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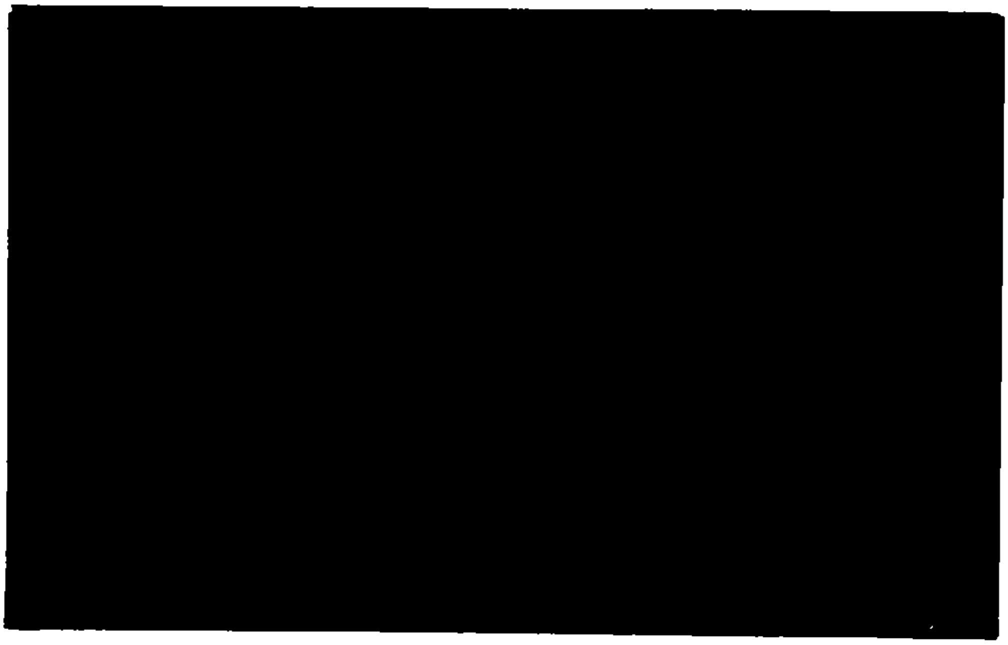

National System for Groundwater Recharge Assessment

NRA National R&D Project: 449

Interim Report

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Executive Summary

This report describes the first stage of the project to develop a national methodology for the NRA regions to assess groundwater recharge. This project is limited in its scope to considering the mean annual recharge of the drift-free areas of the major aquifers of England and Wales.

The first activity was to carry out a review of the existing practices used by the NRA regions. This showed that there was a remarkable variety of methods in use with more than one method being used by some regions. MORECS data is used by several of the regions as at least the starting point of calculations, whilst Penman-Grindley methods are also widely used, particularly in distributed groundwater models. In addition, a hybrid model using MORECS data with a Penman-Grindley soil moisture model is also in use. The Thames NRA region is unique in having a single methodology for all applications of groundwater recharge. It is based on a soil moisture accounting model and calibrated against streamflow hydrographs.

In addition to the NRA regions, a wide ranging consultation was carried out with other organisations with an interest in groundwater recharge . These included the University of Birmingham. WRC, BGS, ADAS and Mott Macdonalds. This showed general acceptance of MORECS as the basis for estimating groundwater recharge but concern was expressed about various aspects of the calculations. In particular, there was concern about the size of the MORECS grid cells, 40x40 km, and some aspects of specific soils and land covers. The need to incorporate land use information and lateral transfers of water were also emphasised.

A critical review of the soil moisture models has been carried out. The Penman-Grindley model has the weaknesses of only implicitly including the surface resistance term and the root constant being independent of soil type. The MORECS model suffers from the same weakness as the Penman-Grindley in that the definition of the field capacity and soil moisture deficit are implicit. MORECS has the advantage of using the physically based Penman-Monteith model.

The methodologies used for dealing with the unsaturated zone generally employ some form of direct method, usually in the form of a transfer function covering both losses and lags. The Thames model and Stanford Watershed model are both catchment models with the unsaturated zone handled as one of the component models.

A conceptual framework has been developed which links the physical processes in groundwater recharge with the component models. The next stage of the project will be to develop the methodology but it is likely that a Penman-Monteith model will be used to provide the evaporation component. The soil model is not so clearly defined but a form of the Penman-Grindley model will be investigated and bypass flow will be incorporated in the methodology.

Contents

1. Introduction

The recent period of reduced winter rainfall in the southeast of the UK has highlighted the vulnerability of groundwater resources to variations in recharge. Normally, the NRA do not license more abstraction than recharge from an aquifer unit. As more units become totally licensed there will be increasing pressure to ensure the groundwater recharge calculations are as accurate as possible. There is also continuing concern about the threat of nitrate pollution to groundwater supplies. A major source of this pollution is the leaching from fertilisers applied to crops in the outcrop areas of the major aquifers, the Chalk and Permo-Triassic Sandstones. This has resulted in the need to define 'groundwater protection zones' within which the use of nitrate fertilisers will be controlled. An accurate estimation of mean annual groundwater recharge is an essential precursor to defining these zones on a scientific basis.

A variety of methods for estimating recharge are currently in use in the UK. There is clearly a need for a robust, national methodology, founded on appropriate and accepted scientific procedures such as were developed 20 years ago for flood estimation methods (IH Flood Studies Report). This would avoid problems such as discontinuities across regional boundaries and give clear guidelines for methodologies to be applied to different combinations of terrain, geology, land use etc.

The requirement is for a management tool which can be used to investigate a variety of scenarios at local and regional scales and also has an ability to provide geographic analysis and data visualisation. A modern methodology using models based on process studies is needed to predict recharge and a distributed model is required in order to include spatial variations.

The solution is to provide a system capable of modelling groundwater recharge on the regional and local scales consisting of a simple daily vegetation water use model coupled to an unsaturated zone model with geographic analysis and data visualisation provided by linking the models to a GIS. The system must be designed to be used at a number of temporal scales, depending on the particular requirement. There is the operational time scale of a season where the models can predict the amount of recharge in response to a range of rainfall scenarios in the coming season. A strategic time scale of decades needs to be incorporated to explore the long-term effects on groundwater recharge of changes such as land use and climate.

The development of a consistent and widely accepted method to estimate the amount and timing of groundwater recharge can be achieved through two linked projects. The first will review current NRA practices and develop a national framework procedure to estimate mean annual groundwater recharge in drift-free areas. The second project would produce an integrated software system to estimate both total recharge over an aquifer unit and its timing.

This report deals with the first stage of the first project, i.e. the development of a procedure to provide a consistent method for estimating mean annual groundwater recharge. The procedure will be applicable at drift-free sites over the unconfined portions of the Chalk and Permo-Triassic Sandstone aquifers of England and Wales. The objectives covered by this report are:

- To assess the current methods of estimating groundwater recharge used by the NRA regions.

- To develop a conceptual framework of a procedure for estimating mean annual groundwater recharge, at a range of scales, that can be consistently applied by the NRA regions.

The first chapter of the report describes the existing methods of calculating groundwater recharge in use currently by the NRA regions and also comments on methods in use by other organisations. This is followed by critical descriptions of the soil moisture models and unsaturated zone models, chapters 3 and 4. The bibliography compiled as part of the survey is included as Annexe 2. This is not a fully comprehensive literature review of groundwater recharge but documents the reports and papers collected during this first part of the project.

The development of a conceptual framework for a national method of calculating groundwater recharge is described in chapter 5.

2. Existing Practices

The first activity of the project has been to establish the existing methods of calculating groundwater recharge being used currently within the NRA regions. This was achieved by visiting each of the eight regional offices to obtain information from the relevant staff and also to obtain copies of relevant reports, papers and other literature. The following section gives a brief account of the results of this survey. In addition, other relevant organisations have been contacted for their views on methods of calculating groundwater recharge and the results of this are summarised in the final part of this chapter.

2.1 ANGLIAN

The main aquifers of the region are the Chalk, Lincolnshire Limestone, the Spilsby Sandstones and the Greensand as well as the Oolites and the Crag. Significant areas are covered by Boulder Clay which has a tendency to be more sandy in Norfolk and clayey in Essex. A variety of methods of calculating groundwater recharge are in use.

The crudest method is based on streamflow analysis. It is used for studies of regional strategy with each unit's water balance being estimated to give the groundwater resource. The model uses information from previous studies, with groundwater recharge related to baseflow, and hence the methods used are inconsistent as they vary from area to area.

A series of lumped catchment models were developed in the early 1980s. These were used for a wide range of applications and had various forms of the recharge component . The recharge model was further developed with the objective of making it consistent with MORECS. It takes as its input the potential evapotranspiration from MORECS and distributes it throughout the catchment on the basis of geology and land use. A range of root constants are used to obtain actual evapotranspiration. However, attempts to compare the results with the MORECS real land use data have shown significant differences even in the simple case of grass. Further work on this model has been abandoned. In its place, the model used by Thames NRA (Mander & Greenfield, 1978; Wilby, Greenfield & Glenny, 1994) is being used and has given good results.

Eight distributed groundwater models have been acquired from a variety of contractors. Each has a different method of calculating groundwater recharge although most embody some form of the Penman-Grindley model and all include some form of lateral transfers. The most recent, notably the South Lincolnshire Limestone model, use MORECS potential evapotranspiration data as input to a the recharge model. The models are:

- Northern and Southern Chalk
- Spilsby
- South Lincolnshire Limestone
- Thetford
- Lark

- Lodes and Granta
- Gipping
- Pant

The Spilsby Sandstone report (Anonymous, 1989) represents a rare case of direct validation of groundwater recharge, here using soil moisture data. The most recent of the distributed models has been produced by Birmingham University's Dept. of Civil Engineering for the South Lincolnshire Limestone. This incorporates bypass of the soil moisture store. The bypass flow is taken as 15% of actual precipitation greater than 5 mm, implying that the source of the bypass is runoff accumulating in ditches etc. and then directly feeding into the aquifer. Two other mechanisms of groundwater recharge are incorporated in the model. The first describes percolation through the beds overlying the aquifer, including the Boulder Clay. The second is of runoff from the overlying beds to areas of the aquifer outcrop where some or all of this water then recharges the aquifer.

2.2 NORTHWEST

The Northwest region has a wide range of aquifers although the dominant resource is from the Permo-Triassic Sandstones. These are often covered with thick deposits of drift. The major areas are the West Cheshire, Wirral and Mersey Basin, the Fylde and the Eden Valley. The aquifer in the Eden Valley consists of two hydraulically separate units, the Penrith Sandstone and the St. Bees Sandstone.

Little effort is made to calculate groundwater recharge in the hard rock areas or the Eden Valley as the resources are generally considerably in excess of demand. For the Permo-Triassic Sandstone values of 300-350 mm y^{-1} are used in the drift free areas and a value of 50 mm y^{-1} in areas of thick drift cover. These values are obtained from several studies, particularly the Saline Groundwater Study of the Mersey area (Anonymous, 1981; Anonymous, 1984a), nitrate investigations (Vines, Lucey & Brassington, 1980; Anonymous, 1984b) and a study of recharge through drift (Vines, 1984). For the Saline Groundwater study, potential recharge for the drift free areas was calculated using a Penman-Grindley type model (Rushton & Ward, 1979; Howard & Lloyd, 1979) for a variety of land cover types. The spatial distribution of recharge was calculated on the basis of an empirical regression of rainfall data against data from a single climatic station at Widnes for the Lower Mersey Basin, and a second station at the Rock for North Merseyside. The value for groundwater recharge through the Boulder Clay was quantified from laboratory measurements of permeability and tritium from borehole cores as well as a water balance study.

2.3 SEVERN-TRENT

The major aquifers of the region are the Permo-Triassic Sandstones of the Shropshire-Cheshire Basin and Nottinghamshire. A single method of calculating groundwater recharge is used, except in the case of distributed groundwater models.

The method was devised in 1979 (Anonymous, 1979). All the aquifers were divided into self contained units of about 30 km^2. This was done on the basis of aquifer boundaries and flow lines while also attempting to ensure that rivers were within one unit. The Meteorological

Office was commissioned to calculate values, using the Penman-Grindley soil moisture model (Grindley, 1967) and assuming a medium capacity soil for 15 selected units for the standard period of 1941-70. The results were used to devise a regression equation of potential evapotranspiration against rainfall, for different land use, to enable effective rainfall to be estimated. The calculations were on a daily basis but the potential evapotranspiration estimates were monthly and so had to be disaggregated to daily data. The rainfall and potential evapotranspiration data were for the period 1941 to 1970. The land use data were based on the Meteorological Office's coarse scale data but modified on the basis of local knowledge, e.g. for urban areas.

Groundwater recharge is then estimated using a points scoring system, Table 1, on the basis of soil type, sandstone lithology, topography and stream density/thickness of the unsaturated zone. For each area, the points were added up to produce a total score which was referred to a lookup table to get the percentage of effective rainfall that goes to groundwater recharge. The values are further modified if other conditions are present, e.g. drift cover. The figures have been reviewed in the light of experience and found to generally work well. An exception is in the area of the Nottinghamshire Sherwood Sandstones where the values are 25% less than are expected. This has since been shown to be due to vertical flows from the overlying Cowlick formation consisting of interbedded thin mudstones and sandstones.

Some short term calculations have been made using MORECS or the Penman-Grindley model. In addition a model, HYSIM, has also been used. This is a fairly simple catchment based rainfall-runoff model. MORECS data is used as the input effective rainfall.

There are also a number of distributed groundwater models, the most recent of which is for the Nottinghamshire Sherwood Sandstone aquifer (Bishop & Rushton, 1993). This study used spatially interpolated rainfall values based on five raingauges. The model area was divided into eight zones and the daily rainfall estimated either directly from one of the raingauges or by multiplying the data from the nearest raingauge by a factor determined from the long term mean of the area. Weekly MORECS potential evapotranspiration values were obtained and disaggregated to daily values. The soil moisture deficit was calculated using the Penman-Grindley model (Grindley, 1969) with root constants and wilting points obtained from the literature (Lerner, Issar & Simmers, 1990). Remotely sensed data from the LANDSAT satellite were used to calculate the percentage of each land use type for each 1 km^2 and then the groundwater recharge for each square was calculated as the sum of the recharge for each land use type within the square. Runoff is accounted for as an empirical relationship with rainfall intensity and soil moisture deficit. Additional recharge from river/aquifer interaction, inputs from overlying formations and urban leakage are also accounted for.

Severn-Trent have plans to update the system for calculating groundwater recharge. They have approached the Meteorological Office for a long term average rainfall data, on a 1 km grid, for 1961-1990. They also plan to acquire a similar data set for potential evapotranspiration for each land use type given by MORECS. These will be used to establish a regression equation, for each land use type, to estimate effective precipitation. Each 1 km grid cell will have its percentages of land use determined from remotely sensed data. The soils will also be classified, for each cell, as low, medium and high water availability. Negotiations with the Soil Survey are underway to acquire the 1 km data set with selected soil parameters. The methodology will be developed for Nottinghamshire and then applied to other areas.

