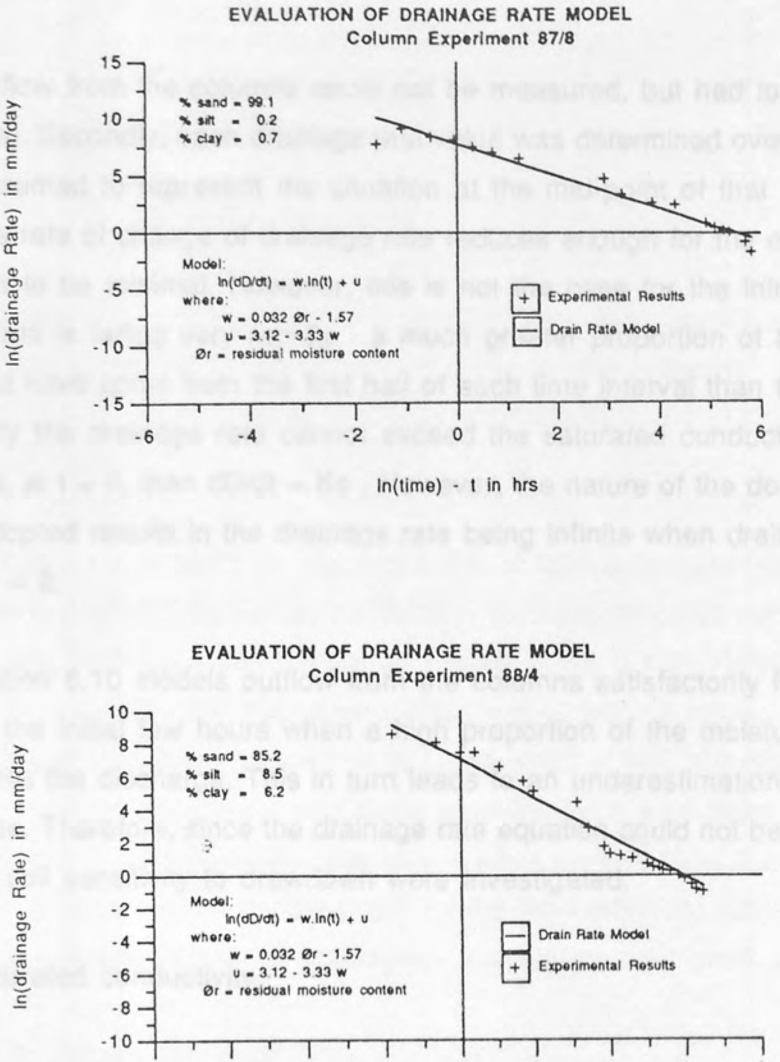


Fig 6.12 Comparison between Observed and Predicted Drainage Rate Decay:
Soil Columns 87/8, 88/4 and 88/12.

Firstly, the initial outflow from the columns could not be measured, but had to be estimated (see above). Secondly, each drainage rate value was determined over a specific time interval and assumed to represent the situation at the mid-point of that interval. After a few hours the rate of change of drainage rate reduces enough for the errors arising from this assumption to be minimal. However, this is not the case for the initial situation when the drainage rate is falling very rapidly - a much greater proportion of the collected outflow volume would have come from the first half of each time interval than the second half. Thirdly, in reality the drainage rate cannot exceed the saturated conductivity - thus when drainage starts, at $t = 0$, then $dD/dt = Ks$. However, the nature of the double logarithmic model adopted results in the drainage rate being infinite when drainage begins - i.e. $dD/dt = \infty$ at $t = 0$.

Thus, although equation 6.10 models outflow from the columns satisfactorily for the main drainage period, for the initial few hours when a high proportion of the moisture loss occurs it overestimates the discharge. This in turn leads to an underestimation of the time of drawdown response. Therefore, since the drainage rate equation could not be used, other means of predicting soil sensitivity to drawdown were investigated.

6.4.3.2 Saturated conductivity.

The saturated conductivity (Ks) had fortunately been determined for a total of 48 field and column soil samples using the constant head permeameter described in Sect 6.1.2. A number of the soil samples from the columns were destroyed in a laboratory flood and thus it was only possible to determine saturated conductivities for 14 of the 22 different soils used. Since the saturated conductivities from topsoil samples proved highly variable, these results were discarded and analysis of the remaining data set yielded the following relationship:

$$\log (Ks) = 4.42 - 0.0188\ S - 2.48\ BD \qquad \text{- Eqn 6.13}$$

(r = 0.62: 39% of the variance in log (ks) accounted for)

where: Ks = saturated conductivity in m/day
S = % silt content
BD = bulk density in gm/cc

A logarithmic relationship had been adopted for Eqn 6.13 as Jaynes and Tyler (1984) had found this to be the best form for predicting unsaturated conductivity from soil properties. Their equation incorporated soil water potential, which when set to zero (ie. saturated moisture content) and modified to give units compatible with Eqn 6.13 gave:

$$\log (Ks/100) = 0.044\ Sd - 0.61\ BD \qquad \text{- Eqn 6.14}$$

where: Sd = % sand content

Fig 6.13a is a comparison between Eqn 6.13, the modified version of Jaynes and Tyler's equation (Eqn 6.14) and measured values of Ks. It is clear, for the range of soils analysed, that Eqn 6.14 overestimates saturated conductivity and that Eqn 6.13 is an acceptable predictor of Ks.

If a bulk density of 1.65 g/cc is taken as representative of field soils (determined from the analysis of samples: see also Hall et al, 1977), Eqn 6.13 predicts that the saturated conductivity will fall with increasing silt content as shown in Fig 6.13b. However, even for a silt content as high as 40% the saturated conductivity is still 0.4 m/day, and in the absence of a suitable yardstick it is not possible to judge whether this is indicative of sensitivity to drawdown or not. An attempt was made to define such a yardstick using data from the laboratory columns. Unfortunately, due to the small sample size, it was not possible to relate the value of Ks to the time taken for the laboratory soil columns to achieve field capacity with any degree of confidence (correlation coefficient, $r = 0.3$).

6.4.3.3 The Drawdown Response Time.

The rate at which moisture drains from an initially saturated soil under the influence of gravity can be regarded in terms of the rate of depletion of a store or reservoir of water. Under these circumstances, if it is assumed that there is a linear relationship the drainage rate (dD/dt) is related to the moisture remaining in the profile (D) by:

$$\frac{dD}{dt} = -a\ D$$

which can be integrated to give:

$$PDM = e^{-at}$$

where: PDM = the *proportion of drainable moisture* remaining at time t - the *drainable moisture* is the total moisture which can drain under gravity from an initially saturated profile as a result of drawdown:
a is a constant.

Alternatively, if the relationship between the rate of drainage and time is not linear the relationship can be expressed as:

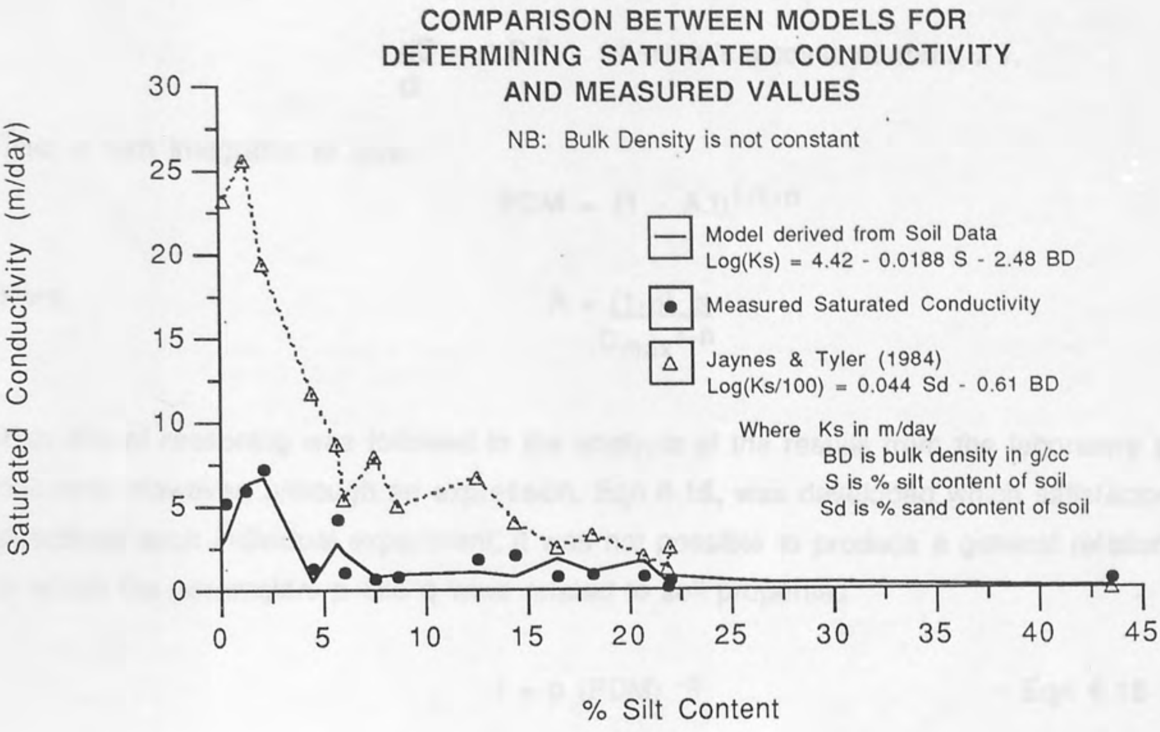


Fig 6.13 (a)

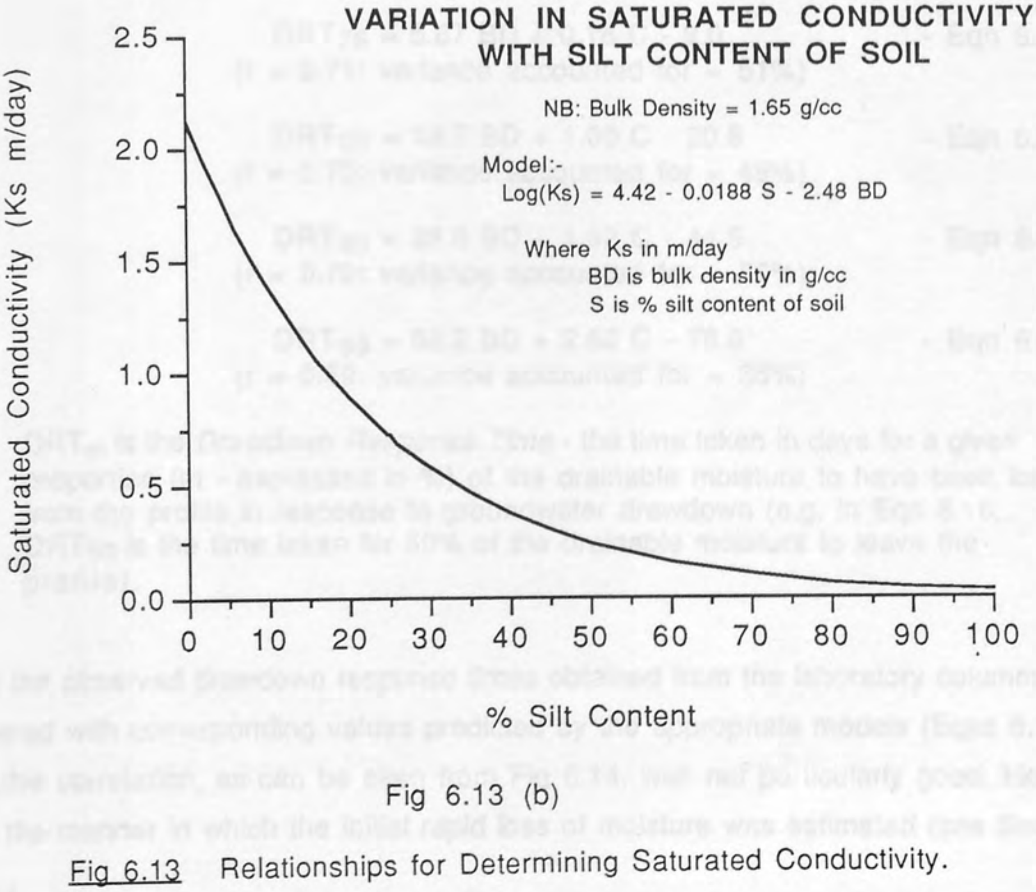


Fig 6.13 (b)

Fig 6.13 Relationships for Determining Saturated Conductivity.

$$\frac{dD}{dt} = -a\,D^{n} \quad \text{where n is a constant and } n \neq 1.$$

This in turn integrates to give:

$$PDM = (1 - A.t)^{1/1-n}$$

Here,

$$A = \frac{(1-n)\ a}{D_{max}^{1-n}}$$

This line of reasoning was followed in the analysis of the results from the laboratory soil columns. However, although an expression, Eqn 6.15, was developed which satisfactorily described each individual experiment, it was not possible to produce a general relationship in which the parameters p and q were related to soil properties.

$$t = p\ (PDM)^{-q} \qquad \text{- Eqn 6.15}$$

However, in preparing the drainage data for the analysis described above, for each column experiment it was necessary to determine a value of the proportion of drainable moisture remaining (PDM) when each observation was made. Using these data the following series of regression equations were derived:

$$DRT_{50} = 1.90\ BD + 0.016\ C - 2.91 \qquad \text{- Eqn 6.16}$$
(r = 0.67: variance accounted for = 45%)

$$DRT_{75} = 5.67\ BD + 0.18\ C - 9.0 \qquad \text{- Eqn 6.17}$$
(r = 0.71: variance accounted for = 51%)

$$DRT_{90} = 12.7\ BD + 1.00\ C - 20.8 \qquad \text{- Eqn 6.18}$$
(r = 0.70: variance accounted for = 49%)

$$DRT_{95} = 28.6\ BD + 1.62\ C - 44.5 \qquad \text{- Eqn 6.19}$$
(r = 0.70: variance accounted for = 50%)

$$DRT_{99} = 55.2\ BD + 2.62\ C - 78.6 \qquad \text{- Eqn 6.20}$$
(r = 0.59: variance accounted for = 35%)

DRT_m is the *Drawdown Response Time* - the time taken in days for a given proportion (m - expressed in %) of the drainable moisture to have been lost from the profile in response to groundwater drawdown (e.g. in Eqn 6.16, DRT_{50} is the time taken for 50% of the drainable moisture to leave the profile).

When the observed drawdown response times obtained from the laboratory columns were compared with corresponding values predicted by the appropriate models (Eqns 6.16 to 6.20) the correlation, as can be seen from Fig 6.14, was not particularly good. However, given the manner in which the initial rapid loss of moisture was estimated (see Sect

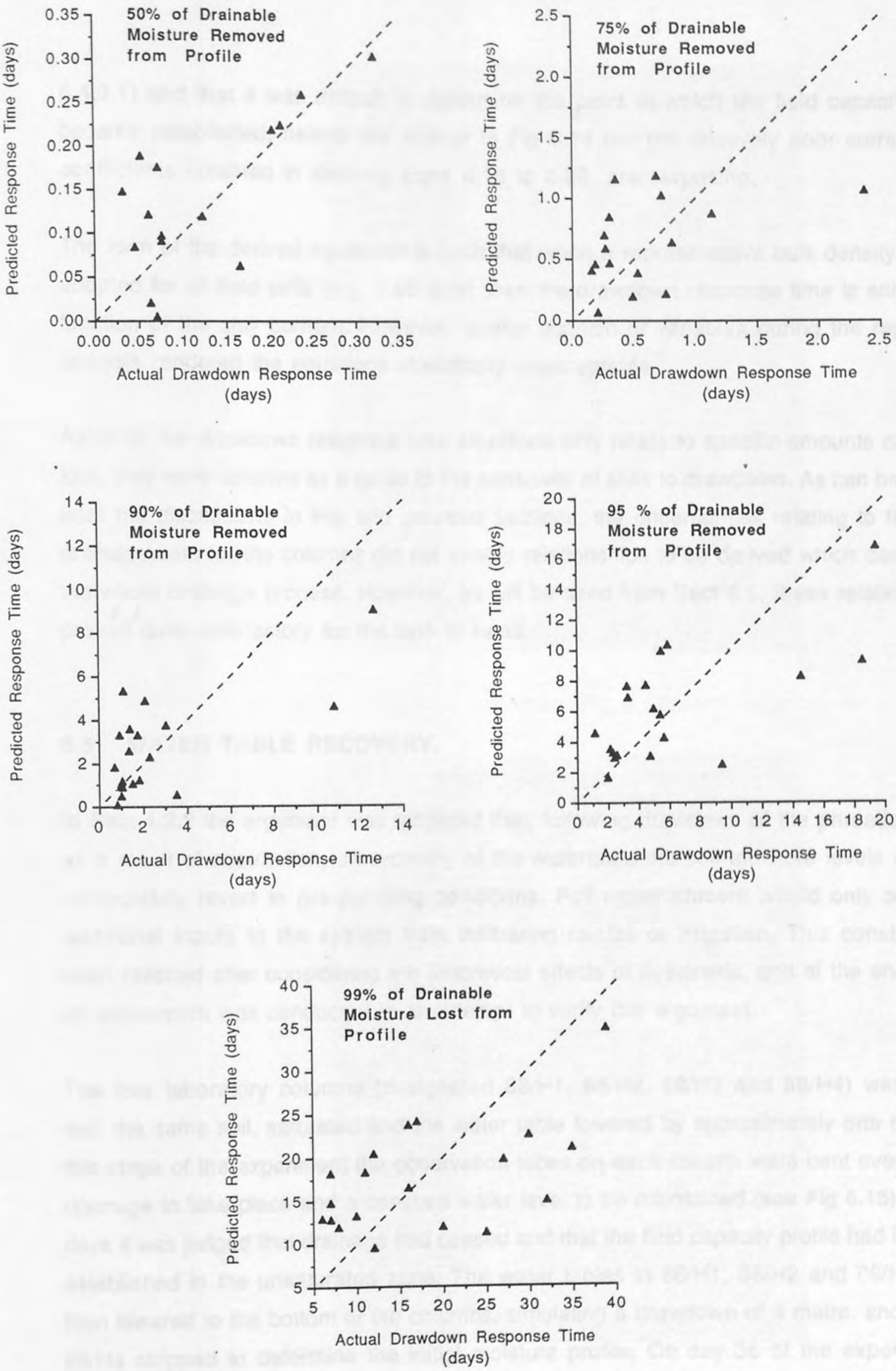


Fig 6.14 Comparison between Predicted and Actual Drawdown Response Times.

6.4.3.1) and that it was difficult to determine the point at which the field capacity profile became established, neither the scatter in Fig 6.14 nor the relatively poor correlation coefficients obtained in deriving Eqns 6.16 to 6.20, are surprising.

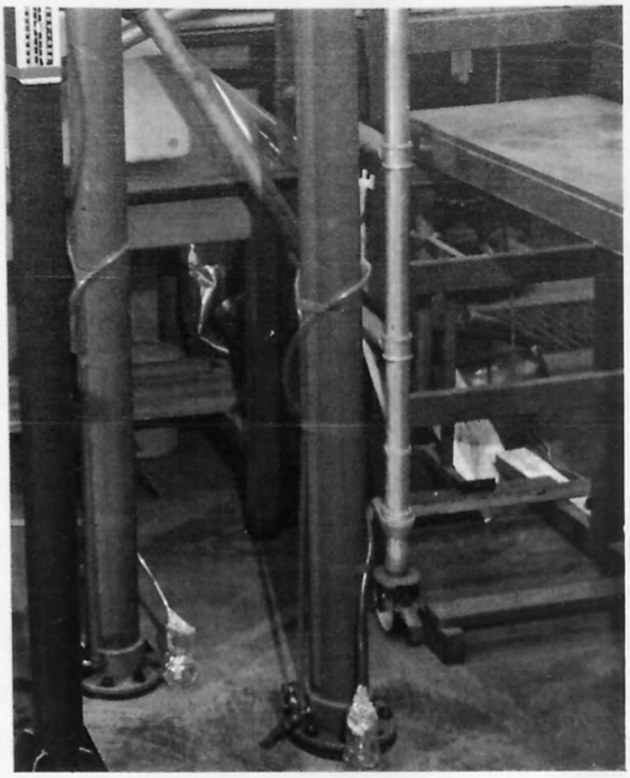
The form of the derived equations is such that when a representative bulk density is adopted for all field soils (e.g. 1.65 g/cc) then the drawdown response time is solely a function of the clay content. However, further addition of variables during the regression analysis rendered the equations statistically unacceptable.

Although the drawdown response time equations only relate to specific amounts of moisture loss, they were adopted as a guide to the sensitivity of soils to drawdown. As can be seen from the discussions in this and previous sections, the uncertainties relating to the drainage data for the columns did not enable relationships to be derived which described the whole drainage process. However, as will be seen from Sect 6.6, these relationships proved quite satisfactory for the task in hand.

6.5 WATER TABLE RECOVERY.

In Sect 4.2.2 the argument was tendered that, following drawdown of the phreatic surface as a result of abstraction, on recovery of the watertable the soil moisture levels would not immediately revert to pre-pumping conditions. Full replenishment would only occur with additional inputs to the system from infiltrating rainfall or irrigation. This conclusion had been reached after considering the theoretical effects of hysteresis, and at the end of 1988 an experiment was conducted in an attempt to verify this argument.

The four laboratory columns (designated 88/H1, 88/H2, 88/H3 and 88/H4) were packed with the same soil, saturated and the water table lowered by approximately one metre. For this stage of the experiment the observation tubes on each column were bent over to allow drainage to take place and a constant water level to be maintained (see Fig 6.15). After 16 days it was judged that drainage had ceased and that the field capacity profile had been established in the unsaturated zone. The water tables in 88/H1, 88/H2 and 88/H3 were then lowered to the bottom of the columns, simulating a drawdown of a metre, and column 88/H4 stripped to determine the initial moisture profile. On day 36 of the experiment the moisture profile of column 88/H3 was determined and the water levels in columns 88/H1 and 88/H2 raised by one metre to simulate groundwater recovery. Raising the water level was achieved by cutting the observation tubes and inserting simple constant head devices



(a) Arrangement for Maintaining a Constant Head.

(b) Device for Raising the Column Water Table Level.

Fig 6.15 Constant Head Arrangement and Device for Raising the Water Table Level in Simulation of Groundwater Recovery Experiment.

into which water was trickled (see Fig 6.15). Finally, after a further 15 days the last two columns were stripped.

Thus, at the end of the experiment the four moisture profiles shown on Fig 6.16 had been obtained - two resulting from lowering the water level and two from raising it. Analysis showed that the average bulk densities for columns 88/H1 and 88/H3 were similar, as were the values obtained for columns 88/H2 and 88/H4. Consequently in evaluating the effects of groundwater recovery the profiles were considered in pairs of matching bulk density.

Fig 6.17 shows that when the water tables were raised back to their pre-drawdown positions, full replenishment of the moisture profile did not occur - 24mm of water was lost in the case of Fig 6.17a and 26mm in Fig 6.17b. These losses were not as great as had been anticipated from theoretical considerations. However, the experiment confirmed the conclusion that groundwater recovery will not result in the full replenishment of moisture lost due to the effects of pumping.

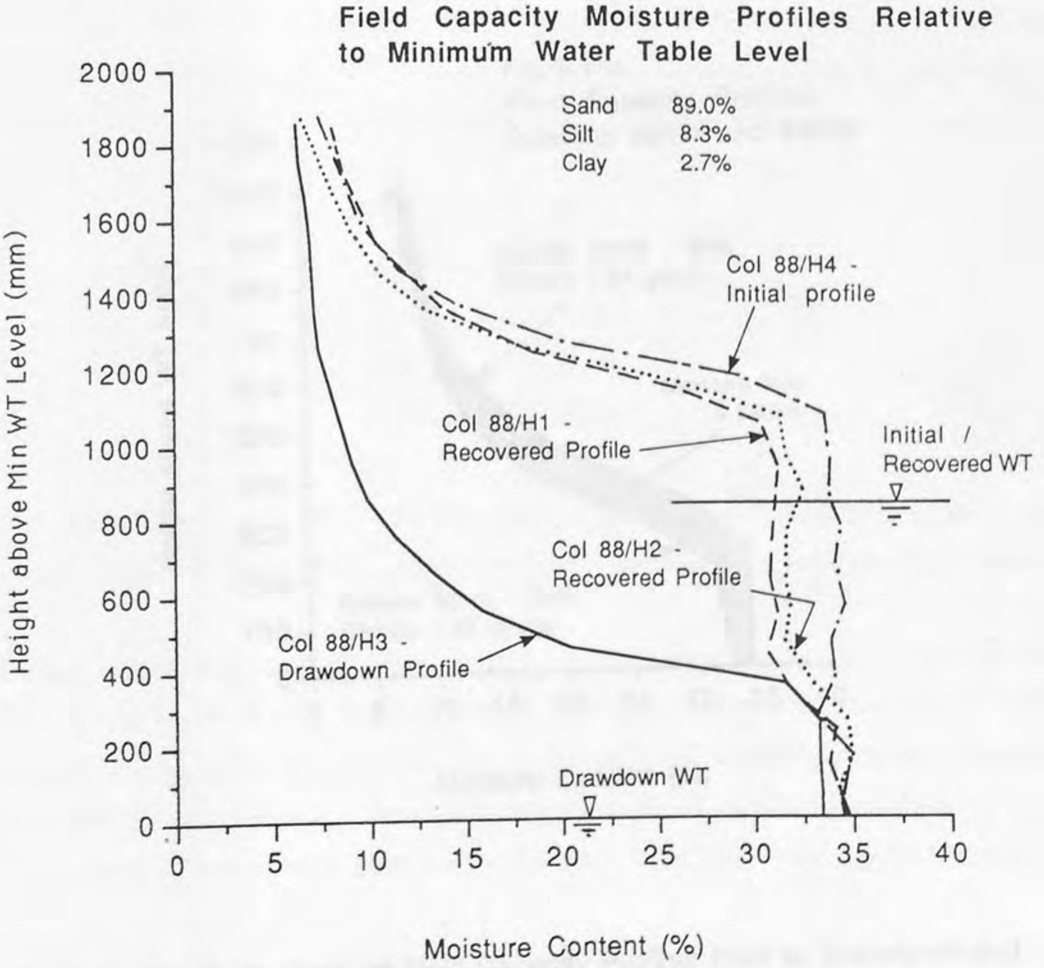


Fig 6.16 Moisture Profiles Obtained from Groundwater Recovery Experiment.

Fig 6.17a.
Field Capacity Profiles:
Columns 88/H3 and 88/H1

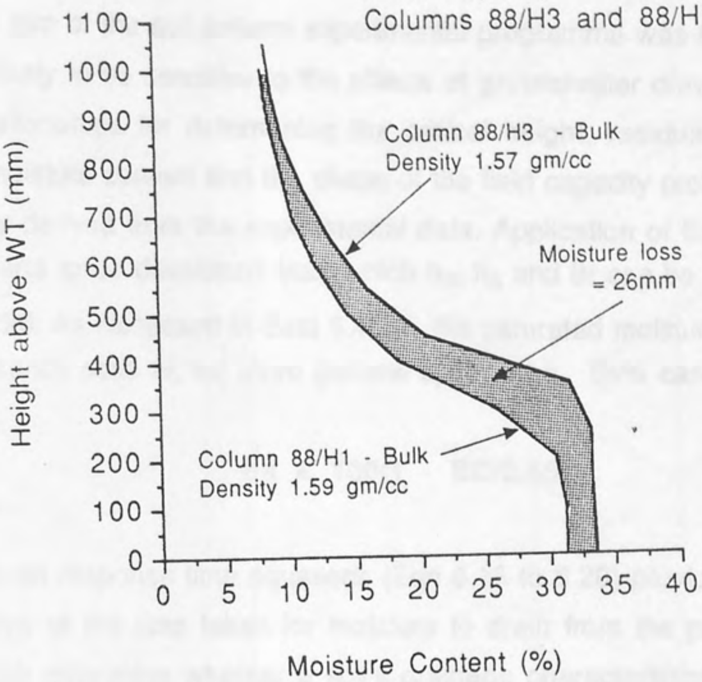


Fig 6.17b.
Field Capacity Profiles:
Columns 88/H4 and 88/H2

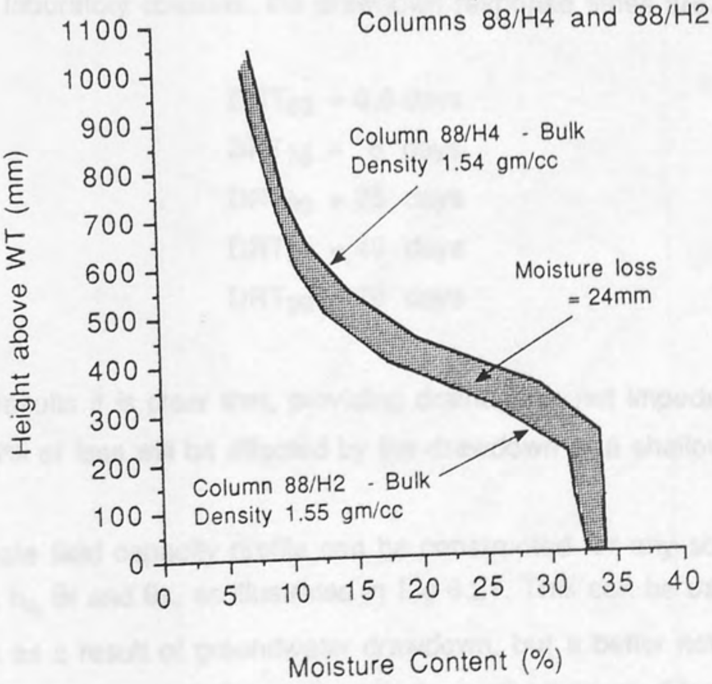


Fig 6.17 Comparison of Field Capacity Profiles Prior to Drawdown and Following Groundwater Recovery.

6.6 THE IDENTIFICATION OF SENSITIVE SOILS.

The overall aim of the soil column experimental programme was to enable those soils which are likely to be sensitive to the effects of groundwater drawdown to be identified. Simple relationships for determining the critical height, residual moisture content, saturated moisture content and the shape of the field capacity profile have been successfully derived from the experimental data. Application of Eqns 6.1, 6.2 and 6.3 has enabled charts to be developed from which h_o, h_c and θr can be read directly - Figs 6.18, 6.19 and 6.20. As discussed in Sect 6.4.2.4, the saturated moisture content can be taken as 33.5% for sandy soils or, for more general application, $\theta s\%$ can be calculated from:

$$\theta s = 100(1 - BD/2.65) \qquad \text{- Eqn 6.21}$$

The drawdown response time equations (Eqn 6.16 to 6.20) provide a means of classifying soils in terms of the time taken for moisture to drain from the profile. However, the criteria which determine whether a soil's drainage characteristics are such that the moisture removal rate is too slow for vegetation to be affected adversely has not been ascertained. Taking 1.65 g/cc as the bulk density of field soils (see Sect 6.4.3.2) then for a clay content of 25%, the limit of Figs 6.18 to 6.20 and 2.5 times greater than any soil tested in the laboratory columns, the drawdown response times are:

DRT_{50} = 0.6 days
DRT_{75} = 5 days
DRT_{90} = 25 days
DRT_{95} = 40 days
DRT_{99} = 78 days

From these results it is clear that, providing drainage is not impeded, all soils with a clay content of 25% or less will be affected by the drawdown of a shallow water table.

An approximate field capacity profile can be constructed for any soil from the relevant values of h_o, h_c, θr and θs, as illustrated in Fig 6.21. This can be used to estimate the moisture lost as a result of groundwater drawdown, but a better estimate of the profile can be determined using Eqn 6.7. This latter was the method adopted for assessing the impact of the Shropshire Groundwater Scheme on the Tern Area (see Sect 8.5 for details).

Anyone employing the relationships presented in this chapter should be fully aware of their limitations. Firstly, they have been derived from soils with a uniform profile for

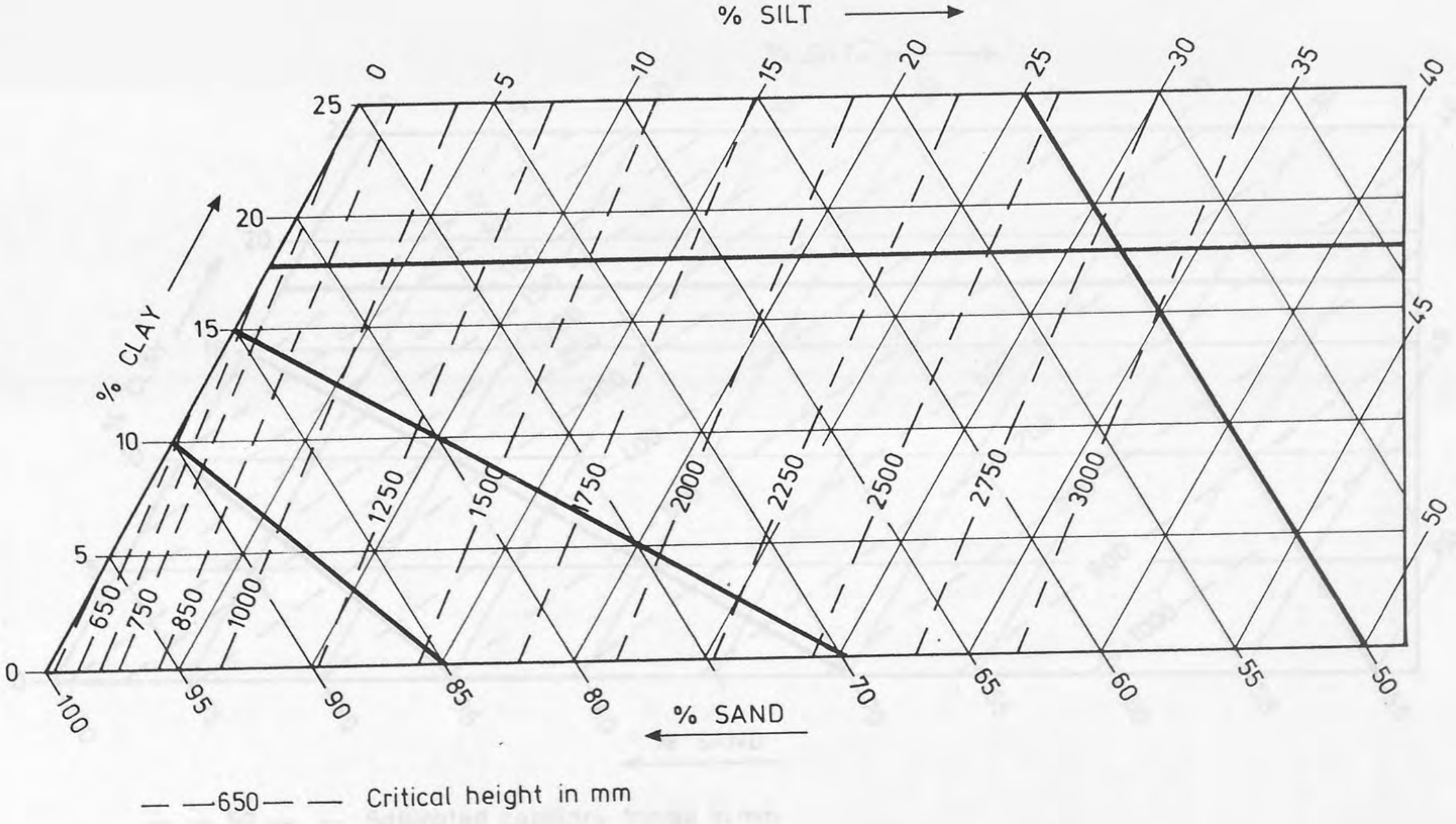


Fig 6.18 Chart for Determining the Critical Height from Particle Size Analysis.

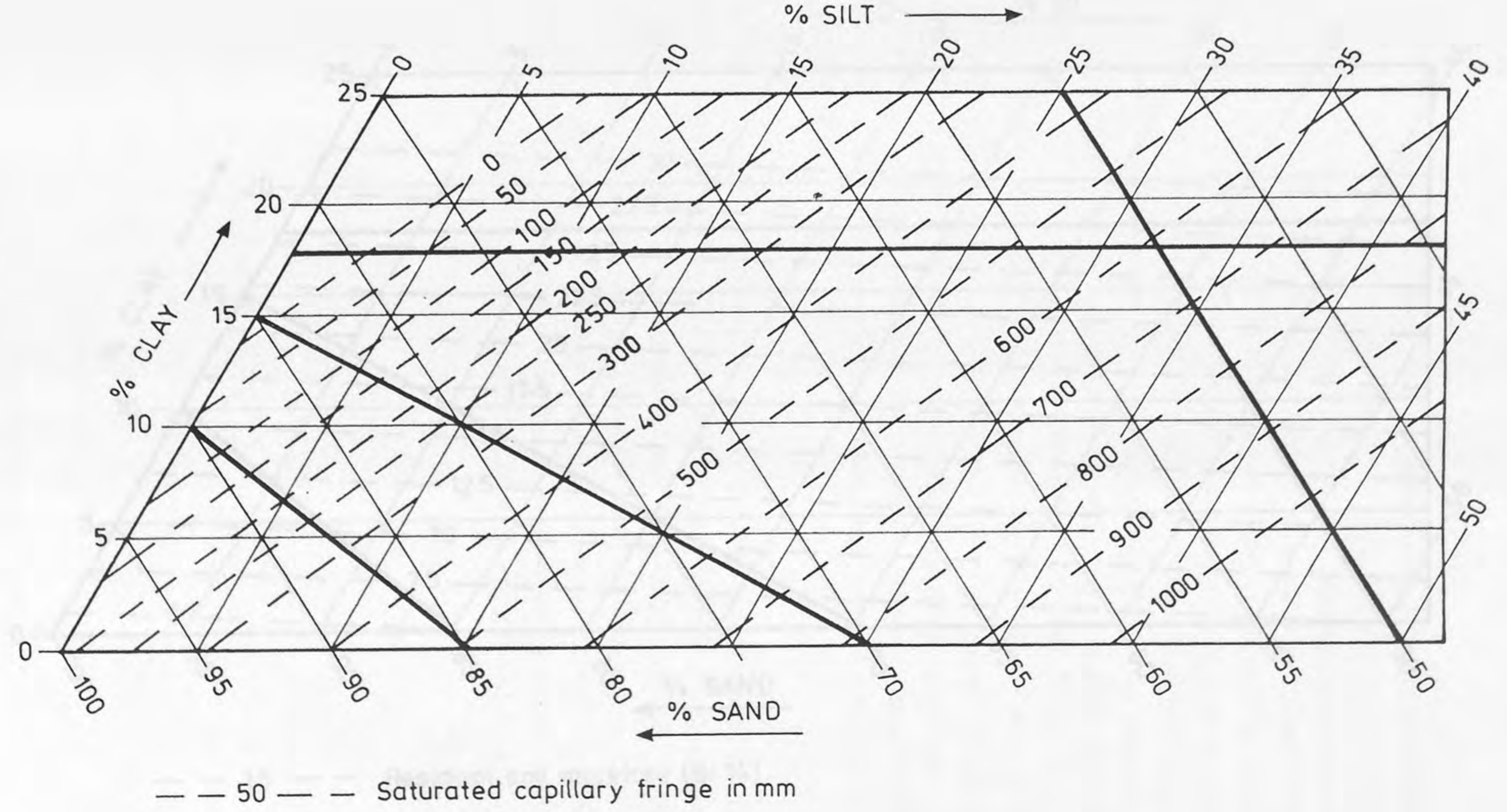


Fig 6.19 Chart for Determining the Saturated Capillary Fringe from Particle Size Analysis.