Table 1 *Severn-Trent NRA's method of assessing the percentage of the effective rainfall for recharge*

Areas of aquifer outcrop

1 Award points to aquifer outcrop on the following basis:-

SOIL TYPE	Thin sandy soils with little clay content.	3
	Deeper sandy soils with noticeable clay content	2
	Deep soils with significant clay content	1
SANDSTONE LITHOLOGY	No significant marl bands	3
	Frequent thin, or infrequent thick marl bands, but sandstone clearly predominant	2
	Frequent marl bands, marl content equivalent to sandstone content	1
TOPOGRAPHY	No part of area higher than 200 m AOD.	2
	Part of area higher than 200 m AOD.	1
STREAM DENSITY /THICKNESS OF UNSATURATED ZONE	Low density of perennial streams, thick unsaturated zone	2
	High density of perennial streams, thin unsaturated zone	1

2 Determine appropriate percentage as follows:-

Points Sum	Percentage
10	95
9	90
8	85
7	80
6	75
5	70

Areas covered by drift or urban development

3 Where the aquifer is overlain by permeable sands and gravels the percentages are determined as above.

4 Where the aquifer is overlain by mixed drift not exceeding 5 m thick, 50% of effective rainfall is considered to percolate to groundwater storage.

5 Where the aquifer is overlain by mixed drift greater than 5 m thick, 10% of effective rainfall is considered to percolate to groundwater storage.

6 Where the aquifer is overlain by thick clays or is artesian, percolation to groundwater storage is considered to be zero.

7 All the above factors are multiplied by 0.5 in suburban area and 0.1 in urban areas.

2.4 SOUTHERN

The major aquifers of the region are the Chalk and the Lower Greensand whilst minor aquifers include Hastings Beds, Tunbridge Wells Sands and the Ashdown Beds. Tertiary aquifers are locally important.

Recharge calculations were made using a program based on the Penman-Grindley model to calculate the effective rainfall. This has mainly been superseded by MORECS data. The 40 km grid data is used, either in weekly values which include real land use, or monthly values which are based on grass. Recharge is assumed to only occur in winter and the MORECS effective rainfall value is taken to be the recharge value.

Distributed ground water models have been commissioned for several areas. The most recent are:

- River Meon and River Hamble, Hampshire - Over-abstraction Studies, 1994 (Mott MacDonald Ltd.)
- Chichester Chalk Investigation, 1993 (Sir William Halcrow & Partners Ltd.)
- Water Resources Study of East Kent Aquifer, 1991 (University of Birmingham and Acer Consultants Ltd.)
- Darent Catchment Investigation, 1993 (Groundwater Development Consultants)
- Wallop Brook and Bourne Rivulet, Hampshire - Over-abstraction Studies, 1991 (Mott MacDonald Ltd.)

The studies carried out by Mott MacDonald use a modified Stanford Watershed Model (Wardlaw, Wyness & Rippon, 1994) to estimate recharge whilst the other tend to use MORECS potential evaporation data as input to a Penman-Grindley type model. Early studies used a root constant of 25 mm but, following a study in Hampshire which incorporated soil moisture measurements, higher values tend to be used. The values used tend to be around 75 mm for short vegetation and 200 mm for tall vegetation but seasonal or monthly profiles of root constants can be applied, according to land use. Where appropriate, a bypass flow of between 10 and 15% is used. This is applied to the annual rainfall, effective rainfall or a threshold can be applied. Both the bypass and direct flow are lagged through the unsaturated zone using a distribution function that handles variable thicknesses.

2.5 SOUTHWEST

The major aquifers are the Permo-Triassic sandstones, Chalk, the Carboniferous Limestone in the Mendip area and the Jurassic Great and Inferior Oolites. Two methods of estimating groundwater recharge are in use and a variety of methods are incorporated in the distributed groundwater models.

In the west of the region, the resources are from hard rock areas which are of local importance although the size of the resource is small. A simple calculation is done by subtracting the long term average potential evaporation from the long term average rainfall and multiplying the result by a factor, generally 20%, to take into account slope runoff. The long term average potential evaporation is read from a map compiled by the Meteorological Office for the period 1967-75. The long term average rainfall is obtained from a similar map.

In other areas, the Penman-Grindley equations are used. For the Otter valley, meteorological data used to be obtained from the station at Exeter airport but this has since closed. Rainfall data are used from an appropriate, nearby raingauge. The calculation is done for grass.

Distributed groundwater models are available for the Otter Valley, River Allen, River Piddle and the Malmesbury area. These use a variety of methodologies to calculate the groundwater recharge. The Penman-Grindley equations are again used for the Otter Valley model, produced by MRM Partnership, with a single root constant of 75 mm. Mott Macdonald's modified Stanford Watershed model is used to calculate the recharge input for the River Allen groundwater model.

2.6 THAMES

A single methodology is used by the Thames NRA for the purposes of calculating groundwater recharge. The region has been divided into 15 areas, mainly on the basis of the geology. No further action is taken for areas where the surface is considered impermeable, due to urbanisation or the nature of the geology. For the remaining areas, representing the Chalk, Greensand and Cotswold Limestone aquifers, a method of soil moisture accounting is used (Mander & Greenfield, 1978; Wilby, Greenfield & Glenny, 1994; Greenfield, 1984).

The method takes as its input rainfall and potential evaporation data provided by the Meteorological Office and is calibrated against streamflow hydrographs. The rainfall data are daily data and are spatially averaged using the Meteorological Office's method by which the rainfall for each gauge within the area is weighted according to ita long term annual mean rainfall. The potential evaporation data are monthly and are based on the Penman-Grindley model (Anonymous, 1993a; Grindley, 1967). These data are used by Thames as their method pre-dates MORECS. A distance weighting algorithm is used to interpolate areal data from the station locations and the data are disaggregated to daily time step on the basis of a standard annual distribution of daily values. These are used to calculate the effective rainfall.

The soil moisture model is a modified version of the Penman-Grindley model. The major difference lies in the slope of the drying curve for which a value of 0.3 is used, compared to that of 0.08 originally used by Penman (1949). The value of 0.3 was arrived at by experience within the Thames region (Hyoms, 1980). A root constant of 75 - 100 mm is used on the Chalk. In the Cotswolds a lower value, around 30 mm, is used whilst a slightly higher value is used in the Greensand areas. There is also no maximum deficit Originally, four land cover types were used but these were discarded as the areas were felt to be sufficiently large to be assumed to be homogeneous. Direct recharge, i.e. allowing recharge to occur when there is a soil moisture deficit, is handled by allowing between 15 and 20% of the effective rainfall to bypass the soil moisture store.

The recharge is routed to the saturated zone using a linear store and, through the groundwater zone, using a non-linear store, to the river to generate the streamflow hydrograph, Figure 1. The model parameters, such as the root constants and the percentage of direct recharge, have been manually optimised, by inspecting the resultant hydrograph, with particular attention paid to reproducing the time of onset of recharge. Some rivers show a response to heavy rainfall even in dry conditions. This is thought to be due to the runoff coming from the riparian zone

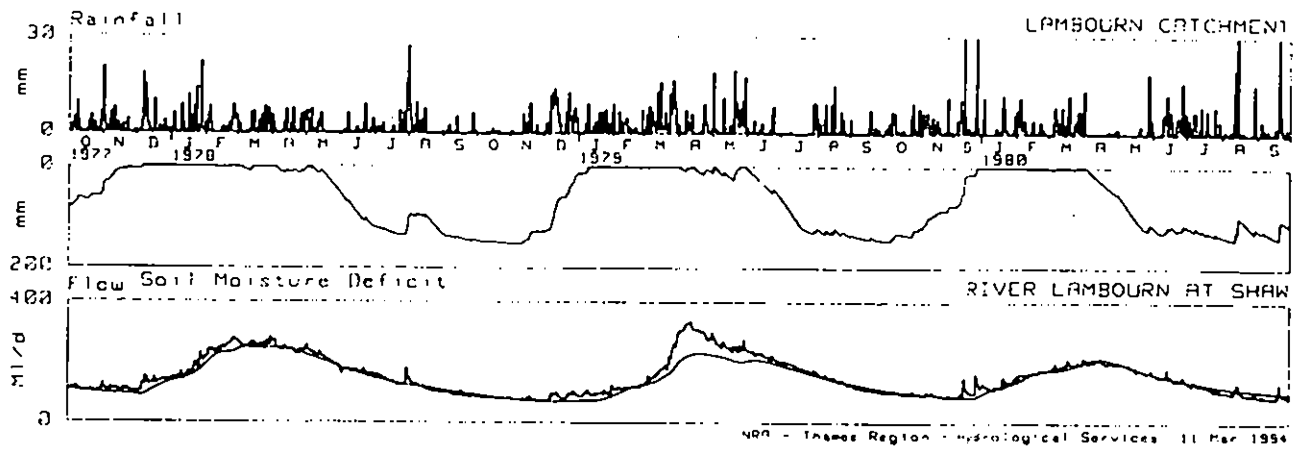

Figure 1 Comparison of observed and modelled hydrographs from the Thames NRA model. Courtesy of Thames NRA

and/or paved areas. This response can be modelled by making an appropriate adjustment of the soil moisture parameters. The river hydrograph is preferred to borehole hydrographs as it represents the integrated response of the catchment. Inspection of the borehole hydrographs has shown that the model sometimes underestimates recharge which may be due to localised thunderstorms. Also some borehole hydrographs show double peaks, due to lateral transfer effects, which are not reproduced by a simple model.

Thames NRA hydrogeologists make use of three distributed groundwater models. That for the London Basin was developed by WRC whilst Birmingham University was responsible for the models of the Kennet valley and the Cotswolds. In addition, MODFLOW is available and FLOWPATH is used for defining nitrate protection zones. The values of recharge input to these models are obtained from the values calculated for the 15 areas. These are spatially distributed using weighting factors varying between 0.5 and 1.3. The weighting factors are derived from a map of the long term average rainfall on a 1 km grid, obtained from IH, and a map of the long term average potential evaporation on a 5 km grid, obtained from the Meteorological Office. The potential evaporation was disaggregated to a 1 km grid by Thames NRA personnel. Use is then made of a nomogram, Figure 2, produced from the soil moisture model. A series of runs were made of the soil moisture model with +10% and -10% of the long term average rainfall and potential evaporation which allowed the ratio of point recharge to the areal average recharge to be estimated.

For the future, Thames NRA personnel recognise the need to change from the Meteorological Office potential evaporation estimates based on Penman-Grindley as these will be discontinued. There is also a need to improve the areal distribution of recharge, probably including variations in land use, for use in groundwater studies.

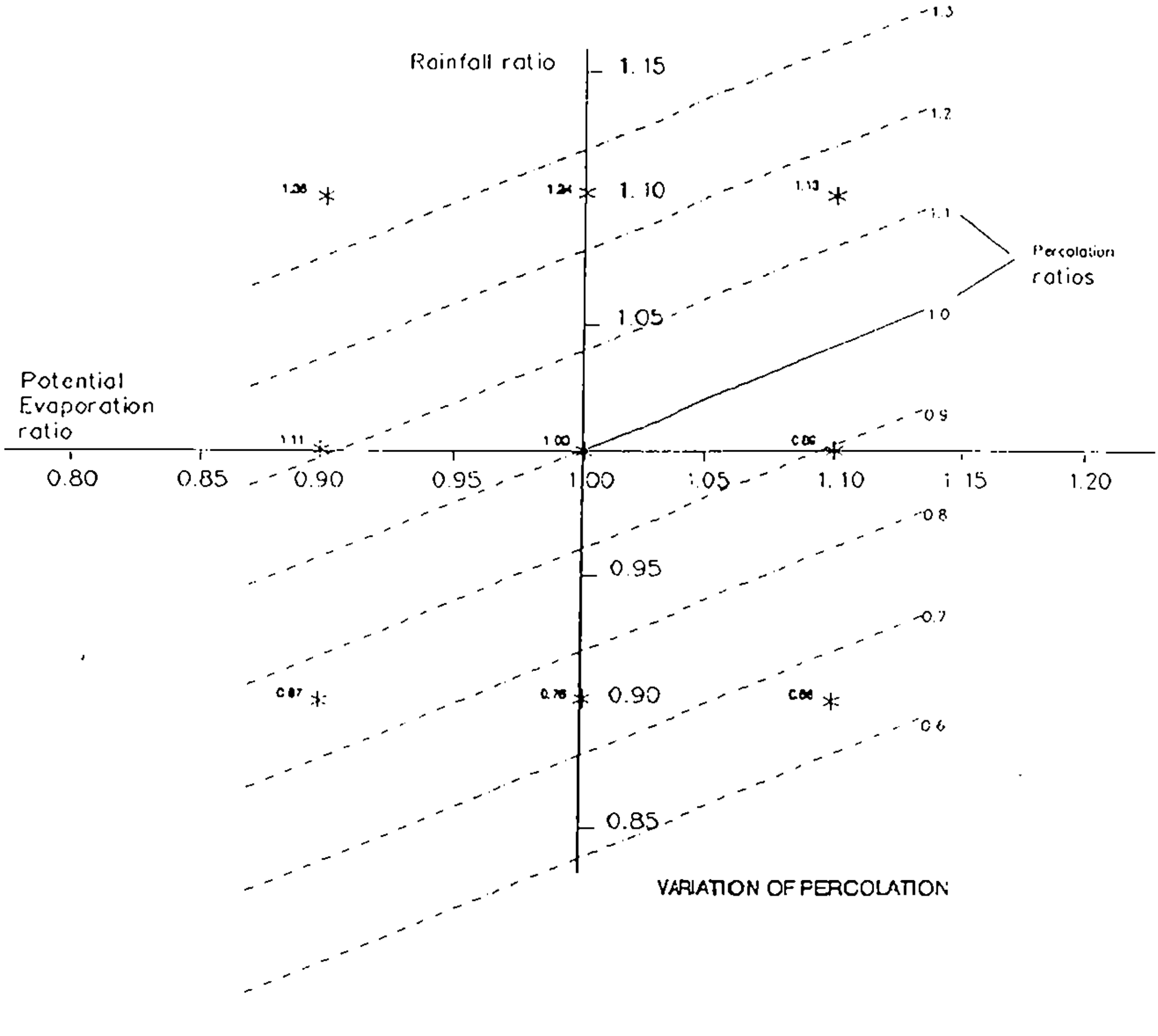

Figure 2 Nomogram for the estimation of point recharge. Courtesy of Thames NRA

2.7 Northumbria & Yorkshire

This region has a range of aquifers with the major aquifers being the Sherwood Sandstones and the Chalk. Minor aquifers include the Millstone Grit and Carboniferous Limestone. The main method of calculating recharge is based on the average effective rainfall and is simply the rainfall minus the potential evapotranspiration. The rainfall values are the long term average and were determined during a survey of water resources carried out in 1963. Tables are available for all the subcatchments, which are further subdivided on the basis of the geology. The thickness and nature of the drift are used to form an opinion on the reduction of the effective rainfall. The recharge is reduced to 50 mm if the drift is greater than 5 m thick and 25 mm if the thickness exceeds 10 m. The Sherwood Sandstones in the Vale of York have a thick drift cover and there is a tendency to overestimate groundwater recharge for this area.However, the drift tends to surround the Chalk at outcrop so the situation is simpler and the estimates of groundwater recharge more reliable. The information on the thickness and nature of the drift was revised in 1987 based on the NRA's own work.

Distributed groundwater models have been contracted from various organisations and the most reliable is considered to be that for the Chalk by Birmingham University's Dept. of Civil Engineering. This has since been extended to cover the whole of the Chalk outcrop by Aspinwall & Co. Ltd. In addition, there is an interest in the Sherwood Sandstones around Doncaster. This area has been included in a model of the Nottinghamshire Sherwood Sandstones, commissioned from Birmingham University's Dept. of Civil Engineering by Severn-Trent NRA. This model makes use of the Penman-Grindley soil moisture model but includes factors for surface runoff, distributed land use and the lag introduced by movement through the unsaturated zone.

2.8 WELSH

The major groundwater resources within the region are the Triassic aquifers of North Wales, whilst the Coal Measures and Quaternary and recent deposits are minor aquifers. The Lower Palaeozoic units are exempt from licensing but are very important locally as they may be the only source of supply.

MORECS data are used for groundwater recharge calculations. Monthly values for the 40 km grid squares have been obtained for the period 1961 to 1991. The values used are for grass as no land cover data is available at the office. To calculate the data at a specific site the recharge is taken to be the difference between rainfall and the actual evapotranspiration. If there are data from a local raingauge available then these are used to modify the value of recharge as the proportion between the measured rainfall and that given for the MORECS square.

2.9 OTHER ORGANISATIONS

The views of members of staff from other relevant organisations have been elicited during this phase of the project. The organisations concerned are:

- WRC Ltd.
- Hydrogeology Unit, British Geological Survey
- ADAS
- Soil and Water Research Centre, ADAS
- Soil Survey & Land Research Centre, Silsoe

- Mott MacDonalds Ltd.

- School of Civil Engineering, University of Birmingham

- Dept. of Geological Sciences, University of Birmingham

Several general points were identified from visiting these organisations. The first was the general acceptance of MORECS data as the starting point for groundwater recharge estimations, although this was not without some reservations about aspects of the data, particularly the coarse scale, 40x40 km, of the gridded data. There were also some concerns expressed about the model applied to specific crops and soil types.

The importance of using realistic land use distribution data was also emphasised, confirming the results given by Wheater (1981). In particular the need to distinguish between winter and spring cereals and to identify cereals and vegetables from grass. A good soil data set was also required by some.

The need to take into account lateral transfers was of concern to some. These can occur both in the soil and the unsaturated layers. In some areas the transfer of water from areas of impermeable strata may be important. The ability to provide a mechanism for rapid recharge, bypassing the soil store, was generally required.

There was a general consensus that calculations on a 1 km grid with a time step of a week or 10 days was acceptable although there was also the need to be able to aggregate up to coarser spatial and temporal scales.

Another point made was that temporally variable data, such as rainfall, should cover an agreed time period in order to ensure that the results are comparable between regions. Concern was also expressed that rigorous algorithms should be used for spatially distributing data, an example where this was required was with rainfall data where the procedure of Theissean polygons makes no use of topographic data.

3. Review of Soil Moisture Models

The visits to the different regions of NRA have indicated that there are three main methods which are commonly used to estimate the evaporation component of ground water recharge. These are based on Penman-Grindley (1969), The Meteorological Office Rainfall and Evaporation Calculation System, MORECS, and a hybrid between these two i.e MORECS potential evaporation with a root constant. Table 2 shows which methods are in use with each NRA region. A brief description of each method, its advantages and its weaknesses are presented below.

Table 2 Soil moisture models in use with the NRA regions

NRA Region	Penman-Grindley	MORECS	Hybrid
Anglian	✓	✓	✓
Northwest	✓		
Severn-Trent	✓	✓	✓
Southern	✓	✓	
Southwest	✓		
Thames	✓		
Northumbria & Yorkshire			✓
Welsh		✓	

3.1 PENMAN-GRINDLEY MODEL, ESMD

This model calculates the potential ground water recharge rate as a difference between measured rainfall, estimated actual evapotranspiration and the soil moisture deficit (Lerner, Issar & Simmers, 1990). The latter is calculated as:

$$PSMD_{i+1} = SMD_i + AE_i - P_i \qquad (1)$$

$$GWR_i = -PSMD_{i+1} \qquad PSMD_{i+1} < 0 \qquad (2)$$

$$SMD_{i+1} = PSMD_{i+1} - GWR_i \qquad (3)$$

Where PSMD is the potential soil moisture deficit, AE is the actual evapotranspiration, P is rainfall, GWR is the ground water recharge, i is the day index and SMD is the soil moisture deficit.

The actual evapotranspiration, AE is calculated from the potential evapotranspiration, PE under different conditions as follows:

$$AE_t = PE_t \qquad SMD_t < C \tag{4}$$

or

$$AE_i = PE_i \qquad P_i \geq PE_i \tag{5}$$

$$AE_t = P_i + F(PE_i - P_i) \qquad D > SMD_t \geq C \text{ and } P_t < PE_t \tag{6}$$

$$AE_t = P_i \qquad SMD_i = D \text{ and } P_t < PE_t \tag{7}$$

Where C is a root constant, mm, D is SMD at wilting point, mm and F is an empirical constant relating actual to potential evapotranspiration when deficits are greater than the root constant. Figure 3 illustrates the relationship between AE/PE ratio to SMD as well as the C, D and F parameters.

A value of 8% for F has been adopted for UK application. C and D are related to vegetation cover and are not dependant on the soil characteristics. Table 3 shows C and D values for various land covers over 12 months. These land covers are: cereals (Sept. harvest), cereals (Aug. harvest), cereals (July harvest), potatoes (Sept. harvest), potatoes (May harvest), vegetables (May harvest), vegetables (July harvest), vegetables (Aug. harvest), vegetables Oct. harvest), bare fallow, temporary grass, permanent grass, rough grazing, woodland, riparian (not shown in the Table 3; C and D are effectively infinite). C and D determine the shape of the relation as shown in Figure 3.

Table 3 *Monthly root constant (C) and wilting point (D) values for the Penman-Grindley model in the UK (mm) (After Lerner et al. 1990).*

		Crop type (see notes)													
Month		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Jan & Feb	C	25	25	25	25	25	25	25	25	25	25	56	76	13	203
	D	25	25	25	25	25	25	25	25	25	25	102	127	51	254
Mar	C	56	56	56	25	25	56	25	25	25	25	56	76	13	203
	D	102	102	102	25	25	102	25	25	25	25	102	127	51	254
Apr	C	76	76	76	76	56	56	56	25	25	25	56	76	13	203
	D	127	127	127	102	102	102	102	25	25	25	56	76	13	203
May	C	97	97	97	56	56	56	56	56	25	25	56	76	13	203
	D	152	152	152	102	102	102	102	102	25	25	102	127	51	254
Jun & Jul	C	140	140	140	76	76	25	56	56	56	25	56	76	13	203
	D	203	203	203	127	127	25	102	102	102	25	102	127	51	254
Aug	C	140	140	25	97	97	25	25	56	56	25	56	76	13	203
	D	203	203	25	152	152	25	25	102	102	25	102	127	51	254
Sept	C	140	25	25	97	25	25	25	25	56	25	56	76	13	203
	D	203	25	25	152	25	25	25	25	102	25	102	127	51	254
Oct	C	25	25	25	97	25	25	25	25	56	25	56	76	13	203
	D	25	25	25	152	25	25	25	25	102	25	102	127	51	254
Nov & Dec	C	25	25	25	25	25	25	25	25	25	25	56	76	13	203
	D	25	25	25	25	25	25	25	25	25	25	102	127	51	254

Notes
1. Values originally quoted in inches (1 in = 25.4 mm) and rounded to nearest mm for this table.
2. Valid for England and Wales only.
3. Crop types are:
   1 cereals, Sept harvest
   2 cereals, Aug harvest
   3 cereals, July harvest
   4 potatoes, Sept harvest
   5 potatoes, May harvest
   6 vegetables, May harvest
   7 vegetables, July harvest
   8 vegetables, Aug harvest
   9 vegetables, Oct harvest
   10 bare fallow
   11 temporary grass
   12 permanent grass
   13 rough grazing
   14 woodland
   15 riparian (not shown) - C and D effectively infinite
4. Based upon Grindley (1969).

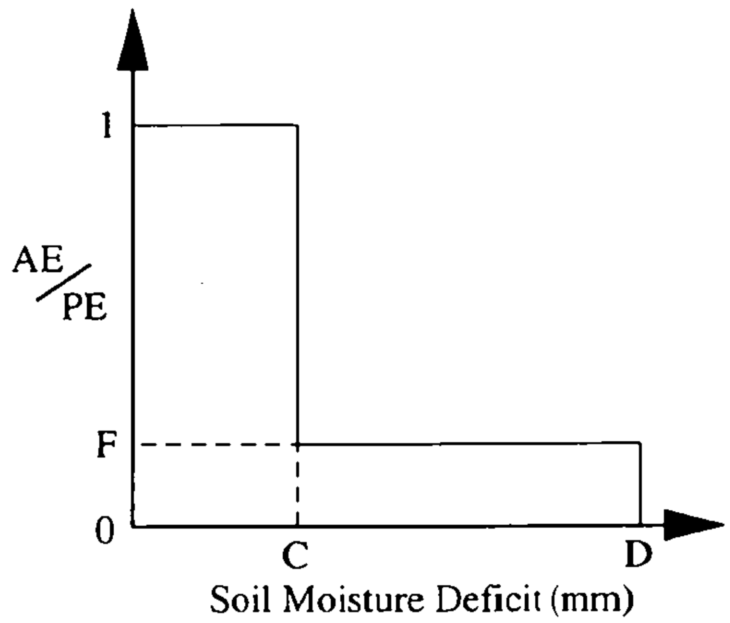

Figure 3 Actual/potential evapotranspiration ratio versus soil moisture deficit in Penman-Grindley model (1969)

The PE is calculated from the Penman equation 1948 and 1949:

$$PE = \frac{\Delta \frac{R_n}{\lambda} + \gamma E_a}{\Delta + \gamma} \tag{8}$$

where

$$E_a = 0.026(0.54U + 0.5)(e_s - e) \tag{9}$$

where R_n is the net radiation, Δ is the slope of the saturated vapour pressure curve, γ is psychometric constant. E_a is the aerodynamic term of the Penman equation (mmd^{-1}), e_s is saturated vapour pressure at air temperature (mb), e is the prevailing vapour pressure (mb), U is wind speed (ms^{-1}) and λ is latent heat of vaporization. The PE calculated here is for short well watered green grass. The net radiation is derived from standard meteorological measurements using empirical formulae, such as given by Thompson, Barrie & Ayles, 1981.

The Penman equation is widely accepted because of its physical basis, despite some drawbacks. The surface resistance is only implicitly included by underestimating the aerodynamic term, as reported by Thom and Oliver (1977). This is only strictly applicable to the short grass surface for which it was calibrated. However empirical relationships have been developed between it and the evaporation from other vegetation types which have proved quite successful.

Other uncertainties in Penman-Grindley model are related to the root constant being a single parameter used to characterize each crop regardless of soil type. Also all crops are assumed to behave in an identical manner once the deficit exceeds the appropriate root constant.

In this model, drainage only occurs from the soil after it has received enough rainfall to increase its moisture content above field capacity. The drainage occurs instantaneously to restore the soil moisture to the field capacity. Consequently, the soil moisture stays closer to the field capacity during the winter and considerably below that during the summer when evaporation exceeds rainfall. As a result, the drainage is assumed to cease abruptly at the beginning of the growing season and does not start again until late autumn. This does not reflect the real field conditions. Soil moisture distribution with depth is not taken into account, only the total water of an unspecified depth is considered.

According to MacKenzie *et al.* (1991), the method does not operate satisfactorily where the surface or the subsurface runoff is a significant component of the soil water balance. It is recommended for studies requiring modest accuracy over long periods in extensive areas of homogeneous land use, soil cover and shallow lithology.

The Penman-Grindley system was used by the Meteorological Office for regular bulletins of PE and SMD since the early 1960s, the ESMD system. Calculations were made for the main synoptic stations and issued as site values. This obviously is a serious disadvantage if areal estimates are required. However the potential evaporation estimates can be used by the user along with catchment specific rainfall, soil and vegetation data to produce a true areal average. MORECS was designed to supersede the ESMD system and the routine issue of ESMD finally ceased in April 1994.

In conclusion this method is a site specific and does not offer areal estimates on a grid-square basis. It uses the well known and widely used Penman equations. These equations have a variety of limitations, particularly if estimates are required for a range of vegetation and soil types.

3.2 METEOROLOGICAL OFFICE RAINFALL AND EVAPORATION CALCULATION SYSTEM, MORECS

Meteorological Office Rainfall and Evaporation Calculation System, MORECS, provides weekly and monthly averages of evaporation and soil moisture deficit over 40x40 km squares (Thompson, Barrie & Ayles, 1981). Great Britain is covered by 190 grid squares and the MORECS uses daily data of 140 synoptic weather stations as inputs. The potential evapotranspiration, PE, is calculated by a modified form of the Penman-Monteith equation. The PE is reduced to actual evapotranspiration, AE, as the available soil moisture decreases. The calculations are made for soils with high, medium and low available water. The daily water balance is calculated under various types of surface covers and a 'real land use' value, using relative proportions of the various surfaces in each grid-square, is produced.

The combination equation used in MORECS, where R_n has been calculated assuming that the bulk surface temperature is the same as the meteorological station's screen temperature, reads as follows:

$$\lambda E = \frac{\dfrac{\rho c_p \Delta}{\rho c_p + b r_a}(R_n - G) + \rho c_p \dfrac{(e_s - e)}{r_a}}{\Delta + \gamma\left(1 + \dfrac{r_s}{r_a}\right)} \qquad (10)$$

where b is calculated as:

$$b = 4\varepsilon\sigma(273.1 + T)^3 \tag{11}$$

Where G is the soil heat flux, ρ is the air density, ε is the emissivity of the surface and σ is the Stefan-Boltzman's constant. The other terms are as in Penman's equation.