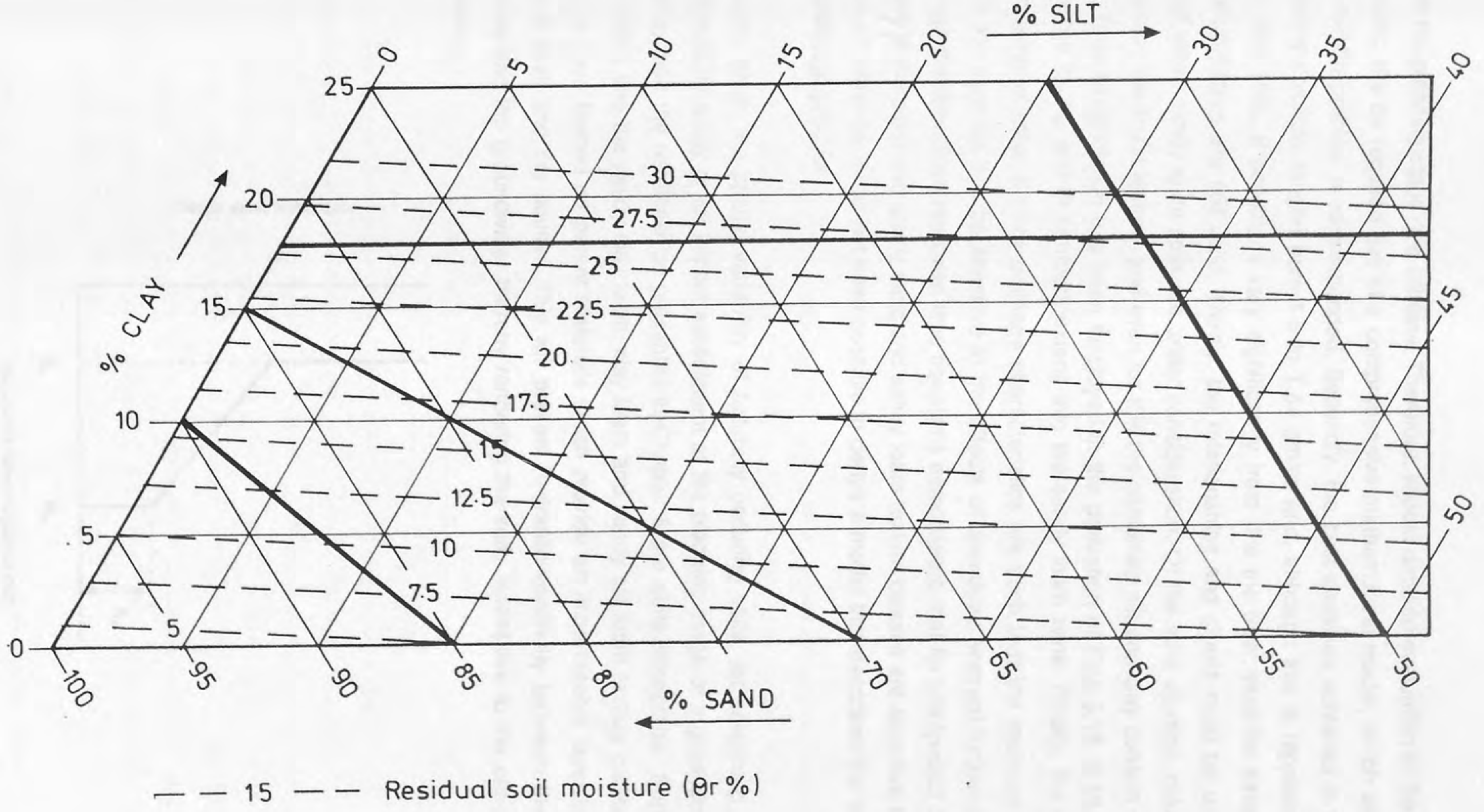


Fig 6.20 Chart for Determining the Residual Moisture Content from Particle Size Analysis.

use at the planning stage of a scheme. Therefore, should detailed evaluation of the effects at a specific site be required use of a comprehensive mathematical model, which allows for non-uniform profiles, is recommended. Secondly, the bulk densities achieved in the laboratory columns ranged from 1.5 to 1.64 gm/cc and, although this is representative of many field soils, if conditions vary significantly from this the user must be satisfied that the relationships are still valid. Thirdly, the relationships and charts must be used with caution when sandy loam soils are under consideration. Of the soils studied, column 88/12 possessed the finest texture, and even for this the combined silt and clay content was only 21%. Thus extrapolation has been employed in the derivation of Figs 6.18, 6.19, and 6.20 where the h_o, h_c, and θr contours extend into the sandy loam zone. Finally, the criteria for determining whether a soil's drainage characteristics are such that the moisture removal rate is too slow for it to be sensitive to the effects of drawdown warrant further study. Although the drawdown response time equations demonstrate that for unimpeded drainage all soils in the sand and loamy sand and sandy loam texture classes are sensitive to the effects of pumping, it has not been possible to derive a model that describes the whole of this drainage process

However, given the spatial variability of naturally occuring soils, for screening purposes in a feasibility study or for impact assessment at the planning stage of a groundwater scheme, then the relationships presented in Chapter 6 are quite acceptable. Furthermore, soils falling into the sandy clay loam, clay loam and sandy silt loam texture classes are likely to have formed on parent materials which provide an impermeable layer between the soil itself and the aquifer. This will prevent hydraulic continuity between the soil moisture and the groundwater thereby rendering the soils insensitive to the effects of drawdown.

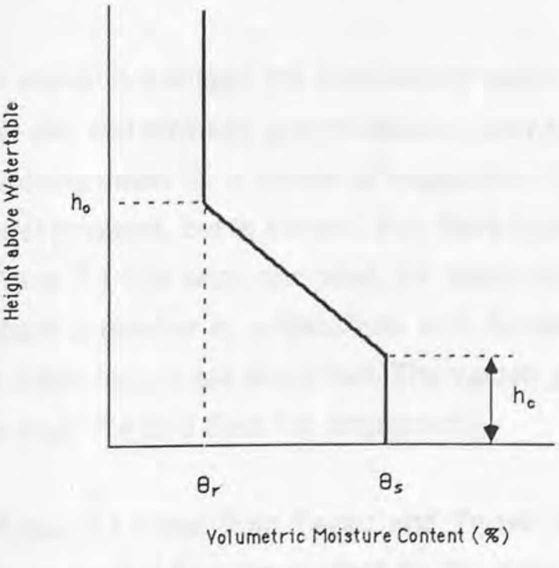


Fig 6.21 Approximation of the Field Capacity Profile.

Chapter 7. VEGETATION - FEATURES HAVING A BEARING ON THE STUDY.

7.1 CROPS IN THE TERN AREA.

With the exception of some small areas of woodland and heath, all the Tern Area of the Shropshire Groundwater Scheme is under agriculture. Rough grazing is found in the northern part of the Tern valley, and the heavier poorly drained soils are generally under permanent pasture. A survey of the agriculture in the area showed, as will be described in Sect. 8.3.4, that the main arable crops are barley, wheat, sugar beet and potatoes. Short term leys are common on many of the mixed farms and there are a few specialist horticultural holdings. Although not observed during the 1980 crop survey, it has been noted that brassicas are an important cash crop on some farms (Soil Survey of England and Wales, 1982).

Fig 7.1 shows the cropping patterns for the Tern Area as revealed by the 1980 survey. The major part of the agriculture survey was undertaken early in the summer of that year, and at that time it was difficult to differentiate between the various cereal crops - especially those distant from the roads. Consequently, although barley was by far the most dominant, all grains have been classified together as 'cereals'. Other crops, which have been grouped together and labelled 'miscellaneous crops', include maize, peas and strawberries.

7.2 CROP ROOTING DEPTHS.

In the fields of irrigation and land drainage the crop rooting depth is used in the assessment of crop water use and drainage system design. Many publications on these topics supply tables of rooting depth for a variety of vegetation. Often the original sources of the values given are not provided, but in general they have been produced from reviews of available literature. Table 7.1 has been compiled, for those crops etc. identified during the 1980 crop survey, from a number of publications and, for comparison, crop rooting depths discussed at the public inquiry are presented. The values given for grass and trees are discussed further in Sect. 7.4 and Sect 7.5 respectively.

The rooting depths in Table 7.1 taken from Taylor and Terrell (1982) deserve particular comment as they tend to be greater than those given by the other authors listed. In their very brief paper Taylor and Terrell provide a long table of rooting depths and lateral

spread of roots produced from an extensive literature review. For each item of vegetation in their table two rooting depths are listed: the 'working root depth' which is decribed as "the average depth reached by many roots or root branches and to which a considerable absorption must take place"; 'the maximum rooting depth' is "that at which a root was found at the particular site". In Table 7.1, where Taylor and Terrell's results are given, the first value is the 'working root depth' and the second the 'maximum rooting depth'. The former was used when the 'average of published values' was determined.

Groundwater table depths giving optimum crop yields were discussed by Williamson and Kritz (1970), who summarised the results obtained by several workers in the field - notably the dutch. These findings are included in Table 7.1 for comparison only, and it must be remembered that for land drainage the objective of groundwater table control is to seek optimum conditions for crop growth. Such conditions not only include an adequate zone of aerated soil for root development within which the available moisture is utilised, but crops will also benefit from a continuous supply of moisture resulting from capillary rise. Under these circumstances it is unlikely that crops will achieve their maximum potential rooting depth as, unlike vegetation on well drained soils, they have no need to penetrate deeper in order to make maximum use of the available moisture store during dry summer months. However, the optimum groundwater table depths do emphasise the point that the lowering of very shallow water tables to below these levels as a result of pumping in dry years will be to the detriment of crop yields (see also Fig 5.24).

Table 7.1 shows that, for crops in the Tern Area, the maximum rooting depths suggested by Drennan (1979b) agree well with the average of the depths given in the literature. For the purpose of identifying potentially sensitive areas it is more appropriate to use the maximum rooting depth that has been observed for each crop. It is commonly acknowledged that roots will grow in search of water - a point made by both Drennan and Ede at the inquiry (see also Milthorpe and Moorby, 1976). Walter (1963) quotes a study by Kausch (1960) of desert plants around Cairo, in which it was recorded that roots penetrated down to depths of 5m in response to deep drainage. It is reasonable to assume that, if a rest water table exists at the limit of a crop's potential root penetration depth, then the roots will extend to that depth in pursuit of water when the available moisture has been exhausted in the upper horizons. Therefore, in determining the areas sensitive to groundwater drawdown the maximum rooting depths given in Table 7.1 were employed. The exceptions to this were permanent pasture, where a value of 1.75m was taken (see Sect. 7.4 for details), and cereals which were grouped together and for which a rooting depth of 2.1m was used. A representative rooting depth of 1.5m has been selected for crops in the category 'miscellaneous'. This falls approximately midway between the maximum

Reference	Barley	Wheat	Rye	Oats	Potatoes	Sugar Beet	Peas	Vegetables	Maize	Ley Grass	Perm Past	Fruit Trees	Trees
Doorenbos and Pruitt, 1977	1.0 - 1.5	1.0 - 1.5			0.4 - 0.6	0.7 - 1.2	0.6 - 1.0	0.3 - 0.6	1.0 - 1.7	0.4 - 0.6	0.5 - 1.5	1.0 - 2.0	
Shalhevet et Al,1979		0.9							1.0 - 1.5				
Wessling and van Wijk, 1957	1.25	1.25	1.25	1.25	1.0					0.5			
Shockley, 1956	1.2	1.2	1.2	1.2	0.9 - 1.2	1.2 - 1.8	0.9 - 1.2	0.6	1.2 - 1.5		0.9 - 1.2	1.8 - 2.4	
van de Goor, 1972	1.5 - 1.8	1.5 - 1.8	1.5 - 1.8	1.5 - 1.8	0.6	1.5 - 1.8		0.6	1.5 - 1.8	0.6	0.6	1.5 - 2.1	
van Keulen and Wolf, 1986	1.25	1.25			0.5				1.35				
Doneen, 1972	1.2	1.2	1.2	1.2	0.6	1.8	1.2	0.6	1.8		1.2	1.8	
Feddes et al, 1978					0.6			0.4 - 0.9					
Schwab et al, 1971					0.3 - 0.6				0.6 - 1.2		1.5 - 2.5		
Withers and Vipond, 1974	1.3	1.3	1.3	1.3	1.0 - 1.3	1.3 - 2.0	1.0 - 1.3	0.7 - 1.0	1.0		1.0		
MAFF, 1974												> 1.2	> 1.2
Taylor and Terrell, 1982	1.35 - 1.95	1.5 - 2.0	1.5 - 2.3	1.5 - 2.0	0.9 - 1.5	1.8 - 2.1	0.9	0.6 - 1.37	1.8 - 1.88		0.3 - 3.65 *		1.8 - 3.5
Tayler, 1965											> 0.9		
(Average of published values)	(1.31)	(1.28)	(1.35)	(1.35)	(0.74)	(1.56)	(1.02)	(0.62)	(1.35)	(0.53)	(1.2)	(1.8)	(2.7)
(Maximum published value)	(1.95)	(2.0)	(2.3)	(2.0)	(1.5)	(2.1)	(1.3)	(1.37)	(1.9)	(0.6)	(3.65) **	(2.4)	(3.5)
Drennan, 1979 (from root const)	0.5 - 1.3	0.5 - 1.3	0.5 - 1.3	0.5 - 1.3	0.3 - 0.6	1.0 - 1.5				0.3 - 0.6	0.3 - 0.6		2.0 - 2.5
Ede,1979													5
Williamson and Kriz, 1970 #	1.5	1.5		1.5	0.6	1.5	0.9	0.3 - 0.9		0.15 - 0.3			
NOTES:													
* large number of grasses listed :-	from fescues	(0.3 - 0.7)	to clover	(1.2 - 3.0)									
** representative rooting depth for	permanent	pasture taken	as 1.75m										
# groundwater depth for optimum	yield												

Table 7.1 Crop Rooting Depths.

rooting depths of peas and maize - the two crops which, in the Aston survey, dominated this category.

7.3 THE DEVELOPMENT OF RELATIONSHIPS BETWEEN MOISTURE LOSS AND CROP YIELD.

7.3.1 ALTERNATIVE APPROACHES.

Over the years many researchers have investigated the effect of moisture tension on crop yield (eg. Bierhuizen and de Vos, 1959; Johnson, 1981; Cheema et al, 1983) whilst others have studied the relationship between crop yield and transpiration (eg. de Wit, 1958; Penman, 1962; Stewart et al, 1977). Although the results from many of these studies have been presented in an easily accessible graphical form, a model for evaluating actual transpiration or soil moisture tension would have been required for them to have been of use in this project. As many crop yield models were already in existence their potential was investigated.

Underlying all the crop yield models that were examined was the principle that the yield was directly proportional to the ratio of cumulative actual evapotranspiration to cumulative potential evapotranspiration (as first adopted by de Wit, 1958). Most models used, as their starting point, the following relationship for evaluating yield:

$$\frac{Y}{Y_p} = \frac{\Sigma E_a}{\Sigma E_p} \qquad \text{- Eqn 7.1}$$

where:
Y = actual crop yield
Y_p = potential (maximum possible) yield
ΣE_a = cumulative actual evapotranspiration
ΣE_p = cumulative potential evapotranspiration

Subsequently a stress factor (k_s), as first employed by Hanks (1974), was introduced to relate actual and potential evapotranspiration such that:

$$\Sigma E_a = k_s . \Sigma E_p$$

which reduces Eqn 7.1 to:

$$Y = k_s . Y_p$$

The stress factor itself is a function of the root zone depth and a root extraction term (the rate at which the root removes moisture from the soil) and can be expressed in a number of ways.

A relatively simple approach was adopted by Martin et al. (1984) who defined k_s as:

$$k_s = 1.0 \quad \text{if} \quad E_w > 0.5 \quad \text{and} \quad k_s = \frac{E_w}{0.5} \quad \text{if} \quad 0.0 \leq E_w \leq 0.5$$

where E_w is the fraction of extractable water remaining in the crop root zone. An alternative method (eg. Schmidt and Plate, 1983) involves the use of an appropriate crop coefficient which depends on the stage of crop growth (see also Doorenbos and Pruitt, 1977). At their most sophisticated models attempt to simulate the physical processes associated with the uptake of water by crop roots (eg. Walley and Hussein, 1982). Input data for such models include moisture characteristics, unsaturated conductivity / moisture content relationships, and root moisture extraction and growth functions.

Although many authors besides those mentioned above have published computer crop yield models (eg. Feddes at al, 1978; Hanks and Hill, 1980; van Keulen and Wolf, 1986), all those investigated were too sophisticated for the planning technique under development. Consequently, a more simple model, which embodied the same principles, was sought for evaluating the effects of groundwater drawdown on crop yields.

An extensive literature search, undertaken in November 1985, failed to identify any publications discussing the relationship between soil moisture loss and reduction in crop yield - most studies were concerned with the increase in yield resulting from irrigation. The idea that the effects of groundwater drawdown could be regarded as a "with and without" irrigation situation had first been considered in 1981; after the 1985 literature search this concept was examined further. If the yield after drawdown were equated with the "without" irrigation situation, then the no drawdown case could be regarded as the "with". For the latter, the yield would be that which would have occurred had the crop been irrigated with an amount of water equivalent to the moisture lost as a result of drawdown. Thus, if a total of 25mm of water were removed from the crop root zone due to drawdown, the resultant reduction in yield would be equivalent to the increase in yield after one irrigation application of 25mm. Shalhevet et al (1979) had obtained reasonable relationships between relative crop yield and net water application for a variety of crops, but their work was undertaken under semi-arid conditions in Israel.

In 1981 passing interest had been shown in the irrigation studies at Gleadthorpe Experimental Husbandry Farm (EHF) reported in a booklet titled *Sandland Irrigation* (MAFF, 1977). Attention again focused on this work and, following a visit to Gleadthorpe and acquisition of more detailed experimental results, a more detailed analysis of the data was undertaken. As Section 7.3.2 shows, the Gleadthorpe data enabled a set of relationships to be derived which could be used for assessing the effects of groundwater drawdown on crop yield.

7.3.2 MOISTURE LOSS / CROP YIELD FUNCTIONS FOR POTATOES, SUGAR BEET AND CEREALS.

Gleadthorpe EHF is located to the north west of Nottingham on the Bunter sandstone. The main soil series, Newport, Bridgnorth and Crannymore, are the same as those found on sandy parent material within the Tern Area. Since the two locations are at approximately the same latitude, only some 100 km apart and with similar geology and soils, it was reasonable to assume that, for the two sites, crops would follow similar growth patterns and react to irrigation in the same way.

For sugar beet the records of irrigation/yield studies at Gleadthorpe EHF date back to 1955, and they begin in 1960 for potatoes and spring barley. Access to the library at Gleadthorpe enabled records and annual reports to be examined, and from these the following data were gathered:

a) the operating rules for each experiment;
b) irrigation dates;
c) quantity of water applied to each experimental plot;
d) increase in crop yield for each irrigated plot;
e) date in the autumn on which the soil returned to field capacity.

In the latter case SMD records were often missing towards the end of the growing season and it was not possible to obtain a complete set of data. A decision, therefore, was taken to regard the period of irrigation benefit as lasting from the time of application through to either the harvesting date or senescence, whichever was earlier. Data, shown in Table 7.2, relating to the growth characteristics for the crops under consideration were gleaned from Gleadthorpe EHF annual reports.

For each crop under consideration two relationships were examined: that between increase in crop yield (ΔY) and irrigation application (A); and, that between increase in crop yield (ΔY) and moisture benefit (B). *Moisture benefit* was defined as the irrigation application in mm of water multiplied by the period of irrigation benefit - the time in days between the date of application and harvest or senescence. Researchers have shown that most crops have a particular period (or periods) during their growth cycle when they receive particular benefit from irrigation. Some details are given below, but for a more extensive discussion the reader is referred to Salter and Goode (1967).

i) Sugar Beet:
  irrigate to maintain active growth till August (Haddock, 1949);
  no irrigation before late June/early July (Brouwer, 1959);
  irrigate to establishment - early growth most critical (Penman, 1952; Orchard, 1960);
  irrigate through July and August if SMD>75mm (MAFF, 1977);
  for max sugar content, irrigate mid season to Aug (North, 1960).

ii) Spring Barley:
  irrigate to maintain SMD<50mm mid May to Mid June (MAFF, 1977);
  irrigate at booting - 7th and 8th leaves appear (Kreigbaum, 1955);
  irrigate from earing to flowering (Brouwer, 1959);
  irrigate from shooting onwards (Moliboga, 1927).

iii) Maincrop Potatoes:
  irrigate at tuber initiation (MAFF, 1977);
  irrigate when tubers reach marble size - early June at Gleadthorpe (North, 1960; Carter, 1960);
  for scab control irrigate from tuber initiation for at least 6 weeks (MAFF, 1977).

iv) Early Potatoes:
  irrigate to maintain SMD<25mm throughout growing period (North, 1960; MAFF, 1977).

To undertake a detailed evaluation of the effects of groundwater drawdown requires a comprehensive model for each crop which includes the actual timing of moisture removal in relation to sensitive periods of crop growth. Given the spatial and temporal variations associated with the parameters which would have had to have been considered, such detailed modelling was unnecessary for a procedure designed to assist developers at the planning stage of a groundwater project. However, a crop yield/moisture benefit function has the advantage over a straightforward crop yield/irrigation application relationship in that the time between the irrigation and harvest or senescence is taken into account. In the former function a measure of the age of the crop, and hence indirectly the stage of growth, when irrigation occurs is incorporated into the relationship.

The results from the analysis of the Gleadthorpe EHF irrigation experiments are given in Table 7.3 and the data are presented in Appendix 4. Attempts to fit polynomials to the data failed to improve the goodness of fit significantly when compared to straightforward linear regression. For use in the analysis of the effects of drawdown on crop yields, the crop yield/moisture benefit functions have been chosen since they incorporate a time factor. When the data for maincrop and early potatoes were combined, marginally better relationships were obtained than for each individually, and hence the combined result was employed.

CHARACTERISTIC	SUGAR BEET	SPRING BARLEY	MAINCROP POTATOES	EARLY POTATOES
Planting	mid March to early April	February to March	1st/2nd week of April	March to April
Emergence	3 weeks after planting	1 to 2 weeks after planting	4 weeks after planting	3 weeks after planting
Full cover	end July	mid April	end June	mid/end June
Senescence	not usually reached: tops cut for feed	late July	end August to end September	lifted before reached
Harvest	October to December	mid August	late September or October	June to July
Final date for 'moisture benefit'	15th October (assumed date tops cut)	31st July (assumed senescence)	15th September (assumed senescence)	15th July (assumed lifting)

Table 7.2 Crop Growth Characteristics.

As no further data could be found for other cereal types, the relationship derived for spring barley was taken as representative of all grains. This assumption was considered reasonable in view of the fact that barley dominated the land under cereals within the Tern Area.

On the basis that the "with and without" irrigation analogy for evaluating the effects of groundwater drawdown on crop yields was valid, the functions given below were used (see Ch 8) to calculate the yield decline (ΔYD) resulting from the *Moisture Debt*.

Sugar Beet $\Delta YD_S = 0.0025\ MD - 7.71$ - Eqn 7.2
(ΔYD_S in tonnes/ha)

Cereals $\Delta YD_c = 0.18\ MD + 104$ (ΔYD_c in kg/ha) - Eqn 7.3

Potatoes $\Delta YD_p = 0.0017\ MD - 0.116$ (ΔYD_p in tonnes/ha) - Eqn 7.4

where: MD = the *Moisture Debt* (in mm.days) - which is defined as the loss of moisture from the root zone multiplied by the period of moisture debt - the time in days between the date of moisture removal from the soil profile and harvest or senescence.

7.4 THE EFFECT OF MOISTURE LOSS ON GRASS.

7.4.1 THE ROOTING DEPTH OF GRASS.

In a study of the *Factors Affecting the Productivity of Permanent Grassland,* Forbes et al. (1980) reported that swards contained a wide variety of grass species, both sown and wild. The crop rooting depths for permanent pasture given in Table 7.1 can, therefore, only be regarded as broad guidelines: the rooting depths for individual grasses vary considerably. Tayler (1965) found that grass swards of perennial ryegrass and cocksfoot removed moisture from a depth of at least 0.9m, and reported another case where for ryegrass the depth of moisture removal was 1.2m. In their literature review Taylor and Terrell (1982) quoted red clover as having a 'working rooting depth' of 1.2m and a 'maximum rooting depth' of 3.0m, which contrasts markedly with sheeps fescue which had rooting depths of 0.3m and 0.7m respectively. The mean 'maximum rooting depth' of 21 grasses listed by Taylor and Terrell was 1.75m, which was accepted as a good representative value to take when considering the effects of groundwater drawdown on permanent pasture.

The three rooting depths given in Table 7.1 for short term leys agree well, and the maximum depth given, 0.6m, has been used in determining their susceptibility to pumping effects.

Crop	Yield Increase/Total Irrigation (ΔY vs A)	Yield Increase/Moisture Benefit (ΔY vs B)
Sugar Beet	$\Delta Y = 0.186 A - 5.95$ $r = 0.820$ ΔY in tonne/ha A in mm	$\Delta Y = 0.0025 B - 7.71$ $r = 0.833$ ΔY in tonne/ha B in mm.days
Spring Barley	$\Delta Y = 11.8 A + 46.7$ $r = 0.525$ ΔY in kg/ha A in mm	$\Delta Y = 0.18 B + 104$ $r = 0.643$ ΔY in kg/ha B in mm.days
Maincrop Potatoes	$\Delta Y = 0.174 A - 8.16$ $r = 0.861$ ΔY in tonne/ha A in mm	$\Delta Y = 0.0022 B - 5.78$ $r = 0.795$ ΔY in tonne/ha B in mm.days
Early Potatoes	$\Delta Y = 0.067 A - 0.131$ $r = 0.602$ ΔY in tonne/ha A in mm	$\Delta Y = 0.0016 B + 1.2$ $r = 0.603$ ΔY in tonne/ha B in mm.days
All Potatoes	$\Delta Y = 0.156 A - 5.79$ $r = 0.868$ ΔY in tonne/ha A in mm	$\Delta Y = 0.0017 B - 0.116$ $r = 0.806$ ΔY in tonne/ha B in mm.days

Table 7.3 Crop Yield Functions Derived from Gleadthorpe EHF Irrigation Data
(r = coefficient of correlation)

7.4.2 MOISTURE LOSS AND GRASS PRODUCTION.

Grass yield models fall into the same categories as those outlined for crops in Sect. 7.3.1, and, as stated earlier, in the context of this research the application of a sophisticated model is unnecessary. However, before discussing the actual relationships employed it is worth drawing the reader's attention to the *Grassland Simulation Model* published by Innis (1978). This not only deals with those aspects relating to the growth of grass, but also covers mammalian consumers, grasshopper populations and decomposition!

No data in the same form as that acquired for sugar beet, potatoes and barley, were found for grass. It was not possible, therefore, to derive a yield function of the same form as was produced for those crops (see Sect. 7.3.2). However, by combining information from a number of sources two relationships were derived for the irrigation of pasture supporting either dairy or beef cattle. In these relationships the increase in production per unit of irrigation application was determined. The absence of a time factor was not felt to be of significance as, although grass growth rate reaches its peak in spring, production continues throughout the year (Ivins, 1959) and benefits from irrigation at intervals from May to August have been observed (Penman, 1970).

Unfortunately no models have been produced by the author for grass yields in relation to hay and silage. In the case of hay, de Wit (1958) reviewed work undertaken in the United States and provided a series of relationships between yield and available moisture which could possibly have been adapted. However, since the loss of grass intended for hay or silage would necessitate the purchase of additional feed, the effects would be similar to the loss of pasture supporting beef cattle (see Sect 8.5.1.4). Thus the lack of hay and silage production models was considered acceptable. Furthermore, for the Tern Area no data on either the production of hay and silage or its consumption were available.

7.4.2.1 Grass Supporting Dairy Cattle.

Tayler (1965) stated, when evaluating the benefits of irrigation, that the increase in herbage yield of grass swards was between 350 and 400 lb dry matter per acre-inch (0.18 tonne/ha per 10mm). From the results obtained from grazing experiments with two different stocking rates, he deduced that this would result in an increase of 15 grazing days per acre per annum for each inch of irrigation - 37 grazing days/ha per 25mm. Converting this to milk yields he estimated that, for an average seasonal application of 5 inches (127mm), production would be raised by 60 - 180 gallons per acre. Therefore, summarising Tayler's evaluation of the effects of irrigation on dairy farming:

> 10mm of irrigation water results in an increase in milk yields of 110 litres per ha.

Penman (1970), on the other hand, suggested an increase in yield of 0.24 to 0.4 tons/ha for 10mm of irrigation. Taking the average of Penman's and Tayler's values as being representative (ie. 0.25 tons/ha per 10mm) and using Tayler's conversion rate for enhanced milk production from an increase in grass yield, the effect of irrigation on dairy farming becomes:

> 10mm of irrigation water results in an increase in milk yields of 153 litres per ha.

Can this relationship be applied to the case where there is a loss of moisture? Tayler, in the same paper, reported experimental findings had shown that moisture deficits of 38mm and 50mm led to reductions in annual grass yields of 5% and 10% respectively, whilst 178mm of irrigation resulted in an increase in grazing days of 44%. Assuming that the number of grazing days is directly proportional to the grass production, the above figure indicates that 50mm of irrigation would result in a yield increase of 12%. The magnitude of the increase in yield resulting from 50mm of irrigation is, therefore, very similar to the reduction in yield caused by a deficit of 50mm. On this evidence it would seem reasonable to equate an increase in yield from irrigation with a decrease resulting from loss of moisture, and the following relationship has been used in determining the effects of moisture loss on dairy pasture (see Ch 8):

Pasture: Dairy Cattle $\Delta YD_d = 15.3\ ML$ - Eqn 7.5

where: ΔYD_d is the loss of milk production in litres per ha;
ML is the total loss of moisture from the root zone in mm.

7.4.2.2 Grass Supporting Beef Cattle.

In addition to their *Sandland Irrigation* booklet Gleadthorpe EHF have also produced a *Beef and Grass Booklet* (MAFF, 1978). This booklet showed that at Gleadthorpe beef cattle were turned out to graze in mid-April and returned to the yard in mid October. Assuming a similar pattern for beef farming in Shropshire, this gave approximately 180 days of grazing per annum under normal conditions.

From Tayler's estimations (1965), 10mm of irrigation results in an increase in grass production of 0.18 tonne/ha, which in turn allows an increase in grazing days of 15 per ha. Taking the average of Tayler's and Penman's estimates of grass production increase (as in Sect. 7.4.2.1 above) and using Tayler's conversion rate, then 10mm of irrigation will result in an increase in grazing days of 21 per ha.

Forbes et al (1980) found that nationally the average stocking rate for beef fattening farms was 2.6 beasts per ha. If this stocking rate is accepted, then under normal conditions, each hectare supports 2.6 x 180 = 468 grazing days per annum. Thus 10mm of irrigation, in producing an increase in grazing days of 21 per ha, allows one hectare to support an additional 0.12 of a beast per annum.

Taking an alternative approach, Davison (1959) stated beef cattle consume 20.5 lb of grass per day, which over a period of 180 grazing days gives 1.65 tons . At 2.6 beasts per ha, each hectare must therefore yield 4.29 tons of dry matter per annum. If, as deduced above, 10mm of irrigation produces an additional 0.25 tons/ha then it will allow an additional 0.15 beast to graze.

From the average of these two results an additional 0.135 beef cattle can be supported each year per ha per 10mm of irrigation applied. Using the arguments forwarded in Sect. 7.4.2.1, the following relationship for evaluating the effects of groundwater drawdown on pasture grazed by beef cattle was therefore adopted:

Pasture: Beef Cattle $\Delta YD_b = 0.0135\ ML$ - Eqn 7.6

where: ΔYD_b is the reduction in number of beef cattle supported per ha;
ML is the total loss of moisture from the root zone in mm.

7.5 TREES.

Although trees possess greater rooting depths than most other vegetation, where shallow water tables are present roots are restricted to the unsaturated zone and, during a period of drought, they may follow a falling water table down in search of water. If these roots are then flooded as a result of groundwater recovery the tree will be weakened (Ruark et al, 1983). Moisture stress affects trees directly by reducing cell turgor and interfering with metabolism and cell enlargement and, although this is unlikely to kill the tree directly, it will be weakened and made vulnerable to disease and attack by insects.

The very fact that trees are deep rooting means that determination of their rooting depths is difficult, and consequently there is very little useable data in the literature. Zahner (1955) found moisture depletion to depths of 1.8m under stands of both pine and hardwoods, and Fletcher and Lull (1963) recorded losses to 1.1m. In both instances the depths quoted were to the limit of hand soil sampling, and the maximum depth to which depletion occurred was not ascertained. Soil moisture removal has been recorded to a depth of 3.5m under white oak, 3m under larch, 2.5m under maple and white pine, and 2m under green ash (Gaertner, 1963). However, in all these instances the depths given denote the water table level and thus further root penetration by the trees concerned was unnecessary, and would indeed have been restricted.

In their irrigation guide MAFF (1974) advise the use of rooting depths greater than 1.2m for mature fruit and nut trees. Data for fruit trees is more readily available as can be seen from Table 7.1, and a value of 2.4m would seem sensible when considering the effects of groundwater drawdown. No orchards were reported during the 1980 crop survey, so where fruit trees existed they were solitary, or in small groups, and for domestic, not commercial, use. Fruit trees were therefore too few to warrant detailed consideration.

In the Tern Area the small areas of planted woodland mainly consisted of conifers. However, it was the individual or small groups of trees that the County Council considered, at the public inquiry, to be most important as they formed a "valuable part of the landscape" (Gray, 1980). The "native" trees that Severn Trent WA were planning to use to screen their works were: oak, ash, beech, field maple, pine, bird or gean cherry, and hornbeam (Gray, 1980). The only trees in this list for which rooting depths were known were hornbeam and scots pine for which Taylor and Terrell (1982) quoted maximum rooting depths of 3.5m and 1.83m respectively.

When reviewing the effects of moisture stress on trees, Kozlowski (1958) concluded that in general restrictions in moisture supply during the growing season affected diameter growth more than height growth - a view supported by Gaertner (1963). Bassett (1964), from studies of pine and mixed hardwood in Arkansas, produced linear relationships between basal area growth and number of 'no-growth days' per annum - the 'growth day' unit being an index of the degree to which water stress reduced the daily potential diameter increase. Had commercial forestry been significant within the Tern Area Bassett's approach could have formed the basis of a method for determining the effects of drawdown. However, since it was the aesthetic aspect of the Tern Area which was at risk if trees were affected by moisture loss, no attempt was made to evaluate the effect in monetary terms.

Ede (1979) at the public inquiry produced evidence to suggest that 10m rooting depths for trees were not impossible, whilst Kramer (1952) quoted the example of an apple tree in Nebraska drawing on water to a depth of 10m. However, in the absence of firm data to support such claims, the maximum acceptable known rooting depth, 3.5m, was used to find the extent of the area within which trees could be affected by groundwater pumping (see Chapter 8).

Chapter 8. AN ENVIRONMENTAL ASSESSMENT TECHNIQUE FOR EVALUATING THE IMPACT OF GROUNDWATER SCHEMES ON CROPS AND TREES.

Chapter 3 was devoted to a discussion of the environmental impacts associated with groundwater schemes, and in particular the effects on agriculture. Involvement with the Shropshire Groundwater Scheme, as discussed in Chapter 5, emphasised the ad hoc way in which the effects of drawdown on crops and trees was assessed. This chapter is devoted to the development of a technique which enables: (i) the areas sensitive to the effects of groundwater drawdown to be identified; and (ii) the effects on crops and trees to be evaluated.

Initially the ideas and principles underlying the method will be introduced. This will be followed by a discussion of the technique's development during its application to the Tern Area of the Shropshire Groundwater Scheme. In Chapter 9 the principal steps of the technique will be put into a generalised form, and its potential and suitability for incorporation into a Geographical Information System (GIS) evaluated.

8.1 BACKGROUND TO THE TECHNIQUE.

When it was decided in 1980 to undertake a research project based on the involvement with, and the field work undertaken for, the Shropshire Groundwater Scheme public inquiry, McHarg's book *Design with Nature* (1971) immediately sprang to mind. McHarg was a champion of the 'ecological' planning method and an outspoken critic of the traditional notion that urban development must be imposed upon the landscape regardless of the ecological consequences. In *Design with Nature* he set out to demonstrate that man-made structures could be incorporated successfully within the existing natural order, and that their impact on the environment could be minimised. Of particular interest was his technique of using map overlays to identify ecologically sensitive areas and to rank the effects of a particular development project on the environment.

The overlay technique involved preparing coloured transparent maps of each feature, or ecological parameter involved or likely to be affected. The maps identified the incidence of each factor, and different colours or colour intensities were used to indicate their relative importance with respect to the study in question. Subsequently, by simply overlaying the transparancies one on the other, the effect on the environment could be assessed through visual interpretation of the combined maps or 'composites'.

The application of the overlay method for the identification of areas sensitive to groundwater drawdown appealed to the author, and the preparation of relevant maps began in 1981.

Although the use of computers was considered when this work started, in the early 1980's the facilities at Aston University were still in their infancy relative to those available today. However, shortly after it came on to the market the author acquired a BBC B microcomputer with a 32K memory. After some experimentation, it was decided that each map could be digitised by storing the data in a two dimensional array, and that the original principle of overlaying individual maps to produce a composite could still be retained. The latter would be achieved by employing a set of rules whereby the elements representing the same ground area in two different arrays would be interrogated to produce a third parameter embodying the essence of the first two. These new parameters could then be stored in a third array - thereby producing a composite map of the first two. Further details of the method and the programs which were developed are given in Sect. 8.2.

Although the approach has proved successful, the memory available in the early BBC micros was limited and, in spite of acquiring an addional 20K of RAM, in order to digitise just one map covering the Tern Area four arrays were required. If Personal Computers (PCs) such as the current generation produced by IBM had been available when the work began, the task would have been easier and a more sophisticated approach could have been adopted. Although technological progress, such as the advent of packages for digitising maps, has overtaken the author's original concept, the principles involved are still valid and their potential for incorporation into todays state of the art GIS systems is discussed in Chapter 9.

8.2 DIGITISING THE MAPS.

For the reasons given in Sect. 8.1, a BBC B microcomputer with an additional 20K RAM board was used for all work associated with the maps of the Tern Area. The BBC was served by one single disc drive providing 40K of data storage on each $5^1/_4$ inch floppy disc. Programs were written in BBC BASIC using the machine's in-built ROM, which enabled the bulk of the available 52K of memory to be used for running the programs and processing the data.

The programs were written to be as 'user friendly' and as versatile as possible so that they could be made available to other BBC operators. To date copies have been given to several schools, and a small company of environmental consultants has used the package to map variations in nitrous oxide across Birmingham.

8.2.1 DEVELOPMENT OF THE SUITE OF COMPUTER PROGRAMS.

Development of the programs has taken place over a number of years and with the acquisition of experience their sophistication has increased. Each one of the five programs written for the input and output of data has one specific objective. However, each also has facilites for performing other operations which may be common to several of the programs. This has been made possible by the use of procedures, a feature unique to BBC BASIC and somewhat similar to sub-routines, but simpler to operate. Procedures written initially for one program have been transferred wholesale to others with no editing necessary. It has thus been possible to build up a range of operations for each program around its prime function, thereby providing maximum versatility whilst working at the limit of the available memory.

In order to process the map data within the available memory the Tern Area has had to be divided into four. Thus, for each subject being considered (eg. geology, soils), four sub-maps have been produced each of which covers an area of six by five Ordnance Survey grid squares - 30 sq km. As each grid square is sub-divided into 100 elements, each representing 100 sq m, a 60 by 50 two dimensional array has been required to store the information. Again the constraints imposed by limited computer memory meant that it was only possible, for an array of this size, to store the data in integer form.

Furthermore, working at the limit of the computer's memory has resulted in programs not being as user-friendly as the author would have wished. For example, it has not been possible to incorporate error trapping facilities and the design of the key for each map has been restricted to ten variables.

One further feature of the map digitisation process needs to be considered in this section. For ease of operation a decision was taken early in the program design process to separate the map data from that necessary to 'control' the input process and annotate the map. The former will in future be referred to as the *map data file*, and the latter the *command file* - their use is explained further in Sect. 8.2.2. There were several reasons for the decision to separate these data:

a) it was necessary to provide the array size and map key before the map data file was set up;
b) the small size of the command file enabled it to be edited with ease without having to handle all the map data;
c) the size of the map data file was such that it took 40 secs to read, whilst the command file could be input in milliseconds.

A total of ten programs have been written for digitising and manipulating the map data. Six programs provided a variety of input and output functions, and two catered for the production of composite maps. The nineth program enabled appropriate values for each element of a grid square to be obtained from contour maps, and the final program determined the effect of drawdown on crop yields. The purpose of the eight programs written for delineating the area sensitive to drawdown is outlined in Sects. 8.2.2, 8.2.3 and 8.2.4, whilst documentation is provided in Appendix 5. The remaining two programs are discussed in Sect 8.5.1.3 and Sect 8.5.1.5.

8.2.2 THE PROCESS OF DIGITISING THE MAPS.

The production of the computer maps involved five stages:

i. acquisition of data and preparation of original map for data abstraction;
ii. production of command file;
iii. the setting up of the map data file;
iv. inputting information to map data file and editing the data;
v. outputting the digitised map in an appropriate form.

Fig 8.1 is a diagramatic representation of this process.

The acquisition of information on the various characteristics of the Tern Area which were required for the Evironmental Assessment is discussed in Sect. 8.3. Once obtained, information was transferred to 1: 25000 paper maps, a process that facilitated the act of digitisation. This was found to be particularly difficult if the map scale was too small since confusion often occurred. Where the transfer process involved scaling up a source map a transparent overlay grid was employed to locate points of reference. These points were subsequently drawn on appropriate 1:25000 Ordnance Survey maps using an overlay frame around the appropriate grid square (see Fig 8.2).

The program MAPCOM was written for construction of the command files (for documentation see Appendix 5). Input information to these files included: map title; the bounding grid lines, from which the array size was calculated; and the map key. Ten separate one digit numbers were available to define the features of each map, and those areas where information was lacking were automatically denoted by an 'x' on hard copy output (input, if required, using -1). Each key was restricted to a maximum of ten items

Fig 8.1 Diagramatic Representation of Map Digitisation Process

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Fig 8.2 The Use of Overlay Frames for Scaling and Digitising Maps so that it was possible to obtain a direct paper printout of the map in terms of the input codes.

MDATIN was used both to set up the original data file and to input map data. Setting up a data file involved obtaining the array dimension from the command file and then simply setting all elements to -1 (ie. no information), defining the data file name, and saving the file to disc. Data input began with the selection of the grid square to be processed, next an appropriate key code was entered to represent the information in each of the 100 sq m map elements identified on the 1:25000 map using a transparent grid overlay (see Fig 8.2). Incorrect entry of information could be corrected by use of an edit facility.

Data output could be achieved in three ways (see Fig 8.1). The first programme written for this, MPRINT, allowed hard copies of the data to be obtained by printing the actual key codes for both individual squares and for the entire map. MAPSEE, the second program, also contained the facility for printing out individual squares. However, its prime function was to provide a colour visual display for both map and individual squares. Hard copies were successfully obtained by photographing the VDU screen. The final output programme, MAPDUMP, was initially written as a variation of MAPSEE. Instead of each element of the array being represented by a colour, black and white shading was employed. This enabled the screen and key to be dumped to an Epson printer using a screen dump routine (Powys-Lybbe, 1983). MAPDUMP also possessed the facility for calculating the total area of each parameter represented on a map and for producing a hard copy of the results. Examples of all the types of output are presented in Appendix 5.

8.2.3 THE PRODUCTION OF COMPOSITE MAPS.

Although only one program was written for producing composite maps (MMERGE), it was found that a second (MSIMPLY) was often necessary to rationalise the original digitised maps. The need for the latter was due to the limited memory available on the BBC, which meant that the number of key code combinations that MMERGE could handle was restricted to fifteen. Documentation of these programs, together with examples illustrating their operation, is given in Appendix 5.

Composite maps were built up by combining digitised maps two at a time. The first step of the process involved producing (using MAPCOM) a command file for the product map in which the final key was defined (i.e. codes and descriptions). This was read in by MMERGE together with the command files for the two source maps. Using the three map keys the operator was able to select which codes of the two source maps were to be combined to produce the appropriate pre-defined code of the composite. MSIMPY was a variation of MMERGE, where only the original map and its final rationalised form were considered.

8.2.4 INTERPOLATION BETWEEN CONTOURS.

Several of the maps under consideration presented information as contour lines (eg. depth to the groundwater table). Initially these maps were digitised by providing a single map code to represent the area between two adjacent contours (see Sect. 8.3.5). However, it was felt that, after using these maps for crude delineation of sensitive areas, a more exact analysis would be required. The approach adopted in order to achieve this utilised the concept of shape functions, which are an integral part of parametric finite element analysis. For a full discussion of shape functions and their use the reader is referred to standard texts on the subject such as those by Zienkiewicz (1977), Pinder and Gray (1977), Cook (1981) and Reddy (1984). Inspiration for this approach came from the application of shape functions to the problem of determining areal rainfall from point measurements at different altitudes (Hutchinson and Walley, 1972).

Three methods of determining the levels at each of the individual elements within a grid square were tried, all of which were accessed from the program MAPSURF (see Appendix 5). All three approaches relied upon the values of the parameter under consideration at each grid line intersection (node) being estimated manually from the contours - either graphically or through linear interpolation.

The first method (MAPSR1) considered one grid square, with the input being the levels at the four corners. The second calculated values for all the elements in four adjacent squares, and required input levels for the nine grid nodes involved (MAPSR4). Finally, levels within the central square of a group of nine were determined using the surrounding twenty-four nodes (MAPSR16). This last approach was an adaptation of the second method, and calculated the element levels in the central square by considering it four times. Each time this central square was taken as one corner of a group of four, with the final result being the average of the four separate calculations - in effect a smoothing process.

The reason for writing the third part of the program was that, when the first two were tested against elevations on 1:25000 maps of the Tern Area, discontinuities were found to exist at the junctions between squares where the surfaces produced by two different sets of calculations met. This problem was particularly noticable where the ground level changed rapidly over the one kilometer width of a square. Although the boundary effects were reduced using this last approach, better results would have been obtained by determining the values for the central square using all twenty-four nodes simultaneously. However, the complexity of the shape functions required to achieve this was felt to add an extra dimension to the research, and this option was not pursued further.

Overall the technique proved unsatisfactory for modelling terrain due to the wide spacing of the nodes. To obtain improved results internal nodes within each grid square would have been necessary. However, due to the more gradual changes involved, groundwater levels and drawdown surfaces were simulated with more success although the accuracy, when calculated mid-square profiles were compared with those plotted manually, was still not entirely satisfactory (see example in Appendix 5; Fig A5.16).

8.3 THE PHYSICAL CHARACTERISTICS OF THE TERN AREA.

The extent of the Tern Pilot Study area delineated by Severn Trent Water Authority is shown on Fig 2.7. However, from the figures and drawings presented in the Authority's own reports it was clear that the effects of pumping would extend beyond the boundary shown. It was therefore decided from the outset to gather as much relevant data as possible for the area, shown in Fig 8.3, bounded by longitudinal grid lines 55 to 67 and latitudinal grid lines 20 to 30 on Ordnance Survey 1:25000 Sheets SJ 52 (OS, 1963) and SJ 62/72 (OS, 1976). It was not possible to extend the area beyond these boundaries as in each instance they marked the limit of knowledge for at least one parameter.

8.3.1 PHYSICAL FEATURES.

The study area, as shown in Fig 8.3, covers 120 square kilometers of the southern part of the Cheshire Plain. It is entirely rural in character and the small villages are all mentioned in the Domesday Book (Crompton and Osmond, 1954). The gently undulating, highly cultivated farmlands of the area are interspersed with small areas of woodland, and hedgerows are a common feature of the countryside. Most of the area lies between 60m and 100m above sea level, but the plain is broken to the north west by a chain of low hills with steep slopes. The highest of these is Hawkestone (208m) to the west of Hodnet.

The River Tern rises in Staffordshire and flows almost due south through the eastern half of the area. There are two other rivers of a reasonable size: the Roden in the west, which again flows south; and, the Meese, which enters the area in the south east corner and flows westward until it meets the Tern just south of Great Bolas. The valleys of the area tend to

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Fig 8.3

be broad and subject to flooding. However, between Stoke upon Tern and Great Bolas the Tern itself is confined to a relatively narrow valley with little truely riparian land.

8.3.2 SOLID AND DRIFT GEOLOGY.

For an overview of the geology of the area the reader is referred to Hains and Horton (1969). A more detailed description is provided by Pocock and Wray (1925) in their Memoir of *The Geology of the Country around Wem* , which was written to accompany the Geological Survey's one-inch map Sheet 138 (Wem). The most recent geological map of the area is the Institute of Geological Sciences 1967 revision of Sheet 138, Solid and Drift Edition (IGS, 1967).

The Triassic sandstones form the bulk of the solid geology of the Tern Area, and are the water bearing strata which form the aquifer pumped by Severn Trent Water Authority. The suitability of these sandstones as an aquifer arises both from their high porosity and from their high permeability. The term Triassic sandstones collectively describes a variety of both Bunter and Keuper sandstones and, for the purpose of this study, will in future be referred to simply as the *aquifer*. Also present are Keele Beds just north of Childs Ercall and in the south west corner of the study area, and Keuper Marl to the north west. The Keuper Marl consists of mudstones and siltstones, and the Keele Beds are a combination of marls and sandstones - neither formation possesses the characteristics required of an aquifer.

The drift, which covers the region to the west of longitudinal grid line 55 to thicknesses in excess of 20 m, thins out over the Tern Area and in a number of places the aquifer outcrops. The origins of the drift are complex and are the result of several periods of glaciation (see Pocock and Wray, 1925). It is believed that in the last phases of the glacial period the drainage patterns, including the course of the R. Tern, were disrupted by the ice sheet and morainic deposits. A large lake, Lake Lapworth, formed which eventually overtopped the original watershed to discharge to the south by what is now the Ironbridge Gorge of the River Severn. Thus, in addition to relatively impermeable boulder clay of direct glacial origin, there are extensive deposits of lacustrine sand and gravel.

Pocock and Wray (1925) discuss the theory that the present River Tern occupies the valley of a much larger stream which, as a result of post-glacial denudation, had its headwaters captured by the River Ducklow, which flows north into the Dee and Mersey basin. This theory explains the alluvial deposits and terracing alongside the Tern and why it occupies, for at least some of its length, a narrow relatively deep valley within a much wider shallow one (see Sect 8.3.1).

Two digitised geological maps have been produced, one based on the one-inch map of the Institute of Geological Sciences (IGS, 1967), and the other a transcription of a Drift Thickness and Lithology Map (ACS 13) presented by Skinner at the 1979 public inquiry. The former, Fig 8.4, shows either where the aquifer outcrops or the drift overlying it, but where the Keuper Marl and Keel Beds are present they alone are shown. This approach was adopted to simplify analysis since these latter formations do not form part of the aquifer, and therefore the areas concerned cannot be affected by pumping. The computer version of Skinner's drift map (Fig 8.5) delineates aquifer outcrop, permeable sandy drift and impermeable clayey drift. The clayey drift is divided into two categories depending on whether the drift thickness is greater than or less than 5m.

8.3.3 SOILS.

There are five main factors which influence the formation of a soil: time, parent material, climate, organisms and topography (FitzPatrick, 1974; Curtis et al, 1976). Given the relatively uniform nature and small size of the Tern Area, it is the parent material which has been primarily responsible for the variation in soil types within the study area. The Memoir (Crompton and Osmond,1954) associated with the Soil Survey map Sheet 138 provides a detailed discussion of the soils of the Tern area.

The dominant soil types and series within the Tern Area, together with their parent materials, are listed in Table 8.1. For the purpose of the soil map (Fig 8.6) the other soil series which were present were grouped, according to their parent material, into miscellaneous till soils and miscellaneous sand soils.

Brown earths are the characteristic soils of temperate deciduous forests. They have a high natural fertility because they are basic (i.e. not acidic) and possess vigorous populations of soil fauna and flora within the upper horizons. Brown earths are freely drained, have no sharply defined horizons and are of a fairly uniform colour. The colour, which for the Tern Area is invariably red or reddish brown, is influenced by the parent material. The soil at the Heath House site belonged to the Newport Series and profile descriptions are given in Appendix 2.

SOIL TYPE	SOIL SERIES	PARENT ROCK TYPE
Brown Earths	Newport Bridgnorth Hodnet	Lower Mottled Sandstone and Glacial Sands Lower Mottled Sandstone and Glacial Sands Keuper Waterstones
Humus-Podzols	Crannymoor	Glacial Sands and Lower Mottled Sandstone
Gley Soils	Salop Wem	Boulder Clay Boulder Clay
Organic	Peaty Loam	River valley peats
Alluvium	Alluvium	River valley alluvium

Table 8.1 The Main Soil Types Present in the Tern Area

The Crannymoor series is the only Humus Podzol present in the area. In their natural uncultivated state these soils form under mixed deciduous / coniferous woodland. Prior to cultivation the main characteristic of this soil would have been a pale grey or white layer, from which the colouring agents had been leached, beneath the dark surface organic horizons. Under cultivation the uppermost horizons are mixed and consist of black, or very dark grey, humose sand which is structureless and loose with abundant bleached sand grains (Crompton and Osmond, 1954). These soils have a light texture and are usually freely drained, but their low moisture capacity means that plants can suffer seriously in dry seasons.

Gley soils are characterised either by the presence of grey colours in the subsoil, indicative of impeded drainage, or by the presence of yellow and brown mottlings that indicate a fluctuating water table. In the Tern Area intensely gleyed soils are generally under grassland, but soils with less intense gleying are often cultivated (Crompton and Osmond, 1954). The Salop Series form where the clayey triassic till is lighter in texture or is covered by a thin layer of sandy material. The soil profiles exposed at Greenfields and Childs Ercall were all of the latter type (see Appendix 2). Soils of the Wem Series are formed where the sandy deposits overlying the clayey till are deeper than those of the Salop Series - they are therefore better drained.

As part of the post-inquiry study and monitoring programme associated with the development of Stage 1 of the groundwater scheme (Tern 1), Severn Trent Water Authority commissioned a detailed study of the soils in the Tern Area (Soil Survey of England and Wales, 1982). The intensive nature of this survey resulted in twenty eight different soil series being identified, whereas Crompton and Osmond (1954) had only recognised seventeen for the same area. As it is likely that an authority promoting a groundwater scheme would rely on existing soil maps rather than go to the expense of a special survey, the map of the Wem District (Soil Survey of England and Wales, 1953) was used to produce the computer soil map (Fig 8.6). However, the data presented in the 1982 soil report were used in determining representative soil characteristics.

Information on the physical properties of each of the soil groups identified on the soil map (Fig 8.6) were gathered from the analysis of samples taken by the author, the 1982 Soil Survey report and the Memoir by Crompton and Osmond. Where possible the compiled data were used to determine the representative soil characteristics and textures shown in Table 8.2. As, in certain instances, Crompton and Osmond's texture classifications disagreed with those suggested by the proportions of sand, silt and clay determined from this and the Soil Survey's studies, the results were verified by a comparison with the appropriate soil profile descriptions given in Ragg et al (1984). For those soil groups starred in Table 8.2 representative proportions of sand, silt and clay were estimated from the known texture classes. The characteristics presented in Table 8.2 were used to determine appropriate critical heights for each soil group (see Sect. 8.4.2).

8.3.4 AGRICULTURE.

The long term annual average rainfall for the Tern Area up to the time of the inquiry was 231mm, which gave an average effective rainfall of 185mm (Skinner, 1979). Like most of lowland England the summer rainfall in this part of Shropshire is insufficient to meet the demands of evapotranspiration and the deficiency is made up through crops drawing on the soil moisture store or by irrigation.

Crompton and Osmond (1954) describe the historical background to the agriculture of the area which, in general, has led to a mixed farming economy. Traditionally the lighter soils would have been more suitable for arable cropping and the heavier ones would have been under grass. Mechanisation and modern farming techniques have meant that the current patterns of farming are not as restricted by soil type as in the past. However, the tradition of mixed farming has remained.

The Ministry of Agriculture Fisheries and Food (MAFF) annually undertake an agricultural census. However, as the results from the analysed Returns are presented in summary form for each parish, these data are inadequate for evaluating the effects of

Soil Group	% Sand	% Silt	% Clay	Bulk Dens (gm/cc)	Texture
Newport Series	81	15	4	1.5 - 1.8	sand/loamy sand / sandy loam
Bridgnorth Series	78	14	8	1.65#	sand/loamy sand
Hodnet Series*	45	35	20	1.65#	sandy silt loam / clay loam
Crannymoor Series	81.5	14	4.5	1.65#	sand/loamy sand
Salop Series	47	35	18	1.45 - 1.85	sandy silt loam / clay loam
Wem Series	56	29	15	1.65#	sandy clay loam / sandy loam
Alluvium	84	12	4	1.65#	loamy sand
Peaty Loam	62	21	17	1.65#	
Misc Till Soils*	55	30	15	1.65#	clay / clay loam
Misc Sandy Soils*	80	15	5	1.65#	sandy loam / loamy sand

Table 8.2 Texture Classes and Representative Characteristics of the Soils of the Tern Area.

N.B. * Proportions of sand, silt and clay estimated from texture classifications.
\# Representative value estimated through comparison with analysis results for field samples and reference to Hall et al (1977).

groundwater drawdown, which requires information on a field by field basis. A survey of the agriculture was undertaken on June 19th and 20th 1980, with further visits to the area made on July 16th and August 6th that year. Unfortunately it was not possible to return to the area and complete the survey before harvesting ended and, therefore, the whole area was not covered. Fig 8.7 is a print out of the digitised version of the crop survey, Fig 7.1.

In order to verify the accuracy of the survey, it was decided to compare the results with the Returns of the MAFF census for 1980. Parish boundaries are, of course, not compatible with those of the study area - as clearly illustrated by Figs 8.7 and 8.8. Of the 7395 ha covered by the agriculture survey 27% fell within the parish of Hodnet, 25% within Stanton upon Hine Heath and 24% within Stoke upon Tern, and therefore these three were selected for the comparison. For this exercise to be valid it was also necessary to ensure that the major part of each of the parishes in question fell within the survey area. Since 62% of the parish of Hodnet, 95% of Stanton upon Hine Heath and very nearly 100% of Stoke upon Tern were within the survey area, all three satisfied this criteria.

To enable a direct comparison of the relevant crop, grassland and woodland areas, the areas given in the 1980 MAFF Returns were reduced in direct proportion to the area of each parish that coincided with the survey area. For the survey the corresponding agricultural areas for each of the three parishes were determined using MMERGE from the data shown in Figs 8.7 and 8.8. Agricultural survey results, extracts from the MAFF returns and summaries of the comparisons are given in Appendix 6.

Fig 8.9 provides a visual comparison between the survey and the MAFF data. For the parishes of Stanton upon Hine Heath and Stoke upon Tern, given the constraints of the Aston survey, agreement with the MAFF Returns is acceptable, with the exception of potatoes. However, for Hodnet the results appear poor. Only 62% of this parish was coincident with that of the survey area and to the north, the area not covered by the survey, the topography was more upland in character than the south and hence the ratio of grassland to arable land was higher there. Consequently, as can be seen in Fig 8.9, the direct proportional reduction of 38% in the Returns data has led to the overestimation of the parish's grassland within the Tern Area and underestimation of the arable land.

Two possible explanations that can be given for the discrepancies between MAFF Returns and the survey results for potatoes. Firstly, some of the land which had already been ploughed at the time of the survey was assumed erroneously by the author to have been under this crop. Secondly, field boundaries were assumed to follow those on the 1:25000

Ordnance Survey maps, whereas changes may have occurred with the gradual move towards increased farm size (see Fig 8.10) and mechanisation.

The area devoted to woodland also requires comment. As far as can be ascertained, the MAFF agricultural census only considers land under private ownership. Consequently areas of common land, such as Hodnet Heath, identified as woodland by the Aston survey, were not accounted for in the Returns. This probably explains much of the difference shown in Fig 8.9, particularly for the parish of Hodnet. However, woodland boundaries have been taken as shown on Ordnance Survey maps and it is possible that some clearance may have taken place since these were drawn. The Returns over a period of fifteen years, Fig 8.10, show that this is a distinct possibility in the Stanton upon Hine Heath area, although in the Hodnet area there is evidence of a gradual expansion of woodland.

While the agricultural Returns for 1980 were being obtained, the opportunity was taken to acquire comparable data for the period 1969 to 1985 (see Appendix 6) since agricultural trends were considered important given the long life of the Shropshire Groundwater Scheme. Fig 8.10 shows that there has been a gradual process of amalgamation of farms over the sixteen years of available data. Farming practices themselves have changed little, although there is a continued increase in the areas devoted to sugar beet and potatoes, which appears to have been at the expense of ley pasture.

Given the lack of any alternative, and the reasonable agreement with MAFF Returns for the parishes of Stanton upon Hine Heath and Stoke upon Tern, the agriculture survey was considered to be sufficiently accurate to enable the effects of groundwater drawdown on vegetation to be evaluated. In addition, as agricultural practices have not changed significantly since 1980, the survey could also be used to evaluate the likely current effects.

8.3.5 THE GROUNDWATER TABLE AND DRAWDOWN.

During the public inquiry Walley (1979) presented Fig 5.24, a map of water table depths in the Tern Area. As explained in Section 5.6.4.2 this had been prepared by the author and Walley from ground level contours taken from 1:25000 Ordnance Survey maps of the area, and a drawing of water table contours for February 1972 found in the first pilot study report (Severn River Authority, 1972). As far as the inquiry was concerned, Fig 5.24 was superseded when the Water Authority presented their own map (see Sect. 5.6.4.2). In order to enable a comparison of the two maps both were digitised and are shown in Figs 8.11 and 8.12.

In his Proof of Evidence to the public inquiry Skinner (1979) included maps of pumping drawdowns. These were the end results of two computer simulations for the operation of the full scheme - firstly under 1974 conditions (ACS 8), and secondly for the 1974 to 1976 drought period (ACS 9). Both of these maps were entered into the computer (Figs 8.13 and 8.14) and, as with the maps of depth to groundwater, contours were not reproduced but drawdowns were represented by the areas bounded by two adjacent contours - thus each 'band' in effect represented the area subject to an average drawdown equal to the mean of the two contours.

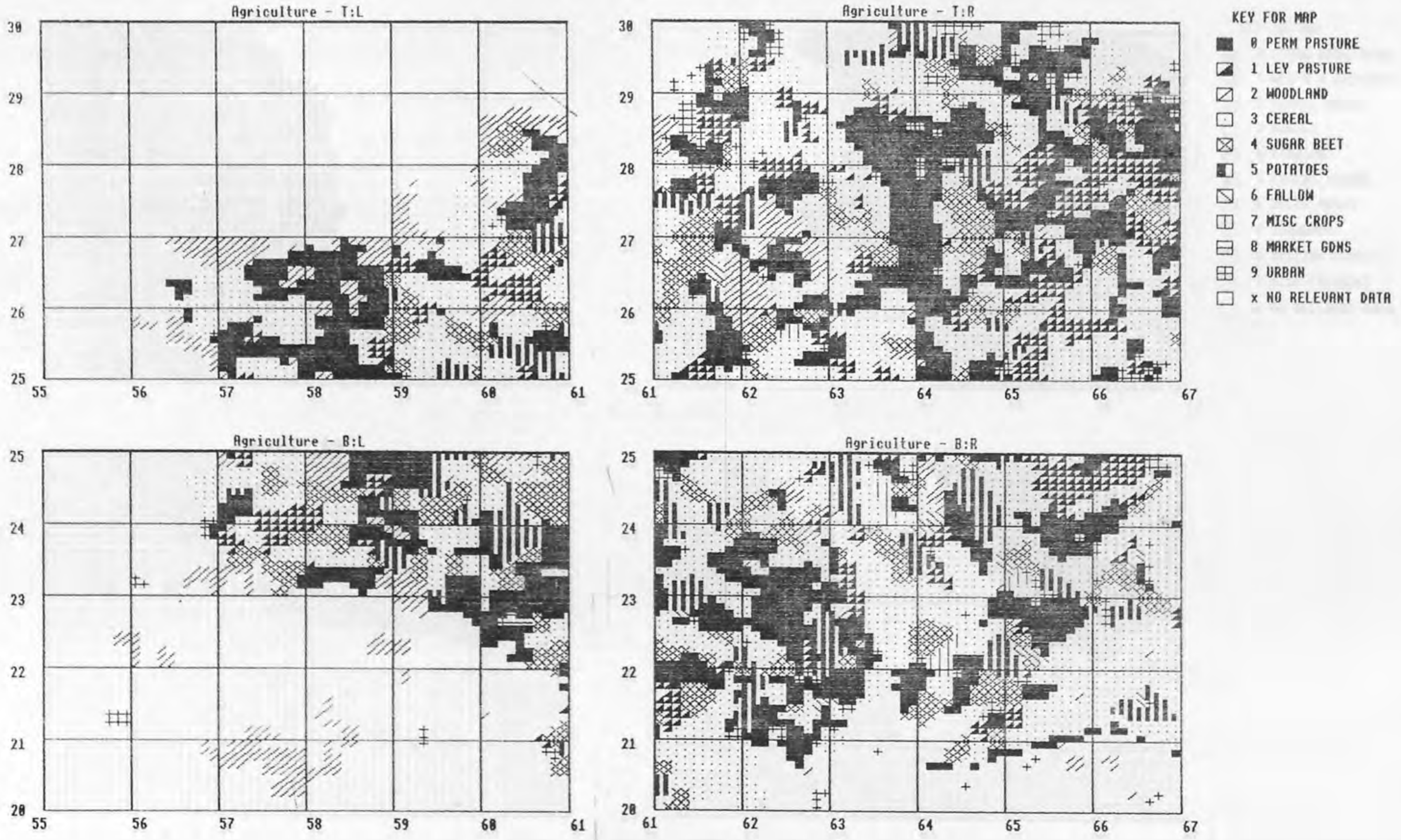


Fig 8.7 Vegetation and Crop Map: Tern Study Area.

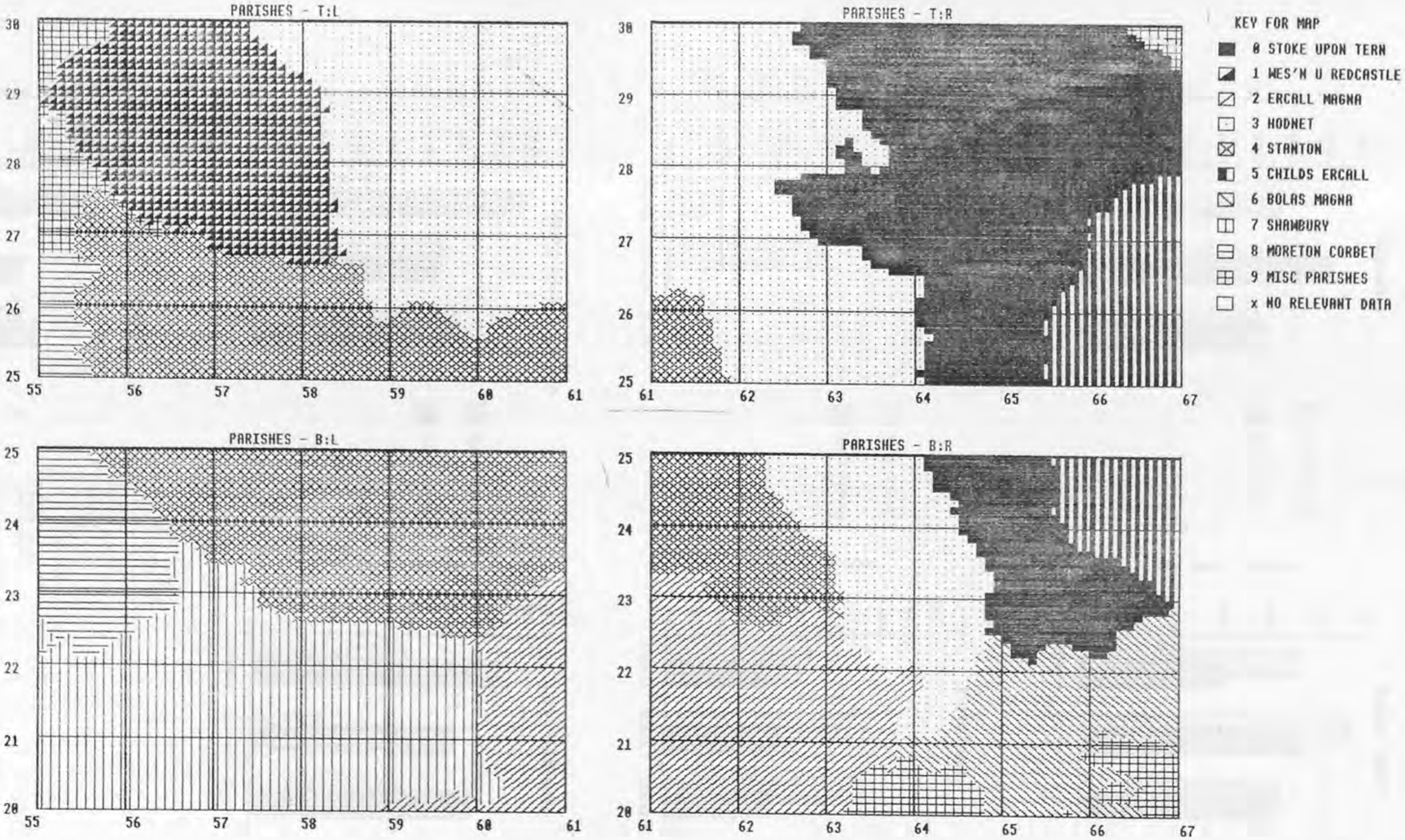


Fig 8.8 Parishes of the Tern Area

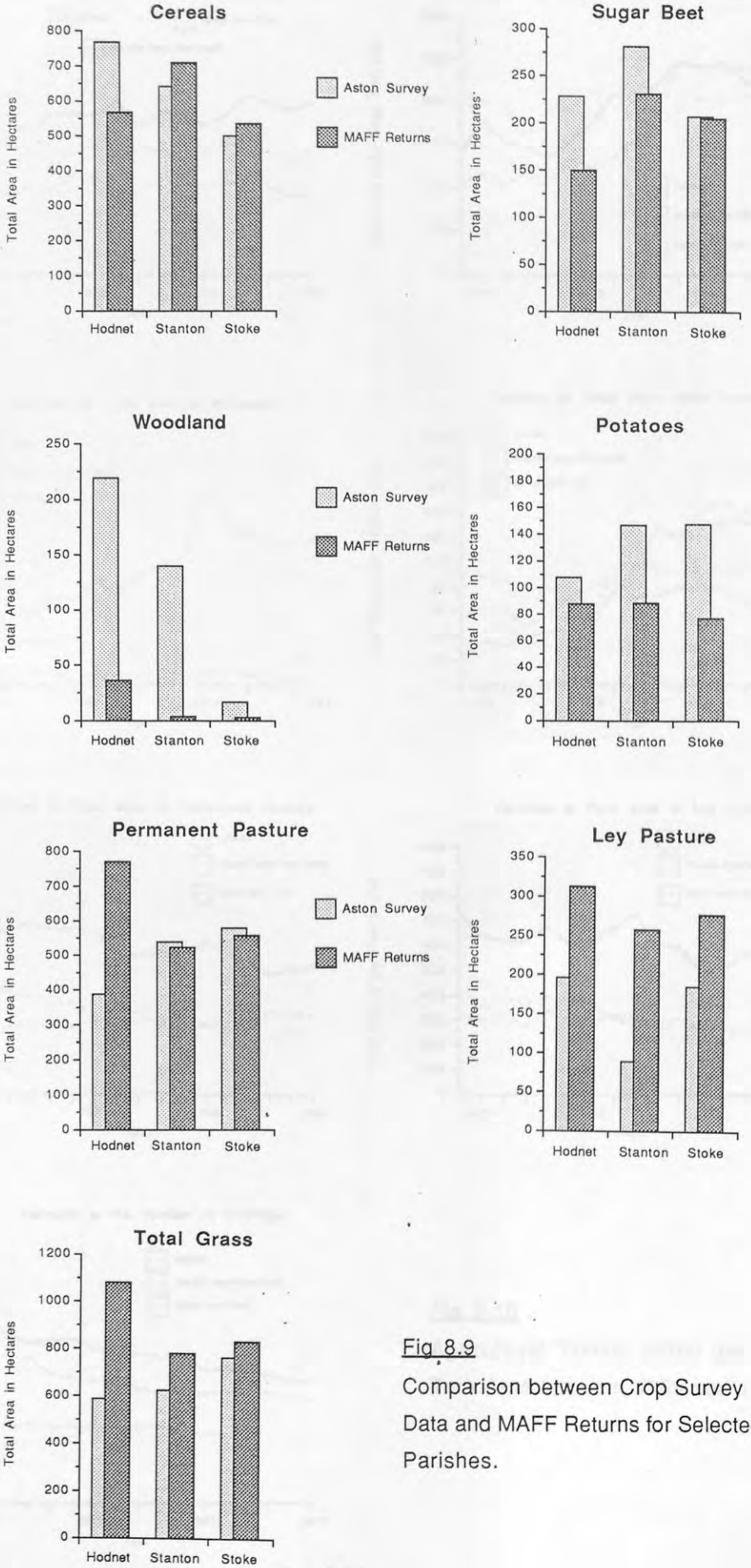
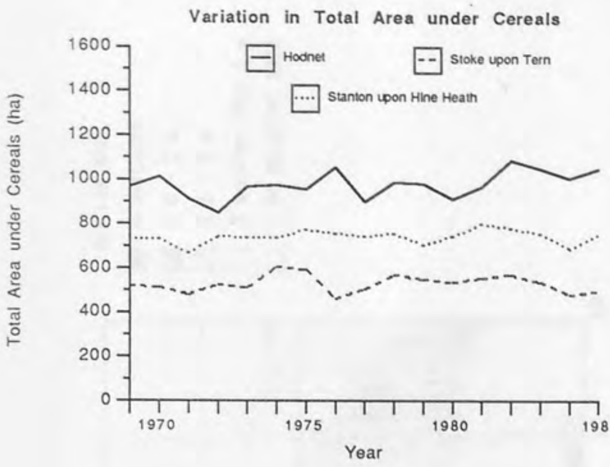
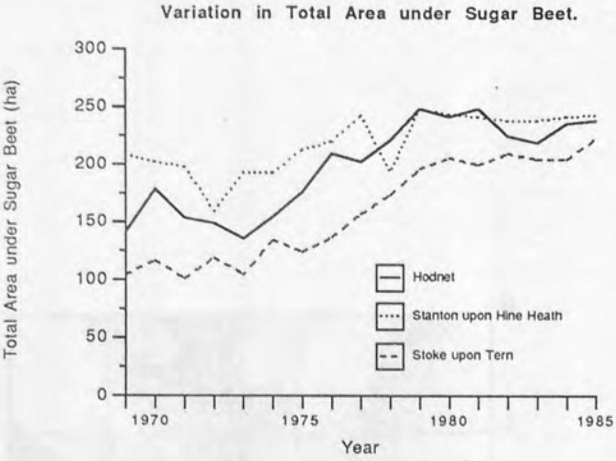


Fig 8.9

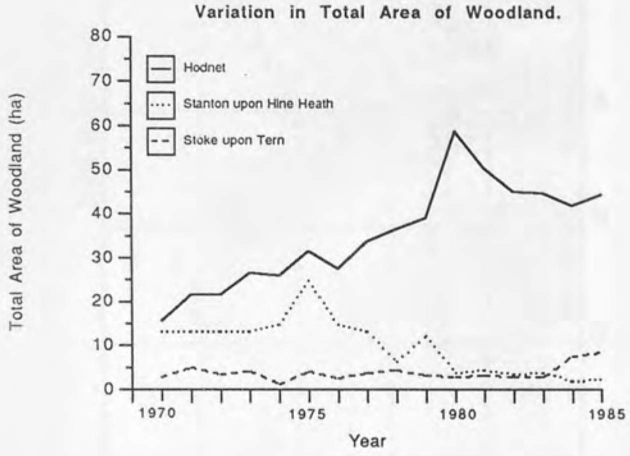
Comparison between Crop Survey Data and MAFF Returns for Selected Parishes.