The surface resistance, at hourly intervals, during the day time is calculated as:

$$\frac{1}{r_s} = \frac{(1-A)}{r_{sc}} + \frac{A}{r_{ss}} \tag{12}$$

While for night time it is calculated as:

$$\frac{1}{r_s} = \frac{2LAI}{r_{sc_{night}}} + \frac{1}{r_{ss}} \tag{13}$$

or

$$\frac{1}{r_s} = \frac{LAI}{2500} + \frac{1}{r_{ss}} \tag{14}$$

where

$$A = f^{LAI} \tag{15}$$

where r_{sc} is the surface resistance of the crop freely supplied with water and dense enough to make soil evaporation negligible, r_{ss} is surface resistance of bare soil (assumed 100 s/m for wet soil), f value was found to be 0.7 for barley and assumed to apply for other crops. Day time values of r_{sc} for grass, riparian land, cereals, potatoes, sugar beet, deciduous trees, conifers, upland, orchards, bare soil and water are given in Annexe 1, Table 1. The maximum leaf area index for the above mentioned vegetation covers are given in Annexe 1, Table 2. The leaf area index (LAI) of cereals are assumed to increase linearly according to:

$$LAI = (LAI_{max} - 0.1)\frac{(d-d_e)}{(d_f-d_e)} + 0.1 \qquad d_e<d<d_f \tag{16}$$

Where d is the day of the year, d_e is the day of emergence and d_f is the day of the maximum height. The LAI between full development and harvest remains unchanged, however the effect of senescence is included in the following equation:

$$r_{sc} = r_{sc_{min}} + 50\left(\frac{d-d_f}{d_h-d_f}\right) + 500\left(\frac{d-d_f}{d_h-d_f}\right)^3 \tag{17}$$

Where d_h is the harvest day. The value of r_{sc} is close to 600 s/m at harvest. The effective heights used in MORECS are given in Annexe 1, Table 3.

The system also computes the evaporation of intercepted rainfall using a relationship between rainfall and leaf area index of different vegetation covers.

In MORECS, for a dense crop fully intercepting the incident radiation, the surface resistance remains constant until the first 40% of the available water is extracted (reservoir X, see below). It increases progressively to a very large value when all available water is consumed. A similar assumption is made for evaporation from bare soil. For the early growth stage, the soil evaporation is accounted for by relating the r_{ss} to soil moisture deficit, SMD and combining r_{ss} with a correspondingly corrected r_{sc}. MORECS calculates the actual and potential evaporation. The potential evaporation here being calculated with a constant, minimum surface resistance (but including interception losses).

The soil water is divided into two reservoirs, X and Y with x mm and y mm of water respectively. All the water in X reservoir is freely available while that in Y becomes increasingly difficult to extract as y decreases. The total maximum of available water, $x_{max} + y_{max}$, is distributed as 40% in X and 60% in Y.

The soil water will be drawn first from X until it is completely depleted then extraction from Y starts. Also, it is assumed that rainfall will recharge X till it is full and then replenish Y.

In MORECS, the values of X_{max} are used as a critical SMD thresholds, similar to root constants. The size of X_{max} and total available water (2.5 X_{max}) vary according to the soil type.

Available water capacity for soils of medium capacity are given in Annexe 1, Table 4, for various soil covers, grass, cereals, potatoes, sugar beet, deciduous trees, conifers, upland, orchards and bare soil. Soils of high or low available water capacity are arbitrarily assigned 25% more or less than the medium soil respectively.

For spring barley and root crops the available water is assumed to increase linearly at emergence from twice that of bare soil to a maximum value when maximum cover is attained. The surface is assumed to be bare soil after harvest. Winter cereals are treated similarly, except that after harvest bare soil is assumed until the end of December. After that a sparse crop of LAI=0.5, height=0.08 m and available water of 3.75 times that of bare soil is assumed until the start of spring growth.

The calculations are made daily. However, weekly and monthly grid square average values are calculated of PE, AE, SMD and HER (the hydrologically effective rainfall which can be assumed to be synonymous with groundwater recharge) for 14 crops/surface covers on soils with medium available water capacity, Annexe 1, Table 5. The five basic meteorological parameters of sunshine, temperature, vapour pressure, wind speed and rainfall for the 190 MORECS squares, are available as daily, weekly or monthly values.

As in Penman-Grindley, in MORECS, the definition of field capacity, FC, and SMD are implicit. Soil drying below FC is assumed to take place only as a result of evapotranspiration. This means that, drainage ceases 48 hrs for a medium soil after the soil has been wetted. In reality, under field conditions, the drainage from lower part of the soil profile may cause a deficit. The concept can not explain the deep percolation of rainfall which occurs in some soils when they are relatively dry so that the upper layers are not necessarily restored to field capacity following rainfall. Also soils with low hydraulic conductivity may continue draining for weeks following a complete wetting and obviously the idea of field capacity is not applicable in this case. The concept implies that, drainage is assumed to cease abruptly at the beginning of the growing season and does not start again until late autumn.

The only water input to the soil profile is rainfall and no account is made of lateral flow i.e the surface runoff or runon during intense rainfall or on steep slopes. SMD due to topography alone could be substantial. Also the capillary upward flux from shallow water tables at the base of soil profile is not considered.

In reality, the soil factors that cause the AE to decrease below PE rate are the increase in soil moisture tension and the decrease in the unsaturated hydraulic conductivity as a result of the decrease in soil moisture content. The soil moisture content or SMD is only an index of these factors which are site dependent because the relations between these factors depends on soil type. The effect of these factors on soil moisture extraction is beyond capability of the model. MORECS is better at estimating SMD of sandy soil while it overestimates it for loamy soils. Also it overestimates SMD in late summer and early autumn (Gardner, 1983). It was found that MORECS tends to overestimate SMD for normal rainfall years (average years) but underestimates SMD in dry years such as 1976.

The overestimation of SMD may be attributed to the inaccuracy of individual point measurements of PE, the inadequacy of the model to derive AE from PE or, the inaccuracy of rainfall measurements. MORECS uses standard rainfall gauges which are known to catch less rain than the ground level ones. Also it might be attributed to integration of point measurements over an area of (40x40 km^2) with varied rainfall input, crop cover and soil water conditions.

Wheater (1981) reported that introducing an error of 10% in PE and rainfall data has a much smaller effect on the calculated regional SMD than the inaccurate description of land use distribution. Greenfield (1981) found that the root constant value for grassland varies from 25 mm to 75 mm according to the underlying geology and the drying curve slope (AE/PE) for SMD values greater than the root constant has a constant value of approximately 0.30 for all areas. Davis (1981) reported that MORECS significantly overestimated PE and AE and underestimates the effective rainfall. Moreover, the estimated SMD returns to FC slightly later than the catchment values. McGowan (1981) mentioned that, the root constant for the same species growing on the same soil could differ.

MORECS uses the well known and physically based Penman-Monteith equation which takes into account the surface resistance and rainfall interception, it has a more complex soil model and produces areal estimates of different surface covers on 40x40 km^2 grid-squares. However, for many catchment applications i.e rainfall-runoff models, the 40x40 km^2 grid is too coarse as it does not reflect variations within the catchment. Also the soil model is crude and does not account for lateral flows, macropore flow and drainage under deficit conditions, therefore it is suitable for medium texture soils and is less suitable for chalk soils with macropore flow. The method has not been updated since 1981. This update is now overdue, especially with regard to soil model, soil classification and land use.

3.3 HYBRID MORECS PE + PENMAN-GRINDLEY ROOT CONSTANT

The method takes the potential evaporation of MORECS and Penman-Grindley root constant adjusted for local conditions. It is flexible and allows for adjustment of the soil model to local conditions, rainfall, drainage etc. There is however an inconsistency on this approach because the MORECS potential evaporation contains an interception component which is calculated form the 40x40 km areal rainfall. The practical effect of this inconsistency is probably small but it needs to be checked.

This approach could be fruitful providing areal average potential evaporation combined with rainfall, soil and vegetation distributions tailored to a particular catchment and more realistic soil moisture models.

4. Unsaturated zone methodology

This chapter considers the techniques used by the regions for handling the unsaturated zone. This is the zone of aquifer(s) below the base of the soil and root zone and above the regional saturated groundwater zone.

This unsaturated zone occurs in NRA recharge methodologies in two contexts. First, it is considered, implicitly if not explicitly, in catchment modelling of various types: such modelling is used to determine values of the root constant or recharge by comparison of simulated and observed streamflows or groundwater levels. Second, unsaturated zone processes are considered separately in the direct routing of the base-of-soil drainage term to its incrementation of the saturated zone. The recharge term thus derived is subsequently used in resource assessment and saturated zone modelling. Specific methodologies of these two types are described in the following two sections of this chapter.

This chapter does not deal with saturated zone effects per se on the unsaturated zone transfer, except in the sense of determining a mean unsaturated zone thickness. The question of lateral transfers of water is considered, since such transfers can occur below soil and root zones but above the major regional saturated zone.

4.1 THE UNSATURATED ZONE AS A CATCHMENT COMPONENT

Optimization of model parameters is frequently made against streamflow, or the baseflow component of streamflow, and the purpose is to derive parameters which are otherwise difficult to determine, particularly root constants and effective precipitation. The most formalised of such approaches reported by the regions are the use of the Thames Catchment Model and the Stanford Watershed Model.

4.1.1 Thames Catchment Model

As used by the Thames NRA region (Greenfield, 1984), the model is applied to sub-regions of hydrologically distinct types to derive root constant values by optimization against river baseflow. Beneath the soil, two reservoirs conceptually represent unsaturated and saturated zone processes. The upper unsaturated zone reservoir is a linear reservoir, that is, outflow is directly proportional to storage volume. The lower reservoir is non-linear, with flow proportional to the square of storage volume. The model produces good baseflow fits. A quickly responding 'riparian zone', clay zone or paved area can be invoked, without specific reference to unsaturated zone behaviour, to match peaks.

Applications of this model are reported by, for example, Moore *et al.* (1993) who assess rainfall input for flood forecasting, and Wilby *et al.* (1994) who explore water resource issues under climatic change.

4.1.2 Stanford Watershed Model

This long-standing conceptual rainfall-runoff model (Crawford & Linsley, 1966) has been modified by a number of users for particular applications (for example Fleming and Mackenzie, 1982). It is used in consultants reports to estimate groundwater recharge and other parameters, for example, for the Darent catchment in Kent (Anonymous, 1993b; Wyness, Rippon & Wardlaw, 1994), the River Allen, Dorset (Wyness, Rippon & Wardlaw, 1994; Wardlaw, Wyness & Rippon, 1994), the Meon and Hamble, Hampshire (Anonymous, 1993a), the Wallop Brook and Bourne Rivulet, Hampshire (Anonymous, 1991a).

The unsaturated zone as defined in this chapter does not correspond exactly with the conceptual definition of the original Stanford model: in the early documentation, the closest concept is a 'lower zone store'. Water enters this from direct and delayed infiltration. From the lower zone store water enters a groundwater store at a rate increasing, non-linearly, with the water content of the lower zone store. This store is not exactly analogous to the unsaturated zone of this chapter since, limited, evapotranspiration can occur from the lower zone store. A criticism frequently cited of the Stanford model is that it has some thirty parameters, of which four are commonly optimized: these govern infiltration, interflow and store sizes.

Though essentially a lumped model, the Stanford model can be applied to zones differing with respect to surface or subsurface characteristics to build up a semi-distributed system.

4.2 DIRECT UNSATURATED ZONE METHODS

In direct methods, the incoming flux is known and the outgoing flux to the saturated groundwater zone is derived. A terminology often employed is that of potential recharge (that is, after consideration of evapotranspirative losses) and actual recharge on arrival at the saturated zone. Direct methods are not used in a number of the regions because of the occurrence of unsaturated zones of limited thickness, or because emphasis is placed on the long term estimation of recharge, in which the short term time distribution is not important, if lateral transfers in this zone are not significant.

4.2.1 Losses

Lateral transfers of water can occur in the unsaturated zone although vertical movement predominates. These can be modelled specifically in the unsaturated zone, as defined here, or can be part of a general lateral flow term which does not distinguish the depth(s) at which the transfers occur. The major processes of lateral transfer include surface flow, artificial drainage transfers, fissure flow, and throughflow or interflow, for all depths above the regional saturated zone. Topographic configuration, permeabilities, water contents and materials can give rise to a significant non-vertical component of flow.

An empirical but formal methodology for dealing with losses, which are implicitly largely lateral losses and some of which are unsaturated zone losses, is used by Severn-Trent NRA (Anonymous, 1979) for the Triassic sandstones. A coefficient is applied to effective rainfall to derive the recharge reaching the saturated zone. This coefficient is determined on a points-scoring basis and includes, on the grounds of general experience and from hydrograph analysis, the effects of soil texture, aquifer lithology, unsaturated zone thickness, surface drainage density, drift thickness and urban development, Table 1.

Similar but less detailed systems are reported elsewhere, for example, by the University of Birmingham and Acer Consultants (Anonymous, 1991b) for the Chalk of East Kent and by Wilson *et al.* (1994) for the Chalk of the Chichester area, where the principal determinant of the 'recharge factor' is the presence and texture of superficial deposits. An extreme case is afforded by the Thames Great Oolite study (Rushton, Owen & Tomlinson, 1992) where a proportion of potential recharge above 40 mm per month passes directly to streamflow, representing the effect of rapid lateral transfer via fissures.

4.2.2 Lags

A simple delay can be imposed on travel time to the regional water table. In parts of the Chalk of East Kent, for example, earlier estimates of lags of 0.5 to 2 months based on the response of observation wells have subsequently been modified (Anonymous, 1990; Anonymous, 1991b) to try to remove the effect of lateral saturated zone transfer.

The lag can be distributed in time. Thames, for example, use a distributed lag with the peak response after 3-4 weeks for the Kennet but much less in the Cotswold areas. For the Nottinghamshire Sherwood Sandstone (Bishop & Rushton, 1993), monthly distributions of unsaturated zone lag are defined for four categories of unsaturated zone thickness. These are estimated from the response of observation borehole rest levels in relation to precipitation events. The maximum lag suggested is six months for an unsaturated zone thickness of greater than 30 m.

These are in effect linear transfer function models, which, in a general way, integrate unsaturated zone recharge processes. Generally, the precise form of the function is, in regional practice, derived on the basis of experience and revised in that light. Oakes (1981), however, provides an example of the derivation of a response function. For the Chalk of parts of the Rhee and Cam catchments, south of Cambridge, a deconvolution against observed groundwater levels provides a distribution of unsaturated zone transfer times which, in this case, cover up to seven monthly intervals for thicknesses of unsaturated zone depth up to 70 m.

A number of additional issues concerning recharge are included in this chapter for convenience though they are not necessarily wholly unsaturated zone features. They include percolation recharge or leakage from overlying semi-permeable material, leakage from urban areas, and river-aquifer transfers. In regional practice as a whole these are not major features of methodology, but they are increasingly features of more detailed modelling, particularly of the linked surface and groundwater type. Reports on the Sherwood Sandstone (Bishop & Rushton, 1993) and South Lincolnshire Limestone (Rushton, Bradbury & Tomlinson, 1993) provide good examples of the handling of these issues in cases where NRA practice is to commission detailed studies. River-aquifer flows are head-dependent transfers; sources of urban leakage data are evaluated; principles and examples are given of flow from overlying semi-permeable strata; and fast flow or by-pass mechanisms are explored, with reference to borehole logging and tracer experiments in addition to more commonly-available hydrological data.

4.3 SYNTHESIS

The unsaturated zone is generally dealt with by inference in recharge estimation because of the inherent difficulties of establishing its detailed behaviour.

If the estimate is required for the long term, the timing of flow through the unsaturated zone is not significant, although any lateral transfers may be significant, depending on hydrological and geological circumstances. For shorter term recharge estimation where time distribution is important, much existing NRA practice falls into the category of response or transfer function approaches of varying complexity. The linearity of these formulations is in general not formally tested in, for example, recent drought conditions and the subsequent recovery.

The unsaturated zone can also be used in the deriving of catchment parameters which may subsequently be used in recharge estimation. Here the methodology is primarily that of linear or non-linear stores with various process linkages. The question arises, on occasion, of some inconsistency in the method of handling the unsaturated zone. A parameter, for example a root constant, may be derived assuming particular unsaturated zone behaviour. However, base-of-soil drainage using that parameter may be subsequently routed through the unsaturated zone which is treated in a different manner. Practical reasons for this type of approach are apparent, particularly when different departments are involved in different stages of the methodology: results may be acceptable but an awareness of their derivation is appropriate. Where spatial variability of unsaturated zone behaviour is included for a particular aquifer, it is in terms of its vertical thickness/extent. Methods are deterministic and conceptual: no stochastic methodology has been reported, nor formal statements of error or uncertainty.

Full numerical modelling using flow equations in the unsaturated zone (for example, variably saturated Darcian flow plus continuity considerations) is not reported as a feature of current practice. This is pragmatic because such simulation is particularly subject to the complexity of process representation and parameter uncertainty, despite the advantage of potential continuity of modelling methodology with the soil above and, in some formulations, with the saturated zone below. Unsaturated flow complexity is increased over that of the saturated zone because of the dependence of both water content and hydraulic conductivity on pressure heads which are transient and spatially variable. Dual or fracture flow models offer possibilities of greater process matching in some aquifers, but at the cost of unwieldy parameterisation. The role of very detailed unsaturated zone modelling in recharge estimation is perhaps more that of establishing understanding of field behaviour, which one would then aim to approximate adequately by a simpler formulation for routine determinations.

It is important to note that in the current emphasis on stores and transfers it is not always clear whether in fact one is modelling the pulse of water or the transmission of the water itself. For many purposes, this is a distinction which does not need to be drawn. However, there is a potential danger that, if water quality considerations are added to NRA recharge estimation, subsequent parameterisation may be more difficult in practice and may become further removed from the process represented. It should perhaps be borne in mind that this disadvantage can also apply, in some degree, to more complex modelling. A related point is that no 'long-tailed' unsaturated zone transfer functions were reported from the regions which would specifically account for slow background chalk matrix flow (see, for example, Smith *et al.*, 1970; Foster, 1975).

In areas where NRA resources have been directed to the detailed study of surface/groundwater behaviour, recharge assessments have been made taking practical account of a number of key surface and subsurface hydrological processes, whether natural or man-induced, appropriate to the area of concern. From such studies some degree of practical generalisation of process representation is beginning to emerge. The question of testing wider applicability remains, as does the assessment of the trade-off between simple and more complex methodologies in terms of efficiency of recharge estimates for particular NRA purposes.

5. Conceptual Framework

This chapter develops the conceptual framework for the groundwater recharge model. The conceptual framework is the necessary link between the physical processes involved in recharge and a model that allows the recharge to be predicted from input parameters.

Figure 4 illustrates the processes occurring with groundwater recharge. For convenience, the processes can be categorised as occurring in three zones; the surface/atmosphere zone, the soil zone and the unsaturated zone. Processes occurring in the surface/atmosphere zone include interception of precipitation by the vegetation canopy as well as evaporation and transpiration. In addition, surface runoff may occur which can result in concentration through ponding and gains from surface runon and losses from surface runoff. The soil zone encompasses drainage to the underlying unsaturated zone and root uptake. As such, it is a zone in which both upward and downward water movements can occur. In addition, lateral flow through the soil layer can result in gains and losses of water. The unsaturated zone is defined as the zone lying between the soil zone and the regional saturated groundwater system. As such, it is a zone where no upward movement of water occurs. A vertical profile through this zone might encounter several lithologies with a range of hydraulic properties. It is in part due to this heterogeneity that lateral flow can potentially occur in this zone.

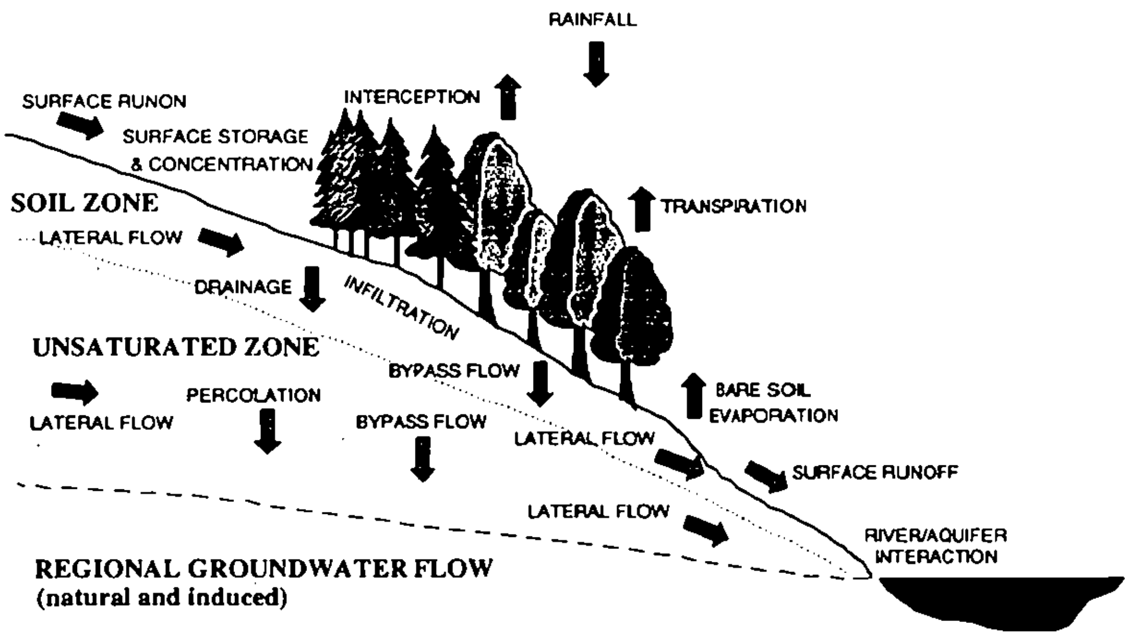

Figure 4 *The physical processes involved in groundwater recharge*

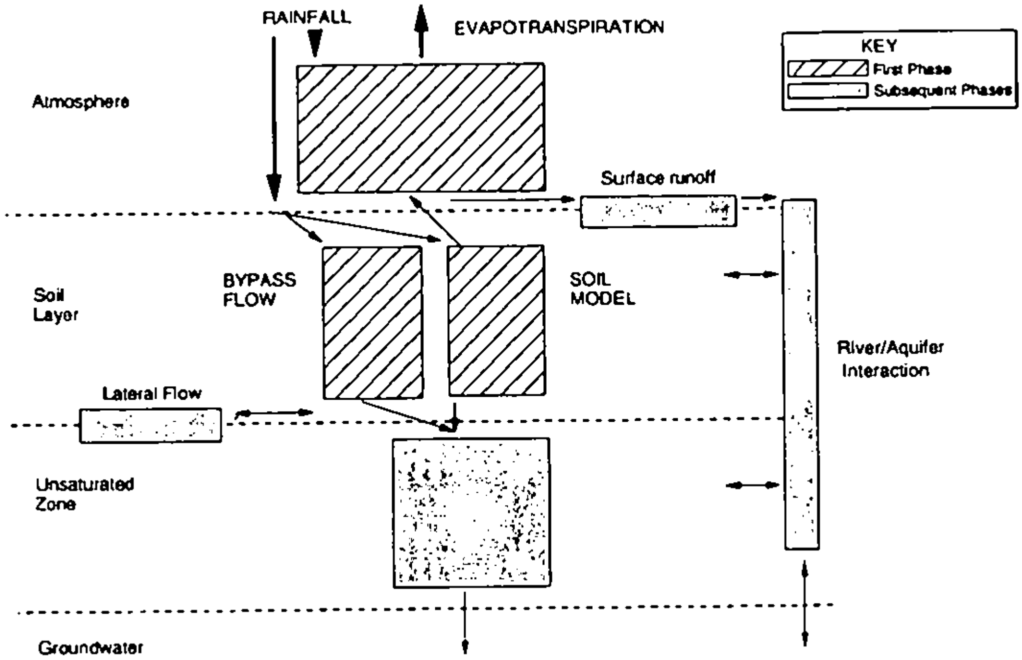

Figure 5 *Diagram of the conceptual framework*

The groundwater recharge processes can be grouped together, in a convenient manner, as the basis of the component models, Figure 5. In this project, only the models covering evapotranspiration and the soil zone are being developed. However, to consider these without also considering the other models may limit future developments of the procedure and so the development of the conceptual framework has been carried out to encompass all the component models.

In developing a model to enable groundwater recharge to be assessed, a modular approach has several advantages. Firstly, it allows components of the model to be updated as the results of both experience and research become available. Secondly, it allows a phased introduction of the complete model. Thus, for this project, we have used a modular approach as the specification for the model restricts its use to drift free areas of the major aquifers of England and Wales and for estimating mean annual recharge. However, at a later date it will be necessary to extend the model to increase the range of hydrological conditions it can handle. Using a modular approach it will be possible to accomplish this by progressive enhancements rather than a complete replacement of the model.

At this stage it is not possible to be definite about the models that will be used as this can only be determined by verification against field data, i.e. the next stage of the project. The following sections explore possible options for the methodology.

5.1 EVAPORATION COMPONENT

The evaporation schemes generally consist of three components: an equation to estimate potential evaporation (PE), an equation to reduce the evaporation from potential depending on the soil moisture and a set of equations to describe interception losses. In some schemes, such as the Penman equation, the interception losses are included implicity within the potential evaporation equation.

There is a large range of possible potential evaporation equations but the two most widely used the Penman equation (Penman, 1948) and the Penman-Monteith equation (PM). The Penman equation is the basis of the Penman-Grindley method whereas the PM equation provides the basis for MORECS. At this stage it is not necessary to make a decision between these two options but it can be said that the PM approach has a number of advantages:

- it can handle different land covers explicitly, although the parameters for all land cover types are not necessarily well known.

- it is readily available through the MORECS system, although the Penman-Grindley estimates have been available these have now been discontinued.

- it is more physically realistic than the Penman system.

Within the PM equations there are a number of options on implementation. For example, the actual evaporation output from MORECS can be used directly; or the MORECS PE, which is independent of soil type and moisture, can be combined with a custom built soil (and possibly interception) model. This latter course would seem the most fruitful, combining the availability and acceptability of MORECS with the flexibility of soil models tailored to a particular geological type. It is likely that updates in MORECS may be produced to incorporate improvements suggested within this project.

The mode of introduction of the soil moisture stress term will depend on the model. Thus, for the Penman model, this term must be introduced as a multiplicative factor to the potential evaporation whereas for the PM equation the more physically correct way is for the factor to operate on the surface resistance only, although for convenience many schemes do operate on the PM potential evaporation directly. Details of possible soil models are discussed in the next section.

The PM scheme requires an interception component to allow free water to gather on the vegetation and be evaporated. MORECS does contain a simple, empirical interception model; however this model almost certainly underestimates the true losses and could be improved using studies which have taken place since MORECS was introduced. Many complex interception models exist which make a running water balance on the canopy (see for example Rutter, 1963). These models are very successful but are inappropriate in this case, requiring at least hourly measurements. Gash (1979), Calder (1986) and Harding *et al.* (1992) have described daily interception models which include a increased degree of empiricism, however, being calibrated on UK data these models are well suited to be used within this project.

For operational reasons, it must be assumed that the evaporation models (and soil models) will operate on a daily basis. It can be shown that the soil water accounting must be done on a daily basis and realistically it is unlikely that hourly meteorological data will be readily available for long-term estimates of ground water recharge. The Penman equation was designed for use with daily data. The Penman-Monteith is generally used with hourly data, with a diurnally varying surface resistance. It is, however, possible to use the PM equation with daily data but the surface resistance is then an effective parameter.

Within the analysis phase of this project a limited range of evaporation models, coupled with soil water models outlined in the next section, will be tested against soil moisture measurements from the test sites.

5.2 SOIL COMPONENT

The output of the soil model will be an estimate of surface runoff, by-pass flow, soil water flow or deep percolation and actual evapotranspiration. This section outlines several possible models which will be investigated.

The actual evapotranspiration is a reduced potential evapotranspiration with the reduction factor an output of the soil model. In some models it is a combined effect of crop and soil. The crop factor (or crop coefficient) changes with growth stages, being small at the beginning and at harvest and maximum at the end of vegetative growth or when maximum leaf area index is established. The crop coefficients for different crops are published by FAO (Doorenbos & Pruitt, 1984) and are internationally recognised and used. The soil coefficient, whether it is used alone or together with the crop coefficient, is associated with the soil water stress. The latter can be expressed in different forms such as a ratio between either soil moisture and soil moisture at field capacity or the available soil moisture and maximum available soil moisture. FAO are currently develping a method to supersede this method.

The soil moisture deficit, SMD, can also be used as a reduction factor. The SMD concept is used in Penman-Grindley method. The shape of the relation of SMD versus the actual/potential evapotranspiration is controlled by three parameters. The most important is the so called the root constant which is a critical value below which the actual evapotranspiration is reduced below the potential rate. These three parameters for 15 land covers are available in tables. A SMD factor similar to the root constant is used in MORECS being 40% of the total maximum available water. The maximum available water for various soil covers of soils of medium capacity is available in a form of table. Soils of high or low available water capacity are assigned 25% more or less than the medium soil respectively.

The hybrid between MORECS and Penman-Grindley can be employed so that the potential evapotranspiration, as calculated from Penman-Monteith equation in MORECS, can be reduced to actual evapotranspiration using the root constant of Penman-Grindley method. A similar approach is now under investigation by FAO where the potential evapotranspiration as calculated from an operational form of Penman-Monteith equation can be reduced to actual evapotranspiration using a crop and a soil coefficient.

Soil water movement can be described by a capacity/storage approach or by physically based models based on Darcy's law. The capacity approach is adopted in MORECS and in the Penman-Grindley methods. In this approach, if the inflow (rainfall) to the first layer exceeds its storage capacity, the water drains down to the second layer until the water available for infiltration is dissipated within the root zone. Some models use a single layer whilst others use two, i.e a time dependent 'dynamic' root zone and a fixed maximum depth of the soil profile. Other models use a multi-layer approach, e.g. ten layers to cover the entire root zone. No drainage takes place under deficit conditions. and, at this time, water can only be lost via evapotranspiration as upward flow.