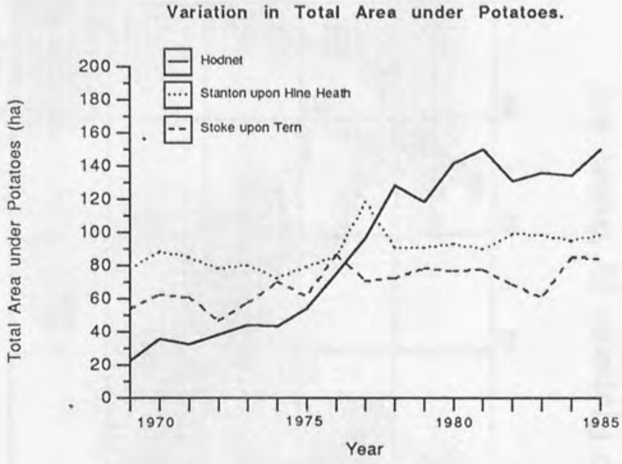
Variation in Total Area under Cereals



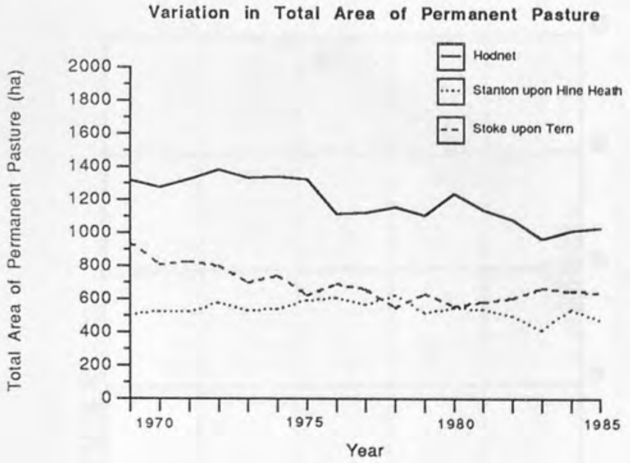
Variation in Total Area under Sugar Beet.



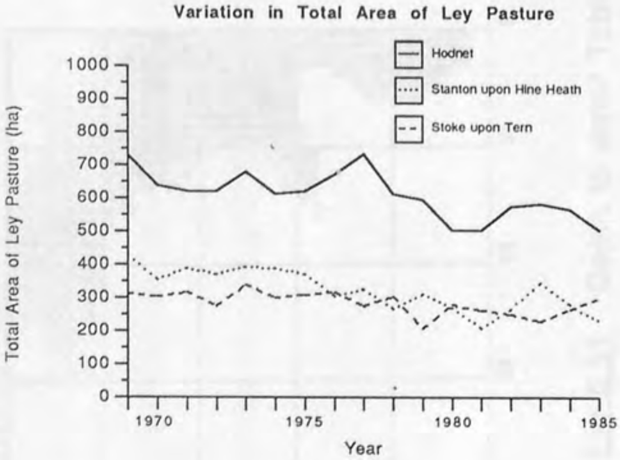
Variation in Total Area of Woodland.



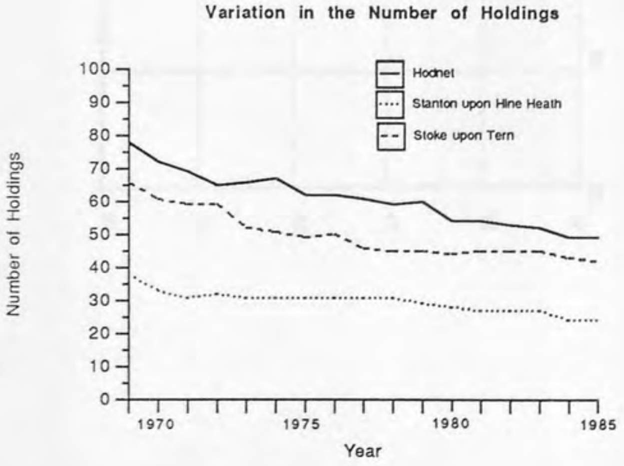
Variation in Total Area under Potatoes.



Variation in Total Area of Permanent Pasture



Variation in Total Area of Ley Pasture



Variation in the Number of Holdings

Fig 8.10

Agricultural Trends within the Tern Area between 1969 and 1985.

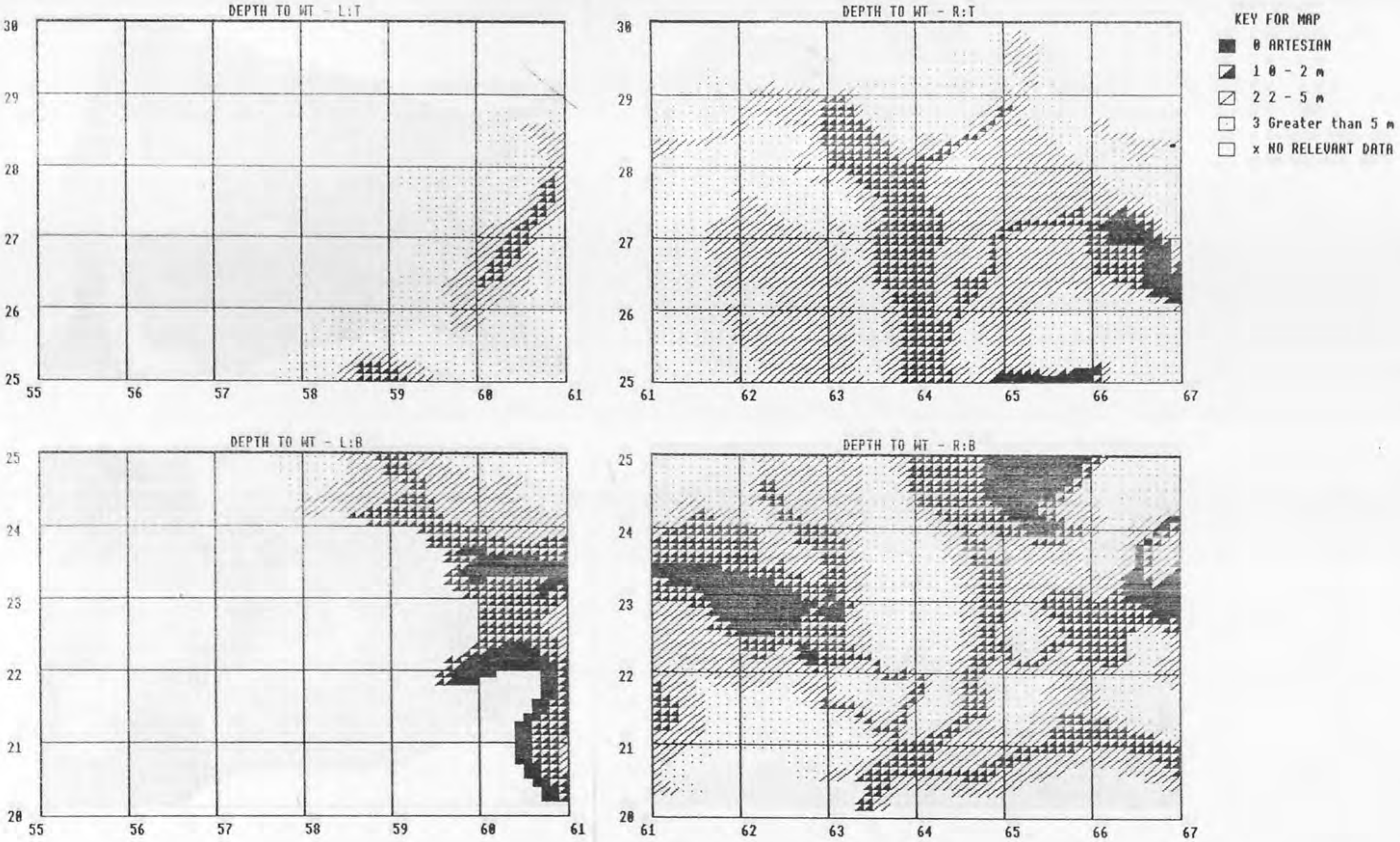


Fig 8.11 Depth to water Table Map Prepared by Walley and Hedges (1979b).

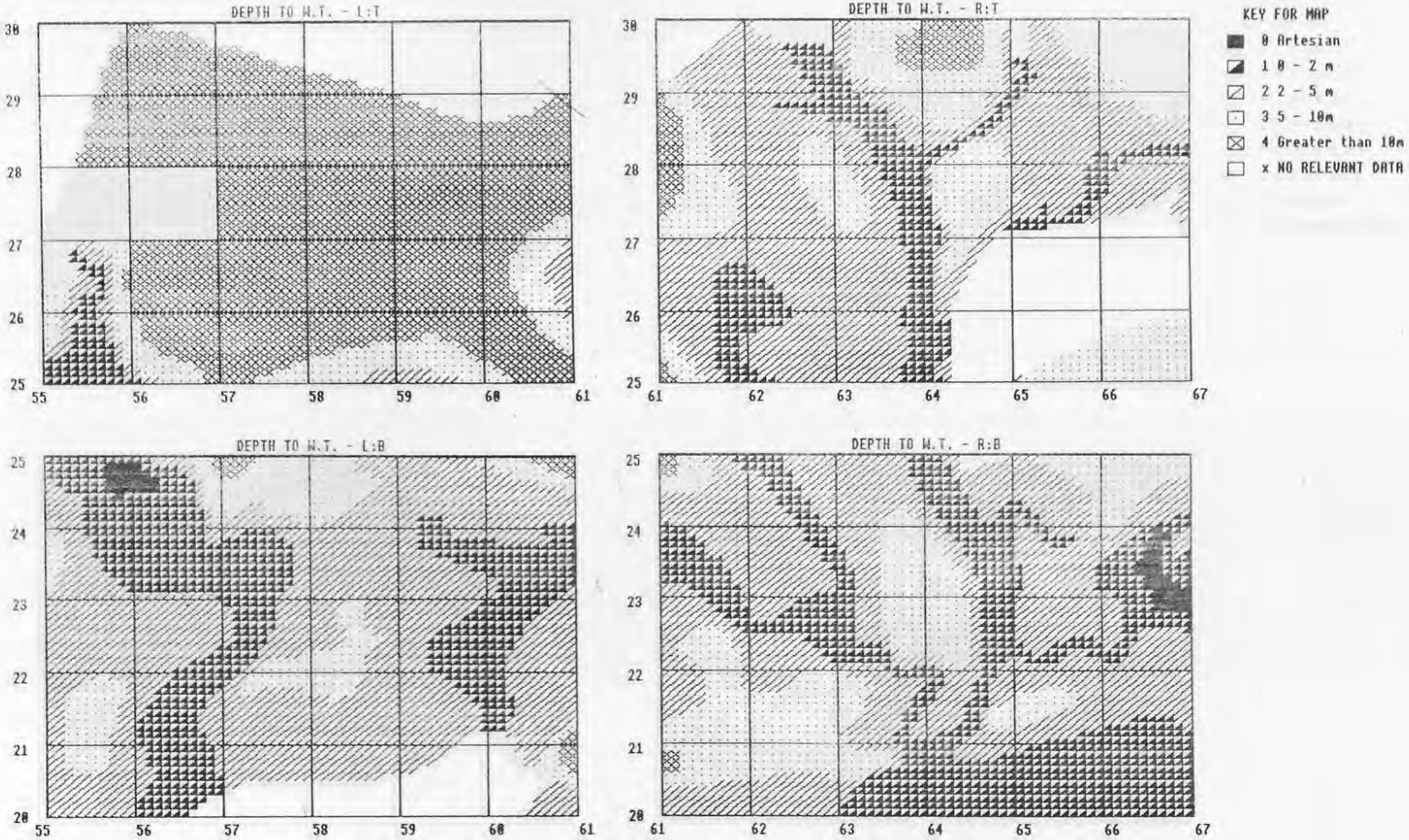


Fig 8.12 Depth to Water Table: Severn Trent Water Authority
(public inquiry document ACS 17).

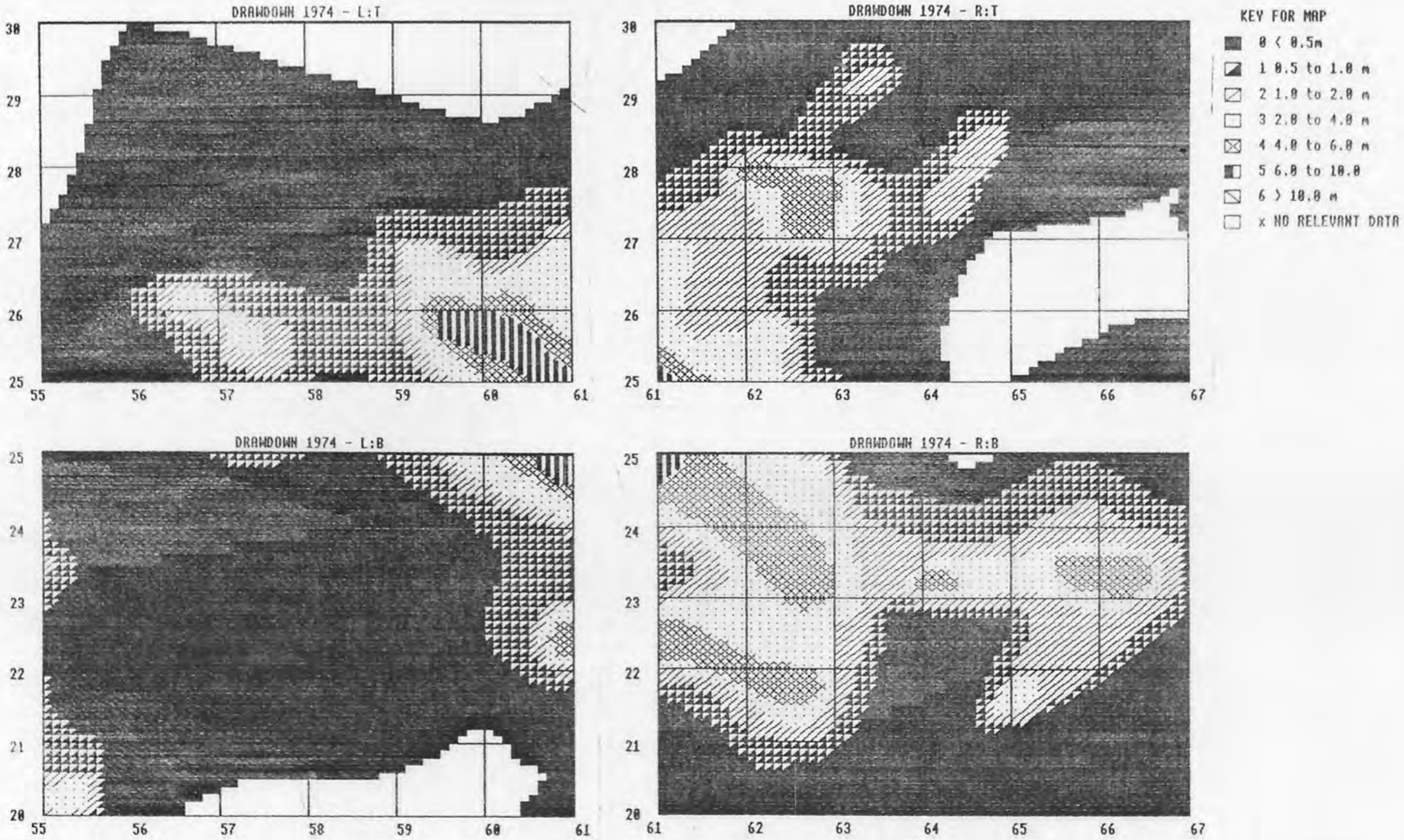


Fig 8.13 Groundwater Drawdown: Simulation for 1974 Conditions
(after Severn Trent Water Authority public inquiry document ACS 8).

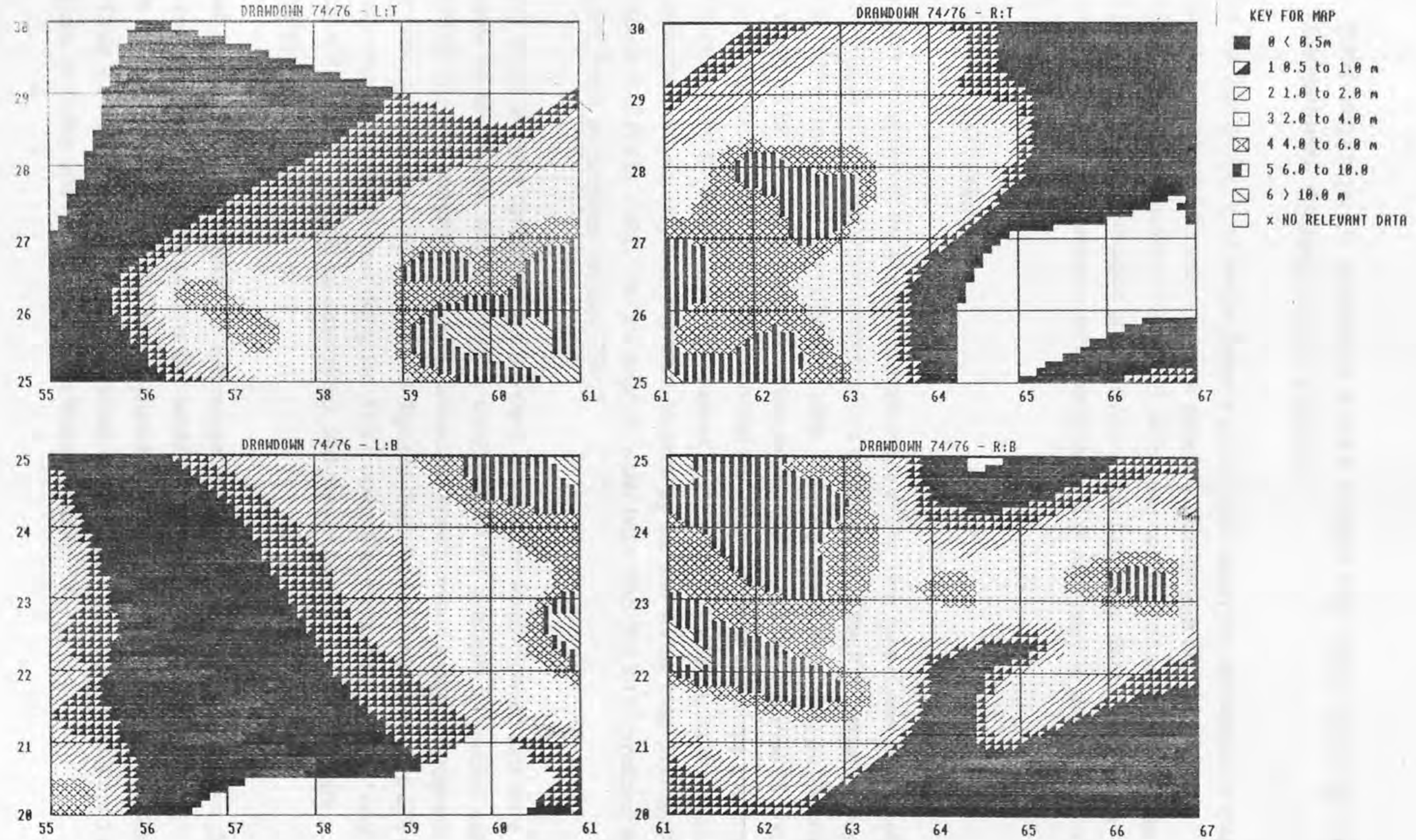


Fig 8.14 Groundwater Drawdown: Simulation for 1976 Conditions
(after Severn Trent Water Authority public inquiry document ACS 9).

8.4 IDENTIFICATION OF SENSITIVE AREAS WITHIN THE TERN AREA OF THE SHROPSHIRE GROUNDWATER SCHEME.

During the Shropshire Groundwater Scheme public local inquiry the delineation of areas sensitive to groundwater drawdown was the subject of considerable debate (see Sect. 5.6.4.2). The method described in Sect. 5.5, which was commended at the inquiry, has been adopted for the identification of sensitive areas in this study. Before expounding further on the subject of sensitive area identification it is necessary to define the final study area.

8.4.1 THE STUDY AREA.

During the discussion of the physical characteristics of the Tern Area it was pointed out that the effects of pumping would extend beyond the boundary of the Pilot Scheme study area as defined by Severn Trent Water Authority. Consequently as much data as possible were collected for the area bounded by Ordnance Survey longitudinal grid lines 55 and 67, and latitudinal lines 20 and 30. It was found that the degree to which the whole area could be covered varied between the various features of interest. This was particularly true of the agricultural survey (Fig 8.7), the area covered by the soil survey map (Soil Survey of England and Wales, 1952), and the depth to water table map (Fig 8.11) produced for Walley's Proof of Evidence (Walley, 1979).

So that all the analysis conformed to a standard, the area for which digitised data were available for all features was identified by combining all the available information using MMERGE. The final composite, Fig 8.15, defined the environmental impact assessment study area - the *EIA area*. Subsequently all digitised maps were combined with the EIA area and any data falling outside were discarded. This process also enabled the extent of each feature within the EIA area to be determined, and the results from this exercise are presented in Table 8.3.

At this juncture it is worth noting the differences, highlighted in Table 8.3, between the total combined area of aquifer outcrop and sandy drift shown on the IGS 1:50000 map (3370 ha) and that shown on the map produced by Severn Trent Water Authority (2994 ha). Table 8.3 also shows clearly the differences between the maps of depth to groundwater produced by Walley and Hedges and by the Water Authority.

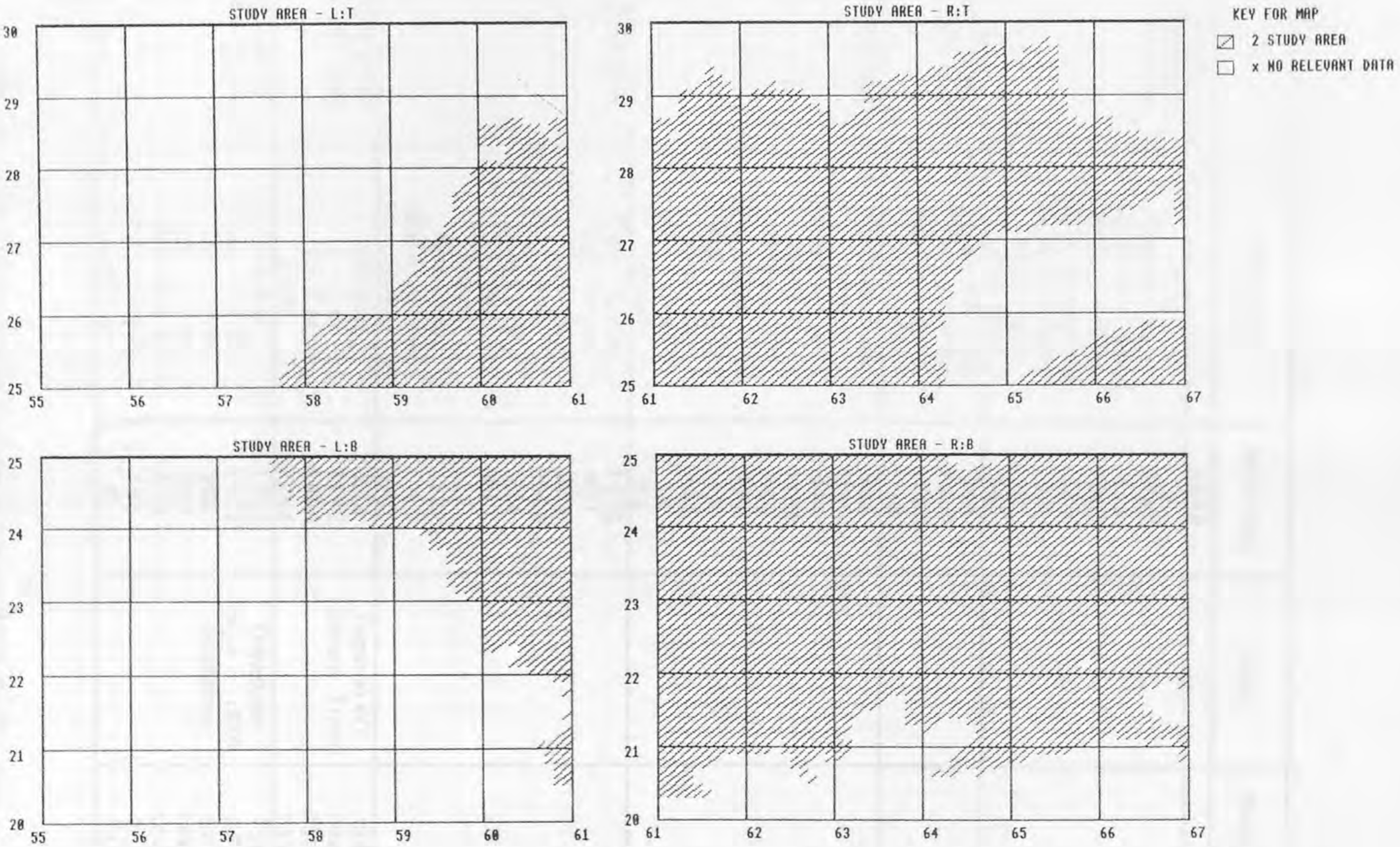


Fig 8.15 Environmental Impact Assessment Study Area.

MAP	FEATURE	AREA (ha)	Map	Area (ha)
EIA area		5589		
Geology (IGS map)	Peat	0		
	Boulder Clay	2127		
	Glacial sand/gravel	649		
	Aquifer Outcrop	1851		
	River sand/gravel	330		
	Marle Keele Beds	11		
	Keuper Marl	81		
	Alluvium	540		
Drift Geology (Severn Trent)	Clayey drift > 5m	348		
	Clayey drift < 5m	2247		
	Aquifer outcrop	2056		
	Sandy drift	938		
Soil Series	Peat/peat loam	533		
	Wem	1081		
	Crannymoor	974		
	Newport	1185		
	Bridgnorth	990		
	Salop	494		
	Misc till soils	43		
	Alluvium	186		
	Misc sand soils	19		
	Hodnet	84		
Agriculture	Perm Pasture	1473		
	Ley Pasture	451		
	Woodland	233		
	Cereals	2080		
	Sugar beet	714		
	Potatoes	430		
	Fallow	32		
	Misc crops	32		
	Market gardens	4		
	Urban	140		
Depth to WT (Aston map)	Artesian	293	Depth to WT (Severn Trent)	34
	0 - 2 m	1142		1090
	2 - 5 m	1890		2592
	> 5 m	2264		1837
Drawdown 1974 cond'ns	< 0.5 m	1934	Drawdown 1974 - 1976 conditions	799
	0.5 - 1.0 m	1172		369
	1.0 - 2.0 m	932		563
	2.0 - 4.0 m	902		1689
	4.0 - 6.0 m	545		1070
	6.0 - 10.0 m	104		957
	> 10.0 m	0		142

Table 8.3 Total Area Covered by Features of Interest Within the EIA Area.

8.4.2 SENSITIVE AREA IDENTIFICATION.

8.4.2.1 The Methodology.

The key to the sensitive area identification process is Eqn. 5.1:

$$D = h_o + d_r$$

where: h_o is the critical height, as defined in Sect. 4.2.1;

d_r is the crop rooting depth;

D is the maximum depth to the water table for which the vegetation under consideration will be affected by the removal of available moisture due to drawdown caused by pumping. If the water table is at a depth greater than D below the ground surface the vegetation will not be affected. This parameter will in future be referred to as the *soil sensitivity depth*.

The development of relationships enabling the critical height to be determined from known soil properties was described in Sect. 6.4., and for the purpose of sensitive area identification Eqn 6.1 was used to evaluate the relevant critical heights of the soils in the EIA area. Since the difference between the calculated critical heights for Alluvium, Bridgnorth, Crannymoor, Newport and Miscellaneous Sandy Soils was so small (see Table 8.4) it was decided to combine them into a single category, *Sandy Soils*, with a critical height of 1.5m. This was justified on the grounds that the properties used in determining the critical heights were idealised representative values for each soil type, and in practice would vary spatially, both horizontally and vertically, to an unquantifiable degree. Conveniently two other groupings could also be formed on the basis of similar critical height values - Wem / Miscellaneous Till, and Hodnet / Salop.

The rooting depths of crops and trees found within the Tern Area were considered in Chapter 7, and on combining these with appropriate critical heights the soil sensitivity depths listed in Table 8.4 were obtained.

When the practice of crop rotation is taken into account it becomes clear that potentially any field may be planted with the deepest rooting crop, and thus the largest soil sensitivity depths must be used to find the extent of the area which could be affected by groundwater drawdown. Therefore, for crops the appropriate soil sensitivity depths were obtained by combining the rooting depth of cereals / sugar beet (2.1m) with the critical heights of the Tern soil groupings (see Table 8.4). Table 8.5 gives the soil sensitivity depths which were used to determine the sensitive areas for both crops and trees.

Crop			Cereals	Sugar Beet	Potatoes	Misc Crops	Permanent Pasture	Grass Ley	Woodland
Rooting Depth - dr (m)			2.1	2.1	1.5	1.5	1.75	0.6	3.5
Soil Series	Critical Height: ho (m)		Soil Sensitivity Depth D (m)						
	Calculated	Accepted							
Alluvium Bridgnorth Crannymoor Newport Misc Sandy	1.4 1.5 1.5 1.6 1.6	1.5	3.6	3.6	3.0	3.0	3.25	2.1	5.0
Peaty Loam	2.1	2.1	4.2	4.2	3.6	3.6	3.85	2.7	5.6
Wem Misc Till	2.6 2.6	2.6	4.7	4.7	4.1	4.1	4.35	3.2	6.1
Salop Hodnet	3.0 3.0	3.0	5.1	5.1	4.5	4.5	4.75	3.6	6.5

Table 8.4 Derivation of Soil Sensitivity Depths.

Soil Group	Crops (m)	Trees (m)
Sandy Soils	3.6	5.0
Peaty Loam	4.2	5.6
Wem / Misc Till	4.7	6.1
Hodnet / Salop	5.1	6.5

Table 8.5 Soil Sensitivity Depths Derived for Determining Areas Sensitive to Groundwater Drawdown.

The next step in the identification process was to delineate where the water table depth was equal to or less than the appropriate soil sensitivity depth. Groundwater depths at grid line intersections (nodes) were determined by plotting cross sections using the relevant maps, Figs 8.11 and 8.12. MAPSURF was then run using these node values, and the water table depth was calculated for each of the 100 m^2 elements within each grid square of the EIA area. Soil sensitivity depth contours were drawn manually on the hard copy output for each grid square and the results digitised. This allowed four new depth to groundwater maps to be produced from the original Aston and Severn Trent data - two new maps with depth to groundwater contours equal to the soil sensitivity depths for crops, and two for trees.

Up to this point in the process it has been assumed that the sensitivity of soils to drawdown is solely a function of soil sensitivity depth (D). However, the rate at which a soil drains is also of prime importance. As was pointed out in Sect 6.4.3, if drainage is extremely slow the effects of moisture removal from the profile will not be noticed during the growing season, and therefore crops and trees will not be physically affected.

It was not possible to derive a simple model for simulating the entire drainage process, from saturated soil to establishment of the field capacity profile, using the data obtained during the laboratory soil column experiments (see Sect 6.4.3). However, the drawdown response time equations (Eqn 6.16 to 6.20) enable the number of days that it takes an initially saturated soil to lose a given proportion of its drainable moisture to be estimated.

Applying these equations to the soils of the Tern Area, using the soil properties presented in Table 8.2, gave the drawdown response times (DRT) shown in Table 8.6. As this table shows, the DRT values for Newport, Alluvium, Crannymoor and Miscellaneous Sandy soils shows, the DRT values for Newport, Alluvium, Crannymoor and Miscellaneous Sandy soils were very similar enabling them to be classed together - the same was true for Wem and Miscellaneous Till Soils. The resulting DRT values are presented graphically in Fig 8.16, from which it can be clearly seen that for all soils 50% of the drainable moisture is lost from the profile within the first day of drawdown, and there is 90% loss within 20 days. Furthermore, it takes approximately the same time for the last 4%, which brings the moisture loss up to 99%, to be lost from the soil as it does for the initial 95% of the drainable water to be removed. Clearly, therefore, providing drainage is not impeded by an impermeable layer, all the soils of the Tern Area will be sensitive to the effects of groundwater drawdown.

Soil Group	Drawdown Response Time (days)				
	Proportion of Drainable Moisture Lost				
	50%	75%	90%	95%	99%
Newport	0.3	1.2	4.2	9.2	23.0
Alluvium	0.3	1.2	4.2	9.2	23.0
Crannymoor	0.3	1.3	4.7	10.0	24.3
Misc Sand Soils	0.3	1.4	5.2	10.8	25.6
Bridgnorth	0.4	2.0	8.2	15.7	33.4
Wem	0.5	3.2	15.2	27.0	51.8
Misc Till Soils	0.5	3.2	15.2	27.0	51.8
Peaty Loam	0.5	3.6	17.2	30.2	57.0
Salop	0.5	3.8	18.2	31.9	59.6
Hodnet	0.5	4.2	20.2	35.1	64.9

Table 8.6 Drawdown Response Times for Soils of the Tern Area

By combining the four new maps of the phreatic surface with the soil map, composites were obtained which showed where each of the potentially sensitive soil groups could be affected by groundwater drawdown. Two maps were produced for trees and two for crops. In each case the first of the two showed where the soil was in hydraulic continuity with the aquifer (i.e. underlain by the aquifer itself or by sandy drift). The second two displayed where soils were underlain by boulder clay where it was shown on Severn Trent's superficial drift map to be less than 5m thick. These latter were produced to indicate the extent of the area which could be subject to the effects of groundwater pumping if the confining layer were leaky - it was considered that a boulder clay layer thicker than 5 m would not be subject to leakage. The areas delineated in the first two maps would definitely be sensitive to the effects of drawdown, those in the second two were potentially sensitive.

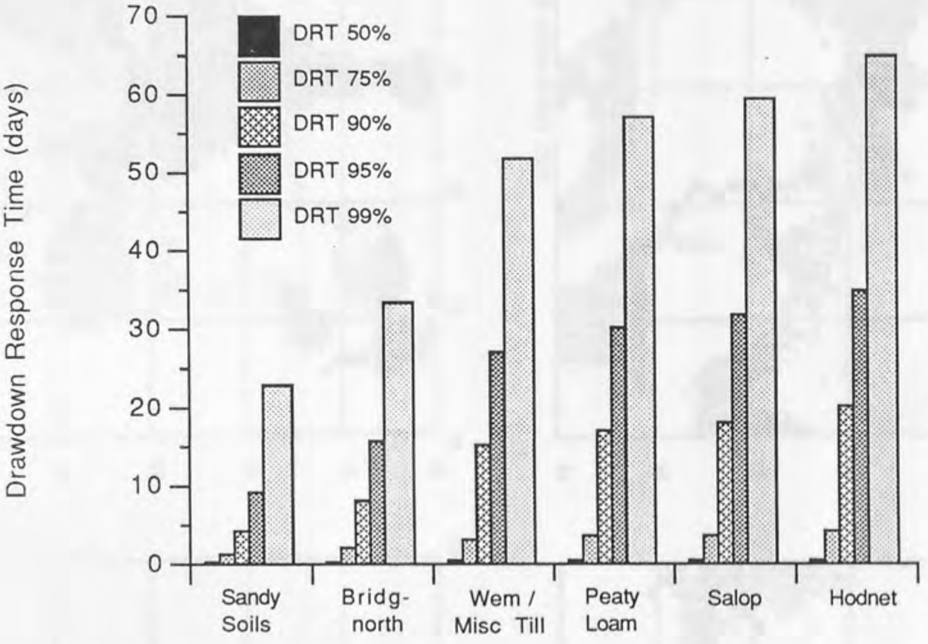


Fig 8.16 Drawdown Response Times for Tern Area Soils.

8.4.2.2 The Sensitivity of Soils in the Tern Area to Groundwater Drawdown.

By following the methodology detailed in Sect 8.4.2.1, Figs 8.17 to 8.24 were produced. Figs 8.17 and 8.18 show those areas where crops are sensitive to drawdown, with Fig 8.17 based on Severn Trent's groundwater depth map and Fig 8.18 based on that produced by Walley and Hedges. Similarly Figs 8.19 and 8.20 show the areas where trees will be at risk. Figs 8.21 to 8.24 are comparable to Figs 8.17 to 8.20, but indicate where crops and trees are potentially at risk if the boulder clay confining layer is leaky. The actual areas delineated on these Figures are presented in Table 8.7.

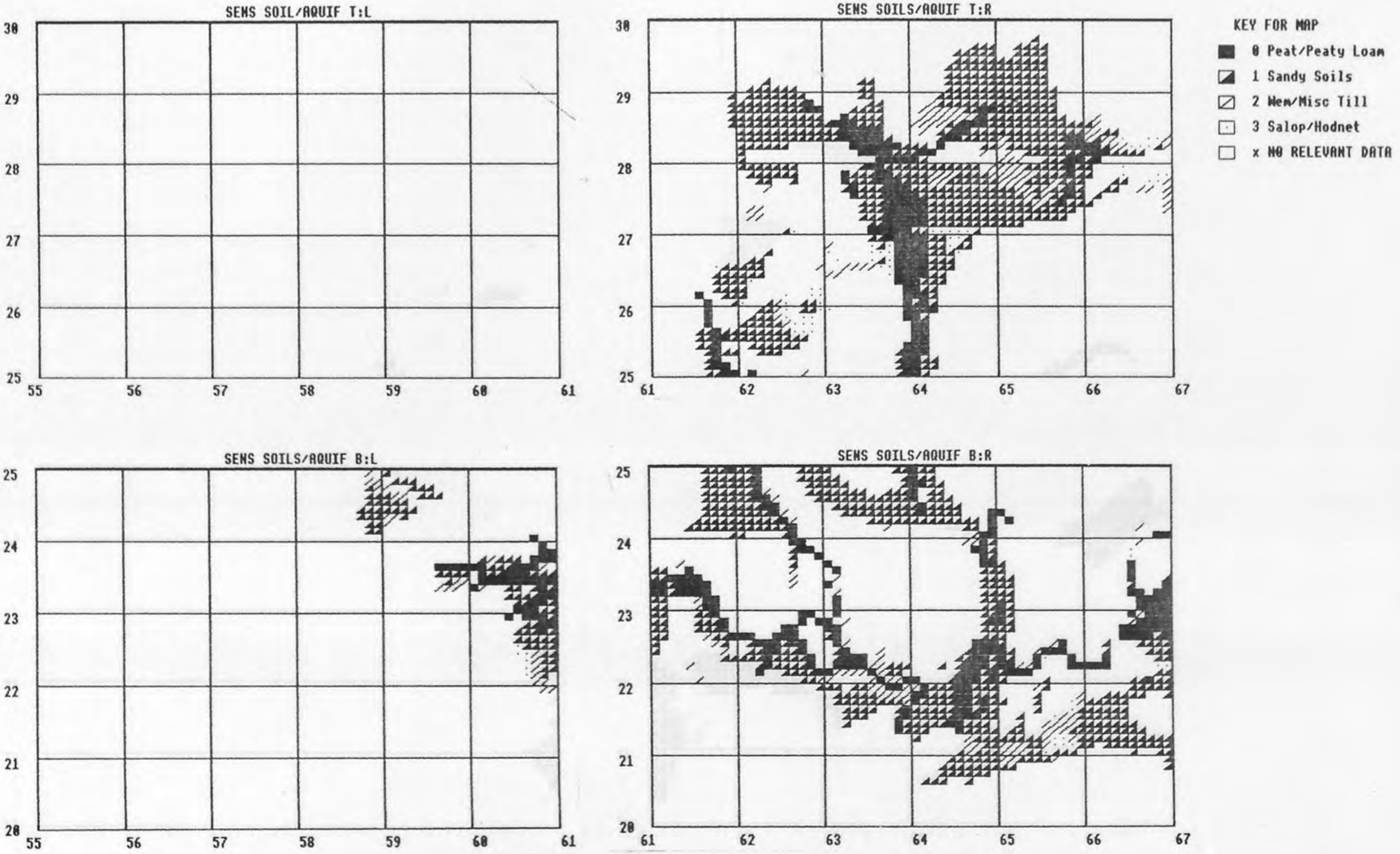


Fig 8.17 Area Where Crops are Sensitive to Groundwater Drawdown: from Severn Trent WA Depth to Groundwater Map.

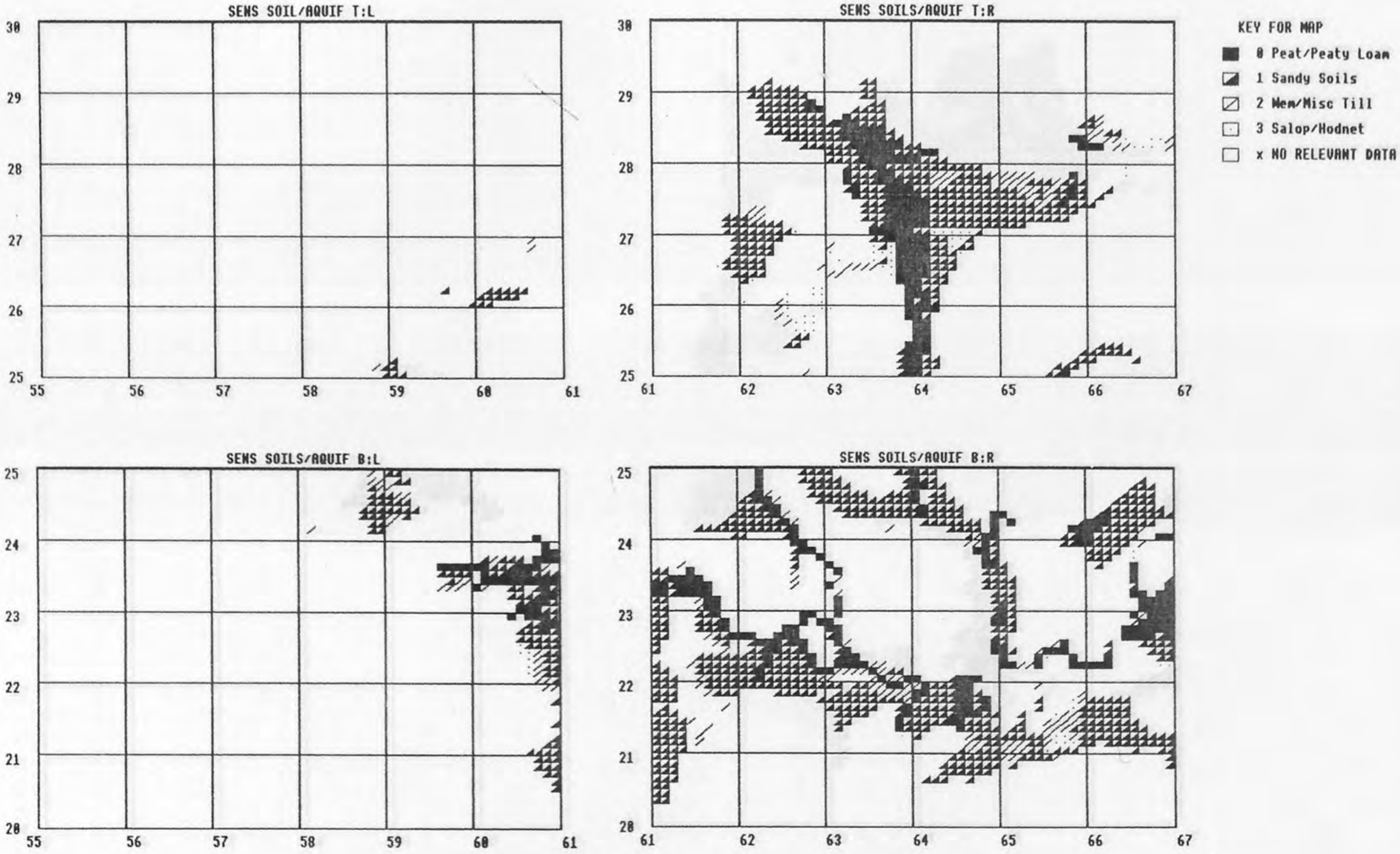


Fig 8.18 Area Where Crops are Sensitive to Groundwater Drawdown: from Walley and Hedges's Depth to Groundwater Map.

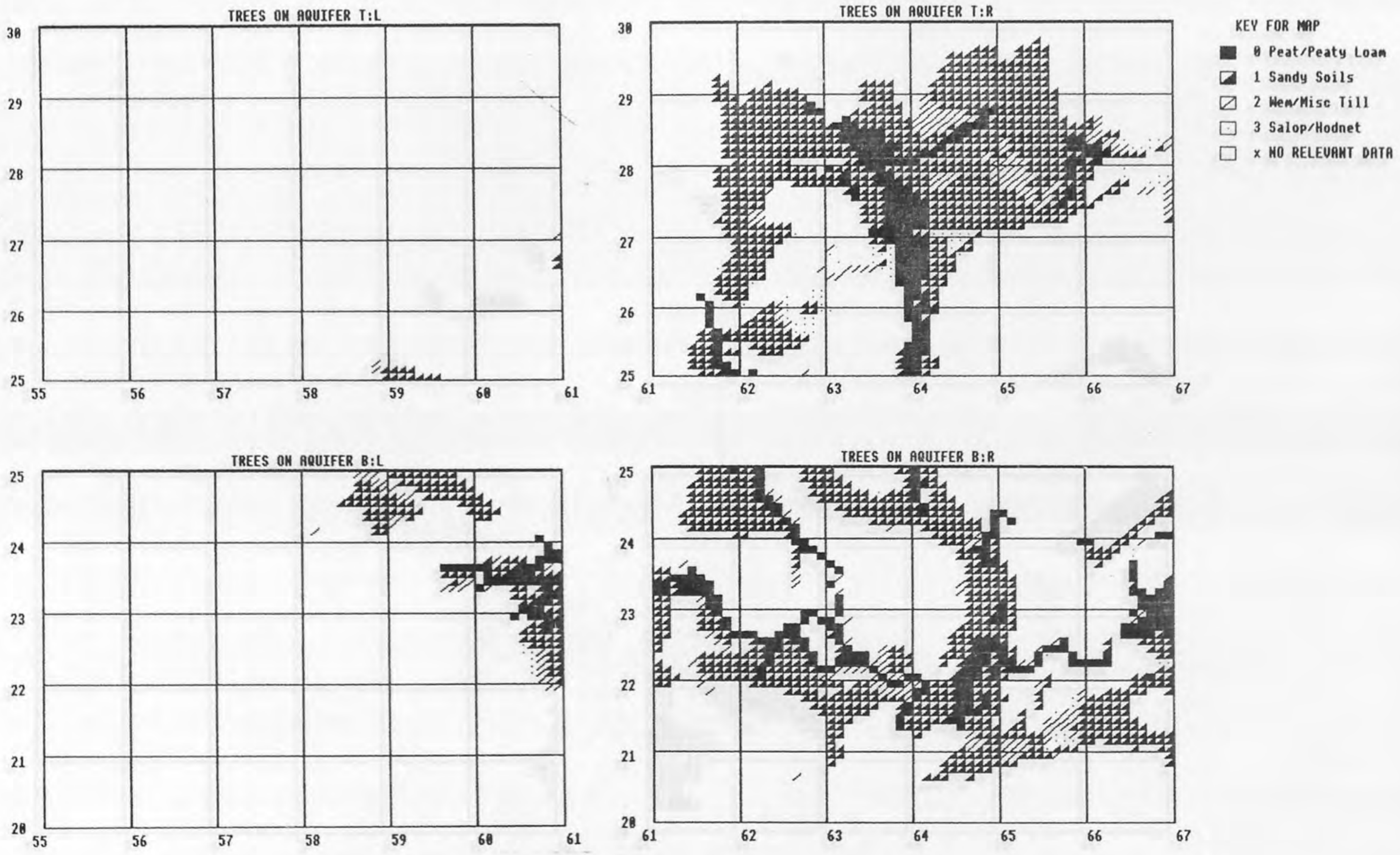


Fig 8.19 Area Where Trees are Sensitive to Groundwater Drawdown: from Severn Trent WA Depth to Groundwater Map.

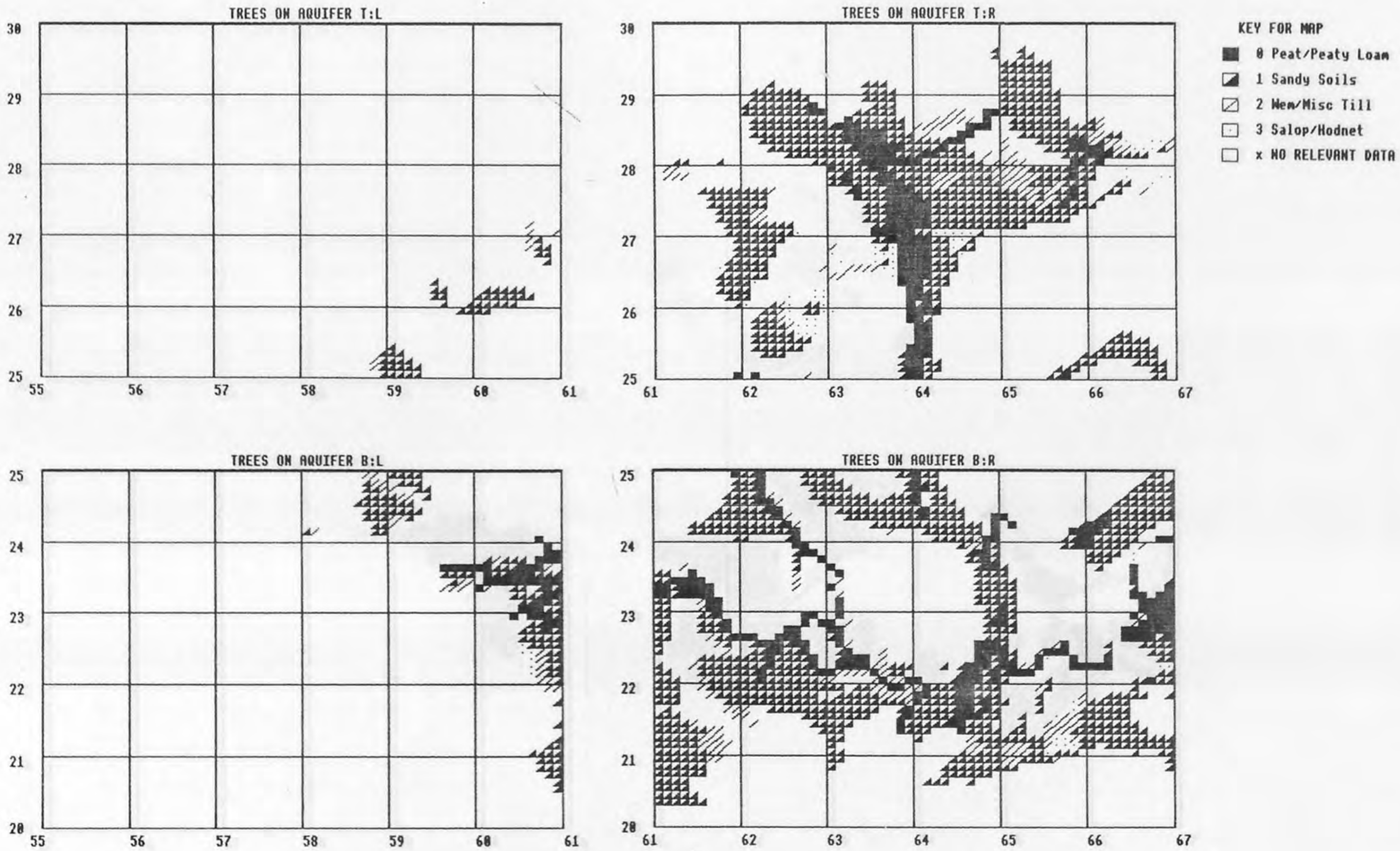


Fig 8.20 Area Where Trees are Sensitive to Groundwater Drawdown: from Walley and Hedges's Depth to Groundwater Map.

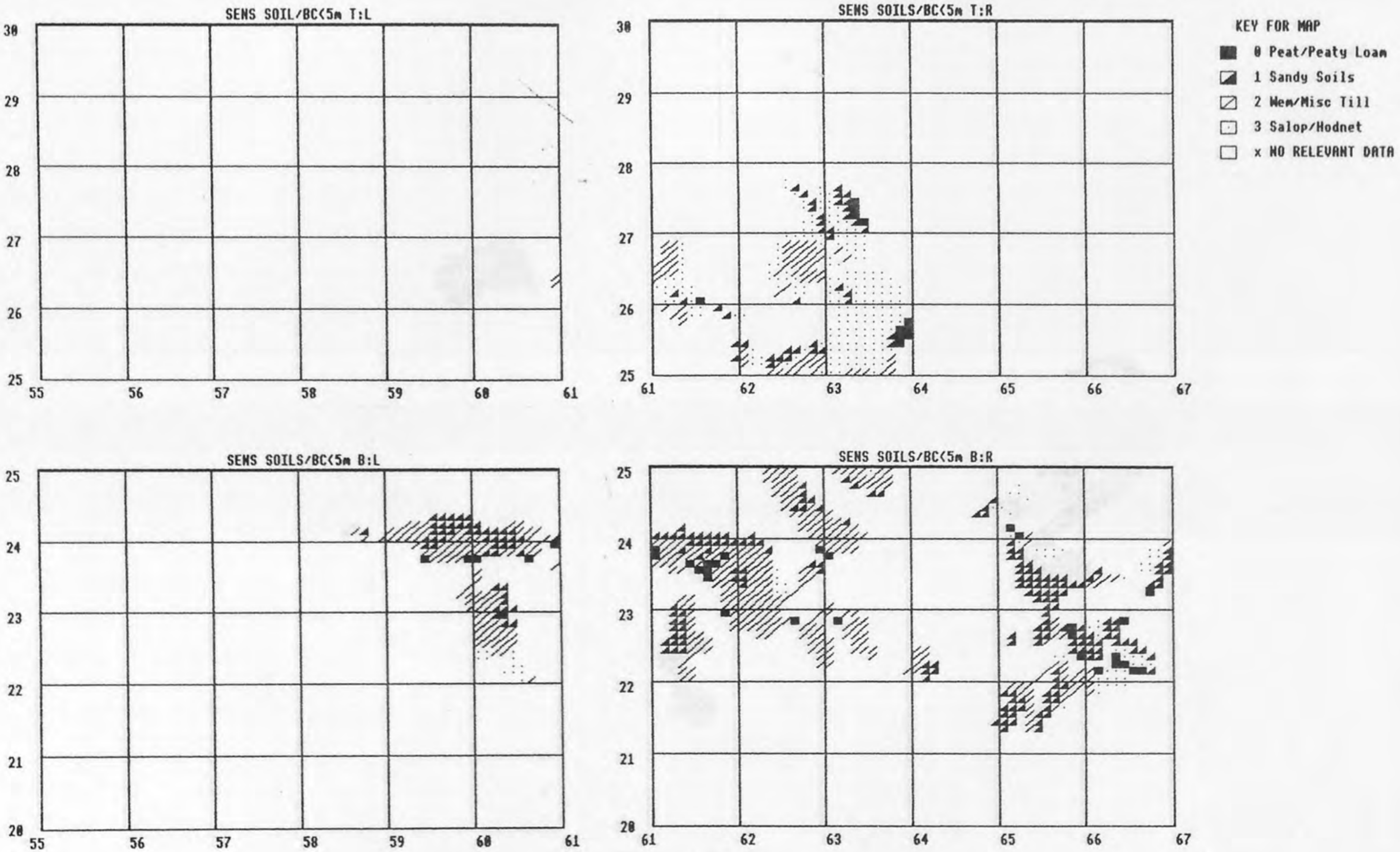


Fig 8.21 Area Where Crops are Potentially Sensitive to Groundwater Drawdown if the Boulder Clay is Leaky: from Severn Trent WA Depth to Groundwater Map.

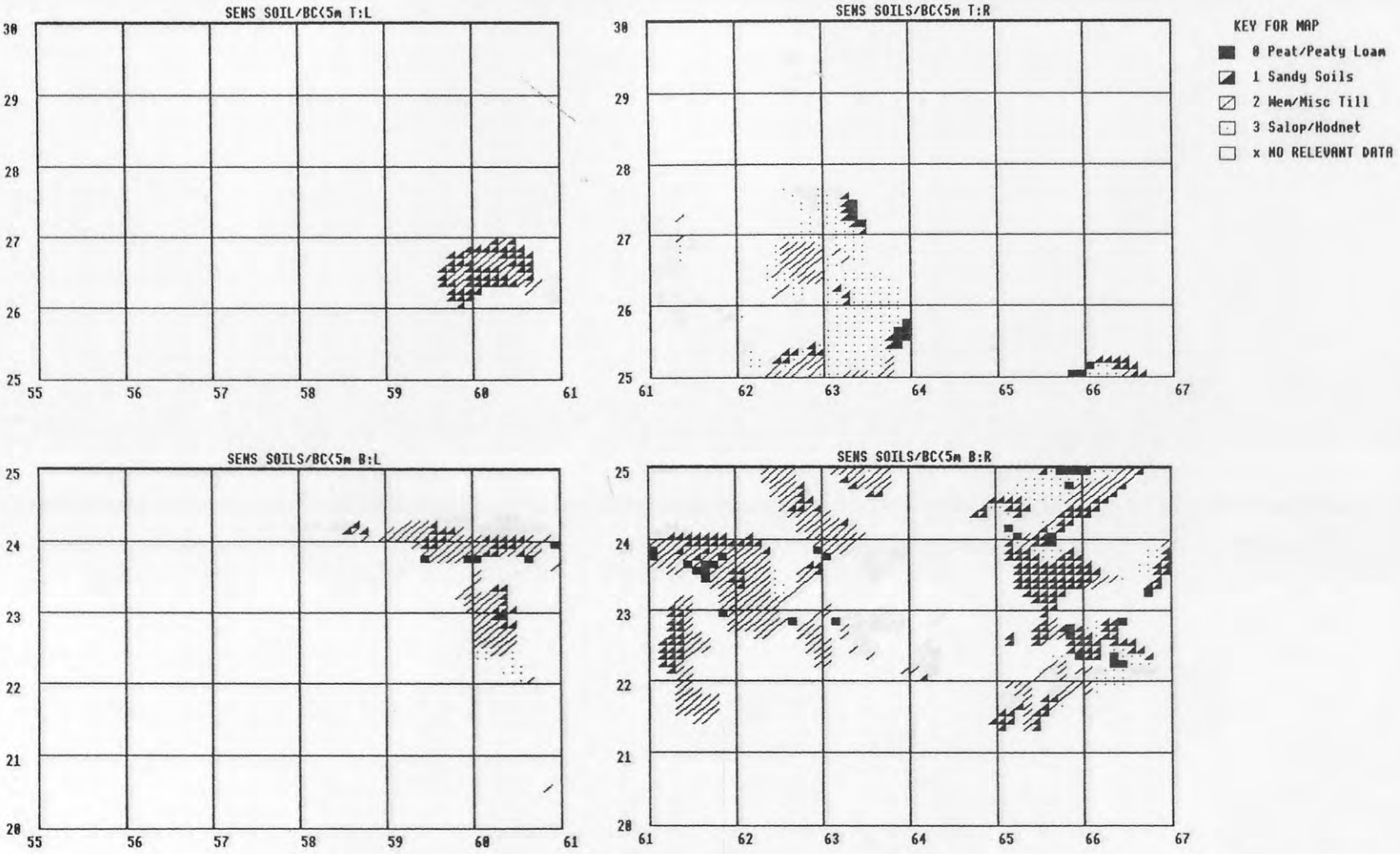


Fig 8.22 Area Where Crops are Potentially Sensitive to Groundwater Drawdown if the Boulder Clay is Leaky: from Walley and Hedges's Depth to Groundwater Map.

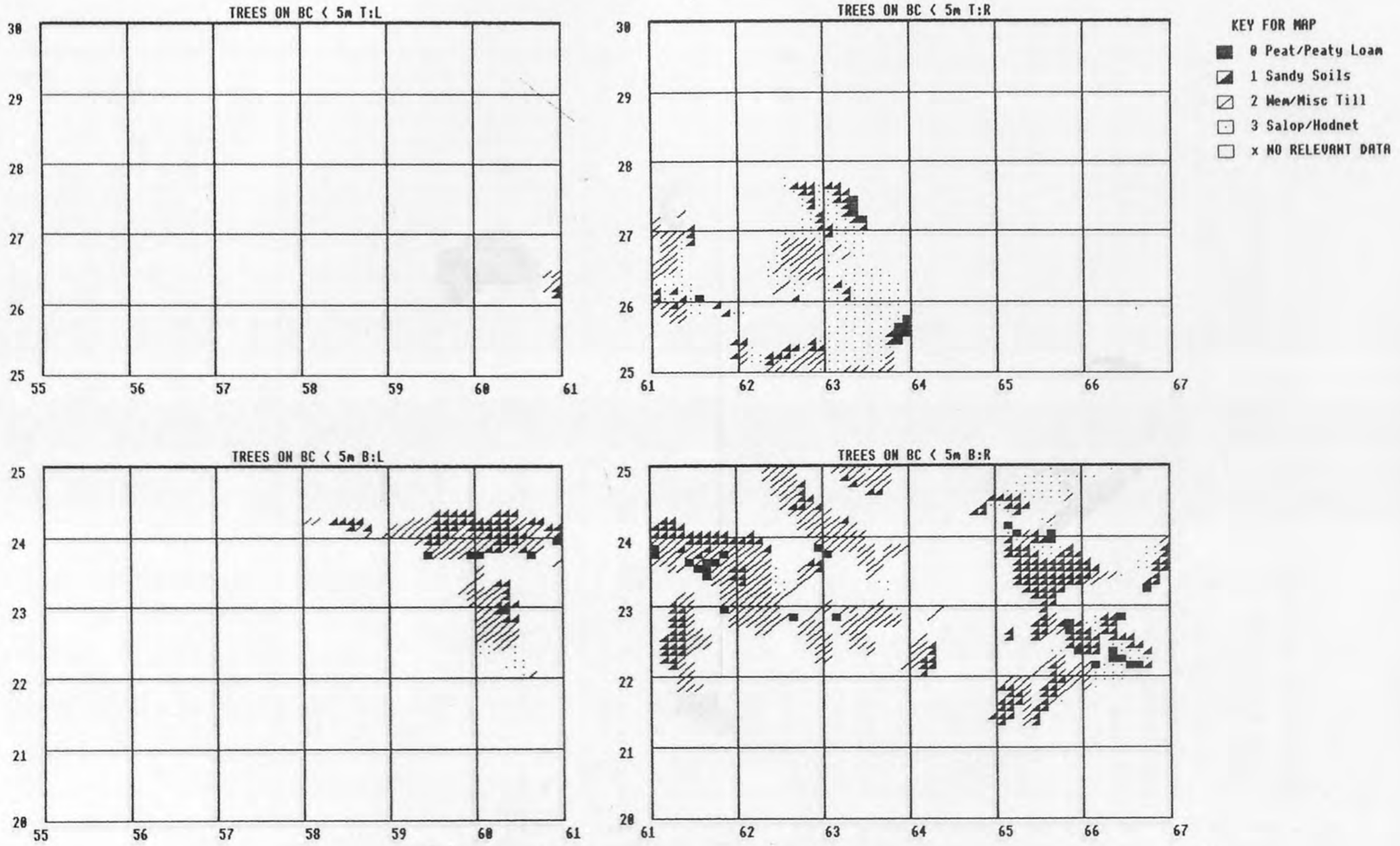


Fig 8.23 Area Where Trees are Potentially Sensitive to Groundwater Drawdown if the Boulder Clay is Leaky: from Severn Trent WA Depth to Groundwater Map.

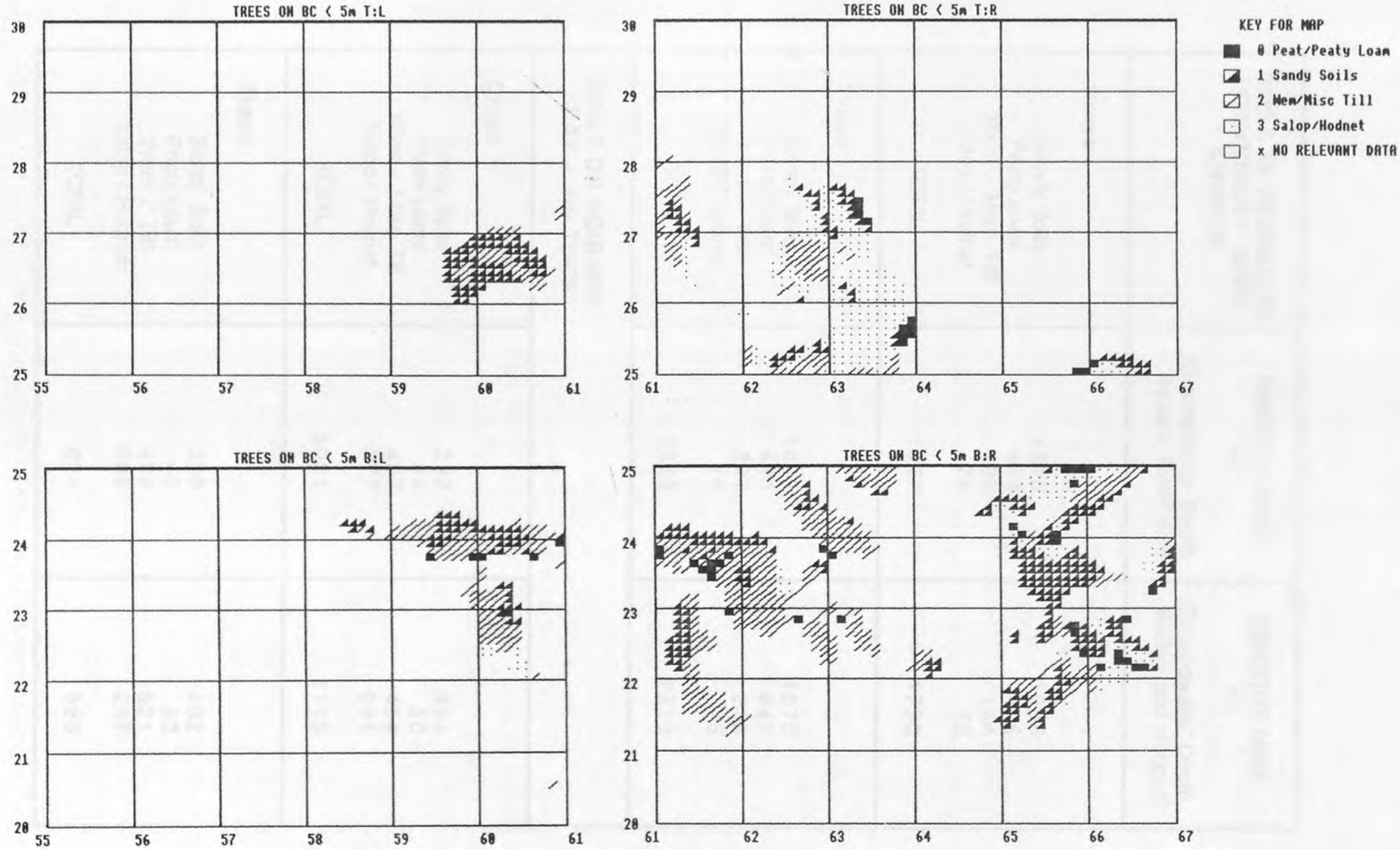


Fig 8.24 Area Where Trees are Potentially Sensitive to Groundwater Drawdown if the Boulder Clay is Leaky: from Walley and Hedges's Depth to Groundwater Map.

SOILS IN HYDRAULIC CONTINUITY WITH AQUIFER	SENSITIVE AREA ha (Groundwater Depth - Severn Trent WA)	SENSITIVE AREA ha (Groundwater Depth - Walley and Hedges)
Crops		
Sandy Soils	1215	1088
Peaty Loam	444	406
Wem / Misc Till	192	164
Salop / Hodnet	76	72
TOTAL	1927	1730
Trees		
Sandy Soils	1633	1570
Peaty Loam	450	447
Wem / Till	207	218
Salop / Hodnet	76	75
TOTAL	2366	2310
SOILS ON BOULDER CLAY < 5m THICK		
Crops		
Sandy Soils	263	324
Peaty Loam	44	50
Wem / Misc Till	437	454
Salop / Hodnet	277	291
TOTAL	1021	1119
Trees		
Sandy Soils	335	402
Peaty Loam	46	53
Wem / Till	489	521
Salop / Hodnet	309	297
TOTAL	824	923

Table 8.7 Extent of EIA Area where Crops and Trees are Sensitive, or Potentially Sensitive, to Groundwater Drawdown.

From Table 8.7 it can be seen that, for soils in hydraulic continuity with the aquifer, the sensitive areas obtained using the Severn Trent WA's depth to groundwater map are 11% greater for crops and 2% greater for trees than the corresponding areas obtained using Walley and Hedges's data. For both crops and trees where the soils overlie potentially leaky boulder clay the areas obtained using the Severn Trent data are approximately 8% less than those obtained from Walley and Hedges's groundwater depth map. However, for both the sensitive and the potentially sensitive area determinations the degree of agreement between the areas obtained from the Severn Trent data and those from Walley and Hedges's data is remarkably good. These results, therefore, vindicate the evidence put forward by Walley at the public inquiry where he argued that Drennan had seriously underestimated the sensitive area as being 2 to 3 km^2 (see Sect 5.6.4.2).

Despite the differences in the location of depth to groundwater contours (see Figs 8.11 and 8.12), since the map presented by Skinner at the inquiry (Fig 8.12) was accepted as superseding Walley's evidence (Fig 8.11), the former alone will be considered in future discussions relating to the areas sensitive to groundwater drawdown. In addition, further consideration of those areas which are potentially sensitive, by virtue of the boulder clay confining layer being thin and thus possibly leaky, would be mere speculation without further field evidence.

The evidence presented above suggests that the figure for the sensitive area of 2 to 3 km^2 quoted by Drennan at the inquiry (McRae, 1979) is a factor of six to ten times too small. Composites obtained by combining the sensitive area and crop survey maps revealed that in 1980 the land use for the 1927 ha sensitive area (Fig 8.17) was as shown in Table 8.8

CROP	AREA	PROPORTION OF SENSITIVE AREA
Cereals	619 ha	32.1%
Sugar beet	237 ha	12.3%
Potatoes	139 ha	7.2%
Miscellaneous crops	19 ha	1.0%
Grass Ley	125 ha	6.5%
Permanent Pasture	677 ha	35.1%
Woodland	111 ha	5.8%

Table 8.8 Land Use Within the Sensitive Area Derived Using the Severn Trent WA Depth to Groundwater Map

In 1980, therefore, even if the areas under grass and woodland were excluded, had pumping taken place some 10 km^2 (1014 ha) of agricultural land would have been subject to the effects of drawdown.

It has already been shown (Sect 8.3.4) that the agricultural trends within the Tern Area have changed little over fifteen years, and therefore the cropping patterns observed in 1980 can be considered as representative of any given year. Thus, whenever pumping takes place, the yields from approximately 10 km^2 of crops and 8 km^2 of grassland are potentially at risk. The magnitude of the actual impact is investigated in the following Section.

8.5 EVALUATION OF THE IMPACT OF GROUNDWATER PUMPING ON THE VEGETATION OF THE TERN AREA.

Identification of the area sensitive to drawdown is one important component of an environmental assessment of the effects of a groundwater pumping scheme. However, the sensitive area only delineates the extent of the possible effects - the actual effects within this area will depend upon the soil characteristics and the vegetation or crop at each individual location. Thus the next logical step in the assessment process is to attempt to determine the actual effects of a pumping event, in terms of both areal extent and economic cost.

As already pointed out in Sect 7.5, it was the aesthetic value of trees that was at risk within the Tern Area and there was no commercial forestry interest of any significance. The effect on trees will therefore not be assessed in this section, and attention will be focused on the main agricultural interest at risk - crop and grass production.

The method developed for evaluating the impact of groundwater drawdown on agriculture will be described first. This will be followed by a discussion of the results obtained from the application of this method to two simulated pumping events.

8.5.1 A METHOD FOR EVALUATING THE IMPACT OF GROUNDWATER DRAWDOWN ON AGRICULTURE.

Careful thought had to be given to the design of the method for determining the impact of pumping, since the process was constrained by the limited memory of the BBC micro which was being used.

8.5.1.1 Structure of the Method.

It was clear that for any given site, data relating to soil type, crop present, groundwater depth and drawdown were required to determine the moisture lost to the crop concerned. Soil properties would enable the field capacity profile to be derived using Eqn 6.7 (see Sect 6.4.2.5). The crop rooting depth, groundwater depth and height of drawdown were required in order to determine whether the crop would be affected or not. Once it had been established that there was an effect, these data would not only enable the height of the field capacity profile removed from the crop root zone to be determined, but also from what part of the field capacity profile this moisture had been lost. Combining these findings with the field capacity moisture profile would give the quantity of moisture lost, from which the effect on the crop could be determined by employing the appropriate yield decline equation (see Chapter 7). The steps associated with this process are illustrated in Fig 8.25.

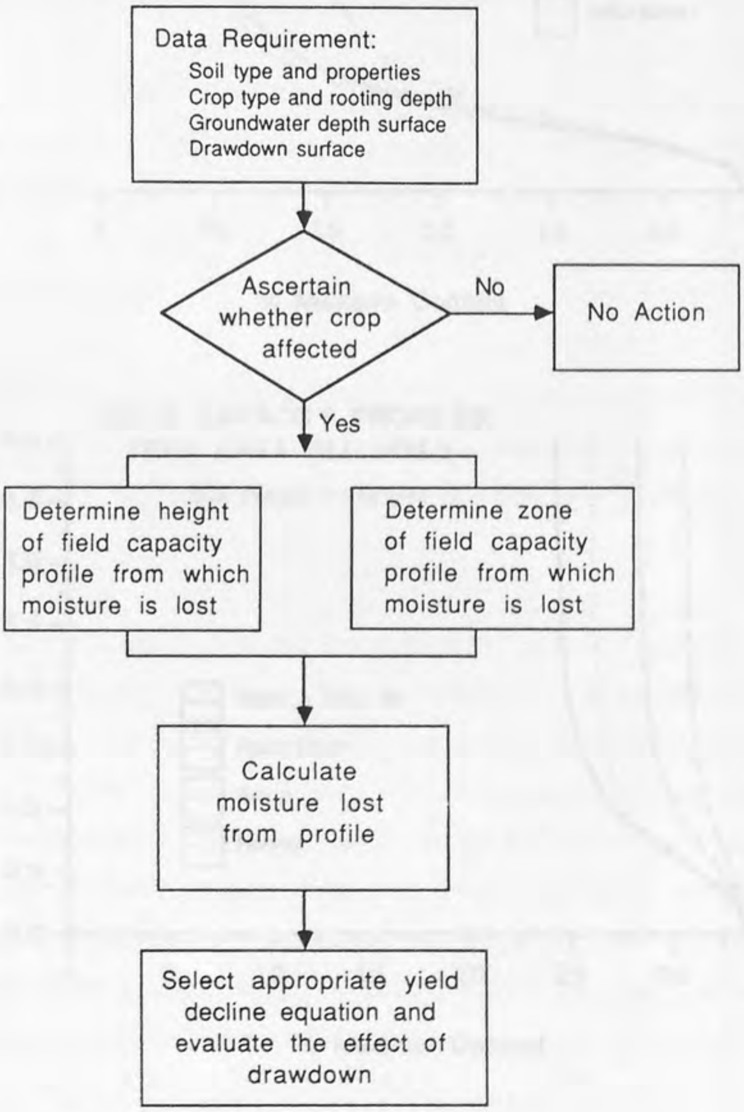


Fig 8.25 Structure of Impact Evaluation Method

8.5.1.2 The Field Capacity Profiles of Sensitive Soils in the Tern Area.

For each of the soil types within the Tern Area the field capacity profiles were derived by inserting the appropriate soil properties (Table 8.2) into Eqns 6.2, 6.8 and 6.9, to find the parameters a, b and θr, and then by applying Eqn 6.7. The resulting profiles are presented in Fig 8.26.