The Darcy's law approach can be used to describe mathematically the water flow in saturated and unsaturated conditions. The soil water flux is calculated as a product of soil hydraulic conductivity and hydraulic gradient. In a homogeneous medium, the hydraulic conductivity at saturation is a single value whilst, under unsaturated conditions, it is a function of either soil moisture or the soil water potential.

The combination of Darcy's law and the continuity equation produces the well known Richards equation for soil moisture flow under unsaturated conditions. It is a partial non-linear differential equation. It calculates the changes in soil moisture as a function of time at a given distance. This equation requires two relations, the unsaturated hydraulic conductivity/soil moisture or soil potential and the soil moisture/soil water potential. The latter is known as soil water retention curve or soil water characteristics curve or pF curve. These two relations can be obtained from field or laboratory measurements or can be obtained from predictive models which make use of the readily available soil survey data (bulk density and percentages of sand, silt and clay). This approach would be suitable at a small scale, e.g 1 km^2, since the spatial variability of these parameters, especially the hydraulic conductivity, is on a comparable scale.

The soil moisture of the surface layer plays an important role in generating the runoff. Surface runoff occurs when the effective rainfall exceeds the maximum infiltration rate at the soil surface. When this occurs, the excess water accumulates until it exceeds the surface storage then, it runs off. There are different approaches in estimating this runoff. The simplest one is to assign a ratio of the rainfall based on long term record of measurements of both rainfall and runoff. Another approach would be to employ a threshold value of moisture content at saturation or saturated hydraulic conductivity or specified maximum infiltration rate, above which the runoff occurs.

The US Department of Agriculture Soil Conservation Service's (SCS) approach, known as the Curve Number (Williams, Jones, & Dyke, 1984), can be used when databases are available for soil water storage (e.g. HOST), land use and slope for different soil types. In this approach, the runoff is calculated from rainfall and a retention parameter which is related to soil water content, the upper limit of soil water storage and a maximum value for retention. The retention parameter varies according to soil type, land use and management, slope and time. This value can be obtained from tables and curves for a number of conditions.

Bypass flow occurs under similar conditions to those that create surface runoff. Flow through cracks, fissures and macropores occur when the rainfall exceeds the maximum infiltration rate of the soil matrix. This flow contributes to the deep percolation and hence the groundwater recharge. It can be assigned a certain ratio of the rainfall. This is usually obtained either as a matching factor from calibration or as water in excess of a threshold value in a similar manner to surface runoff. Also, it can be calculated from more complex models for turbulent non-Darcian flows, analogous to open channel flow. Often these models take into account the geometry of the cracks or macropores and are mostly used at a small scale.

5.3 UNSATURATED ZONE COMPONENT

The general level of complexity of unsaturated zone methodology should be commensurate with the current conceptual knowledge of unsaturated zone behaviour. The current detailed quantitative knowledge is not sufficient to justify a more complex solution. The primary method used for unsaturated zone transfer is likely to be in the form of a response function. The input flux is transformed according to a specified function to derive a distribution of arrival times at the regional saturated zone. The key advantage of this methodology is its flexibility of process representation within a general type of formulation, albeit in a summarised form.

The definition of the precise form of the function is not straightforward: some NRA regional experience exists which is an advantage of this procedure. Thickness of the unsaturated zone will need to be accurately classified with respect to the use of differently parameterised transfer functions within a particular aquifer. The linearity of the model may need modification in the light of experience.

Spatial and temporal resolution are likely to be coarser than in the consideration of near-surface processes. The methodology does not inherently demand fine discretisation in space and time, the intervals will be chosen on the basis of meaningful variation in parameter values and on the rates of change of soil-base fluxes.

Transfer functions may model the pulse effect as opposed to the flow of water itself, and this distinction may differ between aquifers. This means that water quality cannot be added directly to the procedure, which could be a disadvantage. More complex unsaturated zone methods can also have this problem but parameterisation of a chemical pulse may provide an acceptable solution.

The 'full' numerical modelling of the unsaturated zone is seen as being too complex for a general procedure, but the experience that can be derived from such studies will be incorporated into simpler models for routine use.

Lateral transfers within the unsaturated zone will be considered in relation to the three-dimensional variations of material permeabilities and the magnitude/frequency characteristics of the soil-base fluxes. Generalisations will be made to introduce a separate term into saturated zone arrival and/or to modify the response function described above. Approximations in this field have not been generalised and need investigation. Experience in 'type' areas, which is available in NRA consultants' reports to some degree, will be a primary source in the development of a simplified, spatially continuous procedure.

The amount of validation of recharge to the regional saturated zone that can be accomplished will be heavily dependent on time availability. Saturated zone behaviour as a whole is involved at this stage, and it is only in rare cases that this is simple. Observations and modelling will need to be employed with feedback to the recharge methodology and/or parameterisation made accordingly.

5.4 INTERACTION WITH RIVERS

In places, a complete spatial assessment of recharge will require consideration of the role of rivers as a source of recharge and as a lateral transfer mechanism. Identification of zones where this is likely to be important will be made on a geological basis, supplemented by flow frequency statistics from the National Water Archive.

Within relevant zones, in-bank river stages will be considered in the light of relative river and aquifer heads and bed and bank conductances: however, detailed examples are very few. For overbank stages, recharge will be viewed in the light of flood durations and floodplain material characteristics. Both these aspects are research areas and it is expected that their early representation will be somewhat crude, but updated as information becomes available.

5.5 OTHER CONSIDERATIONS

Other processes can also influence groundwater recharge and of these, leakage from distribution systems, particularly in urban areas, may make a significant contribution. Quantifying this parameter will probably require detailed information about the distribution system. However, it need not be considered within this project but provision for its inclusion in the soil model will be required in future developments. Other factors, which may have a less significant effect, are frozen ground and snow cover and melt. However, these are likely to be rare and minor events in terms of mean annual recharge and so will not be considered further in this project.

The scale of spatial and temporal resolution does need some consideration. Since the objective of this project is the estimation of mean annual recharge there will be the requirement to aggregate up as the evapotranspiration calculations are likely to be performed using a daily time step. Thus the scale of these calculations is likely to be at a higher resolution than any subsequent requirement since the finest resolution requested is likely to be weekly or ten day averages. Similarly, any lags due to the soil and/or unsaturated zone are unlikely to be significant on the mean annual basis. However, lags will be important for subsequent developments. In addition, it will be necessary to standardise on a time period for the calculation of mean annual recharge in order to ensure that inter-comparisons can be made.

The spatial resolution is an important factor. Although the spatial resolution required is of an average value over the area being considered, there will potentially be significant variations in land use, soil type and topography within that area. Consideration will therefore need to be given to how these variations can be accounted for within the model.

Final considerations are the availability of data to the users and the compatibility of any preferred system with existing or parallel methodologies. It must be assumed that the user has access to long-term MORECS estimates (PE and AE) and rainfall, land cover and soil maps. Complete compatibility with MORECS in the short term is difficult, although the comparisons with field observations will give an indication of the differences in the two systems. In the longer term, discussions are well advanced between IH and the UK Meteorological Office to produce an updated MORECS. This collaboration will ensure compatibility in the future.

6. The next stage

There are five objectives to be achieved to complete this project. These are:

- To develop a procedure for estimating mean annual groundwater recharge, at a range of scales, that can be consistently applied by the NRA regions.

- To test that procedure at two sites.

- To produce a manual that documents the procedure and provides the equations, graphs and maps needed to implement the method.

- To produce recommendations for further work to produce a process based software system for modelling groundwater recharge at a variety of temporal scales.

- To hold a one day seminar to present the results of the project to staff of the NRA regions.

The next stage will be to develop the models outlined in this report and test them against field data from two sites. These sites will be chosen to be representative of conditions encountered in the drift free areas of the Chalk and Permo-Triassic Sandstones. The results of these tests will enable the appropriate models to be selected and developed to produce the manual.

The methodology for using the procedure will be presented in the form of appropriate graphs, tables, maps and equations suitable for hand calculation. Although the most desirable method of presenting the procedure would be in the form of computer software; this is not one of the objectives of this project. The development of computer software would allow the development of the procedure to handle a greater range of hydrological conditions and a range of temporal and spatial resolutions. It will also provide the NRA staff with a fast and flexible method of estimating groundwater recharge. Another advantage would be that the software could be updated by adding or changing modules as the results of experience or research became available.

References

Anonymous 1979. *Groundwater resource assessment of the Triassic Sandstones*, Severn Trent Water Authority, Directorate of Operations.

Anonymous 1981. *Saline groundwater investigation phase 1 - lower Mersey basin*, University of Birmingham, North West Water Authority.

Anonymous 1984a. *Saline groundwater investigation phase 2 - North Merseyside*, University of Birmingham, North West Water Authority.

Anonymous 1984b. *Nitrate in groundwater investigation - final report*, North West Water, Report No. 155.

Anonymous 1989. *Spilsby sandstone investigation - final report*, Groundwater Development Consultants Limited, Anglian Water.

Anonymous 1990. *Water resources study of East Kent aquifer: mathematical modelling of the Chalk aquifer: data review and mathematical model development*, University of Birmingham, Dept. of Civil Engineering and Acer Consultants Ltd., Folkestone & District Water Company.

Anonymous 1991a. *Wallop Brook and Bourne Rivulet, Hampshire - overabstraction studies*, Mott MacDonald, National Rivers Authority Southern Region.

Anonymous 1991b. *Water resources study of East Kent aquifer - mathematical model of the Chalk aquifer - final report, appendices*, University of Birmingham, Dept. of Civil Engineering and Acer Consultants Ltd., Folkestone & District Water Company.

Anonymous 1993a. *River Meon and River Hamble, Hampshire - overabstraction studies*, Mott MacDonald, National Rivers Authority Southern Region.

Anonymous 1993b. *Darent catchment investigation - catchment model calibration report*, Groundwater Development Consultants, Cambridge, National Rivers Authority Southern Region.

Bishop, T.J. & Rushton, K.R. 1993. *Water resource study of the Nottinghamshire Sherwood Sandstone Aquifer System of Eastern England. Mathematical model of the Sherwood Sandstone Aquifer*, Dept. of Civil Engineering, The University of Birmingham.

Calder, I.R., Harding, R.J. & Rosier, P.T.W. 1983. An objective assessment of soil-moisture deficit models. *J. Hydrol.*, **60**, 329-355.

Crawford, N.H. & Linsley, R.K. 1966. *Digital simulation in hydrology: Stanford watershed model IV*, Stanford University, Stanford, California.

Davis, G. 1981. Comparison of MORECS with catchment data. *The MORECS discussion meeting*, Institute of Hydrology, Report No. 78.

Doorenbos, J. & Pruitt, W.O. 1984. *Guidelines for predicting crop water requirements*, FAO Irrigation and Drainage Paper 24, FAO, Rome.

Fleming, G. & McKenzie, R.S. 1982. *River basin model for water and sediment resource assessment*, Department of Civil Engineering, Strathclyde University, Report HY-82-7.

Foster, S.S.D. 1975. The Chalk groundwater tritium anomaly - a possible explanation. *J. Hydrol.*, **25**, 159-165.

Gardner, C.M.K. 1983. A comparison of measured soil moisture deficits with those estimated by the Meteorological Office system, MORECS: a brief report. *Agric. Wat. Man.*, **6**, 307-316.

Gash, J.H.C. 1978. An analytical model of rainfall interception by forests. *J. Hydrol.*, **105**, 43-55.

Greenfield, B.J. 1984. *The Thames catchment model*, Technology and Development Division, Thames Water Internal Report.

Grindley, J. 1967. The estimation of soil moisture deficits. *Meteorol. Mag.*, **96**, 97-108.

Grindley, J. 1969. *The calculation of evaporation and soil moisture deficit over specified catchment area*, Hydrological Memorandum 28, Meteorological Office, Bracknell, UK.

Harding, R.J., Hall, R.L., Neal, C., Roberts, J.M., Rosier, P.T.W. & Kinniburgh, D.G. 1992. *Hydrological impacts of broadleaf woodlands: Implications for water use and water quality*, Institute of Hydrology Project Report 115 03/ST, National Rivers Authority.

Howard, K.W.F. & Lloyd, J.W. 1979. The sensitivity of parameters in the Penman evaporation equations and direct recharge balance. *J. Hydrol.*, **41**, 329-344.

Hyoms, C.M. 1980. *Development of a soil moisture model for the estimation of percolation*, M. Phil thesis. The City University, London, unpubl.

Lerner, D.N., Issar, A.S. & Simmers, I. 1990. *Groundwater Recharge : A guide to understanding and estimating natural recharge*, International Contributions to Hydrogeology.

Mander, R.J. & Greenfield, B.J. 1978. *Hydrograph generation and augmented flow analysis*, Proc. of The Thames Groundwater Scheme Conference, Institution of Civil Engineers, London.

McGowan, M. 1981. Discussion. *The MORECS discussion meeting*, Institute of Hydrology, Report No. 78.

Moore, R.J., Austin, R.M. & Carrington, D.S. 1993. *Evaluation of FRONTIERS and local radar rainfall forecasts for use in flood forecasting models*, Institute of Hydrology, National Rivers Authority R & D note 225.

Oakes, D.B. 1981. A numerical model of a stream aquifer system subject to delayed rainfall recharge. *Trans. Geol. Soc. South Africa*, **84**, 135-144.

Penman, H.L. 1948. Natural evaporation from open water, bare soil and grass. *Proc. Roy.*

Soc. Ser. A, **193**, 120-145.

Penman, H.L. 1949. The dependance of transpiration on weather and soil conditions. *J. Soil Sci.*, **1**, 74-89.

Rushton, K.R., Bradbury, C.G. & Tomlinson, L.M. 1993. *The South Lincolnshire limestone catchment*, University of Birmingham - Department of Civil Engineering, NRA - Anglian region.

Rushton, K.R., Owen, M. & Tomlinson, L.M. 1992. The water resources of the Great Oolite aquifer in the Thames basin, UK. *J. Hydrol.*, **132**, 225-248.

Rushton, K.R. & Ward, C. 1979. The estimation of groundwater recharge. *J. Hydrol.*, **41**, 345-361.

Rutter, A.J. 1963. Studies in the water relations of *Pinus silvestris* in plantation conditions. I. Measurement of rainfall and interception. *J. Ecol.*, **51**, 191-203.

Smith, D.B., Wearn, P.L., Richards, H.J. & Rowe, P. 1970. Water movement in the unsaturated zone of high and low permeability strata by measuring natural tritium. *Isotope Hydrology: Proceedings of Symposium*, International Atomic Energy Agency, Vienna

Thom, A.S. & Oliver, H.R. 1977. On Penman's equation for estimating regional evaporation. *Quart. J. Roy. Met. Soc.*, **103**, 345-357.