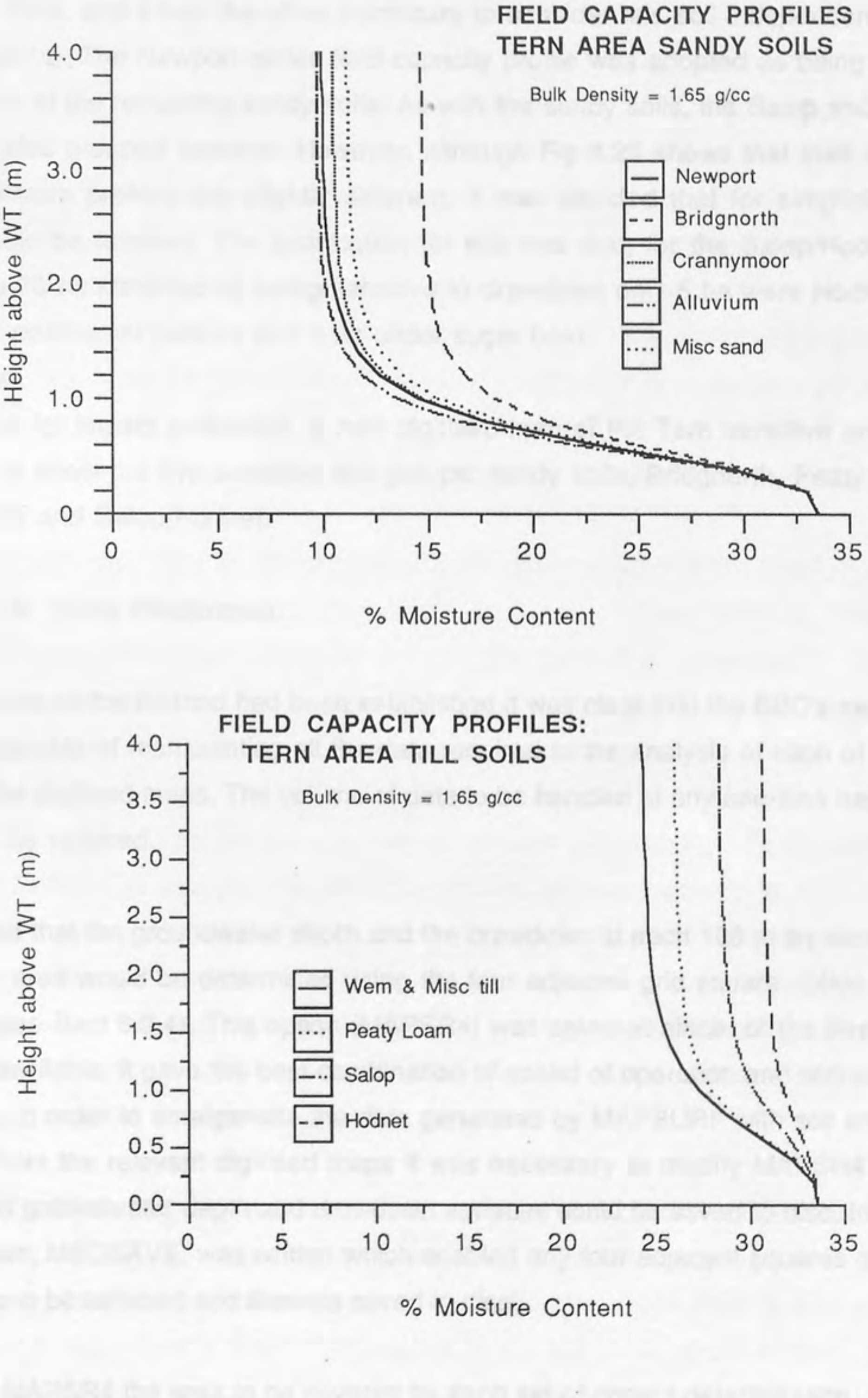


Fig 8.26 Field Capacity Profiles of Soils in the Tern Area.

It had already been established that all soils within the Tern Area were sensitive to the effects of groundwater drawdown (see Sect 8.4.2.1). However, since Newport, Bridgnorth, Crannymoor, Alluvium and Miscellaneous Sandy Soils all possessed critical heights of approximately 1.5m, they were grouped together for the purpose of determining the sensitive area and were referred to collectively as sandy soils. Fig 8.26 shows that the field capacity profile for the Bridgnorth series is significantly different from those of the other sandy soils, and it was therefore necessary to consider this soil independently of the rest of this group. The Newport series field capacity profile was adopted as being representative of the remaining sandy soils. As with the sandy soils, the Salop and Hodnet series were also grouped together. However, although Fig 8.26 shows that their field capacity moisture profiles are slightly different, it was decided that for simplicity this grouping would be retained. The justification for this was that, for the Salop/Hodnet soil group, of the 76 ha identified as being sensitive to drawdown only 5 ha were Hodnet series - 2 ha under permanent pasture and 3 ha under sugar beet.

In preparation for impact evaluation, a new digitised map of the Tern sensitive area was constructed to show the five sensitive soil groups: sandy soils, Bridgnorth, Peaty Loam, Wem/Misc Till and Salop/Hodnet.

8.5.1.3 Data Preparation.

Once the outline of the method had been established it was clear that the BBC's memory would be incapable of manipulating all the data required in the analysis of each of the areas covered by the digitised maps. The volume of data to be handled at any one time had, therefore, to be reduced.

It was decided that the groundwater depth and the drawdown at each 100 m sq element of the sensitive area would be determined using the four adjacent grid square option of MAPSURF (see Sect 8.2.4). This option (MAPSR4) was selected since, of the three alternatives available, it gave the best combination of speed of operation and reduced edge discontinuity. In order to amalgamate the data generated by MAPSURF with soil and crop information from the relevant digitised maps it was necessary to modify MAPSR4 so that the calculated groundwater depth and drawdown surfaces could be saved to disc. In addition a new program, MSQSAVE, was written which enabled any four adjacent squares of a digitised map to be selected and likewise saved to disc.

By selecting MAPSR4 the area to be covered by each set of impact determination calculations was reduced to four grid squares. A further reduction in the computer power required was made when it was recognised that, by producing composites from soil and agriculture maps, only one set of information need be input instead of two. MMERGE was therefore used to produce a suite of digitised maps showing, for each crop within the sensitive area, where it was growing and the soil type at each location - see the example for cereals, Fig 8.27.

At this stage of the method design the field capacity profiles for the five classes of soil sensitive to drawdown had been determined using Eqn 6.7. For groups of four grid squares, groundwater depth and drawdown surfaces could be calculated and saved using MAPSR4. Again for groups of four grid squares, data relating to the distribution of each crop and the soil type on which it was growing had been prepared and saved using MMERGE and MSQSAVE respectively. Yield decline equations had been derived for each of the crop types identified - with the exception of the small group classified as 'miscellaneous'. The only additional data required, before a program could be written to evaluate the impact of a given drawdown, were the current market values of the crops or associated produce.

8.5.1.4 The Yields of Crops Grown in the Tern Area and their Market Value .

The MAFF Regional Office at Shrewsbury was consulted regarding the price which farmers could expect to receive for crops grown in the Tern Area. Arable (Wilkins, 1989) and livestock (Brady, 1989) ADAS advisors provided the 1988 data presented in Table 8.9. Both advisors counselled caution in the use of both the yield rates and the prices given, but admitted that they could suggest no better source of information.

The livestock advisor was unwilling to commit himself to providing figures relating to cattle feed in times of drought. He said that different farmers resorted to different practices, depending on their resources. Many would rely on stocks of silage to supplement grazing, but use would also be made of any fodder crops grown for winter or autumn feed. In effect a policy of utilising available resources would be adopted to delay the purchase of feed, in the hope that the drought would break in time for winter stocks to be at least partially replenished.

It was most unlikely that farmers would 'lose' cattle as a result of the effects of groundwater pumping, but would make up any deficiency in grazing through supplementary feed. A figure of 3.5 kg of barley per head of cattle per day was adopted for supplementary feed since it was representative of the quantities given to cattle during the winter months at Gleadthorpe EHF (MAFF, 1978). Thus, for each beast that could no longer be grazed as a result of reduced grass yields due to pumping (as determined from

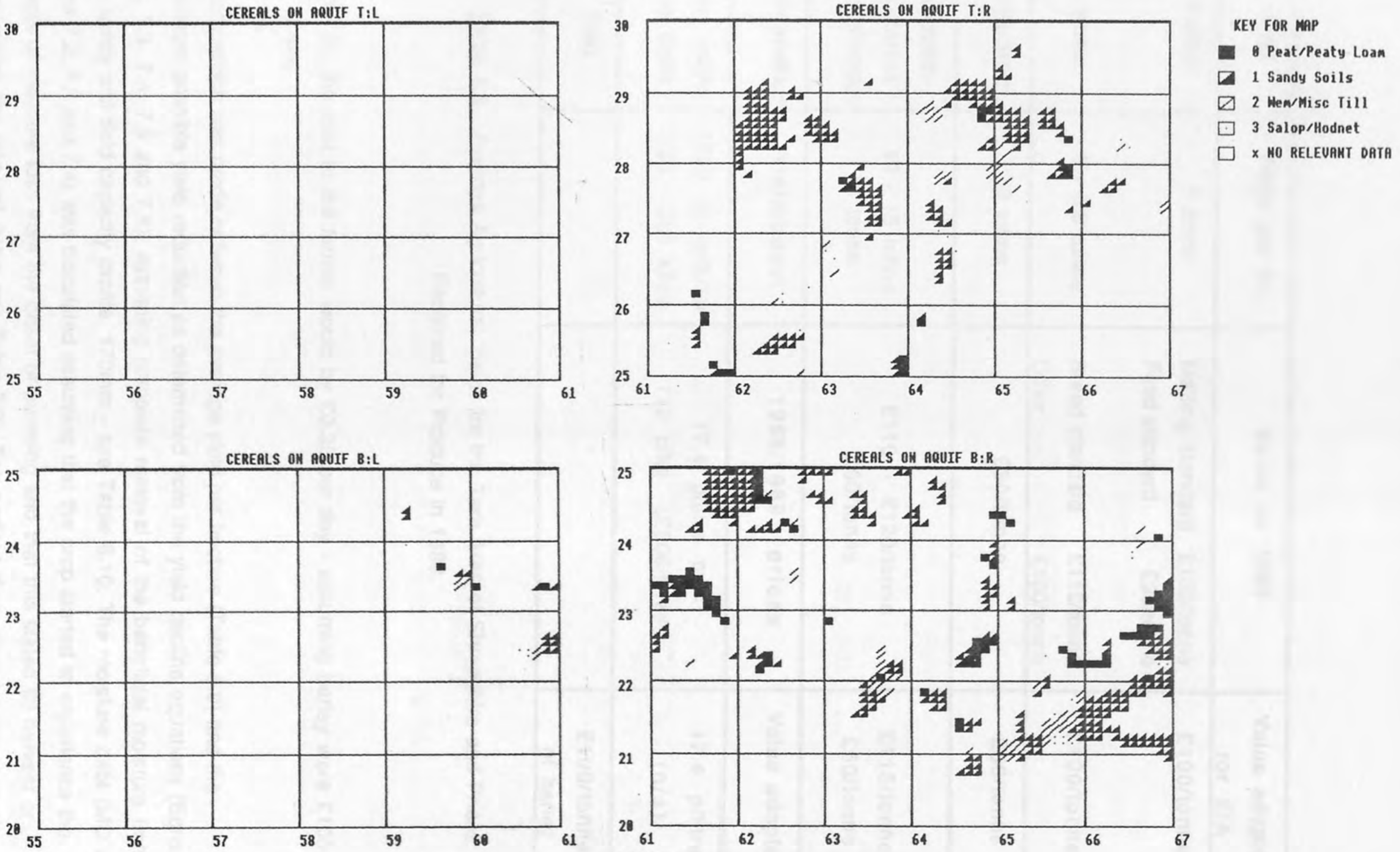


Fig 8.27 Example of Soil / Crop Composite: Cereals.

Crop	Yield per ha	Value in 1988	Value adopted for EIA
Barley	5 tonne	Malting standard £100/tonne Feed standard £95/tonne	£100/tonne
Wheat	5 - 8.5 tonne	Bread standard £110/tonne Other £100/tonne	£100/tonne
Sugar Beet	38 tonne	£30/tonne	£30/tonne
Potatoes:-			
a) Earlies	10 - 15 tonne	£110 - £120/tonne	£115/tonne
b) Maincrop	30 tonne	£60/tonne	£60/tonne
Livestock	**Yield/beast**	**1988/1989 prices**	**Value adopted**
Dairy cattle	4500 ltr milk/ha	17.4 p/litre milk	17.4 p/litre
Beef cattle	330 - 560 kilos	110 p/kg (£500/beast)	(n/a)
Feed			£100/tonne of barley

Table 8.9 Average Agricultural Yields for the Tern Area of Shropshire and Prices Received for Produce in 1988.

Eqn 7.6), the cost to the farmer would be £0.35 per day - assuming barley were £100 per tonne.

A comparison was made between the average yield per hectare (Table 8.9) and the maximum possible yield reduction as determined from the yield decline equations (Eqns 7.2, 7.3, 7.4, 7.5 and 7.6), assuming complete removal of the beneficial moisture from the sandy soil field capacity profile, 170mm - see Table 8.10. The moisture debt (MD in Eqns 7.2, 7.3 and 7.4) was calculated assuming that the crop started to experience the effects of moisture loss from the onset of pumping and that this lasted till harvest or senescence (for relevent dates see Table 7.2). The earliest likely date for the start of pumping was taken to be the 130th day after the start of the year. This date was obtained from Fig 8.28, the Severn Trent Water Authority's analysis of the frequency of use of the

Fig 8.28 Use of Groundwater to Meet Estimated 1991 Demands During the Years 1932-1976 (Severn Trent Water Authority, 1977).

Shropshire Groundwater Scheme had it been operational during the period 1932 to 1975 (Severn Trent Water Authority, 1977).

Fig 8.28 shows that in both 1974 and 1976 pumping would have continued for at least 50 days. Under these circumstances Table 8.6 indicates that, when the drawdown response times are considered, all soils subject to the drawdown of shallow water tables would have lost at least 95% of the drainable moisture by the time pumping ceased - with the exception of Peaty Loam and the Salop/Hodnet group more than 99% would have been removed. However, these latter soils would have less than 4% of the gravitational water remaining in their profiles. In addition, since for all soils the DRT_{50} is no more than half a day, only a small allowance equal DRT_{75} was made for the fact that full moisture loss takes some time to develop, thus:

Duration of Moisture Loss Experienced by the Crop =
(Date of Harvest or Senescence) - (Pumping Start Date) - DRT_{75} - Eqn 8.1

Produce	Days of Moisture Loss	Max Likely Pumping Yield Loss	Expected Yield with No Moisture Loss
Cereals	81	2.6 t/ha	5 t/ha
Sugar Beet	157	59.0 t/ha	38 t/ha
Potatoes:-			
a) Earlies	35	10.0 t/ha	10 - 15 t/ha
b) Maincrop	127	36.6 t/ha	30 t/ha
Permanent Pasture	n/a	2601 ltr milk/ha support lost for 2.3 beef cattle / ha	4500 ltr milk/ha stocking rate = 2.6 beasts / ha

Table 8.10 Comparison between Expected Agricultural Yield and Calculated Maximum Likely Yield Loss Due to Pumping

As can be seen from Table 8.10, with the exceptions of sugar beet and maincrop potatoes, when the maximum likely yield reductions due to groundwater drawdown are compared with the expected yields under normal conditions, the losses are less than normal production and are therefore, on the face of it, realistic. However, the yield losses of sugar beet and maincrop potatoes, as calculated from Eqns 7.2 and 7.4, require further consideration.

If representative annual yields of sugar beet and maincrop potatoes are 38 and 30 tonne per ha respectively, are yields of the magnitude of the calculated losses, 59 and 37 tonne per ha, even possible? The Gleadthorpe EHF data, from which Eqns 7.2 and 7.4 were derived, show that with irrigation total yields as high as 60 tonne of sugar beet per ha and 61 tonne of potatoes per ha have been recorded for sandy soils similar to those of the Tern Area (see Appendix 4 and MAFF,1977). The answer to the question posed is, therefore, yes - but only when the crop receives water to supplement the rainfall (e.g. irrigation in the case of the Gleadthorpe EHF experiments).

It is only possible for all the moisture within the critical height, over and above the residual moisture content, to be removed from the crop's root zone if the roots themselves extend through this region as far as the water table itself - as illustrated in Fig 8.29. Under such conditions the crop would not only benefit from the additional moisture retained within the critical height, but would also benefit from a continual supply of moisture through capillary rise. Drennan (1979b), when presenting evidence at the public inquiry (see Sect 5.4.6.1), produced data which showed that when growing in a medium loam a crop could meet its average summer daily transpiration requirements (3 mm/day) from capillary rise alone, providing its roots were within 0.5m of the watertable. In addition to Rijtema (1968), the source quoted by Drennan, many authors have published the results of studies which demonstrate that crops can benefit directly from capillary rise under such conditions (see for example: Raats and Gardner, 1974; de Laat, 1980; Bouma, 1985; Ragab and Amer, 1986).

Thus, for the circumstances under investigation, where roots penetrate to the water table, although no surface irrigation is applied the crop is in effect receiving subsurface irrigation through capillary rise. Consequently, where shallow water tables exist in the Tern Area, yields of sugar beet and main crop potatoes as high as 60 tonne per ha are quite possible. Therefore, the maximum likely yield losses shown in Table 8.10 are all theoretically feasible. On these grounds the yield decline equations (Eqns 7.2 to 7.6) were all considered acceptable, and were employed to evaluate the economic effects of groundwater pumping. In order to express the impact in monetary terms the crop values given in Table 8.9 were used.

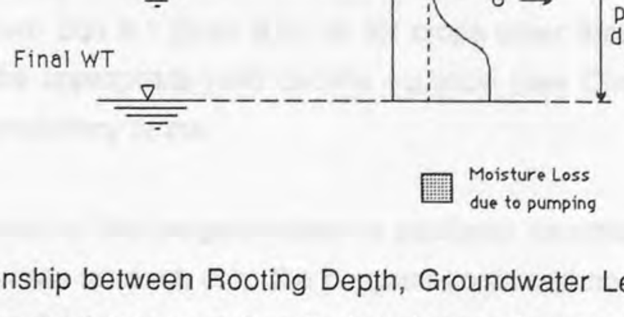


Fig 8.29 Relationship between Rooting Depth, Groundwater Level and Critical Height for Maximum Moisture Loss Due to drawdown to be Possible.

8.5.1.5 EIACOST - a Program for Evaluating the Effects of Groundwater Pumping on Agricultural Production.

Fig 8.30 is a flow diagram illustrating the key components of the program, EIACOST, which was developed to evaluate the effects of groundwater drawdown on crop yields. It was necessary to produce two versions of EIACOST as the length of a single program for handling all five soil groups exceeded the BBC's capabilities. Version one of EIACOST enabled the crop losses on sandy, Bridgnorth and Wem/Misc Till soil groups to be determined, whilst the second program catered for Peaty Loam and Salop/Hodnet. A listing of version one is given in Appendix 7 together with examples of the results output.

Each program run calculated the effects of pumping on one crop for an area of 4 sq km - four adjacent OS grid squares. After the operator had selected the appropriate crop from a menu and input a start date for pumping, data giving the growing locations/soil type, groundwater depth, and drawdown were read into compatible 20 x 20 arrays in which each element represented 100 sq m. These data had previously been prepared as explained in Sect 8.5.1.3. The field capacity profiles, critical heights and drainage rate reduction times for each soil type were incorporated into the program, as were the crop rooting depths and prices.

For each element in the arrays, once the soil type had been identified, it was ascertained whether the crop was affected or not, and if artesian conditions existed. If the piezometric surface indicated artesian conditions, then the fact was recorded but no attempt was made to estimate the resulting yield loss (see below). For normal water table conditions, if there were an effect then, depending upon the position of the groundwater table, the amount of moisture removed as a result of drawdown was calculated. This proved to be the most complex component of the program since there were a range of possible moisture removal patterns depending upon the crop rooting depth, the drawdown, and whether the critical height 'protruded' above the ground surface or not. The alternative possibilities are illustrated in Fig 8.31.

Once the moisture loss had been quantified, after the duration of moisture loss experienced was determined from Eqn 8.1 (Sect 8.5.1.4) for crops other than grass, the yield loss was calculated using the appropriate yield decline equation (see Chapter 7). Finally, the impact was evaluated in monetary terms.

A number of features of the program deserve particular comment. Firstly, other than summing the total area for each crop the program contained no facility for evaluating the economic effects of drawdown under artesian conditions. Although the results from the Childs

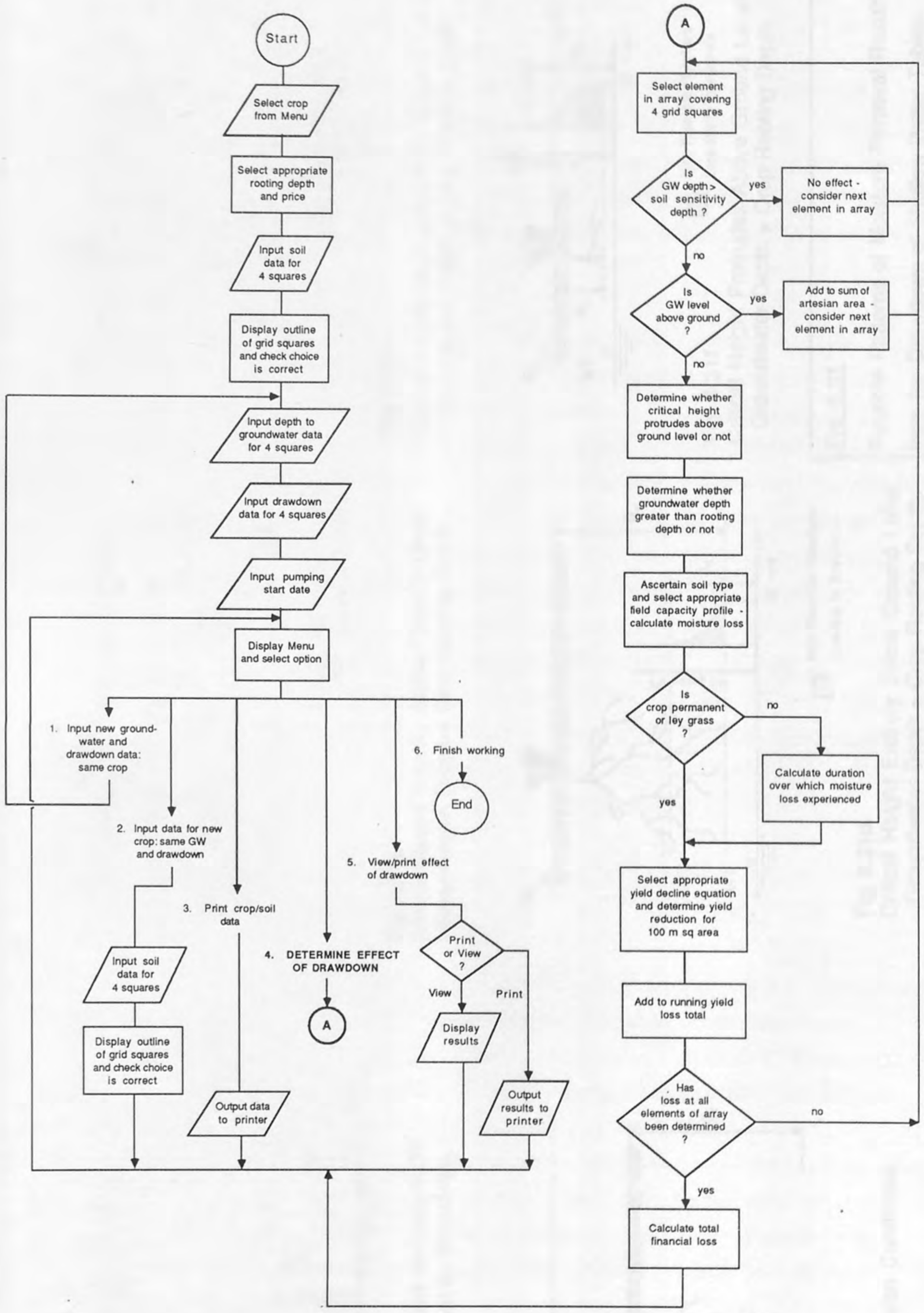


Fig 8.30 Flow Diagram of Impact Evaluation Program - EIACOST.

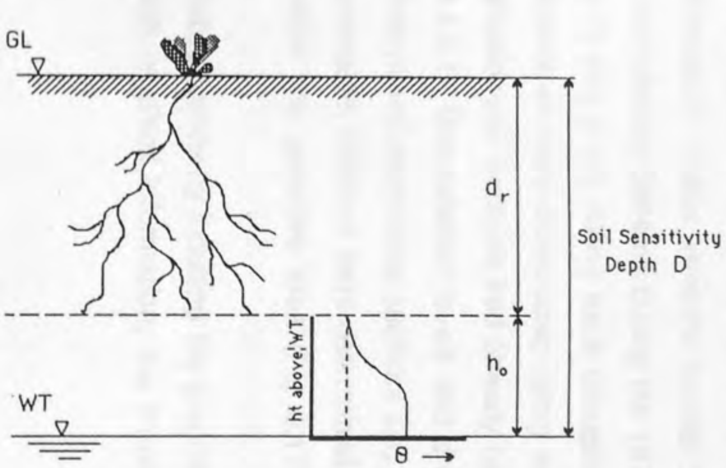


Fig 8.31a Available Moisture NOT Affected by Drawdown.

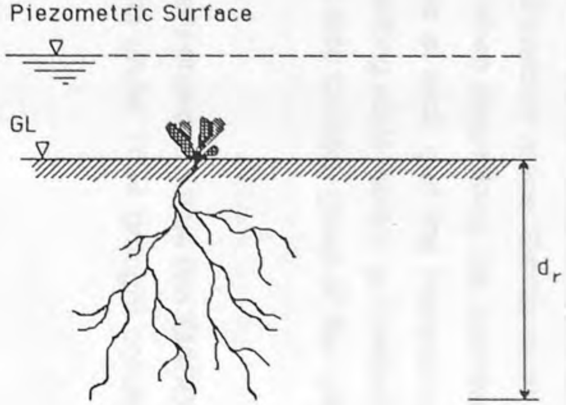


Fig 8.31b Artesian Conditions.

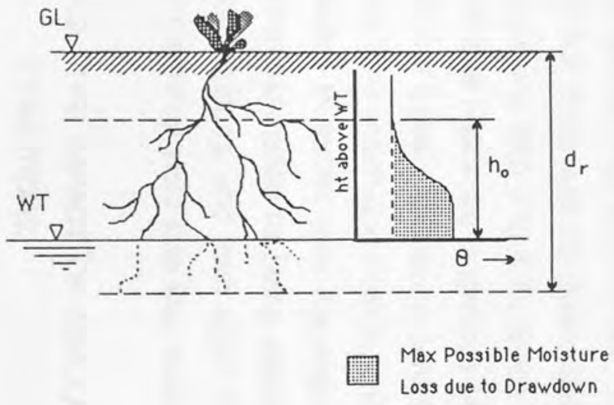


Fig 8.31c
Critical Height Entirely Below Ground Level - Groundwater Depth < Crop Rooting Depth.

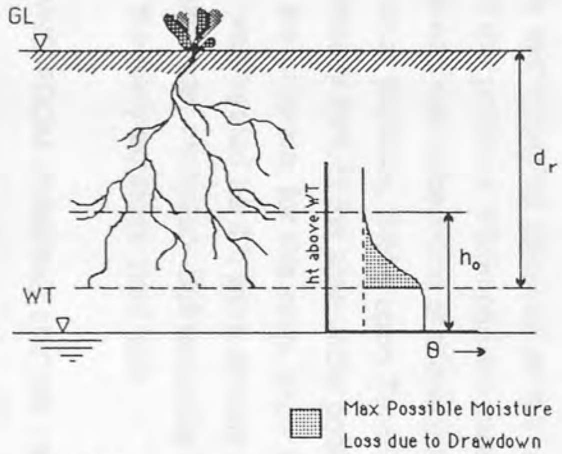


Fig 8.31d
Critical Height Entirely Below Ground Level - Groundwater Depth > Crop Rooting Depth.

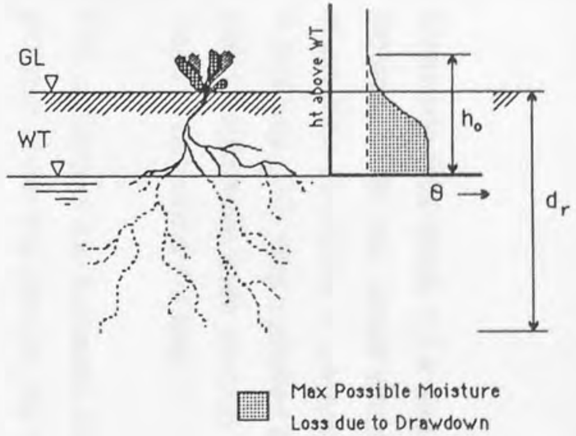


Fig 8.31e
Critical Height Protrudes Above Ground Level - Groundwater Depth < Crop Rooting Depth.

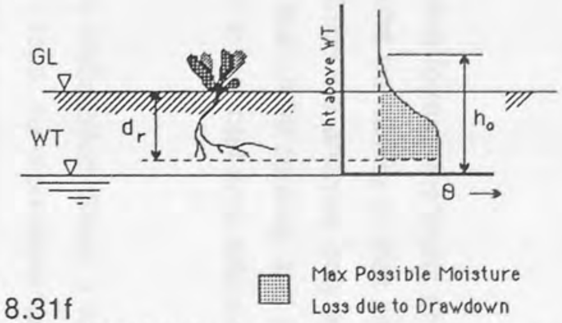


Fig 8.31f
Critical Height Protrudes Above Ground Level - Groundwater Depth > Crop Rooting Depth.

Fig 8.31

Possible Patterns of Moisture Removal Resulting from the Drawdown of Shallow Water Tables.

Ercall site (see Sects 5.4.4 and 5.7.3) could have formed the basis of an appropriate method, it was not known whether the conditions pertaining to that site were representative of artesian conditions in general or not. In practice the analysis only identified 1 ha affected in this way. This was classified as Peaty Loam soil under cereals, and since the economic effect would have been minimal, it was counted in the total area affected but no attempt was made to determine the loss.

Two aspects of the economic evaluation require elaboration. Since a variety of crops were grouped under the general title Miscellaneous Crops, no representative price could be determined for this category of produce although a representative rooting depth of 1.5m was adopted. Consequently, as with artesian conditions, for these crops only the total area which was affected was determined. The second point relating to economic evaluation concerns the fact that there was no differentiation between early and maincrop potatoes on the digitised agriculture map (Fig 8.7). Since the lifting date of the potatoes influenced the moisture debt, and hence the magnitude of the impact, some way had to be found of allowing for the two different types of potatoes. MAFF returns for the three parishes, Stoke upon Tern, Stanton upon Hine Heath and Hodnet, showed that approximately 25% of the area under potatoes was devoted to earlies (see Appendix 6). Thus within the program, for this crop, each 100 sq m element identified as being affected by drawdown was treated as if it were entirely under early potatoes, and then again as if it were entirely under maincrop. Subsequently 75% of the maincrop yield loss was recorded and 25% of the early potatoes yield loss.

8.5.2 THE IMPACT OF SIMULATED DRAWDOWNS FROM PUMPING UNDER 1974 CONDITIONS.

At the public inquiry the Severn Trent Water Authority presented two maps of groundwater drawdown. These were the results of simulations of the operation of the Shropshire Groundwater Scheme during the 1974 and 1974 to 76 droughts (see Sect 8.3.5 and Figs 8.13 and 8.14). Along each latitudinal grid line within the EIA area sections showing the drawdown were constructed using the contoured drawdown maps. Similar depth to groundwater sections had already been prepared when determining the sensitive area (Sect 8.4.2.1). Groundwater levels and drawdown values at each grid line intersection were then determined from these sections and, using the resulting node values, groundwater and drawdown surfaces were determined and saved to disc for each group of four grid squares within the sensitive area (Fig 8.17).

Subsequently by inputting the groundwater depth and drawdown data into EIACOST, together with crop/soil information, the impacts of pumping under 1974 drought conditions for the cropping patterns of 1980 were determined. From Fig 8.28 it was judged that pumping would have started at the end of May on the 150th day of the year.

Table 8.11 provides a summary of the areas affected, the yield loss and the economic effects had groundwater been abstracted in 1974. Details of the results for each group of four grid squares are provided in Appendix 8.

8.5.3 THE IMPACT OF SIMULATED DRAWDOWNS FROM PUMPING IN THE LAST YEAR OF THE 1974 TO 1976 DROUGHT.

The procedure for determining the impact of drawdown as a result of pumping in 1976, the last year of the 1974 to 1976 drought period, were as described for pumping in 1974. In 1976, however, pumping did not commence until mid-June (see Fig 8.28) - taken as the 165th day of the year. The consequences of this were that, although the drawdown was greater than for 1974, the duration of moisture loss experienced by the crop was shorter. As can be seen from Table 8.11, the magnitude of the impacts caused by the drawdown were similar to those of 1974. Further details of the estimated effects of pumping in 1976 are given in Appendix 8.

Since pumping would have started as late as mid-June in 1976, early potatoes would not have been affected by the drawdown, whereas they had been by abstraction in 1974.

8.6 DISCUSSION OF THE ENVIRONMENTAL IMPACT ASSESSMENT RESULTS.

Once appropriate data were collected and computer programs written, there were essentially three stages in determining the impact of groundwater drawdown on the agriculture of the Tern Area. Initially the digitised maps were overlaid to delineate the area for which there were data for all features of interest - the EIA Area. The second stage involved determining the sensitive area, and the third stage saw the evaluation of the extent of the impact and its cost to the farming community.

Fig 8.32 illustrates the extent of the impact of pumping in relation to the full EIA study area. In addition it shows that, although the whole of the sensitive area is potentially at risk, the actual area affected by any particular pumping event is less and depends on what crops are growing at the time and where they are located. The reason that the impact area is less than the sensitive area is that in determining the latter the largest crop rooting depth has

Crop	Total Area Affected (ha)	Total Yield Loss	Economic Effect (£)
1974 Pumping			
Cereals	561	428 tonne	42,765
Sugar Beet	209	2,622 tonne	78,661
Potatoes	76	234 tonne	14,511
Miscellaneous Crops	12		
Permanent Pasture:	552		
a)Effect on Milk Yields		411,907 litres	71,672
b)Feed Required		316.7 cattle	14,715
Grass Leys:	52		
a)Effect on Milk Yields		17,825 litres	3,101
b)Feed Required		15.7 cattle	733
TOTAL IMPACT:	1462		
with Milk Yields for Grass			210,710
with Cattle Feed for Grass			151,385
1976 Pumping			
Cereals	552	380 tonne	37,985
Sugar Beet	200	3,128 tonne	93,839
Potatoes	78	237 tonne	14,194
Miscellaneous Crops	12		
Permanent Pasture:	535		
a)Effect on Milk Yields		401,280 litres	69,823
b)Feed Required		354.1 cattle	14,620
Grass Leys:	50		
a)Effect on Milk Yields		18,284 litres	3,181
b)Feed Required		16.1 cattle	668
TOTAL IMPACT:	1427		
with Milk Yields for Grass			219,022
with Cattle Feed for Grass			161,306

Table 8.11 Impact of the Effects of Pumping in 1974 and in 1976 on the Agricultural Production of the Tern Area.

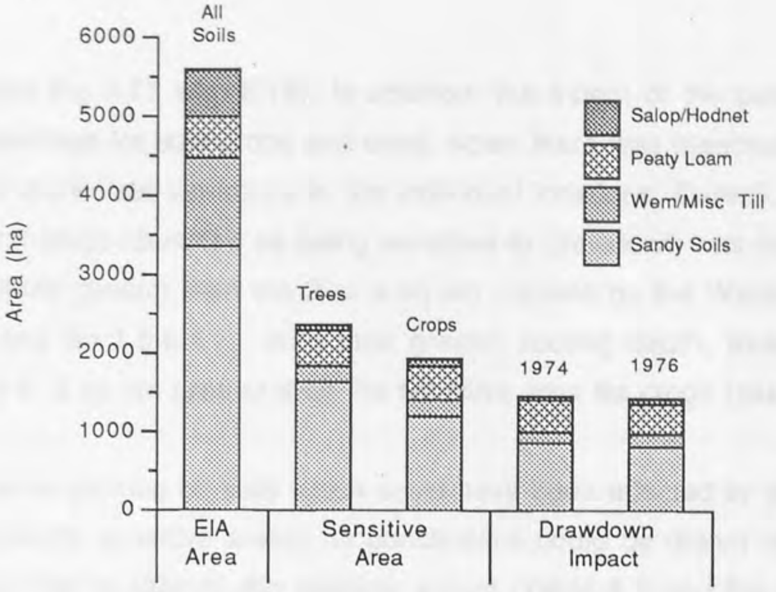


Fig 8.32 The Relationship between the EIA Area, the Sensitive Areas and the Areas Affected by Drawdown.

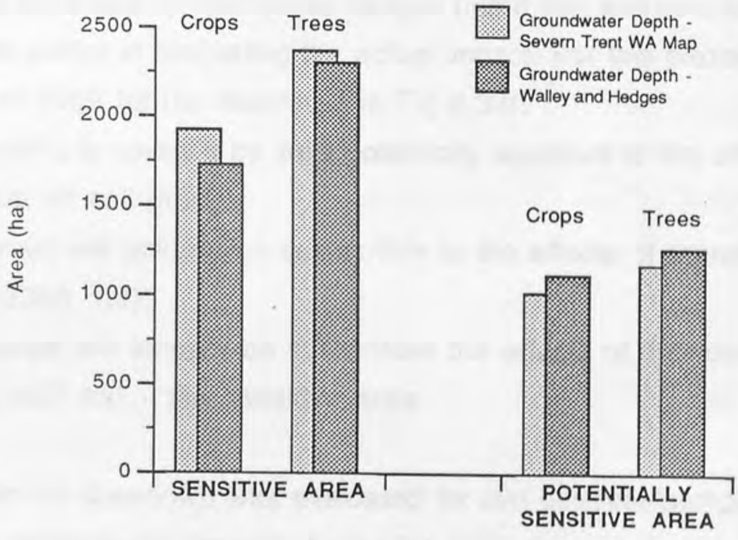


Fig 8.33 Comparison of Sensitive and Potentially Sensitive Areas.

been used (2.1m for sugar beet and cereals), whereas whether an effect is experienced or not will depend on the actual rooting depth (e.g. in the case of grass leys this is only 0.6m).

The sensitive area was determined twice using the same data for the physical features each time, but different depth to groundwater maps (see Sect 8.4.2.2). The sizes of the sensitive areas obtained for these differing groundwater conditions were in reasonably close agreement for both crops and trees (see Table 8.7 and Fig 8.33). However, there were significant differences in the actual locations of some of the individual sensitive areas (for example compare Fig 8.17 with 8.18). In addition, the extent of the potentially sensitive areas were determined for both crops and trees. Again there was reasonable agreement in the total size of the areas, but variations in the individual locations. Overall, however, the area under agricultural crops identified as being sensitive to drawdown was between 17 and 20 sq km - significantly greater than the 2 to 3 sq km claimed by the Water Authority at the public inquiry (see Sect 5.6.4.2). With their greater rooting depth, trees were at risk over an area some 4 to 5 sq km greater than the sensitive area for crops (see Fig 8.33).

For crops and trees growing on soils which could have been affected by leaky confining layers (the potentially sensitive areas) no conclusions could be drawn regarding the risk to agriculture other than to identify the possible extent (Table 8.7 and Fig 8.33). The actual effects within these areas may well be quite significant if the moisture losses observed at the Childs Ercall and Greenfields sites are not exceptional (see Chaper 5).

The Severn Trent WA depth to groundwater map (Fig 8.12) was accepted at the inquiry as superseding that produced by Walley and Hedges (Fig 8.11), and as a consequence it alone was used by the author in evaluating the actual impact. For this piezometric surface, of the total EIA Area of 5589 ha (as illustrated in Fig 8.32):

i) 100% is covered by soils potentially sensitive to the effects of drawdown - i.e. all soil groups;

ii) trees will actually be susceptible to the effects of drawdown over 42% (2366 ha);

iii) crops will actually be susceptible the effects of drawdown over 34.5% (1927 ha) - the sensitive area.

The actual impact of drawdown was evaluated for two different pumping simulations - full operation of the groundwater scheme during the 1974 drought, and in 1976 at the end of the 1974 to 1976 dry period. Crops only were considered in the analysis, the results of which (see Fig 8.32) showed that:

i) 25.5% (1427-1462 ha) of the total EIA area would have been affected by groundwater abstraction;

ii) the effects would have been felt over approx 75% of the area identified as sensitive to drawdown.

Fig 8.34 illustrates the effects of pumping in terms of the proportion of each crop affected. It is clear from both Fig 8.34a and Fig 8.34b that, in terms of area, cereals and permanent pasture are most at risk, followed by sugar beet. There is very little difference between the 1974 and 1976 areas experiencing yield loss, and despite 1976 drawdowns being greater than for 1974 (see Figs 8.13 and 8.14) the area affected was 35 ha less. The reason for this was that in 1976 pumping started in mid-June, some 15 days later than in 1974 and thus the moisture debts (MD) were of a similar magnitude. Furthermore, despite the fact that in 1976 the total area of potatoes affected was marginally greater than that in 1974, because their harvest date was taken as the 15th July, the yield of early potatoes was not adversely affected.

For evaluating the economic consequences of pumping two different relationships were developed for grass yields - one relating to milk production (Eqn 7.5) and the second to the number of beef cattle supported per ha (Eqn 7.6). Since grassland comprised approximately 40% of the area affected by drawdown (Fig 8.34a), as can be seen from Fig 8.35, the method of costing the reduced grass yields had a significant effect on the overall economic impact. For the 1974 drawdown situation, when grass yields were evaluated in terms of milk production, the loss was nearly £60,000 greater than the loss determined in terms of the additional feed required (Fig 8.35). Which of the two methods is more realistic cannot be ascertained without further detailed research. However, it is unlikely that a farmer will allow milk output to fall as grass yields decline - it is more likely that supplementary feed will be provided to maintain production levels. On the other hand, the costing of supplementary feed has been made simply on the basis of the purchase price of barley. This is probably too low, and certainly has no component to cover the additional labour required in distribution of feed etc. The true figure, therefore, probably lies somewhere between the two estimates.

Fig 8.36 compares the economic effects of pumping in 1974 and 1976. The impact in terms of sugar beet production is greater for 1976 than for 1974 - with the reverse for cereals. There is no difference regarding the impact of reduced grass yield, which in this instance is costed in terms of the additional cattle feed required.

Although, as explained above, early potatoes were not affected in 1976, the loss to the farmer was almost the same as for 1974 because larger quantities of available moisture were removed from the soil profiles as a result of the increased drawdown. The fact that the yield reductions in 1976 were not even greater was due to the late pumping start date. This also applied to sugar beet.

Cereals, on the other hand, were harvested earlier than sugar beet and maincrop potatoes. As a consequence, although moisture losses were greater in 1976 than in 1974, the reduced duration over which this moisture loss was experienced meant that the economic effect was not so great.

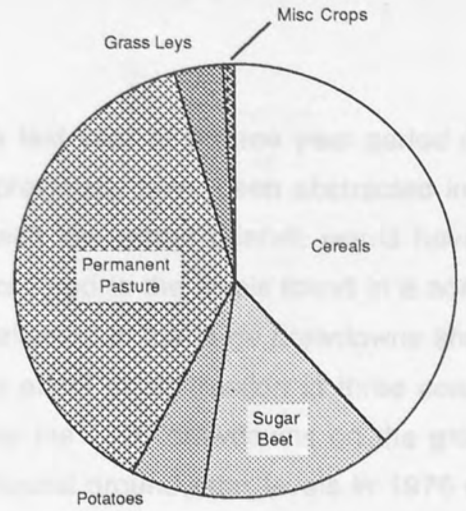


Fig 8.34a
Area Affected by 1974 Pumping in Terms of Crop Distribution

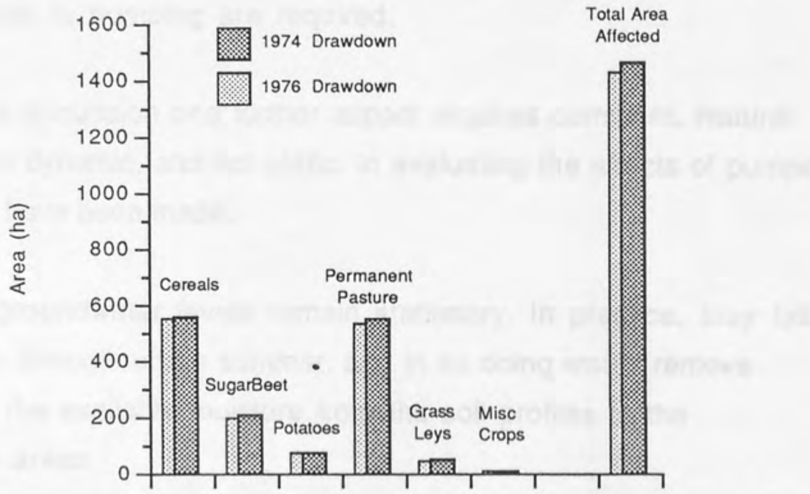


Fig 8.34b Comparison of Effects of 1974 and 1976 Pumping on Cropped Areas

Fig 8.34 The Area Affected by Pumping in Terms of Crop Distribution.

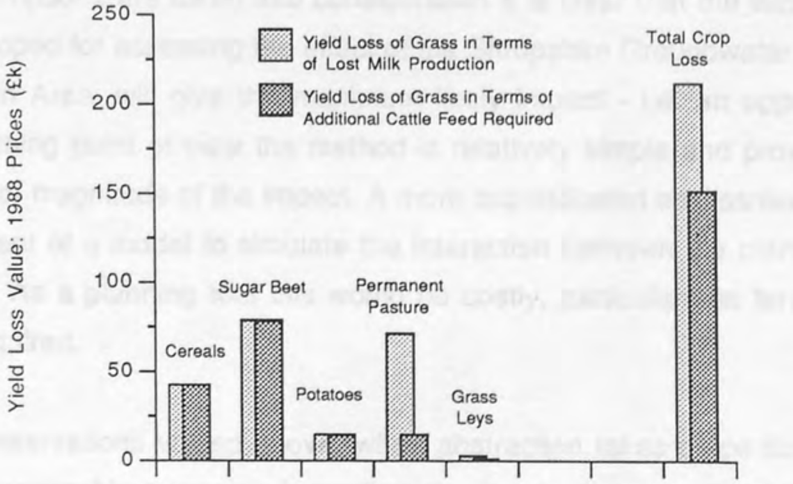


Fig 8.35 The Economic Effects of Pumping in 1974 - Grass Yield in Terms of (a) Milk Production and (b) Cattle Feed.

Pumping in 1976 took place in the last year of a three year period of low rainfall. Fig 8.28 indicates that groundwater would previously have been abstracted in both 1974 and 1975. This pumping pattern, combined with low winter rainfall, would have meant that, in 1976 the groundwater could not have recovered to the levels found in a normal year at the time the pumps were switched on. This is reflected in the large drawdowns shown on the 1976 map, Fig 8.14, which are the cumulative effect of abstraction in three consecutive years. It is therefore unrealistic to superimpose the 1976 drawdowns on the groundwater levels for a typical year, as has been done - natural groundwater levels in 1976 would have been lower. As an exercise for studying the spatial and economic effects it has yielded useful information. However, to truely evaluate what the impact would have been in 1976 the groundwater levels immediately prior to pumping are required.

Before concluding this discussion one further aspect requires comment. Natural groundwater levels are dynamic, and not static. In evaluating the effects of pumping the following assumptions have been made.

(i) Natural groundwater levels remain stationary. In practice, they fall gradually throughout the summer, and in so doing would remove some of the available moisture from the soil profiles in the sensitive areas.

(ii) The moisture content of the soil corresponds to the field capacity profile when pumping commences. If there is a dry period before abstraction starts transpiration is likely to result in moisture levels becoming depleted and a deficit building up.

When these two assumptions are taken into consideration it is clear that the technique, which has been developed for assessing the effect of the Shropshire Groundwater Scheme on agriculture in the Tern Area, will give the maximum likely impact - i.e. an upper bound. However, from a planning point of view the method is relatively simple and provides a measure of the order of magnitude of the impact. A more sophisticated assessment would require the development of a model to simulate the interaction between the plant, the soil and the groundwater. As a planning tool this would be costly, particularly in terms of the development time required.

Clearly, despite the reservations voiced above, when abstraction takes place during dry years there will be a noticeable economic impact on the farming community of the Tern Area. For 1974 conditions, if the cost of reduced grass yields is assumed to be the average of the values determined for milk production and cattle feed, the total loss in income at todays

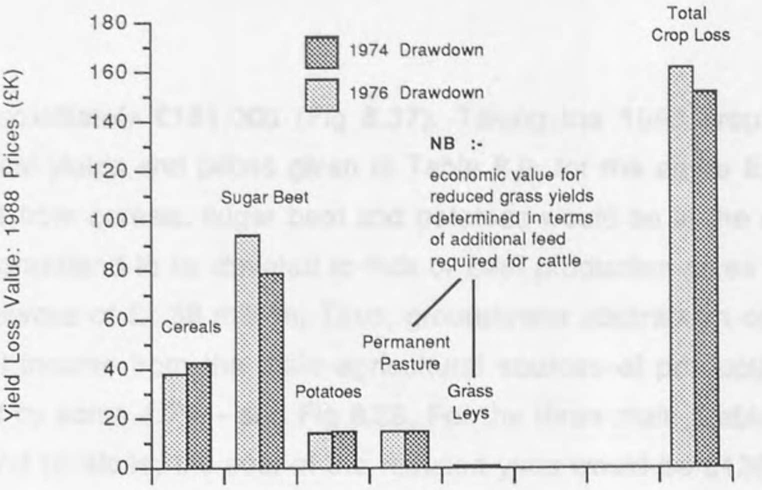


Fig 8.36 A Comparison of the Economic Effects of Pumping in 1974 and 1976.

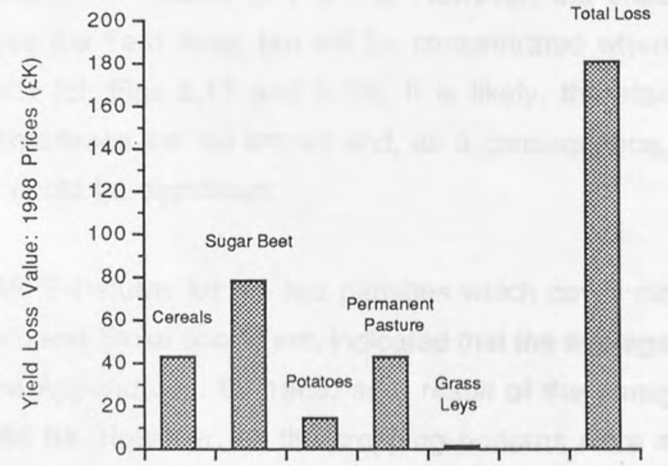


Fig 8.37 The Impact of Drawdown on the EIA Area.

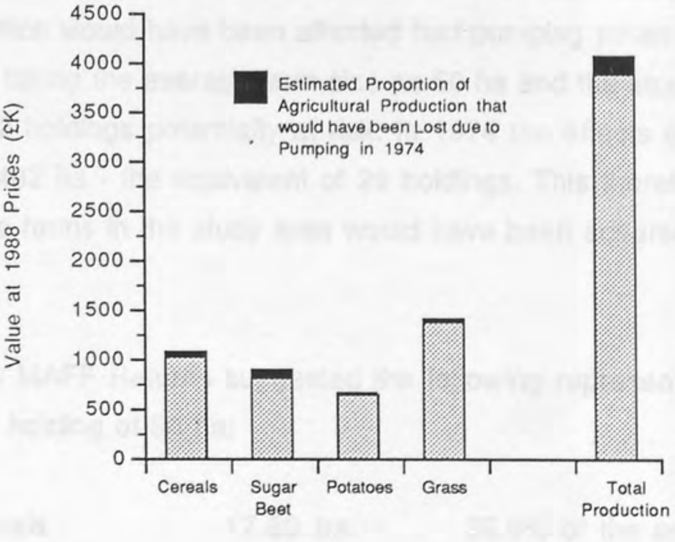


Fig 8.38 Estimated Proportion of Total Crop Production in the EIA Area Lost as a Result of Pumping.

prices would be approximately £181,000 (Fig 8.37). Taking the 1980 crop survey together with the typical yields and prices given in Table 8.9, for the entire EIA area the normal annual income from cereals, sugar beet and potatoes would be in the order of £2.51 million. Assuming all grassland to be devoted to milk or beef production gives an estimated income from these sources of £1.38 million. Thus, groundwater abstraction could have the result that the overall income from the main agricultural sources of production within the study area is reduced by some 4.7% - see Fig 8.38. For the three main arable crops, cereals, sugar beet and potatoes, the cost of the reduced yield would be £136,000 - 5.4% of that expected in a normal year.

As a percentage of the total production in the EIA area the effect of pumping will be relatively small - a reduction in income of 4 to 5%. However, the effects will not be distributed evenly across the Tern Area, but will be concentrated where shallow groundwater tables exist (cf. Figs 8.17 and 8.39). It is likely, therefore, that only a small number of farms will experience the full impact and, as a consequence, for these farms the economic implications could be significant.

Consideration of the MAFF Returns for the two parishes which cover most of the study area, Stanton upon Hine Heath and Stoke upon Tern, indicated that the average size of each holding in 1980 was 50 ha (see Appendix 6). By 1985, as a result of the amalgamation of farms this had increased to 55 ha. However, as the cropping patterns were marginally different in 1985, the 1980 figure of 50 ha has been retained for this analysis for compatibility with the Aston crop survey.

The manner in which the MAFF Returns were presented (see Sect 8.3.4) did not permit the number of holdings, which would have been affected had pumping taken place in 1974, to be ascertained. However, taking the average farm size as 50 ha and the study area as 5589 ha suggests a total of 112 holdings potentially at risk. In 1974 the effects of drawdown would have extended over 1462 ha - the equivalent of 29 holdings. This therefore indicates that, at a minimum, 26% of the farms in the study area would have been adversely affected by pumping.

Further analysis of the MAFF Returns suggested the following representative cropping pattern for an average holding of 50 ha:

cereals	17.80 ha	35.6% of the area
sugar beet	6.25 ha	12.5% of the area
potatoes	2.36 ha	4.7% of the area

grass	23.03 ha	46.1% of the area
misc land use	0.56 ha	1.1% of the area

Combining these areas with the data presented in Table 8.9 gave an estimated annual income of £36,550 per farm. If an entire holding of this size were to suffer from the effects of moisture loss due to groundwater pumping in a year similar to 1974, the resulting reduced yields would mean a loss in income of approximately 17% (£6,170).

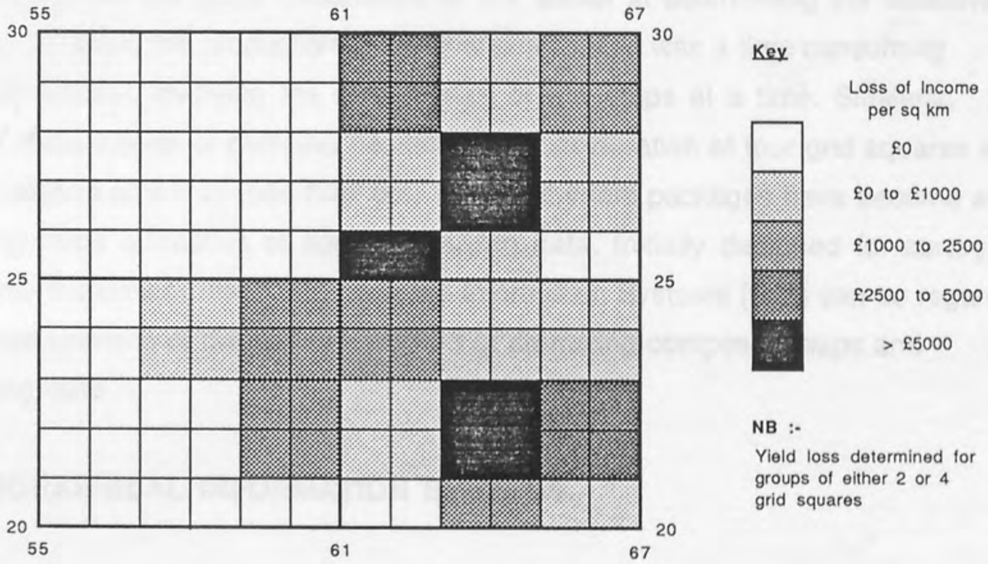


Fig 8.39 Approximate Distribution of Yield Losses within EIA Area.

Chapter 9. EVALUATION OF THE METHODOLOGY.

The steps undertaken both in identifying the areas sensitive to groundwater drawdown (Sect 8.4.2) and in evaluating the effects of pumping (Sect 8.5) were not the most efficient, and thus have not produced the most cost effective technique for use as a planning tool. There are two main reasons for this. Firstly, the process was evolutionary and therefore, although a procedure for obtaining an appropriate sequence of activities had been prepared, to some extent trial and error was involved. Secondly, powerful micro computers are now available which can process the data more quickly and efficiently than was possible with the machine that was used throughout the research.

Fig 9.1 summarises the steps undertaken by the author in determining the sensitive areas and, as can be seen, the production of the final composites was a time consuming incremental process involving the combination of two maps at a time. Similarly, evaluation of the effects of pumping necessitated consideration of four grid squares and one type of vegetation at a time (see Sect 8.5). In recent years packages have become available for handling large quantities of spatially varying data. Initially designed for cartography and land use evaluation, these Geographical Information Systems (GIS) can be regarded as sophisticated versions of the author's method of producing composite maps and manipulating data.

9.1 GEOGRAPHICAL INFORMATION SYSTEMS.

The advent in recent years of fast desk-top work stations, with large capacity memories linked to hard disc storage facilities, has allowed easy access to GIS. However, although an ideal tool for evaluating the effects of groundwater pumping on vegetation, few GIS had been designed at the time the author started his study. At that time Gates and Heil (1980) writing about GIS commented that:

> "the technological field is so newly developed that it has not yet evolved into an ordered discipline."

Furthermore, when discussing the development of GIS in the UK, Rhind in 1987 stated that although several individuals and organisations had been involved in the GIS field for over twenty years, the "term has come into common use only in the past three years".

The UK has been slow to adopt GIS technology, mainly because it is small in area and possesses a well established system of data collection and national mapping (Rhind, 1987). However, in recent years activity has increased rapidly with commercial

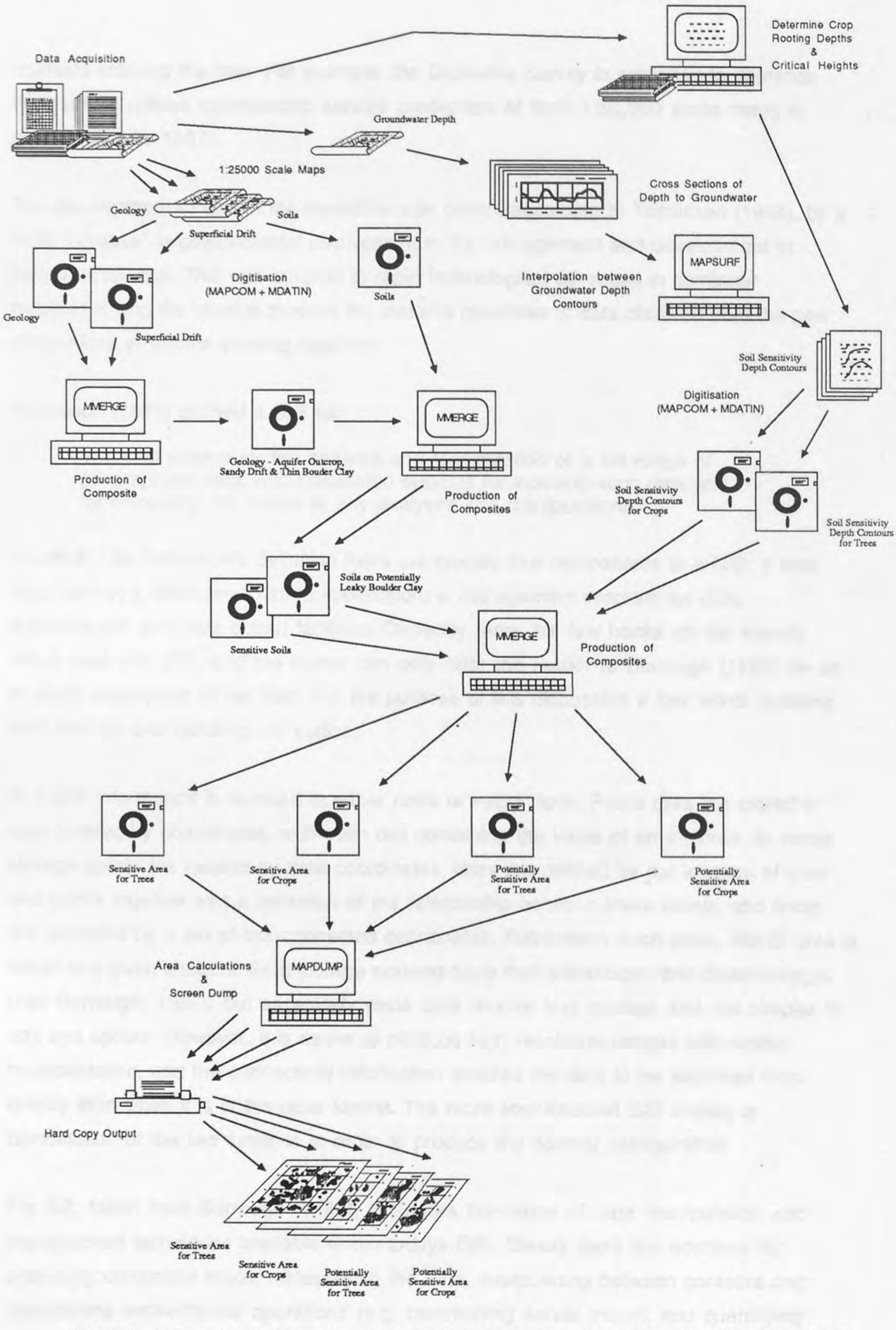


Fig 9.1 Diagramatic Representation of EIA Technique Developed for the Tern Area of the Shropshire Groundwater Scheme.

interests entering the field. For example, the Ordnance Survey in response to demands from public utilities commenced serious production of their 1:50,000 scale maps in digital form in 1987.

The development of GIS in the seventies was driven, according to Tomlinson (1984), by a "vast increase" in governmental involvement in the management and development of natural resources. This was coupled to rapid technological advances in computer capabilities and the need to process the massive quantities of data obtained from the new generations of remote sensing satellites.

Tomlinson (1987) defined a GIS as:

> "a digital system for the analysis and manipulation of a full range of geographical data, with associated systems for inputting such data and for displaying the output of any analyses and manipulations."

As implied by Tomlinson's definition there are crudely four components to a GIS: a data input facility; a database to store information; a management program for data manipulation; and data output facilities. Currently there are few books on the market which deal with GIS, and the author can only refer the reader to Burrough (1986) for an in depth description of the field. For the purpose of this discussion a few words outlining data storage and handling will suffice.

In a GIS information is retained in either rasta or vector form. Rasta data are stored in cells located by coordinates, with each cell containing the value of an attribute. In vector storage points are located by their coordinates, lines are defined by the location of their end points together with a definition of the relationship between these points, and areas are identified by a set of interconnected coordinates. Futhermore each point, line or area is linked to a given attribute. Both storage systems have their advantages and disadvantages (see Burrough, 1986), but essentially rasta data require less storage and are simpler to edit and update. However, it is easier to produce high resolution images with vector representation, and the connectivity information enables the data to be searched more quickly than when it is in the rasta format. The more sophisticated GIS employ a combination of the two systems in order to produce the optimal configuration.

Fig 9.2, taken from Burrough (1986), illustrates the range of data manipulation and management techniques available within todays GIS. Clearly there are functions for producing composite maps, reclassifying the data, interpolating between contours and undertaking mathematical operations (e.g. determining aereal extent, and quantifying moisture removal from a soil profile) - all the necessary requirements for evaluating the

Fig 9.2 Schematic Overview of the Hierarchy of Data Transformation Operations in Geographical Information Systems.

(after Burrough, 1986)

effects of a groundwater pumping scheme. That GIS can be used for sophisticated modelling and EIA applications is beyond doubt: Vang et al (1984) provided examples of their use in water resources management; Walsh et al (1984) have used GIS to model evapotranspiration; and, Miller (1984) discussed the role of GIS in assessing water resources related impacts - especially floodplain mapping and the effects of land-based activities.

9.2. THE EVOLUTION OF THE GROUNDWATER EIA TECHNIQUE INTO A COMPREHENSIVE GIS.

The digitised maps produced by the author (see Sects 8.2 and 8.3) are simple rasta representations of the relevant information. Given the high spatial variability of most of the data, for use in a planning tool the rasta format is quite adequate. The overlay approach to combining information is an accepted technique. When discussing the historical development of GIS, Burrough (1986) even mentions the original inspiration for the author's method - McHarg's transparent overlays (see Sect 8.1) - as one contributing factor!

The main ingredient necessary to convert the current unwieldy method into a more efficient and less time consuming tool is one of todays powerful PCs. The GIS package currently under development at Aston (Flach, 1989) would be ideal for data management and manipulation. Manual input of information may still be necessary, but the process can be eased by the acquisition of one of the purpose built digitisers available on the market. Furthermore, current research work suggests that methods for direct input of maps by frame grabbing, using video cameras, will be available in the near future (Flach et al,1987).

Fig 9.3 illustrates how the EIA methodology for evaluating the effects of groundwater drawdown, developed during the course of this research programme, could be a incorporated into a comprehensive GIS. The two components, shown in Fig 9.3, which have not been dealt with in this project are the groundwater model and the soil-water-plant model.

Since the 1960's groundwater models have been commonplace in the management of water resources (see Sect 2.3). There should therefore be no difficulty in obtaining an 'off-the-shelf' package for simulating pumping and producing relevant groundwater level and drawdown information.

Commercially available plant-water-soil models are known to exist. van Keulen and Wolf (1986) have produced a model, WOFOST, which has been used in feasibility studies by the Food and Agricultural Organisation of the United Nations (FAO). Although a copy of WOFOST was obtained, the author has not had time to evaluate its suitability for determining the impact of groundwater drawdown. Evans (1989) is currently developing the model originally produced at Aston University by Walley and Hussein (1982). When completed it should be possible to adapt this and integrate it into a GIS.

Groundwater levels and drawdown data are certainly required for sensitive area identification and impact evaluation. However, the degree of sophistication required will depend entirely on the purpose of the study to be undertaken. For detailed impact evaluation the dynamic nature of the natural groundwater table would require simulation, but for delineating the sensitive area this would not be necessary. The same argument applies regarding evaluation of the impact on crop yields. At the feasibility stage in the planning of a groundwater development scheme, the simple yield decline equations produced by the author may suffice. However, for settling a compensation claim made by a farmer, a detailed soil-water-plant model would assist in isolating the effects of moisture loss from other factors influencing crop growth.

In the final analysis, were a comprehensive groundwater impact evaluation package available commercially then, no matter what the application, the advantage of being able to obtain a ready made tool without the expense of having to develop one, would ensure its use. Furthermore, although the desire to determine the effects of groundwater abstraction has been the driving force behind its development, the EIA technique has the potential for wider application - particularly in the fields of land drainage and irrigation.

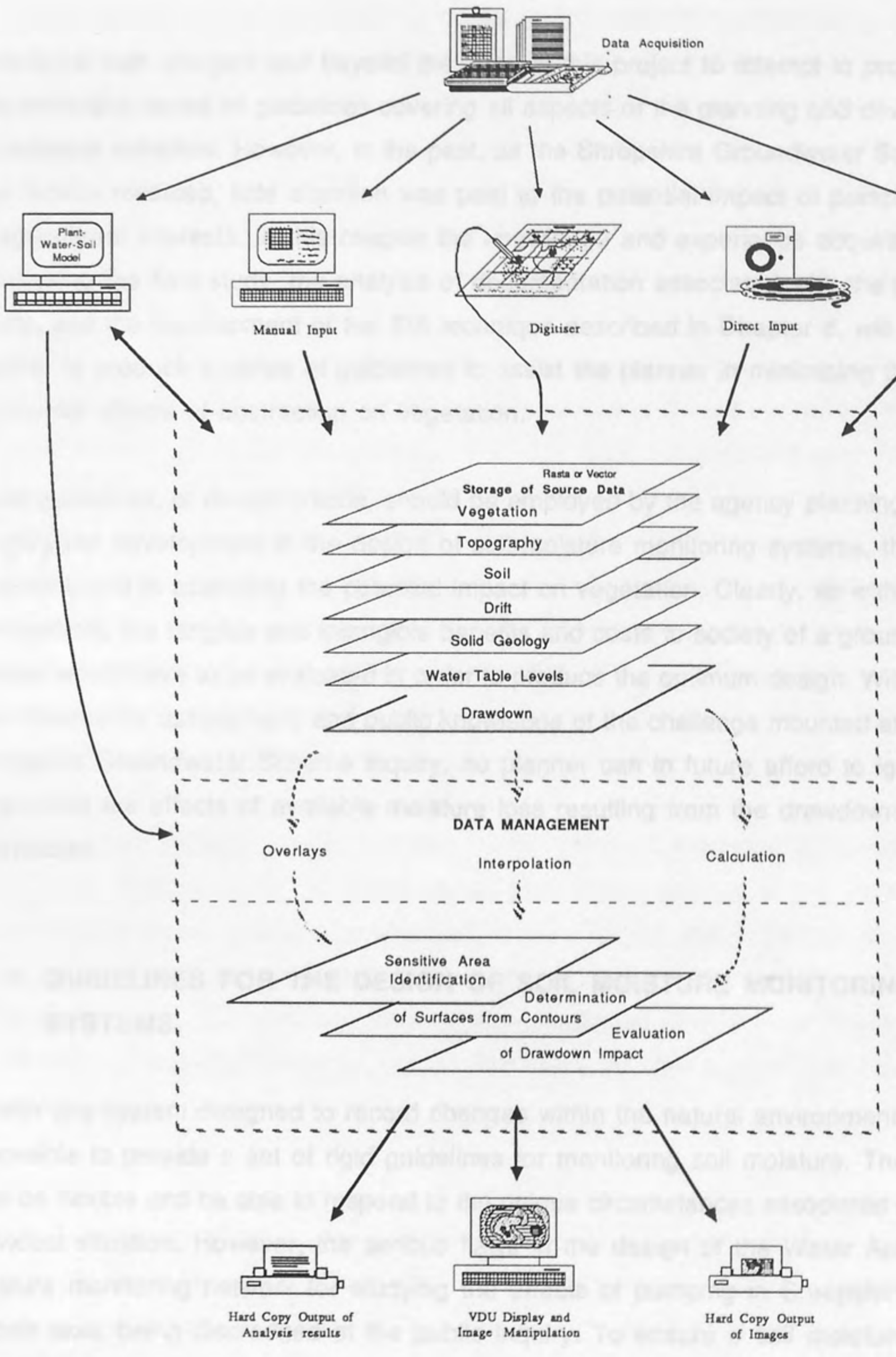


Fig 9.3 GIS for Determining the Impact of Groundwater Schemes on Vegetation.

Chapter 10. DESIGN CRITERIA FOR USE IN THE PLANNING AND DEVELOPMENT OF GROUNDWATER SCHEMES.

It would be both arrogant and beyond the remit of this project to attempt to provide a comprehensive series of guidelines covering all aspects of the planning and development of groundwater schemes. However, in the past, as the Shropshire Groundwater Scheme public local inquiry revealed, little attention was paid to the potential impact of pumping schemes on agricultural interests. In this chapter the knowledge and experience acquired through undertaking the field study, the analysis of documentation associated with the public inquiry, and the development of the EIA technique described in Chapter 8, will be brought together to produce a series of guidelines to assist the planner in minimising the detrimental effects of abstraction on vegetation.

These guidelines, or design criteria, should be employed by the agency planning a groundwater development in the design of soil moisture monitoring systems, the siting of boreholes, and in assessing the potential impact on vegetation. Clearly, as with any form of development, the tangible and intangible benefits and costs to society of a groundwater scheme would have to be evaluated in order to produce the optimum design. With the advent of environmental assessment, and public knowledge of the challenge mounted at the Shropshire Groundwater Scheme inquiry, no planner can in future afford to ignore or marginalise the effects of available moisture loss resulting from the drawdown of shallow watertables.

10.1 GUIDELINES FOR THE DESIGN OF SOIL MOISTURE MONITORING SYSTEMS.

As with any system designed to record changes within the natural environment it is impossible to provide a set of rigid guidelines for monitoring soil moisture. The designer must be flexible and be able to respond to the unique circumstances associated with each individual situation. However, the serious flaws in the design of the Water Authority's soil moisture monitoring network for studying the effects of pumping in Shropshire resulted in their work being discredited at the public inquiry. To ensure a soil moisture monitoring system is as unbiased and as scientifically valid as possible the criteria listed below need to be incorporated into its design.

The following three guidelines are general in nature and relate to the design of any soil moisture monitoring system.

1. Site Selection. The selection of suitable soil moisture monitoring sites depends largely on the objective of the study being undertaken. On a catchment wide basis, random sampling might be the most appropriate approach. Alternatively, since soil parameters, geology, slope, altitude, aspect and vegetation all affect the soil moisture, it may be essential that these factors are taken into account when choosing the location of each monitoring station. In order that interflow does not influence the moisture characteristics of the profiles being investigated, it is desirable that the sites are as flat as possible - unless lateral moisture movements are of particular interest.

   No matter what the final objective of the study, because of the wide spatial variation in the factors which influence soil moisture, site selection should not be left in the hands of anyone who does not fully understand what is to be achieved and why. Furthermore, the actual location of the station within the selected site will influence the readings obtained - even, for example, down to the decision whether observations should be made between or within rows of crops. It is therefore strongly recommended that both site selection and on site location of monitoring instrumentation or sampling remain the responsibility of a fully competent operator who is familiar with any published recommendations relating to the technique adopted - preferably the person responsible for analysis and interpretation of the data collected.

2. Soil Moisture Measurement. Hussein (1979) reviewed the techniques available in 1979 for monitoring soil moisture. Apart from improvements to the instrumentation, the basic methods available commercially have changed little since that time, when the main contenders were: gravimetric methods; tensiometers; electrical resistance blocks; gamma ray attenuation; and, neutron scattering. Each method has its own advantages and disadvantages, but for relatively long term studies of soil moisture the neutron scatter method has much to recommend it.

   The neutron probe is a well tried and tested instrument with readily available documentation advising on site selection, access tube location and installation, calibration and data analysis (eg. Bell, 1976). At the begining of the 1980s use of the neutron probe was so widespread in the UK that the Institute of Hydrology standardised on this method for its soil moisture data bank (Gardner, 1981a). Other advantages include: the probe's robustness and reliability; the method is 'non-destructive' and observations can be made repeatedly for the same profile to the full depth of the access tube; if moisture changes are of prime interest, then calibration errors are minimal. The main disadvantage of the neutron probe is that it has a low resolution due to the sphere of influence (see Sect 5.3.2), and therefore it is often impossible to detect discontinuities or sharp changes in water content accurately. Furthermore, for the same reason, measurements in the top soil are unreliable because of the soil-air interface.

3. Meteorological Data. The majority of soil moisture field studies are concerned with the water balance, and thus in order to interpret the observations additional meteorological data are required. The on-site measurement of parameters which enable evaporation and transpiration to be determined either directly or indirectly is the ideal. However, the instrumentation required is often costly and time consuming to operate and maintain - furthermore, unless the site is very remote or well protected, it is susceptible to vandalism.

   Hussein (1979) found that at low moisture deficits the estimates of potential evaporation published weekly in the UK by the Meteorological Office, using the MORECS system, were reliable, but that at high deficits the actual transpiration from grass was underestimated. On the other hand Gardner (1981b) found that MORECS tended to overestimate the build up of high deficits. Therefore, although it would be desirable to install instrumentation to enable evapotranspiration to be determined, providing high soil moisture deficits do not build up MORECS data can be employed. Alternatively, since the variation in evaporation and transpiration is unlikely to be significant on a regional scale, data acquired from the nearest meteorological station can be utilised in their estimation.