Thompson, N., Barrie, I.A. & Ayles, M. 1981. *The Meteorological Office rainfall and evaporation calculation system: MORECS*, The Meteorological Office.

Vines, K.J. 1984. *Drift recharge*, North West Water - Groundwater section.

Vines, K.J., Lucey, P.A. & Brassington, F.C. 1980. *Nitrate in groundwater investigation - Phase 1*, Northwest Water Authority, Hydrogeological Report No. 40.

Wardlaw, R.B., Wyness, A. & Rippon, P. Integrated catchment modelling. *Surveys in Geophysics. In Press.*

Wheater, H.S. 1981. Comparison of field data with water budget calculations. *the MORECS discussion meeting*, Institute of Hydrology, Report No. 78.

Wilby, R., Greenfield, B.J. & Glenny, C. 1994. A coupled synoptic-hydrological model for climate change impact assessment. *J. Hydrol.*, **153**, 265-290.

Williams, J.R., Jones, C.A. & Dyke, P.T. 1984. A modelling approach to determining the relationship between erosion and soil productivity. *Trans. A. S. A. E.*, **27**, 129-144.

Wilson, E.E.M., Akande, O., Phipps, O.C. & Bathurst, D.P. 1994. *Chichester Chalk investigation*, Sir William Halcrow & Partners Ltd.

Wyness, A.J., Rippon, P.W. & Wardlaw, R.B. 1994. Application of an integrated model to Chalk catchments. *Groundwater - Drought, Pollution & Management*, Balkema, Rotterdam

Annexe 1 - Tables of values used by MORECS

Table 1 *Daytime values of surface resistance for dense green crops freely supplied with water (After Thompson et al. 1981).*

Type of crop	(sm^{-1})
Grass, riparian land	80 (Jan), 80, 60, 50, 40, 60 (June 60, 70, 70, 70, 80, 80 (Dec)
Cereals	40
Potatoes, sugar beet	40
Deciduous trees	80
Conifers	70[a]
Upland[b]	120 (Jan-Mar, Oct-Dec); 100 (Apr-Sept)
Orchards	
(Bare soil	100)
(Water	0)

[a] at zero vapour pressure deficit and 20 deg C: assumed independent of r_a, i.e. $r_s = r_{sc}$
[b] assumed independent of leaf area of ground cover, i.e. $r_s = r_{sc}$

Table 2 *Maximum leaf area indexes (After Thompson et al. 1981).*

Crop	Green leaf area index
Grass, riparian land	2.0 (Jan), 2.0, 3.0, 4.0, 5.0, 5.0 (June) 5.0, 5.0, 4.0, 3.0, 2.5, 2.0 (Dec)
Cereals	5.0
Potatoes	4.0
Sugar beet	4.0
Deciduous trees	6.0
Conifers	6.0[a]
Orchards	

[a] constant throughout year

Table 3 *Effective crop heights used in MORECS (After Thompson et al. 1981).*

Crop	Height (m)	Crop	Height (m)
Grass	0.15	Orchards[c]	0.15, 2.0, 3.0
Spring barley[a]	0.05 - 0.8	Conifers	10.0
Winter wheat[b]	0.08 - 0.8	Upland	0.15
Winter barley[b]	0.08 - 0.8	Impervious urban	10.0
Potatoes[a]	0.05 - 0.6	Bare rock	0.05
Sugar beet[a]	0.05 - 0.35	Water	0.005
Deciduous trees[c]	0.15, 2.0, 10.0	Bare soil	0.05

[a] Range of values for spring-sown crops refer to the period emergence to harvest
[b] Range of values for autumn-sown crops refer to the over-winter period, up to harvest
[c] First value is for defoliated trees, the second at leaf emergency, and the third for full leaf.

Table 4 *MORECS values of available water capacity (After Thompson et al. 1981).*

Crop	Green leaf area index
Grass	125
Cereals	140[a]
Potatoes	90[a]
Sugar beet	140[a]
Deciduous trees	175[b]
Conifers	175
Upland	50
Orchards	150
Bare soil	20

[a] at maximum rooting depth
[b] at full foliation

Table 5 *Relation between real land use and MORECS surface types (After Thompson et al. 1981).*

Real land use		Representation in MORECS outputs
1.	Impervious urban	Impervious urban
2.	Open water	Open water
3.	Riparian	Riparian
4.	Bare rock	Bare rock
5.	Conifers	Conifers
6.	Heather, gorse	Upland
7.	Permanent grass	Grass
8.	Deciduous trees	Deciduous trees
9.	Orchards	Orchards
10.	Rough grazing	Upland
11.	Cereals	((Winter wheat + winter barley)/2 + spring barley)/2
12.	Potatoes	(Main crop and earlies)/2
13.	Temporary grass	Grass
14.	Fallow	Bare soil

Annexe 2 - Bibliography

Anonymous undated. *Guide to the use of a soil moisture balance/recharge program*, NRA - Anglian region.

Anonymous 1975. *Groundwater in the Furness area, Cumbria*, North West Water Authority - Rivers Division.

Anonymous 1978. *Thames groundwater scheme: proceedings of the conference held at Reading University*, The Institution of Civil Engineers, London.

Anonymous 1979. *Groundwater resource assessment of the Triassic Sandstones*, Severn Trent Water Authority, Directorate of Operations.

Anonymous 1980. *The estimation of percolation from soil water balance calculations*, North West Water.

Anonymous 1981a. *Saline groundwater investigation phase 1 - lower Mersey basin*, University of Birmingham, North West Water Authority.

Anonymous 1981b. *Proceedings of the groundwater recharge conference 1980*, Australian Government Publishing Service, Canberra, Australian Water Resources Council.

Anonymous 1984a. *Nitrate in groundwater investigation - final report*, North West Water, Report No. 155.

Anonymous 1984b. *Saline groundwater investigation phase 2 - North Merseyside*, University of Birmingham, North West Water Authority.

Anonymous 1988. *SEROWE - groundwater resources evaluation project*, Republic of Botswana - Ministry of Mineral Resources and Water Affairs.

Anonymous 1989a. *Water resource development in east Devon - the Otter valley catchment study*, MRM Partnership Consulting Engineers, South West Water.

Anonymous 1989b. *Spilsby sandstone investigation*, Groundwater Development Consultants Limited, Anglian water.

Anonymous 1989c. *Spilsby sandstone investigation - final report*, Groundwater Development Consultants Limited, Anglian Water.

Anonymous 1990. *Water resources study of East Kent aquifer: mathematical modelling of the Chalk aquifer: data review and mathematical model development*, University of Birmingham, Dept. of Civil Engineering and Acer Consultants Ltd., Folkestone & District Water Company.

Anonymous 1991a. *Water resources study of East Kent aquifer - mathematical model of the Chalk aquifer -final report appendices*, University of Birmingham, Dept. of Civil Engineering and Acer Consultants Ltd., Folkestone & District Water Company.

Anonymous 1991b. *Wallop Brook and Bourne Rivulet, Hampshire - overabstraction studies*, Mott MacDonald, National Rivers Authority Southern Region.

Anonymous 1993a. *Effective rainfall, runoff, percolation and recharge - a note on soil moisture calculations in the NRA Thames region*, NRA - Thames region - Hydrological services.

Anonymous 1993b. *Darent catchment investigation - catchment model calibration report*, Groundwater Development Consultants, Cambridge, National Rivers Authority Southern Region.

Anonymous 1993c. *River Meon and River Hamble, Hampshire - overabstraction studies*, Mott MacDonald, National Rivers Authority Southern Region.

Al-Muttair, F.F. & Al-Turbak, A.S. 1989. Estimation of recharge from a reservoir using two water budget models. *Wat. Resour. Bull.*, **25**, 727-732.

Allison, G.B., Gee, G.W. & Tyler, S.W. 1994. Vadose-zone techniques for estimating groundwater recharge in arid and semiarid regions. *Soil Sci. Soc. Am. J.*, **58**, 6-14.

Andersson, L. & Harding, R.J. 1991. Soil-moisture deficit simulations with models of varying complexity for forest and grassland sites in Sweden and the U.K.. *Wat. Res. Manag.*, **5**, 25-46.

Armstrong, A., Addiscott, T. & Leeds-Harrison, P.B. undated. *Methods for modelling solute movement in structured soils.*

Armstrong, A.C. 1993. Modelling the response of in-field water tables to ditch levels imposed for ecological aims: a theoretical analysis. *Agric. Eco. Env.*, **43**, 345-351.

Armstrong, A.C., Matthews, A.M., Portwood, A.M., Addiscott, T. & Leeds-Harrison, P.B. 1993. *Modelling the effects of climate change on the hydrology and water quality of structured soils*, NATO Advanced Research Workshop.

Armstrong, A.C., Portwood, A.M. & Matthews, A.M. 1993. Development of improved hydrological models for ACCESS-II., ADAS Soil and Water Research Centre.

Armstrong, A.C., Youngs, E.G. & Arrowsmith, R. 1991. Modelling water-table movement in drained soils with depth-dependent hydraulic conductivity. *Agric. Wat. Man.*, **20**, 101-108.
Barker, J.A. & Foster, S.D. 1981. A diffusion exchange model for solute movement in fissured porous rock. *Q. Jl. Eng. Geol.*, **14**, 17-24.

Barnes, C.J., Jacobson, G. & Smith, G.D. 1994. The distributed recharge mechanism in the Austrailian arid zone. *Soil Sci. Soc. Am. J.*, **58**, 31-40.

Bishop, T.J. & Rushton, K.R. 1993. *Water resource study of the Nottinghamshire Sherwood Sandstone Aquifer System of Eastern England. Mathematical model of the Sherwood Sandstone Aquifer*, Dept. of Civil Engineering, The University of Birmingham.

Borczak, S., Motyka, J. & Pulido-Bosch, A. 1990. The hydrological properties of the matrix of the chalk in the Lublin coal basin (southeast Poland). *Hydrol. Sci.*, **35**, 523-534.

Brown, I.T. & Rushton, K.R. 1993. *Modelling of the Doncaster aquifer - final report*, University of Birmingham, Yorkshire Water Services and NRA - Severn-Trent Region.

Brutsaert, W. 1991. The formulation of evaporation from land surfaces. *Recent advances in the modelling of hydrologic systems*, Kluwer Academic Publishers, Netherlands.

Budyko, M.I. 1956. *The heat balance of the earth's surface*, Gidrometeoizdat, Leningrad.

Calder, I.R., Harding, R.J. & Rosier, P.T.W. 1983. An objective assessment of soil-moisture deficit models. *J. Hydrol.*, **60,** 329-355.

Clausen, B. & Romer Rasmussen, K. 1993. Low flow estimation and hydrogeology in a Chalk catchment. *Nordic Hydrol.*, **24,** 297-308.

Connorton, B.J. & Reed, R.N. 1978. A numerical model for the prediction of long term well yield in an unconfined Chalk aquifer. *J. Engr Geol.*, **11,** 127-138.

Cooper, J.D. 1980. *Measurement of moisture fluxes in unsaturated soil in Thetford Forest*, Institute of Hydrology, Report No. 66.

Cooper, J.D. 1985. *Estimation of aquifer recharge in the area of Fleam dyke pumping station by soil physics methods*, Institute of Hydrology.

Cooper, J.D., Gardner, C.M.K. & Mackenzie, N. 1990. Soil controls on recharge to aquifers. *J. Soil Sci.*, **41,** 613-630.

Cooper, J.D., Shearer, T.R. & Kitching, R. 1986. *Assessment of recharge to groundwater measured by the BGS lysimeter and the IH method at fleam dyke pumping station, Fulbourn, Cambridgeshire.*

Crawford, N.H. & Linsley, R.K. 1966. *Digital simulation in hydrology: Stanford watershed model IV*, Stanford University, Stanford, California.

Cross, G.A., Rushton, K.R. & Tomlinson, L.M. undated. *The East Kent aquifer and the 1988/92 drought*, University of Birmingham.

Darling, W.G. & Bath, A.H. 1988. A stable isotope study of recharge processes in the English chalk. *J. Hydrol.*, **101,** 31-46.

Davis, G. 1981. Comparison of MORECS with catchment data. *The MORECS discussion meeting*, Institute of Hydrology, Report No. 78.

Doorenbos, J. & Pruitt, W.O. 1984. *Guidelines for predicting crop water requirements*, FAO Irrigation and Drainage Paper 24, FAO, Rome.

Downing, R.A., Price, M. & Jones, G.P. 1993. *The hydrogeology of the Chalk of north-west Europe*, Oxford Science Publications, Oxford.

Downing, R.A. & Wilkinson, W.B. 1991. *Applied groundwater hydrology*, Clarendon press, Oxford.

Duffy, D. & Grainger, P. 1993. *Monitoring of soil water movement in the unsaturated zone at Bicton 1992*, University of Exeter - Earth Resources Centre, NRA South West Region.

Edmunds, W.M., Lovelock, P.E.R. & Gray, D.A. 1973. Interstitial water chemistry and aquifer properties in the upper and middle Chalk of Berkshire, England. *J. Hydrol.*, **19**, 21-31.

Fleming, G. & McKenzie, R.S. 1982. *River basin model for water and sediment resource assessment*, Department of Civil Engineering, Strathclyde University, Report HY-82-7.

Forbes, C.L. 1979. The Fleam Dyke lysimeters. *Rep. Inst. Geol. Sci.*, **79/6**, 31-33.

Foster, S.S.D. 1975. The Chalk groundwater tritium anomaly - a possible explanation. *J. Hydrol.*, **25**, 159-165.

Foster, S.S.D., Bridge, L.R., Geake, A.K., Lawrence, A.R. & Parker, J.M. 1986. *The groundwater nitrate problem - a summary of research on the impact of agricultural land-use practices on groundwater quality between 1976 and 1985*, British Geological Survey, Wallingford.

Gardner, C.M.K. 1981. *The MORECS discussion meeting*, Institute of Hydrology, Report No. 78.

Gardner, C.M.K. 1983. A comparison of measured soil moisture deficits with those estimated by the Meteorological Office system, MORECS: a brief report. *Agric. Wat. Man.*, **6**, 307-316.

Gardner, C.M.K., Cooper, J.D., Wellings, S.R. *et al.* 1989. Hydrology of the unsaturated zone of the Chalk of south east England. *International Chalk symposium, Brighton*, Thomas Telford, London.

Gardner, C.M.K. 1990. *Recharge in Lincolnshire: estimates from soil water measurements*, Institute of Hydrology.

Gardner, C.M.K. & Bell, J.P. 1980. *Comparison of measured soil moisture deficits with estimates by MORECS*, IAHS.

Gardner, C.M.K., Bell, J.P., Cooper, J.D., Darling, W.G. & Reeve, C.E. undated. Groundwater recharge and water movement in the unsaturated zone., Institute of Hydrology.

Gardner, C.M.K. & Field, M. 1983. An evaluation of the success of MORECS, a meteorological model, in estimating soil moisture deficits. *Agric. Met.*, **29**, 269-284.