   In contrast to evaporation and transpiration, it is essential that rainfall is measured on site due to its high spatial variability. Standard Meteorological Office raingauges, or similar instruments read manually whenever the observer visits the site, are adequate for this purpose. If a site is protected or isolated so that it is unlikely to be vandalised, installation of an autographic raingauge is advantageous since it enables the duration and intensity of individual storms to be determined.

In addition to the general guidelines given above, there are specific aspects which need to be considered when designing soil moisture monitoring systems for studying the effects of groundwater drawdown.

4. Site Selection for Groundwater Drawdown Studies. A study of the effects of drawdown on soil moisture can clearly only be undertaken if there is some mechanism available for abstracting groundwater. Drawdown can be achieved either by employing well

pointing techniques or through pumping boreholes. The former is an expensive but viable option where a shallow water table exists, and was considered by Walley. and Hedges (1979a) for the Shropshire study (see Sect 5.2). The use of well points has the advantage that the only limitation on site selection is the availability of shallow water tables.

For reasons of economy, however, the most likely approach is the pumping of existing boreholes. This may be achieved either through negotiating an agreement with the owners of private domestic or irrigation boreholes, or by utilising existing wells which are intermittently operated by a water authority or company - as was the case in Shropshire. The disadvantage of using existing boreholes is that selection of moisture monitoring sites is restricted to the immediate environment of the available wells.

Where there is a choice of sites, certain criteria must be born in mind when making a rational selection.

i) Is the watertable close enough to the surface for there to be an observable effect? If the water table is below the soil sensitivity depth (the sum of the crop rooting depth and the critical height) there will be no effect on the moisture available to vegetation.

ii) Will the soil be sensitive to drawdown? If the soil is completely isolated from the aquifer by an impermeable layer, or if it drains so slowly that for practical purposes there is no effect, nothing will be achieved by the study.

iii) Are the chosen sites intended to be typical of the various conditions found in the area under investigation? Of the five sites in the Tern Area where soil moisture was monitored by the Water Authority, three had groundwater levels in excess of 4m deep, and at the remaining two the aquifer was covered by a layer of boulder clay - no site at which the soil was in hydraulic continuity with the aquifer was investigated.

iv) Are there any specific conditions which need investigation? Situations which might necessitate specific attention include artesian groundwater, perched watertables, and where it is suspected that the strata confining an aquifer are not completely impermeable (ie. leaky).

5. Experiment Design. To enable drainage to the groundwater to be isolated from the other processes which influence the moisture store (rainfall, interflow and evaporation) the experimental site must be flat and covered. Economically the construction of a suitable cover structure may not be a viable proposition, and if this is the case then the relationship between drainage and changes in the watertable level can only be investigated if rainfall, interflow and evaporation can be quantified or excluded. A flat or relatively flat site minimises the effects of interflow, and the suggestions made under guideline 3 above will enable rainfall and evaporation to be determined.

   The method adopted for monitoring soil moisture will depend on the exact nature of the study, but since the object will be to investigate changes over a period of time the neutron probe is recommended (see guideline 2 above).

   Whether experimental controls are established or not will depend on the availability of sites which are identical to those subject to drawdown - identical in terms of both the physical environment and the microclimate. If controls are not a viable proposition, then the without pumping situation can be simulated by means of either a computer model or through water balance calculations. The reader is referred to Sect 5.3.3 for a more detailed discussion on the use of experimental controls.

The criteria listed above can only be offered as guidelines in the selection of soil moisture monitoring sites. However, if the guidelines are not adopted the agency promoting a groundwater scheme on the strength of such a study is likely to be vulnerable to the charge that any resulting impact assessment is biased or ill conceived.

10.2 DESIGN CRITERIA FOR THE SITING OF BOREHOLES.

From the hydrogeological standpoint, the criteria used by the Severn Trent Water Authority in selecting the borehole sites for their Shropshire Groundwater scheme can be adapted to give the following general guidelines:

a) where adequate aquifer thicknesses exist;
b) where adequate yields are expected;
c) boreholes to be a specified distance apart depending upon their likely interaction (1km in Shropshire);
d) avoidance of locations which might affect surface pools, springs, streams and rivers;
e) avoidance of poor quality groundwater.

The Water Authority had one further criteria which has not been included in the above list - "avoidance of the deeper drift areas of the Perry Catchment". The reasons for omitting this are twofold: it is site specific; and, were such a site deemed an economic proposition its development would certainly have no deleterious effects on agriculture or trees.

In order to minimise the effects of drawdown on the soil moisture available to vegetation, borehole sites should ideally be located where the resulting drawdown will be restricted to areas where:

a) the groundwater depth is greater than the soil sensitivity depth (crop rooting depth + critical height);
b) soils are not in hydraulic continuity with the aquifer to be pumped - the aquifer is confined by a 'non-leaky' impermeable layer;
c) soils are so slow draining that the effects of soil moisture removal will not be felt during the growing season.

It is recognised, however, that rigid adherence of the above criteria may not be a practical proposition since it is possible that either no such regions exist in the area under consideration, or the costs associated with the deep wells and high pumping lifts which may be necessary could prohibit the adoption of the scheme. Under such circumstances, when it is shown that the benefits to society are such that a scheme involving a number of boreholes should proceed, then the effects on agriculture and trees will have to be minimised through the operating rules which apply to the completed scheme.

A quick glance at Fig 10.1 reveals immediately that even for drawdowns as small as 0.25m significant amounts of the available moisture can be removed from the field capacity profiles of the Tern Area soils. The smallest contour shown on the drawdown map for the 1974 pumping simulation was 0.5m - not 0 (see Fig 8.13). This indicates that the effects of drawdown would be felt over the entire study area, and thus any sensitive region would experience some moisture loss irrespective of its location relative to the boreholes. The 1974 simulation involved abstraction from all the boreholes in the Tern Area, but individual wells when pumped on their own only produce a drawdown over the limited area covered by their cones of depression. Consequently, if individual boreholes could be brought into operation in stages to meet the demand as it arose, the overall drawdown could be minimised. This approach would be even more successful if operating boreholes were as widely spaced as possible so that their cones of depression did not overlap.

An alternative to this approach would be to develop a small area with a high borehole density. This would result in a large average drawdown over a relatively small area - thereby minimising the extent of the effects on vegetation. With this type of development the need for remuneration for crop loss would have to be recognised, and would need to be taken into account when considering the economic viability of the scheme.

Finally, therefore, if boreholes cannot be located so that their drawdowns do not affect sensitive areas then, where groups of boreholes are involved, suitable operating rules should be devised. Where the density of the boreholes is low, these operating rules should be designed so that wells, initially widely spaced or in less sensitive regions, are brought onto line in stages in order to minimise the overall drawdown within the sensitive areas. The operating rules would have to be developed through a series of simulation studies once the sensitive areas had been identified. Where the density of the boreholes is high, a mechanism for recompensing agricultural interests for economic losses would have to be devised.

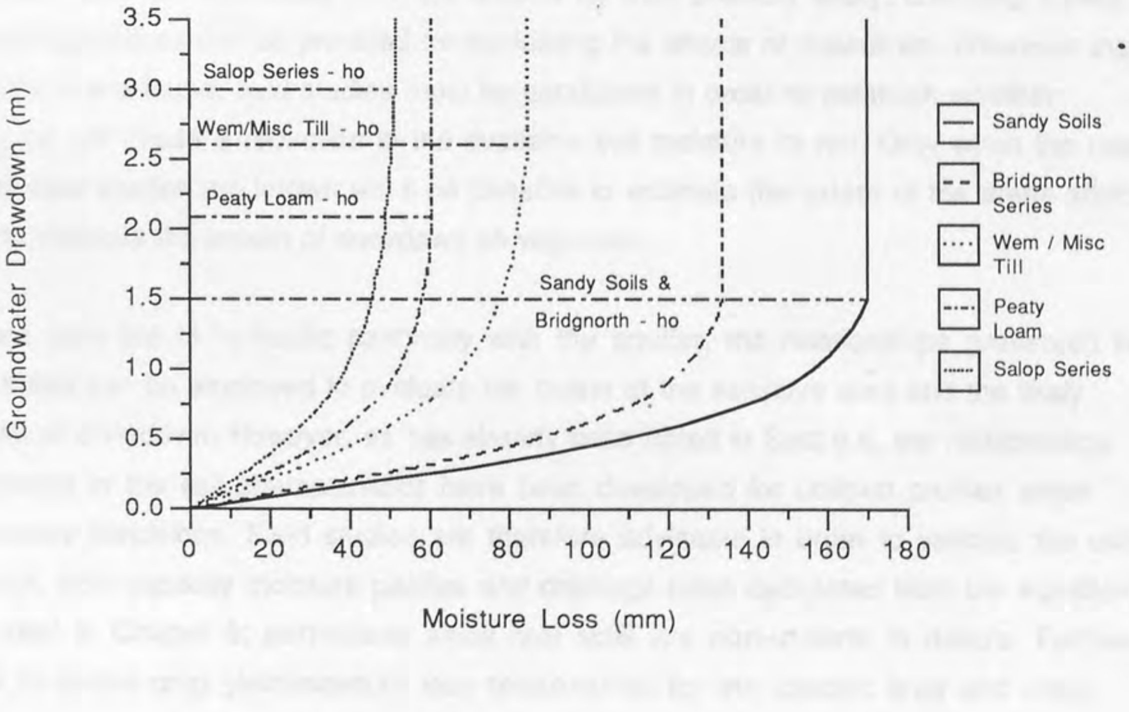


Fig 10.1 Moisture Lost from Tern Area Field Capacity Profiles as a Result of Groundwater Drawdown.

10.3 ENVIRONMENTAL ASSESSMENT OF GROUNDWATER PUMPING SCHEMES.

The development of an environmental assessment technique for evaluating the effect of groundwater pumping schemes on agriculture was discussed in detail in Chapter 8. Chapter 9 examined the possible evolution of this technique by incorporating it into a GIS. The key aspects of the environmental assessment method have been distilled from these earlier chapters to produce the decision network shown in Fig 10.2.

No matter what specific approach is adopted in evaluating the impact of a groundwater pumping scheme, if the steps of the decision network are followed it will be possible to determine:

(i) whether there will be an effect or not;
(ii) the areas sensitive to drawdown; and
(iii) the potential economic consequences.

In areas where the groundwater is artesian, where perched watertables exist, and where sensitive soils are separated from the aquifer by thin, possibly leaky, confining layers, no general guidelines can be provided for evaluating the effects of drawdown. Wherever these conditions are found, field studies must be conducted in order to establish whether pumping will cause a reduction in the available soil moisture or not. Only when the results of the field studies are known will it be possible to estimate the extent of the areas affected and to evaluate the impact of drawdown on vegetation.

Where soils are in hydraulic continuity with the aquifer, the relationships presented in this thesis can be employed to evaluate the extent of the sensitive area and the likely impact of drawdown. However, as has already been noted in Sect 6.6, the relationships pertaining to the soil characteristics have been developed for uniform profiles under laboratory conditions. Field studies are therefore advisable in order to validate the critical heights, field capacity moisture profiles and drainage rates calculated from the equations provided in Chaper 6; particularly since real soils are non-uniform in nature. Further work to derive crop yield/moisture loss relationships for the specific area and crops under investigation would also be beneficial.

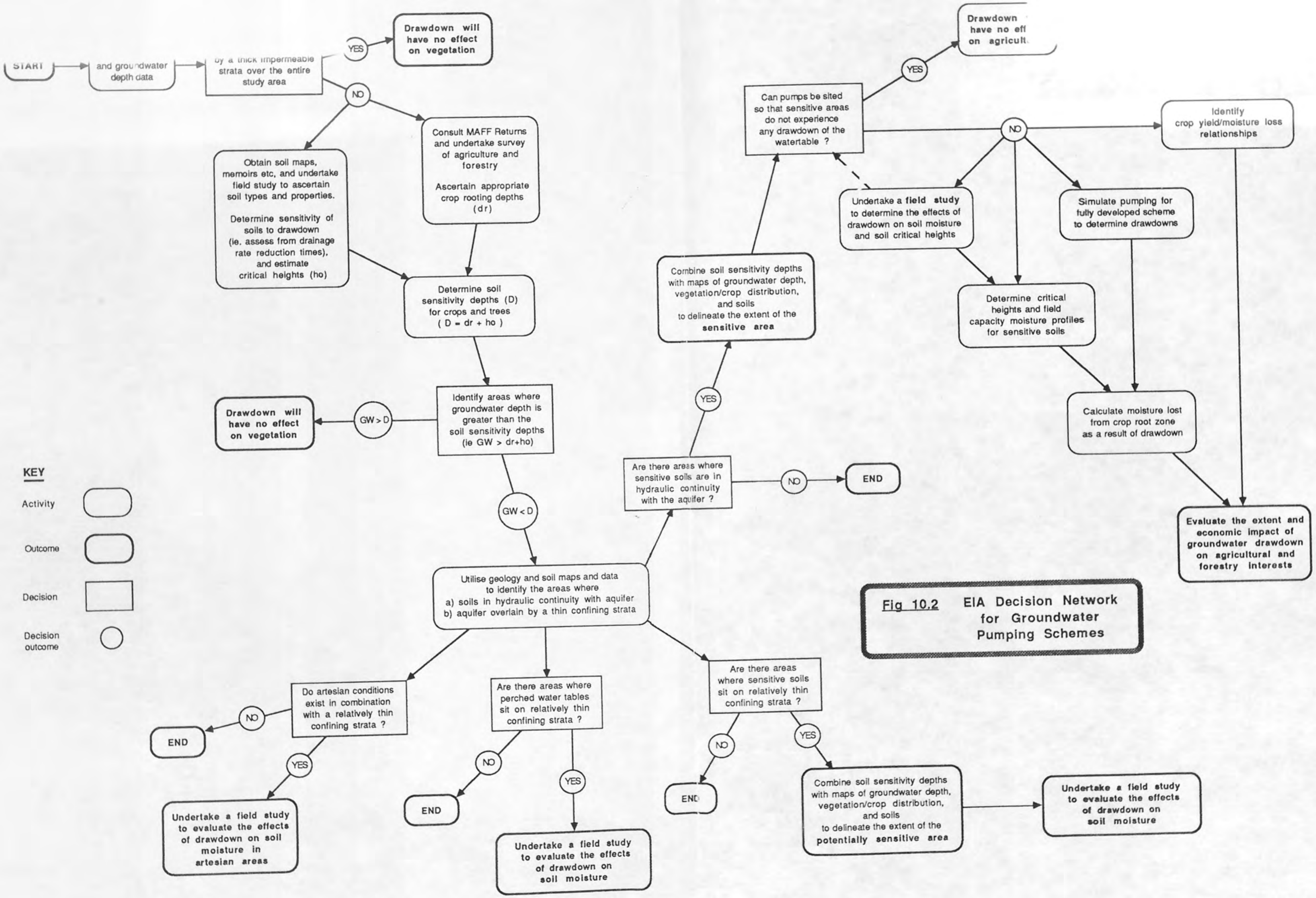


Fig 10.2 EIA Decision Network for Groundwater Pumping Schemes

Fig 10.2

Chapter 11. DISCUSSION AND IDENTIFICATION OF FUTURE RESEARCH NEEDS.

Throughout the thesis particular points and aspects of the work have been considered whenever the need arose. The discussion presented in this chaper will, therefore, be more general in nature and directed to the identification of future research needs.

11.1 THE PROJECT.

In general, undertaking a research project on a part-time basis means that the work extends over several years. This project has been no exception, and from initial involvement with the Shropshire Groundwater Scheme, to completion of the thesis, has spanned the decade of the 1980s - a period in which there have been rapid and significant advances in both the hardware and software of information technology. When the initial idea of employing a computer to overlay maps and manipulate the data contained in them was first conceived, it was quite revolutionary - today GIS systems are relatively commonplace. In the early 1980s the BBC micro, used for the map analysis process was one of the first computers produced at a price that made it accessible to ordinary people. Today machines are available that cost the same, but which possess memories several orders of magnitude greater than that of the BBC.

The 1980s have also seen a period in which the industrial base in the UK has changed rapidly. A severe decline in heavy industry, coupled with more efficient maufacturing methods have led to a reduction in demand for water. Furthermore, the demographic trend through the 80s has also resulted in reduced demands for water from domestic users. When these factors are combined it becomes clear that the predictions made in the 1970s, of a rapid growth in demand for water, were highly optimistic, and have resulted in a surplus of water resource capacity in parts of England and Wales. As a consequence, no new major groundwater schemes, such as those described in Chapter 2, have been initiated. Indeed, the rates of implementation of those schemes with phased development have been reduced to parallel the changes in demand. Where new groundwater developments have taken place there has been a move by the promoters towards public involvement from the outset, thereby negating the need for a public inquiry (see Sect 3.2).

If todays technology surpasses that employed in this research, and there have been no new major groundwater developments in recent years, what is the value of the work which has been undertaken for this thesis? Evaluating the effect of groundwater drawdown on the soil moisture available to vegetation is important for four main reasons.

Firstly, the research is a contribution to knowledge and advances an understanding of the processes involved. It became clear from reviewing the available literature which related to those schemes promoted prior to the Shropshire Groundwater Scheme public inquiry (see Chapter 3), and from discussions at the inquiry itself, that inadequate attention had been paid to this aspect of groundwater development. Although the 'public' instinctively felt that there would be consequences for agriculture (hence the numerous objections to planning applications), because of the complexity of the problem objectors were not able to mount an effective challenge to the arguments forwarded by the promoters. Knowing this, the investment made by promoters in soil moisture studies was minimal and thus little useful information was obtained.

Secondly, groundwater development projects are seen by the public to be more environmentally acceptable than large surface water storage schemes (see Chapter 3). Underground storage does not have a significant visual impact on the landscape, and does not take large tracts of land out of agricultural production or disbar its use for other activities - except those which could result in pollution of the aquifer. As described in Sect 2.3, conjunctive use schemes, river augmentation and artificial recharge provide the high degree of flexibility required by todays resource managers. Furthermore, the development of these schemes can be phased to meet demand as and when it arises. It is likely, therefore, that for the foreseeable future in the UK, groundwater resources will be developed in preference to surface water sources. When such developments are put in hand the EIA method which has been prepared will immediately be available for assessing their feasibility and impact. Furthermore, guidelines are provided in Chapter 10 which enable the planner to design suitable soil moisture monitoring sites, and to locate and operate boreholes so that drawdown effects are minimised.

In July 1988, as the result of an EEC Directive, EIA became a legal requirement for many development schemes. Just how this requirement will be interpreted by the British government still remains to be seen, but, as discussed in Sect 3.1.3, it is almost certain that local planning authorities will demand an EIA whenever the effect on the environment is likely to be disputed. This will undoubtably include groundwater development projects. The third reason is, therefore, that as a result of this research an EIA methodology is now available which provides planners with a framework for impartially evaluating the impact of groundwater schemes on crops, trees and natural vegetation.

Finally, the principles underlying the EIA method presented are not confined solely to the field of groundwater development. They can easily be adapted to other applications relating to agriculture or forestry - two applications which spring immediately to mind are irrigation and land drainage feasibility and impact studies.

The above discussion has been directed primarily towards application of the EIA method in the UK, but there is no reason why it cannot be employed globally. Groundwater meets a significant part of humanities water requirements, but over-exploitation in many parts of both the developed and the developing world has led to falling water tables. Annually throughout the world's arid zones 500,000 ha of irrigated land becomes 'desertified' through waterlogging and salinisation - roughly the same area as is newly irrigated each year (Grainger, 1984). Further development of the principles employed in the EIA method, through integration into a GIS coupled to groundwater and soil-water-plant models, would enable it to be applied to these and similar problems.

11.2 THE FIELD STUDY AND SHROPSHIRE GROUNDWATER SCHEME PUBLIC INQUIRY.

From theoretical considerations it was clear that the field capacity state could not be regarded as one single value of moisture content, but must be considered as the moisture profile which develops at the critical tension. This argument led to the concept of the critical height, as defined in Sect 4.2.1. Further theoretical consideration of the field capacity profile above a water table showed that groundwater drawdown could affect the moisture available to vegetation (see Sect 4.5.2). The field study became necessary since in practice it is not possible to derive the field capacity profile from theory.

Results from the field study confirmed theoretical deductions and at the Heath House site, where the soil was in hydraulic continuity with the aquifer, moisture was lost from the profile when pumping commenced and the water table fell. The field study in turn led to the concept of the soil sensitivity depth (Eqn 5.1); a parameter which could be used to determine the extent of the area sensitive to groundwater drawdown. Combining appropriate values of soil sensitivity depth with a depth to groundwater map (produced using data obtained from a Severn Trent Water Authority report) enabled the extent of the Tern Area which could be affected by pumping to be estimated.

Sect 5.6 describes the main events of the public inquiry as they relate to this research project. At the inquiry the concept of the critical height was commended. Both the

Assessors and the Inspector expressed their concern over the way Severn Trent Water Authority had defined and determined sensitive areas, and all recommended that further research was necessary. Futhermore, during the inquiry the Water Authority's study of soil moisture was discredited, with the result that the only field evidence accepted was that from the Aston investigation (Walley and Hedges, 1979b).

As stated at the end of Sect 5.8, the overwhelming impression left by the inquiry was of "the high degree of uncertainty surrounding the effects of groundwater drawdown on vegetation" - further research was required and the overall aims and objectives of this project, see Sect 1.2, were established. The work undertaken in connection with the promotion of the Shropshire Groundwater Scheme provided a sound foundation and the underlying concepts for the development of the EIA technique.

Although briefly touched upon in later work, three aspects relating to the field study are not yet fully resolved: the effect of drawdown on soils subject to artesian groundwater; the extent of drawdown on soils separated from the aquifer by confining layers which are not completely impermeable (i.e. 'leaky'); and, the effect of groundwater recovery on soil moisture.

At the Childs Ercall site, where artesian conditions existed, moisture was lost from the top of the soil profile as a result of pumping. On recovery of the water table to pre-pumping levels, this moisture loss was replenished in a manner which indicated upward seepage from the confined groundwater - the confining layer was 'leaky'. How this moisture loss could affect crops, and whether this was a site specific phemenon were not ascertained.

At the Greenfields site no moisture loss was observed during the Aston field study. However, an analysis of the Water Authority's data suggested that at a nearby location moisture losses had been experienced (see Sect 5.7.1). These results indicated a confining layer of varying effectiveness.

In evaluating the extent of the Tern Area that could be affected by groundwater drawdown, the area with shallow water tables where soils were underlain by boulder clay which was less than 5m thick, was determined. A thickness of 5m was adopted as likely to be 'leaky' for the simple reason that this contour was provided on the lithology map produced at the inquiry by the Authority (Fig 8.5) - it was assumed that a greater thickness of boulder clay would be impermeable. Thus, although an area was defined as 'potentially sensitive', no data were available on which to base an evaluation of any drawdown effect.

Since soils and surface lithology are spatially highly variable, in all probability it will not be possible to define rules to enable planners to evaluate the extent of the effects of pumping on vegetation where artesian conditions and leaky confining layers exist. It will be necessary to undertake carefully planned field studies in order to ascertain the effects. If the guidelines provided in Sect 10.1 are followed they will enable a suitable soil moisture monitoring system to be designed and operated successfully.

The third aspect of the field study which was not entirely resolved was the effect on soil moisture of groundwater recovery. Theoretical considerations, based on the property of soil moisture hysteresis, indicate that once moisture is lost as a result of drawdown, most of that loss will persist until percolating rainfall returns the soil to the field capacity state (see Sect 4.2.2). Observations made at the Heath House site confirmed this view - soil moisture did not return to pre-pumping levels until the following January. This evidence was accepted, and the principle incorporated into the method developed for evaluating crop losses (Sect 7.3). However, the one experiment undertaken in the laboratory (see Sect 6.5) resulted in a greater recovery than had been expected. There is therefore a need for further research to determine whether some limited recovery does indeed occur, and if so, to evaluate the extent of the recovery for soils of different textures.

11.3 THE EIA TECHNIQUE AND GUIDELINES FOR THE SITING OF BOREHOLES.

The author is confident that the principles embodied in the EIA technique developed as a result of the research project, and presented in the decision network of Fig 10.2, are correct - as are those underlying the guidelines for the siting of boreholes. Once the EIA technique has been transferred to one of the current generation of PCs, it will prove a valuable tool at the planning stage of a groundwater scheme.

The technique is not sufficiently sophisticated to enable actual crop losses resulting from groundwater drawdown to be estimated in the event of a dispute. For this the principle of overlaying and manipulating map data will need to be coupled to groundwater and soil-water-crop yield models as discussed in Sect 9.2. When this has been achieved, the with and without pumping conditions can be simulated, and the resulting difference in crop yields used to estimate the actual loss at a specific site. Even then other factors, such as seed quality, pest control and disease, may seriously complicate the settlement of individual cases.

The EIA technique, as developed for use in the Tern Area of the Shrophire Groundwater Scheme, is quite satisfactory as a planning tool for determining the extent of the sensitive area, and was used successfully to estimate the actual impact of a simulated pumping event (Sect 8.5). Up to the end of 1988 the Shropshire Groundwater Scheme had not been operated except for a short period in 1984. As a consequence, no claims have been made by farmers for yield loss caused by groundwater drawdown. There are therefore no data available for validating, or otherwise, the estimated losses.

As pointed out in discussions in Chapters 6, 7 and 8, there are components of the EIA method which require further refinement. The equations for determining the critical height, residual moisture content, saturated capillary fringe and the field capacity moisture profile were derived for the limited range of soil textures employed in the laboratory experiments. Additional work will therefore be required if it becomes necessary to extend the working range of these equations to soils outside the sand and loamy sand texture classes. Furthermore, it was not possible to derive a simple relationship for modelling the drainage process from saturation to field capacity profile. The Drawdown Response Time equations provide a guide to the sensitivity of soils to the lowering of the watertable, but this too is an area where further research is required. Ultimately the best solution may be a simple computer model which simulates drainage from saturation to field capacity using easily measured soil properties as inputs - a model of this type is currently under development within the Department of Civil Engineering at Aston University (Evans, 1989). When available, such a model will provide the critical height, field capacity profile and a plot of the drainage rate against time as outputs.

In developing the crop yield loss equations, the assumption was made that: the reduction in yield resulting from a moisture loss caused by drawdown, was equal to the increase in yield resulting from irrigating with an equivalent amount of water. The justification for adopting this approach is given in Chapter 7, but essentially data from irrigation experiments were readily available where none could be found pertaining to the effects of moisture loss. There is, therefore, a need for experiments to be conducted to discover the actual effects on crop yields of the moisture loss caused by drawdown - as recommended by the inspector for the Shropshire Groundwater Scheme public inquiry in his report, but rejected by the Secretary of State (Musgrave, 1981).

Chapter 9, Evaluation of the Methodology, ends by discussing the incorporation of the EIA technique into a GIS and coupling this to groundwater and soil-water plant models - a concept which appears again more than once in this chapter. The argument forwarded in the last paragraph of Chapter 9 is that:

> "were a comprehensive groundwater impact evaluation package available commercially then, no matter what the application, the advantage of being able to obtain a ready made tool without the expense of having to develop one, would ensure its use."

This view is reinforced here, and the recommendation made that research be directed to this end.

11.4 FUTURE RESEARCH NEEDS.

A variety of research requirements have been identified in the previous discussion. This section simply summarises these needs and groups them under two headings - broad and specific needs.

11.4.1 BROAD RESEARCH NEEDS.

i) The EIA technique must be adapted for use on one of the current generation of PCs. This should preferably be in a language, and with an operating system, which ensures that the resulting system is as portable as possible.

ii) As discussed in Chapter 9, the EIA technique requires incorporating into a GIS in order to simplify data management. If a package is produced which links the resulting GIS to compatible groundwater and soil-water-plant models, the system has a potential for commercial exploitation.

iii) There is a need for a research programme to examine the actual effect of moisture loss on crop yields, the growth of trees and natural vegetation.

11.4.1 SPECIFIC RESEARCH NEEDS.

i) The relationships developed for determining the critical height, the residual moisture content, the saturated capillary fringe, and the field capacity moisture profile are strictly only applicable to soils with a sand and loamy sand texture. Further research is required to enable these parameters to be determined from easily measured soil properties for other soil texture classes.

ii) It was not possible to derive a simple model to simulate the drainage under gravity of a soil from saturation to the field capacity state. This should be pursued further with the object of producing a simple expression for determining whether, in terms of the time taken for moisture loss to occur, a soil is sensitive to drawdown or not.

iii) Whenever opportunities arise, monitoring systems should be designed and installed to study the effects of groundwater drawdown on soil moisture where: a) artesian conditions exist; b) a slowly permeable or 'leaky' layer overlies the aquifer thereby preventing the soil from being in true hydraulic continuity with the groundwater.

iv) Construction of a soil moisture model for simulating groundwater drawdown on a computer would enable the user to determine the critical height, the residual moisture content, the saturated capillary fringe and the field capacity moisture profile, together with the drainage properties of the soil. This model would preferably only require easily determined soil properties as inputs. Such a model would also obviate the need for 'Specific Research Needs' (ii) and (iii), though the simplicity of the existing method would be lost.

iv) The effect of groundwater recovery on the soil moisture profile should be studied in more detail.

Chapter 12. CONCLUSIONS.

The aims and objectives of the research, as stated in Sect 1.2, have remained constant since the project's formulation. In satisfying each objective it has been necessary to achieve particular goals, and these will be discussed in Sect 12.2.

The overall aim of the project,

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

has been accomplished.

An EIA technique has been developed which enables the area to be identified within which vegetation will be sensitive to groundwater drawdown. If the actual drawdowns and cropping patterns are known, then the impact can be evaluated using crop yield functions. Drawing upon the experiences gained through undertaking the research, guidelines have been prepared which enable boreholes to be sited and managed in such a way that the impact of groundwater pumping is minimised.

12.1 SOIL SENSITIVITY DEPTH AND CRITICAL HEIGHT.

The key to the EIA technique is the use of the *soil sensitivity depth* (D) concept, where:

$$D = h_o + d_r.$$

In this relationship d_r is the crop rooting depth, and h_o the *critical height* - the height above a water table at which the soil moisture tension becomes equal to a critical value at which drainage under gravity effectively ceases. If roots penetrate within the zone of the critical height, then during dry years the vegetation will benefit from a store of moisture which is not available if the watertable is at a depth greater than D.

The EIA technique will be discussed further when the relevant objectives, (i) and (ii), are considered in the following section - it is the actual concepts of soil sensitivity depth and critical height which require further consideration here. The importance of these two parameters was recognised during the initial desk study undertaken in connection with the Shropshire Groundwater Scheme (Walley and Hedges, 1979b). The subsequent field study confirmed the belief that the critical height was important and that the field capacity state could not be represented by a single value of moisture content, but must be regarded in terms of a moisture profile.

On the strength of the desk and field studies, Walley (1979) presented evidence on behalf of a group of local farmers at the Shropshire Groundwater Scheme public local inquiry. At the inquiry, and in subsequent reports, the concepts of critical height and soil sensitivity depth, and their use in defining the area sensitive to groundwater drawdown, were commended. Furthermore, the need for further research was identified - it was at this point that the aims and objectives of this research project were defined.

12.2 OBJECTIVES.

In order to fulfill the aim of the research five distinct objectives were established. Just how successful the project was in achieving each objective will now be evaluated.

i) *The identification of those soil types which, when drawdown of the watertable occurs, experience a loss of soil moisture which could affect the growth of vegetation and crops.*

There are three main requirements which determine whether a particular soil will be sensitive to drawdown or not:

1) the soil must be in hydraulic continuity with the aquifer;
2) the water table must be shallower than the soil sensitivity depth;
3) the moisture must drain from the profile at a fast enough rate for the effects to be felt by the vegetation during the normal growing season.

The first criteria specifies that it must be possible for the soil moisture to drain to the watertable. If an impermeable horizon exists isolating the soil from the aquifer drawdown will not affect the moisture available to crops. However, the fieldwork undertaken in the Tern Area of the Shropshire Groundwater Scheme revealed that for both artesian conditions and where the confining layer is thin, then leakage can occur with moisture being lost from the soil profile as the watertable falls. Where studies of geology, lithology and soils indicate that these conditions may exist, field studies must be undertaken to establish the extent of the area influenced by drawdown and the rate of moisture loss.

In order to establish from depth to watertable maps whether the phreatic surface is shallower than the soil sensitivity depth, crop rooting depths and soil critical heights are required. From a literature search representative rooting depths for a variety of vegetation were determined. In estimating the extent of the area at risk, the crop with the largest rooting depth is selected - for the Tern Area of the Shropshire Groundwater Scheme this was 2.1m for cereals/sugar beet. Establishing a suitable rooting depth for trees was much harder, but 3.5m was finally selected.

The results from a series of laboratory experiments on soil columns enabled equations to be developed for calculating the critical height from easily measured soil properties. In addition to the critical height, relationships were also produced for residual moisture content, saturated moisture content and saturated capillary fringe - all parameters required to define the field capacity profile. The shape of the field capacity profile itself was calculated from a simple model which again used easily measured soil properties as inputs - % silt, % sand, % clay and bulk density. Unfortunately, in the laboratory it was only possible to study the moisture content of uniform profiles for soils in the sand and loamy sand texture classes. Therefore, for soil texture classes other than those from which the equations were derived, care is required in extrapolation of the design curves provided and in the use of the equations themselves.

It was not possible to use the observed soil column drainage rates to develop one single relationship for describing the time taken for a soil to drain from saturation to the field capacity state. This would have been ideal for determining whether the rate of drainage from a soil profile was fast enough for the effects to be felt by vegetation during the normal growing season. However, a series of equations were produced for calculating the time taken for a specified proportion of the drainable moisture to be removed from an initially saturated soil in response to groundwater drawdown - the *Drawdown Response Time*. Application of these equations to the soil groups present in the Tern Area showed that all could be influenced by drawdown.

In the long term it may be necessary to develop a computer model for simulating drainage under gravity from a soil profile. However, a series of easily applied relationships have been derived which will enable water resource planners to identify those soil types which will be sensitive to groundwater drawdown.

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.*

By overlaying maps of the relevant features of the study area, the Tern Area, those regions, where crops and where trees were sensitive to the effects of groundwater drawdown, were identified. Subsequently, knowing the drawdown, the crop present and the field capacity moisture profile, it was possible to calculate the actual moisture lost for each 100m square element within the crop sensitive area - since there was no commercial forestry within the area, trees were not considered. Inputting the actual moisture loss into yield decline relationships, which had been developed for each crop type, enabled the loss which would have occurred had pumping taken place in 1974 to be estimated.

In the final analysis, for the 1974 pumping event, of the 5589 ha of the Tern Area under consideration: 100% was covered by soils sensitive to drawdown; trees were likely to be affected over 42% of the area and crops over 34%; crops yields would have been affected over 25% of the area. The cost to the farming community was estimated as £181,000 - nearly 5% of the normal annual income. It was clear from maps of the sensitive area that the effects would tend to be concentrated in particular locations. Typical drawdowns affecting the entire area of an average sized farm of 50ha would result in a loss of income for that particular holding in the region of 17% of the annual turnover - approximately £6000.

The methodology developed was therefore successfully applied to the Tern Area to evaluate the impact of groundwater drawdown. The overall conclusion being that pumping can indeed have a significant economic impact on a farming community.

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.

The guidelines for the design of soil moisture monitoring systems were based primarily on the experience gained through involvement in all the aspects of the the Shropshire Groundwater Scheme, as described in Chapter 5. The guidelines were presented under six headings - the first three were applicable to any soil moisture monitoring system, the second three related specifically to evaluating the effects of groundwater drawdown.

For monitoring soil moisture changes over a period of time the neutron probe was recommended as, once access tubes are installed, the method is non-destructive and measurements are repeatable over the length of the tube for the same soil profile. The most important points made in the guidelines were that:

i) each site requires its own raingauge;

ii) the site under investigation must be flat to minimise the effects of interflow;

iii) if the site where the effects of drawdown are to be studied cannot be covered, the surface inputs and outpus from the system must be measured or estimated so a record of the water balance can be maintained;

iv) the sites selected should be typical of the various conditions found in the study area, and should include locations where drawdown effects are likely to be experienced.

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

The criteria employed by the Severn Trent Water Authority for selecting boreholes sites on hydrogeological grounds were adapted to provide general guidelines. However, more detailed guidelines were prepared for locating boreholes so that the effects on vegetation are minimised.

In site selection priority should be given to those locations where drawdown will have no effect on available soil moisture - e.g. where the groundwater depth is greater than the soil sensitivity depth. It was recognised, however, that this is not always feasible or economic, and when this is the case boreholes should preferably be widely spaced, and operating rules devised to minimise the drawdown.

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

Objective (v) was added in case it was judged that the work involved in realising the first four objectives did not meet the standard for a higher degree by research. In the event computing became an integral part of the EIA process, but not an end in itself. This objective was therefore only partially achieved.

The EIA technique which was developed for determining the extent of the area sensitive to drawdown, and for assessing the actual impact of a pumping event, were both computer dependent. The approach, however, was cumbersome and it has been recommended that the method be transferred to a powerful PC. This will enable all the steps of the technique to be integrated into one program - in all liklihood a GIS.

12.3 SUMMATION.

The overall aim of this project has been achieved. However, a number of recommendations for further research have been made at the end of Chapter 11. If these recommendations are implemented the final outcome will be a computer based Environmental Impact Assessment package, which will incorporate a GIS, a groundwater model and a soil-water-plant model. It is believed that this tool will be an attractive, commercially viable proposition, which may be adapted for uses other than for evaluating the impact of groundwater pumping schemes.

The first chapter opened with a quotation from Our Common Future (The World Commission on Environment and Development, 1987) - it is fitting that the last chapter closes with one of the final paragraphs of the same document:

> "Over the course of this century, the relationship between the human world and the planet that sustains it has undergone a profound change. When the century began, neither human numbers nor technology had the power to radically alter planetary systems. As the century closes, not only do vastly increased human numbers and their activities have that power, but major, unintended changes are occurring in the atmosphere, in soils, in waters, among plants and animals, and in the relationships among all these. The rate of change is outstripping the ability of scientific disciplines and our current capabilities to assess and advise. It is frustrating the attempts of political and economic institutions, which evolved in a different, more fragmented world, to adapt and cope. It deeply worries many people who are seeking ways to place those concerns on the political agenda"

In conclusion, the author offers the methodology for determining and minimising the effects of groundwater pumping on vegetation, contained within this thesis, as a small contribution towards the global effort required to achieve sustainable development.

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