Gash, J.H.C. 1978. An analytical model of rainfall interception by forests. *J. Hydrol.*, **105**, 43-55.

Geake, A.K. & Foster, S.D. 1989. Sequential isotope and solute profiling in the unsaturated zone of British chalk. *Hydrol. Sci.*, **34**, 79-95.

Gee, G.W., Wierenga, P.J., Andraski, B.J., Young, M.H., Fayer, M.J. & Rockhold, M.L. 1994. Variations in water balance and recharge potential at three western desert sites. *Soil Sci. Soc. Am. J.*, **58**, 63-72.

Greenfield, B.J. 1981. Estimation of soil moisture excess, and verification. *The MORECS discussion meeting*, Institute of Hydrology, Report No. 78.

Greenfield, B.J. 1984. *The Thames catchment model*, Technology and Development Division, Thames Water Internal Report.

Grindley, J. 1967. The estimation of soil moisture deficits. *Meteorol. Mag.*, **96,** 97-108.

Grindley, J. 1969. *The calculation of evaporation and soil moisture deficit over specified catchment area*, Hydrological Memorandum 28, Meteorological Office, Bracknell, UK.

Grindley, J. 1970. *Estimating and mapping of evaporation*, IASH Proc. Reading Symposium, World Water Balance.

Hancock, J.M. & Price, M. 1990. Real Chalk balances the water supply. *J. Wine Res.*, **1,** 45-60.

Harding, R.J. 1981. *Analysis of the Ternhill soil moisture observations*, Institute of Hydrology, Report for Severn-Trent Water Authority.

Harding, R.J. 1993. Evaporation schemes for hydrological models. *BHS 4th National Symposium, Cardiff, 1993.*

Harding, R.J., Hall, R.L., Neal, C., Roberts, J.M., Rosier, P.T.W. & Kinniburgh, D.G. 1992. *Hydrological impacts of broadleaf woodlands: Implications for water use and water quality*, Institute of Hydrology Project Report 115 03/ST, National Rivers Authority.

Hodnett, M.G. & Bell, J.P. 1981. *Soil physical processes of groundwater recharge through Indian black cotton soils*, Institute of Hydrology.

Hodnett, M.G. & Bell, J.P. 1986. Soil moisture investigations of groundwater recharge through black cotton soils in Madhya Pradesh, India. *Hydrol. Sci.*, **31,** 361-381.

Hodnett, M.G. & Bell, J.P. 1990. Processes of water movement through a chalk coombe deposit in southeast England. *Hydrol. Processes*, **4,** 361-372.

Hollis, J.M., Bembridge, C. & Harrod, T.R. undated. *Moisture retention among uncommon soil texture classes, porous rocks and extremely calcareous substrates*, Soil Survey and Land Research Centre.

Hollis, J.M. & Brown, C. undated. *An integrated approach to aquifer vulnerability mapping*, Soil Survey and Land Research Centre.

Hollis, J.M., Hallett, S.H. & Keay, C.A. 1993. The development and application of an integrated database for modelling the environmental fate of herbicides. *Brighton crop protection conference - weeds*, Soil Survey and Land Research Centre.

Howard, K.W.F. & Lloyd, J.W. 1979. The sensitivity of parameters in the Penman evaporation equations and direct recharge balance. *J. Hydrol.*, **41,** 329-344.

Hyoms, C.M. 1980. *Development of a soil moisture model for the estimation of percolation*, M. Phil thesis. The City University, London, unpubl.

Jackson, D. & Rushton, K.R. 1987. Assessment of recharge components for a Chalk aquifer unit. *J. Hydrol.*, **92,** 1-15.

Jones, R.J.A. & Thomasson, A.J. 1985. *An agroclimatic databank for England and Wales*, Soil Survey.

Kirk, S. 1986. *Investigation and development of the ground water resources in the Calder valley, West Cumbria - a case study of a ground water augmentation scheme*, University College London.

Kitching, R. & Shearer, T.R. 1982. Construction and operation of a large undisturbed lysimeter to measure recharge to the chalk aquifer, England. *J. Hydrol.*, **58**, 267-277.

Knisel, W.G. 1972. *Response of karst aquifers to recharge*, Colorado State University - hydrology papers.

Lerner, D.N., Issar, A.S. & Simmers, I. 1990. *Groundwater Recharge : A guide to understanding and estimating natural recharge*, International Contributions to Hydrogeology.

Lewis, M.A., Jones, H.K., Macdonald, D.M.J. *et al.* 1993. *Groundwater storage in British aquifers:Chalk*, National Rivers Authority, Hydrogeology group - British Geological Survey.

Liu, Y. & Zhang, C. 1993. A comparative study of calculation methods for recharge of rainfall seepage to ground water in plain area. *Groundwater*, **31**, 12-18.

Loveland, P.J., Rounsevell, M.D.A., Mayr, T.M. *et al.* undated. *ACCESS : Agro-climatic change and European soil suitability - a spatially distributed model.*

Mackenzie, N., Grainger, P., Cooper, J.D., Roberts, J. & Evans, B.M. 1991. *Assessment of recharge to groundwater measured by the soil physics method and the Grindley method at Bicton College in East Devon*, University of Exeter - Earth Resources Centre, NRA South West Region.

Mander, R.J. & Greenfield, B.J. 1978. *Hydrograph generation and augmented flow analysis*, Proc. of The Thames Groundwater Scheme Conference, Institution of Civil Engineers, London.

McGowan, M. 1981. Discussion. *The MORECS discussion meeting*, Institute of Hydrology, Report No. 78.

Md.Azlin Bin Md.Said 1992. *Groundwater and surface water modelling using spatially distributed data*, University Sains Malaysia.

Miles, J.C. & Rushton, K.R. 1983. A coupled surface water and groundwater catchment model. *J. Hydrol.*, **62**, 159-177.

Monkhouse, R.A. & Reeves, M.J. 1977. *A preliminary appraisal of the groundwater resources of the Vale of Eden, Cumbria*, Central water planning unit, Reading.

Moore, R.J., Austin, R.M. & Carrington, D.S. 1993. *Evaluation of FRONTIERS and local radar rainfall forecasts for use in flood forecasting models*, Institute of Hydrology, National Rivers Authority R & D note 225.

Morel, E.H. 1980. The use of a numerical model in the management of the Chalk aquifer in the Upper Thames Basin. *Q. Jl. Eng. Geol.*, **13**, 153-165.

Morel, E.H. & Wright, C.E. 1978. *Methods of estimating natural groundwater recharge*, Central Water Planning Unit, Reading.

Morel-Sytoux, H.J. 1989. *Unsaturated flow in hydrologic modelling, theory and practice*, Kluwer Academic Publishers, London, NATO ASI Series, vol. 275.

Neal, C., Kinniburgh, D.G. & Whitehead, P.G. 1991. *Shallow groundwater systems*, Oxford Science Publications, Oxford.

Nott, M. 1992. *Towards a better understanding of the flow mechanism of the unsaturated zone of the Chalk*, Imperial College of Science, Technology and Medicine.

Oakes, D.B. 1981. A numerical model of a stream aquifer system subject to delayed rainfall recharge. *Trans. Geol. Soc. South Africa*, **84**, 135-144.

Oakes, D.B. & Pontin, J.M.A. 1976. *Mathematical modelling of a Chalk aquifer*, Water Research Centre.

Parry, E.L. 1979. *Groundwater resource assessment of the Triassic sandstones*, Severn-Trent Water Authority.

Penman, H.L. 1948. Natural evaporation from open water, bare soil and grass. *Proc. Roy. Soc. Ser. A*, **193**, 120-145.

Penman, H.L. 1949. The dependance of transpiration on weather and soil conditions. *J. Soil Sci.*, **1**, 74-89.

Penman, H.L. 1963. Woburn Irrigation 1951-1959: (1) Purpose, design and weather. *J. Agric. Sci. Cambridge*, **58**, 343-348.

Phillips, F.M. 1994. Environmental tracers for water movement in desert soils of the American southwest. *Soil Sci. Soc. Am. J.*, **58**, 15-24.

Price, M. 1987. Fluid flow in the Chalk of England. *Fluid flow in sedimentary basins and aquifers*, Geological Society - special publication No.34.

Rippon, P.W. & Wyness, A.J. 1994. *Groundwater - managing a scarce resource. Paper 1 Water resources management using integrated catchment models*, Groundwater Developments Consultants Ltd.

Rose, D.A. 1991. The variability of winter drainage in England and Wales. *Soil Use Manag.*, **7**, 115-122.

Rushton, K.R., Bradbury, C.G. & Tomlinson, L.M. 1993. *The South Lincolnshire limestone catchment*, University of Birmingham - Department of Civil Engineering, NRA - Anglian region.

Rushton, K.R., Connorton, B.J. & Tomlinson, L.M. 1989. Estimation of the groundwater resources of the Berkshire Downs supported by mathematical modelling. *Q. Jl. Eng. Geol.*, **22**, 329-341.

Rushton, K.R. & Fawthrop, N.P. 1991. Groundwater support of stream flows in the Cambridge area, UK. *Hydrological basis of ecologically sound management of soil and* *groundwater*, IAHS.

Rushton, K.R., Kawecki, M.W. & Brassington, F.C. 1988. Groundwater model of conditions in Liverpool sandstone aquifer. *J. Instn Wat. Env. Man*, **2**, 1-84.

Rushton, K.R., Owen, M. & Tomlinson, L.M. 1992. The water resources of the Great Oolite aquifer in the Thames basin, UK. *J. Hydrol.*, **132**, 225-248.

Rushton, K.R. & Salmon, S. 1993. Significance of vertical flow through low-conductivity zones in Bromsgrove sandstone aquifer. *J. Hydrol.*, **152**, 131-152.

Rushton, K.R. & Ward, C. 1979. The estimation of groundwater recharge. *J. Hydrol.*, **41**, 345-361.

Rutter, A.J. 1963. Studies in the water relations of *Pinus silvestris* in plantation conditions. I. Measurement of rainfall and interception. *J. Ecol.*, **51**, 191-203.

Simmers, I. 1988. *Estimation of natural groundwater recharge*, D. Reidel publishing company, Dordrecht, Holland.

Smith, D.B., Wearn, P.L., Richards, H.J. & Rowe, P. 1970. Water movement in the unsaturated zone of high and low permeability strata by measuring natural tritium. *Isotope Hydrology: Proceedings of Symposium*, International Atomic Energy Agency, Vienna

Smith, P. & Turner, A. 1993. *1992 Groundwater balances review*, Water Resources Planning, Peterborough, NRA - Anglian region

Sophocleous, M. 1992. Groundwater recharge estimation and regionalization: the Great Bend Prairie of central Kansas and its recharge statistics. *J. Hydrol.*, **137**, 113-140.

Sophocleous, M.A. 1991. Combining the soil water balance and water-level fluctuation methods to estimate natural groundwater recharge: practical aspects. *J. Hydrol.*, **124**, 229-241.

Spearman, J. 1991. *The effects of development on the hydrological regime of a small Hampshire catchment*, Imperial College of Science and Technology.

Stephens, D.B. 1991. A perspective on diffuse natural recharge mechanisms in areas of low precipitation. *Soil Sci. Soc. Am. J.*, **58**, 40-48.

Stephens, D.B. 1993. A perspective on diffuse natural recharge mechanisms in areas of low precipitation. *Soil Sci. Soc. Am. J.*, **58**, 40-48.

Stoertz, M.W. & Bradbury, K.R. 1989. Mapping recharge areas using a ground-water flow model - a case study. *Groundwater*, **27**, 220-228.

Thom, A.S. & Oliver, H.R. 1977. On Penman's equation for estimating regional evaporation. *Quart. J. Roy. Met. Soc.*, **103**, 345-357.

Thompson, N., Barrie, I.A. & Ayles, M. 1981. *The Meteorological Office rainfall and evaporation calculation system: MORECS*, The Meteorological Office.
Tzimopoulos, C. 1989. The artificial recharge of groundwater: a solution by successive variations of steady states. *Wat. Res. Manag.*, **3**, 231-239.

Vines, K.J. 1984a. *Nitrate in groundwater investigation - final report*, North West Water.

Vines, K.J. 1984b. *Drift recharge*, North West Water - Groundwater section.

Vines, K.J., Lucey, P.A. & Brassington, F.C. 1980. *Nitrate in groundwater investigation - Phase 1*, Northwest Water Authority, Hydrogeological Report No. 40.

Wardlaw, R.B., Wyness, A. & Rippon, P. Integrated catchment modelling. *Surveys in Geophysics. In Press.*

Wellings, S.R. 1984a. Recharge of the upper Chalk aquifer at a site in Hampshire, England 2. Solute movement. *J. Hydrol.*, **69**, 275-285.

Wellings, S.R. 1984b. Recharge of the upper Chalk aquifer at a site in Hampshire, England 1. Water balance and unsaturated flow. *J. Hydrol.*, **69**, 259-273.

Wellings, S.R. & Bell, J.P. 1980a. Water and nitrate fluxes in unsaturated upper chalk at Bridgets experimental husbandry farm, Winchester, UK. *The influence of man on the hydrological regime with special reference to representative and experimental basins - Proceedings of the Helsinki symposium*, IAHS-AISH.

Wellings, S.R. & Bell, J.P. 1980b. Movement of water and nitrate in the unsaturated zone of upper Chalk near Winchester, Hants.,England. *J. Hydrol.*, **48**, 119-136.

Wellings, S.R. & Bell, J.P. 1982. Physical controls of water movement in the unsaturated zone. *Q. Jl. Eng. Geol.*, **15**, 235-241.

Wellings, S.R. & Cooper, J.D. 1983. The variability of recharge of the English Chalk aquifer. *Agric. Wat. Man.*, **6**, 243-253.

Wellings, S.R., Cooper, J.D. & Bell, J.P. 1982. The physics of solute movement in the unsaturated zone of the British Chalk. *IAH International Symposium: Impact of agricultural activities on groundwater.*

Wheater, H.S. 1981. Comparison of field data with water budget calculations. *the MORECS discussion meeting*, Institute of Hydrology, Report No. 78.

Wilby, R., Greenfield, B.J. & Glenny, C. 1994. A coupled synoptic-hydrological model for climate change impact assessment. *J. Hydrol.*, **153**, 265-290.

Williams, J.R., Jones, C.A. & Dyke, P.T. 1984. A modelling approach to determining the relationship between erosion and soil productivity. *Trans. A. S. A. E.*, **27**, 129-144.

Wilson, E.E.M., Akande, O., Phipps, O.C. & Bathurst, D.P. 1994. *Chichester Chalk investigation*, Sir William Halcrow & Partners Ltd.

Wyness, A.J., Rippon, P.W. & Wardlaw, R.B. 1994. Application of an integrated model to Chalk catchments. *Groundwater - Drought, Pollution & Management*, Balkema, Rotterdam.

Zomorodi, K. 1991. Evaluation of the response of a water table to a variable recharge rate. *Hydrol. Sci.*, **36**, 67-79.

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